Intuitive Instruction of Industrial Robots

A Knowledge-Based Approach

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A Knowledge-Based Approach

by Maj Stenmark

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Thesis for the degree of PhD
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Intuitive Instruction of Industrial Robots: A Knowledge-Based Approach

Abstract

With more advanced manufacturing technologies, small and medium sized enterprises can compete with low-wage labor by providing customized and high quality products. For small production series, robotic systems can provide a cost-effective solution. However, for robots to be able to perform on par with human workers in manufacturing industries, they must become flexible and autonomous in their task execution and swift and easy to instruct. This will enable small businesses with short production series or highly customized products to use robot coworkers without consulting expert robot programmers. The objective of this thesis is to explore programming solutions that can reduce the programming effort of sensor-controlled robot tasks. The robot motions are expressed using constraints, and multiple of simple constrained motions can be combined into a robot *skill*. The skill can be stored in a knowledge base together with a semantic description, which enables reuse and reasoning. The main contributions of the thesis are 1) development of ontologies for knowledge about robot devices and skills, 2) a user interface that provides simple programming of dual-arm skills for non-experts and experts, 3) a programming interface for task descriptions in unstructured natural language in a user-specified vocabulary and 4) an implementation where low-level code is generated from the high-level descriptions. The resulting system greatly reduces the number of parameters exposed to the user, is simple to use for non-experts and reduces the programming time for experts by 80%. The representation is described on a semantic level, which means that the same skill can be used on different robot platforms. The research is presented in seven papers, the first describing the knowledge representation and the second the knowledge-based architecture that enables skill sharing between robots. The third paper presents the translation from high-level instructions to low-level code for force-controlled motions. The two following papers evaluate the simplified programming prototype for non-expert and expert users. The last two present how program statements are extracted from unstructured natural language descriptions.

Key words

robot skills, high-level programming, industrial robot, human-robot interaction, natural language, knowledge representation

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Dedicated to my mother

Abstract

With more advanced manufacturing technologies, small and medium sized enterprises can compete with low-wage labor by providing customized and high quality products. For small production series, robotic systems can provide a cost-effective solution. However, for robots to be able to perform on par with human workers in manufacturing industries, they must become flexible and autonomous in their task execution and swift and easy to instruct. This will enable small businesses with short production series or highly customized products to use robot coworkers without consulting expert robot programmers. The objective of this thesis is to explore programming solutions that can reduce the programming effort of sensor-controlled robot tasks. The robot motions are expressed using constraints, and multiple of simple constrained motions can be combined into a robot *skill*. The skill can be stored in a knowledge base together with a semantic description, which enables reuse and reasoning. The main contributions of the thesis are 1) development of ontologies for knowledge about robot devices and skills, 2) a user interface that provides simple programming of dual-arm skills for non-experts and experts, 3) a programming interface for task descriptions in unstructured natural language in a user-specified vocabulary and 4) an implementation where low-level code is generated from the high-level descriptions. The resulting system greatly reduces the number of parameters exposed to the user, is simple to use for non-experts and reduces the programming time for experts by 80%. The representation is described on a semantic level, which means that the same skill can be used on different robot platforms. The research is presented in seven papers, the first describing the knowledge representation and the second the knowledge-based architecture that enables skill sharing between robots. The third paper presents the translation from high-level instructions to low-level code for force-controlled motions. The two following papers evaluate the simplified programming prototype for non-expert and expert users. The last two present how program statements are extracted from unstructured natural language descriptions.

Acknowledgements

The last five years have been a journey of self-discovery. I started out all optimistic and enthusiastic, ready to solve World Problems, just to be brutally rejected from conferences and broken-in as a robot programmer. It has been a humbling experience. That makes the taste of achievement so much sweeter, when we got our papers accepted or when a demo started working. So, between the *Impostor syndrome* and Messiah complex, resilience prevailed, and here we are, more or less on time. *More* so because of the patience and support from my *awesome* supervisor Jacek Malec and my co-supervisors Elin Anna Topp and Mathias Haage. They have a fantastic ability to squeeze in many hours of paper writing between dinner and midnight anywhere on earth. Thank you, Jacek, for your hard work trying to keep me on course. Thank you, Elin, for teaching me how to run user studies and for the wine we shared on our conference trips. And thank you, Mathias, for sharing your knowledge about robot controllers and networking. *Less* on time, because of our group leader Klas Nilsson, who knows that I cannot say no to a challenging side project, and, if it seems difficult, the answer will be "we need Andreas". So thank you, Andreas Stolt, for the great work as a co-author and co-programmer, especially during the gift-wrapping tour ("who agreed to this insane project?").

To all my co-authors: it has been a pleasure cooperating with you, thank you for the stimulating discussions and hard efforts.

When I was running experiments on bleeding edge robotics software, the odds were even between system failure and success. Successful experiments, regarded with surprise and suspicion, were mainly due to the hard work of my colleagues in the RobotLab. Especially, thank you Anders Robertsson and Anders Blomdell for keeping everything afloat.

The Depts. of Computer Science and Automatic Control are populated with intelligent, industrious, humorous and creative colleagues: you make this a motivating workplace. Talking to you over coffee has been educational, entertaining and awe inspiring, sometimes all three at once.

I want to thank Daniel, for his encouragement and understanding, and Jonas, for his TEX-support, and the rest of my family and friends. This thesis is dedicated to my mother, who has supported my pursuit of knowledge and education all my life: from the day in school when they taught us about *Genesis* and she was called to a parent-teacher conference because her first-grader *argued* too much about the *meaning* of the story, until this very day, when I will argue once more, about the meaning of things.

Popular summary in English

The work presented in this thesis focuses on methods for simplified programming of industrial robots. It is expensive to automate manufacturing processes and consumer products are often manufactured in low-cost countries with poor working conditions. One bottleneck is that it requires an expert roboticist to work with robots. To mitigate this, we developed technologies that make it possible for non-experts to interact with robots using an iconic graphical interface combined with kinesthetic teaching and natural (human) language. The graphical interface has a set of common instructions which makes the programming simple for non-experts while also increasing the efficiency for experienced robot programmers. The robot programs, the so-called *skills*, can be made more general by specifying that the motions should be relative to objects in the work space. For example, if the robot should pick nuts placed in a box, it can locate nuts with its camera system and then always center its gripping position above the piece. The user can add additional abstractions by creating multiple objects of different types, for example, in an emergency stop button box assembly, there are red buttons and grey switches.

The user can name their programs and objects in natural language, in this case English, and create their own small vocabulary that the robot understands. Using statistical language analysis, the meaning of the sentences is interpreted as existing robot programs applied to objects. When instructing the robot to assemble the emergency stop button box, for example, the user can demonstrate for the robot where the objects are while telling ”here is a red button” and, if the program for picking objects is saved as a ”pick” skill, say to the robot to ”pick red buttons”.

The programs are general and reusable and can be shared with other robots through a database, for example the dual-arm robot ABB YuMi in our lab can transfer a program from the right arm to the left. The two arms of the YuMi robot can work independently, but our methods allow the user to rapidly instruct synchronized dual-arm tasks. When a program is transferred from one robot, e.g., the YuMi robot, to another, e.g., a classical ABB robot, the positions must be recalculated to work with the different embodiment of the robot but also adapted to the specific sensors, e.g., a different type of force sensor.

The methods and experimental setups were evaluated using non-experts and experts and different robots in the RobotLab at the Departments of Computer Science and Automatic Control at Lund University.

Populärvetenskaplig sammanfattning på svenska

I avhandlingen presenteras metoder som förenklar programmeringen av industrirobotar. Att automatisera är ofta kostsamt och mycket av produktionen av konsumentprodukter utförs i låglöneländer under dåliga arbetsförhållanden. Ett av problemen är att det ofta krävs expertis inom robotik för att arbeta med robotar. Vi har därför utvecklat teknik som gör det möjligt för oerfarna användare att interagera med maskinerna.

Genom att visualisera varje instruktion som ikoner och låta användaren fysiskt leda robotarmen till rätt positioner går det snabbare för både robotexperter och ovana testpersoner att skapa välfungerande program. Programmen kan göras mer generella genom att specificera att rörelserna ska vara relativt objekt i världen. Till exempel, om roboten ska plocka upp muttrar som ligger lite utspritt i en låda kan den med hjälp av sitt kamerasystem hitta positionen av en bit, men sen måste plockrörelsen alltid centrera robotens gripdon i mitten på biten. Användaren kan abstrahera sitt program ännu mer genom att skapa fler typer av objekt som ska plockas, till exempel har en nödstoppsknapp i plast röda knappar, brytare och en gul låda. Programmen är generiska och kan föras över till andra robotar, t ex kan vår tvåarmade robot YuMi återanvända program både på vänster och höger sida. Armarna kan arbeta helt separat men vi har också utvecklat tillvägagångssätt för att enkelt instruera synkroniserade tvåarmade rörelser.

Genom att ge programmet namn och beskrivningar i mänskligt språk, t ex ”plocka”, kan användaren skapa ett eget ordförråd med objekt i robotens värld och handlingar eller operationer som roboten kan utföra. Med hjälp av språkanalys baserad på statistisk databehandling kan meningar tolkas som just handlingar (verb) på objekt i världen. Vi har kopplat ihop språkanalys och robotprogrammering så att användaren kan prata med sin robot för att skapa nya begrepp, t ex ”här finns en röd knapp” och ”plocka upp den röda knappen” (fast på engelska). Robotprogrammen sparas i en databas tillsammans med den språkliga beskrivningen som kan förstås av människor och data som kan förstås av maskinen. För att återanvända ett program som är skapat för en viss typ av robot, t ex vår YuMi, på en annan, t ex en klassisk ABB robot, måste inte bara rörelserna översättas till en robotarm med annat utseende, utan också mätvärden från olika givare, t ex för kraft, behöver anpassas till den andra robotens sensorer.

Teknikerna vi utvecklat har evaluerats med oerfarna användare och experter på olika robotar i LTH:s robotlabb.

Contents

Part I

Background

Introduction

It's just a matter of semantics.

The robot revolution is yet to come. Robot programming requires expertise in machinery and sensor technologies and application development is time consuming even for professionals. Therefore, manufacturing is outsourced to low-cost countries, with poor working conditions. Also, small enterprises cannot afford to employ an expert to program various repetitive tasks. To reduce the cost of automation and for example make it feasible for small companies to robotize parts of their production, it is necessary to reduce the workload for experts to program robots *and* to make it possible for non-experts to instruct robots about non-trivial tasks.

Instead of aiming for fully automatic assembly lines, human-machine cooperation can result in flexible manufacturing, where the robots can carry out simple repetitive tasks while the human operators can complement with their superior dexterity and perception capabilities. The cooperation reduces the cost of automation because the programming of a fully automated assembly can be very costly and tedious. This is a sharp contrast to traditional industrial robot systems that execute the same tasks for years without any user interaction during regular operation; in fact, they are locked in cages for safety reasons. In the latter case, the programming phase is short compared to the operational phase and the program is seldom updated. In a traditional factory setting, the robot is continuously in production, so the larger part of the program is implemented and optimized *offline* in a simulation environment to reduce the downtime of the robot during deployment and real-world testing.

Recently, a new generation of collaborative robot systems have entered the market. These so-called cobots are designed to work safely side-by-side with human co-workers. The intended applications are small-parts assembly in close cooperation with humans. The robots are often equipped with internal force estimation and sensors, and are small enough to be guided manually using *lead-through*, that is, the robot arms can be moved physically by the operator. This method is used in *online* programming and is considered more intuitive than a joystick which otherwise is used to guide large robots.

Figure 1: A robotized gift-wrapping application.

To illustrate the difficulties faced by the robot programmers, we present three example use case applications that were developed during the research projects *ROSETTA*, *PRACE* and *SARAFun*. The first was a dual-arm gift-wrapping application[1] shown in Fig. 1, developed by the author and Andreas Stolt. The functionality was programmed using only standard industrial tools. Gift-wrapping is something most people can learn and rudimentarily carry out after a few minutes, but the robot on the other hand, was not even physically able to pick up a corner of a sheet of paper from a table without special fixtures or grippers. The paper is an organic material and folded differently every time and, depending on the weight of the gift in the box, the friction varied resulting in slippage. This made it impossible to simulate the program offline. Instead, we programmed and tested the application directly online. We needed to prototype and test many different strategies and create mockup fixtures before we found a working solution. In a traditional assembly application, it is the finger positions that are of interest, but in this application, we often used other contact points along the arms, e.g., the package was fixated with the elbow so that both hands could cooperate to fold the side, as shown in Fig. 1. This required multiple programming and

[1]A video of the application is available at: https://www.youtube.com/watch?v=ASEtz2M1RiY.

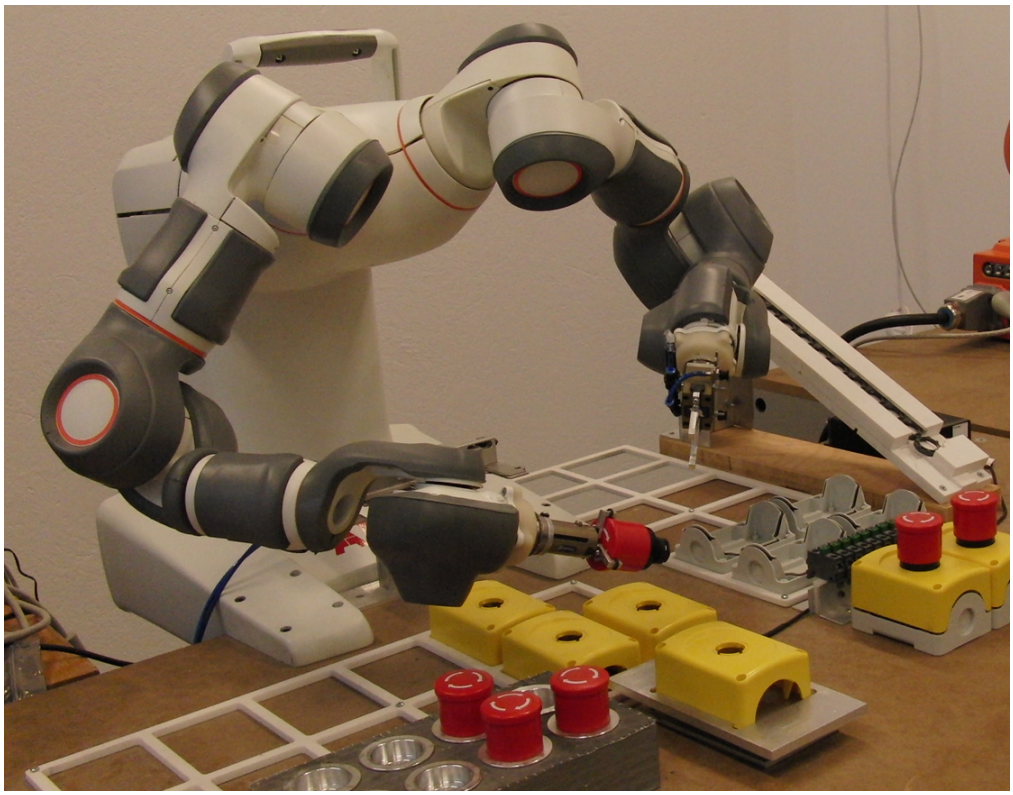


Figure 2: A robotized emergency stop button box assembly task.

debugging sessions, and the standard programming methods were very time-consuming. For example, the arms were programmed as two separate robots and the synchronization needed for dual-arm operations added significant overhead.

The second example that illustrates the challenges faced by the roboticist, is the force-controlled dual-arm assembly task of the emergency stop button box[2] shown in Fig. 2. The application was developed by Andreas Stolt and Magnus Linderoth during the European FP7 project *ROSETTA*. The task consisted of several fine-tuned subassemblies that needed precise force-controlled motions. This required an extension of the standard robotics software to enable real-time control. The resulting implementation included switching controllers and setting the parameters to the sensor-controlled motions. Creating the sensor-based control algorithms and programming the application required an expert in automatic control. In make it possible for non-experts to program similar tasks, it was necessary to develop an abstraction that significantly reduced the level of technical details exposed to the user. Also, after developing the various advanced skills used in the assembly, we wanted to be able to reuse them on other robots to reduce the reimplementation effort.

[2]A video is available at https://www.youtube.com/watch?v=7JgdbFW5mEg

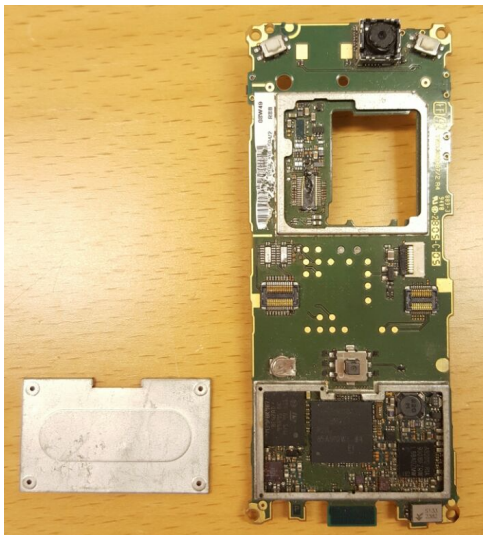


Figure 3: A shield can (left) and a printed circuit board (PCB) to the right.

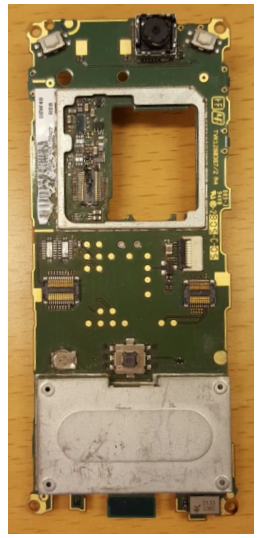


Figure 4: The intended position of the shield can on the PCB.

The last example application that we will discuss was part of a cell phone assembly, where a metal plate, a so-called *shieldcan*, was attached to a printed circuit board (PCB) by aligning the two sides of the shieldcan in parallel with the slot on the board, as shown in Figs. 3 and 4. The application is interesting because it had low error tolerances which made the assembly fail when the parts did not attach properly. Also, due to position uncertainties, the execution of the insertion could either align the horizontal or vertical side of the parts first and then rotate the remaining side into position. That is, the program logic had to include both branching and error handling.

In the following sections, we will summarize the identified problems and the approaches that were investigated to address them. The following chapters will introduce the terminology, robot software and systems, and a survey of related work both from low-level and high-level perspectives. Besides, each included paper has a separate related work section. This part is followed by a description of the methodological approach, implementations and summary of the included papers. The final chapter wrap together the work in a discussion. The bibliography is shared for the entire document.

1 Research Questions

The previously described examples illustrate several problems that have to be studied in order for industrial robots to be truly collaborative and easy-to-use. The overall research question that we investigated in this thesis is

How can the gap be bridged between human-comprehensible task representations and executable robot programs?

This entails the following more detailed ones:

How can robot programming interfaces be designed to increase usability and efficiency?

How can the technical details be hidden from the instructor?

How can we decrease the effort of programming sensor-controlled tasks with low error tolerances that require specification of multiple low-level parameters and sensor signals?

How can the interaction become more intuitive and user-centric to enable non-experts to instruct robots?

Because of the difficulty to program a task, can reuse reduce the reimplementation effort?

How can the tools support creation of reusable robot programs from scratch?

How can reuse be supported by useful abstractions?

What does this representation have to contain to be understandable both by the user and the robot system?

What information must be included in the representation, e.g., what device requirements or parameter specifications do we need, to be able to create an executable procedure?

To address these questions, we created a representation for robot programs, *skills*. We also developed programming methods and interfaces that reduced the programming workload for experts and enabled non-experts to instruct robots. They will be described in more detail in the following section.

2 Contribution Statement

The four main contributions of the work presented in this thesis are the following:

1. **Knowledge representation for robot devices and skills.** The symbolic knowledge of the system is expressed as modular ontologies. The core ontology includes robot devices, such as robots, sensors, tool changers and fixtures. Tasks and skills are represented by graphs, hence we developed a graph ontology which includes different state machine descriptions. Each step in the state machine has parameters, these parameters are semantically described in separate ontologies for relative coordinate frames and quantities. Skills are represented by a small sub-ontology that describes the device requirements, parameters for each action and pre-and post-conditions (Paper I). The knowledge is shared between robots and tools in a cloud-based software architecture (Paper II).

2. **Generation of executable code for sensor-controlled skills.** It is necessary to be able to execute the complete task on a physical system. The contribution of Paper III is an implementation of a code generation service that takes high-level semantically annotated tasks and creates executable task-level state machines by combining force-controlled and position-controlled motions and reusable skills by automatically handling the handover between controllers and setting up the kinematic chains.

3. **Simplified programming methods.** We developed and evaluated a prototype for end-to-end robot programming that simplified task instruction and debugging for non-experts, and for experts it decreased the workload significantly for both single and synchronized dual-arm tasks (Papers IV and V). The methods allow the users to incrementally add abstractions, create reusable parameterized skills and reduce the overhead for bi-manual task programming by handling synchronized motions in pairs.

4. **A service for natural language programming of robots.** The users can build their own vocabulary of objects and skills and instruct the robots using unstructured natural language. The language analysis is carried out by using the semantic output from a statistical parser combined with the knowledge in the system about the object relations and skills to generate executable code. This was evaluated for e.g., loops, sensor-based motions and multiple conditions (Papers VI and VII).

Terminology

Robotics is an interdisciplinary field connecting computer science areas such as artificial intelligence (AI), machine learning and distributed computing with hardware and sensor technologies from automatic control, electronics and computer vision, and cognitive science, linguistics, design, psychology and philosophy. Within this broad community, there is not even a consensus what a *robot* is, therefore let us begin by establishing a common vocabulary.

The following definitions are made by the International Organization for Standardization, edited for readability:

ISO 8373:2012: Robots and robotic devices – Vocabulary

Robot: *actuated mechanism programmable in two or more axes with a degree of* **autonomy***, moving within its environment, to perform intended tasks.*
Note 1 to entry: A robot includes the **control system** *and interface of the control system.*
Note 2 to entry: The classification of robot into **industrial robot** *or* **service robot** *is done according to its intended application.*

Manipulator: *machine in which the mechanism usually consists of a series of segments, jointed or sliding relative to one another, for the purpose of grasping and/or moving objects (pieces or tools) usually in several degrees of freedom.*

Autonomy: *ability to perform intended tasks based on current state and sensing, without human intervention.*

Physical alteration: *alteration of the mechanical system.*

Reprogrammable: *designed so that the programmed motions or auxiliary functions can be changed without physical alteration.*

Multipurpose: *capable of being adapted to a different application with physical alteration.*

Control system: *set of logic control and power functions which allows monitoring and control of the mechanical structure of the* **robot** *and communication with the environment (equipment and users).*

Industrial robot: automatically controlled, **reprogrammable**, **multipurpose**, **manipulator**, *programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications.*

Note 1 to entry: The industrial robot includes:

— the manipulator, including actuators.

— the controller, including teach pendant and any communication interface (hardware and software).

Industrial robot system: *system comprising* **industrial robot**, **end effectors** *and any machinery, equipment, devices, external auxiliary axes or sensors supporting the robot performing its task.*

Service Robotics: *robot that performs useful tasks for humans or equipment excluding industrial automation applications.* **Personal service robot***: used for a non-commercial task, usually by lay persons, for example: domestic servant robot, automated wheelchair, personal mobility assist robot, and pet exercising robot.*

Intelligent robot: robot *capable of performing tasks by sensing its environment and/or interacting with external sources and adapting its behaviour.*

Note that a robot has a physical representation, and manipulates objects in the real world. The program execution of the robot can be simulated in a virtual environment with more or less advanced simulations of perception and physics, but in general, virtual agents are **bots** and not robots. The embodiment of industrial robots can vary significantly, the links and the *joints* can be connected e.g., serially as the classic orange single arm manipulator with six links joined by revolute (rotating) joints (see Fig. 1), or in *parallel* with spherical and prismatic (translational) joints (see Fig. 2). The links and joints of the robot create a a *kinematic chain*. The *degrees of freedom* (DOFs) of a robot is the number of parameters required to specify the configuration of the mechanical system, e.g., the classic industrial arm has 6 DOFs. To specify a *target* position in the *workspace*, that is, the physical space that the robot can reach, either the respective position (in degrees or radians) of each joint should be specified as a *joint target*, or the position of the end-effector can be specified in Cartesian coordinates. Throughout this work, *position* will refer to the *pose*, that is, both translation (x, y, z) and orientation (values given in quaternions or Euler angles). When the joint values are specified, the *forward kinematics* of the robot is used to calculate the position (and velocity and acceleration) of the end-effector. It is often desired to specify the position in Cartesian coordinates of the end-effector, in so-called *task space*, and then the *inverse kinematics* is used to compute the actuator torques for each joint so that the position is reached. The Cartesian coordinates can either be specified in absolute coordinates, usually

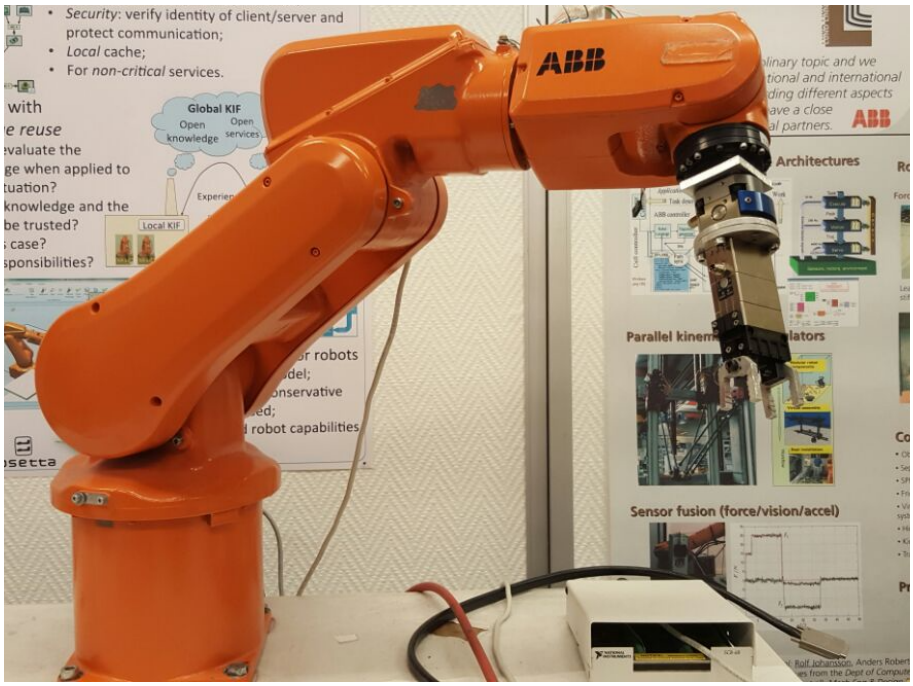


Figure 1: A serial manipulator.

relative to the base of the robot, or relative to *reference coordinate systems*, or points, placed in the workspace or on the robot.

Controller refers to the control system of the robot which can either be *native*, that is, provided by the robot manufacturer and motions are specified in vendor specific code and executed using the motion controller on the robot, or, *external*, meaning that e.g., the motor torques for the robot joints are calculated in an external control loop and sent to the robot over a real-time network. In colloquial terms, *arm* means the manipulator and *gripper* or *tool* refer to the end effector, the *wrist* of the robot is the last link on the arm, the *flange*, where the gripper is attached. For the YuMi robot, each arm has 7 DOFs similarly to the human arm, and thus we call the middle link *elbow*.

In an industrial setup, the robot workspace, the so-called *work cell*, contains for example *fixtures* where the *workpieces* (parts) are secured during the assembly as well as sensors, part feeders, trays and tool changers. The robot can be mounted on top of railings, as shown in Fig. 2 or on a mobile platform, as the robot in Fig. 3, to extend the workspace of the robot. The latter is a dual-arm *collaborative* robot, meaning that it can safely inhabit the same workspace as a human during operation. The user interaction is carried out through an interface, a *teach pendant* (shown in the lower right corner of Fig. 3).

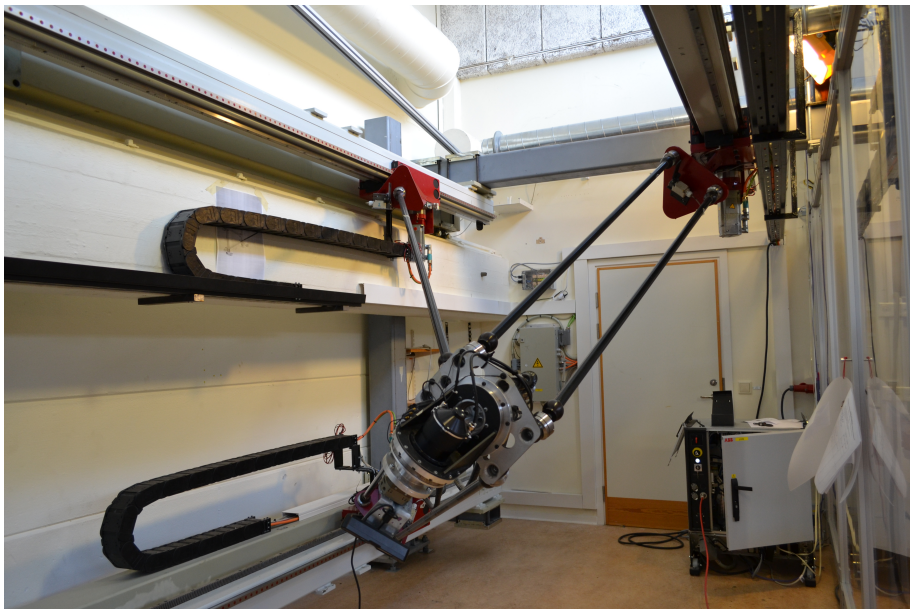


Figure 2: A parallel manipulator.

Each time the robot is commanded to move to a specific joint position, it should move to the same configuration with low error, that is, with a high *repeatability*. The YuMi for example has 0.02 mm repeatability. Each robot is unique due to small manufacturing differences and tear and wear, so when two robots of the same model are given positions with the same joint values they will move to slightly different Cartesian positions. The measurement of how close a robot reaches a specific Cartesian position in the workspace with low error is *accuracy*, this typically requires calibration of the robot.

Even with external sensors for part localization, e.g., a camera system, and even if the parts in the assembly are placed in fixtures and the robot has high repeatability, the measurements will have small inaccuracies and the parts have small deviations in the shape, slip and slide in the grippers or jam together, hence there is an *uncertainty* when manipulating objects in the physical world. Therefore, tasks with low error tolerances need reactive execution with sensor feedback and control. Sensors and devices and communication signals can be integrated into the system by a *system integrator*. This often puts *hard real-time requirements* on the system, that is, the computation and communication tasks must be scheduled in a timely manner and must *guarantee* a response within their deadlines (Shin and Ramanathan, 1994), which often are measured in milliseconds. These deadlines must *always* be met, no matter, e.g., the load on the communication link. A system without this guarantee can still have fast average, actual or expected response times.

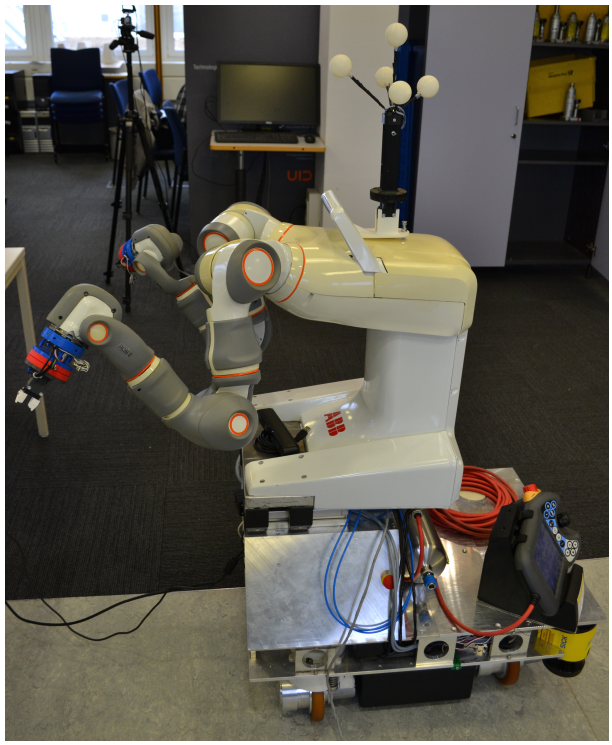


Figure 3: A dual-arm robot mounted on a mobile platform.

In the ISO definition, the bar is set very low for a robot to be considered intelligent. In the scientific community, this is not always the case, rather, some high-level reasoning or understanding is frequently required. The following terms are often used to describe research problems in the AI and robotics literature:

Manipulation primitive: A semantically described atomic action that functions as an interface to the low-level robot control, see e.g., Kröger et al. (2010).

Embodiment: in robotics, it refers to the physical form of an agent, e.g., the robot or the human body. The embodiment of the robot can be anything from a standard industrial manipulator mounted on a table and equipped with a two-finger gripper and a force sensor, to a full-sized humanoid with vision system and five finger end-effectors. In artificial intelligence and especially cognitive science or philosophy, embodiment can refer to virtual bodies or interaction with the world.

Correspondence Problem: the difficulty to transfer a task description between entities with different embodiment and perception capabilities (Nehaniv, 2007).

Non-expert: A person who would not be hired to program robots but might need to interact with it in work or home environments.

End-to-end robot programming interfaces: User interfaces that let the intended operators (end-users) create the complete robot program.

Wizard-of-Oz experiment: An experimental setup in user studies where the subjects believe that they interact with a machine but it is controlled by a human experimenter. This enables evaluation of user interfaces without implementation e.g., when evaluating modality preferences.

Semantics: the meaning of a word, sign or symbol.

Knowledge base: in the field of artificial intelligence, knowledge representation refers to the symbolic modeling of information about the world and logical rules (using e.g., *Description Logic*) that describe relations between symbols. That is, there are assertions, or facts, about entities, and logical rules so that the a system can automatically infer more information about the entities (see the example below).

Ontology: a way to describe a taxonomy, that is, the symbolic model describing types, properties and relationships between the entities. A knowledge base can contain multiple ontologies. In our work, we use the *Web Ontology Language* (OWL) to model the assembly domain. There are object types, or classes, modeled in a class hierarchy (comparable to object-oriented programming but allowing, among other things, multiple inheritance), for example, the class `DualArmRobot` is a subclass of `Robot`, and instances of classes, e.g., `theLundYuMiRobot`, which is an instance of the class `DualArmRobot` (and by inference, `Robot`). Additional rules specify that a dual-arm robot has exactly two manipulators.

The Open World Assumption: given the knowledge in a system, if a statement cannot be proven true, we cannot draw the conclusion that it is false, rather, it is *unknown*.

The Symbol Grounding Problem: a symbol in an ontology must be connected to some real-world entity, otherwise the knowledge is simply a meaningless abstract exercise (Harnad, 1990). Using the (biologically dubious) example given by Harnad (1990), if an ontology has the concept of `Horse` and `Stripes`, their combination can represent `Zebra`. If the symbols for `Horse` and `Stripes` are grounded in real world data, in, e.g., a description of the physical characteristics of a horse and a pattern describing stripes, the system should be able to recognize a zebra as well. Creating and maintaining this connection between symbols and real world sensor data that refer to the same object, so-called *anchoring*, is a special case of the symbol grounding problem only referring to physical objects.

Affordance: A possible action offered by objects or environments (Gibson, 1986).

Cognitive Robotics: is the field of robotics that tries to enable robots to learn, reason and react in complex real-world situations, that is connect perception and action to a symbolic representation that allows them to reason and replan its behavior.

Natural Language: human languages and biologically evolved languages, such as whale song. In contrast to formal languages such as programming languages or description logic, natural language sentences can be ambiguous and mean different things depending on context and the receiver, using implicit assumptions about the receiver's belief and knowledge. Also, there are many ways to express semantically equivalent statements grammatically and by using synonyms and sarcasm, making implicit assumptions about common sense reasoning and culture, etc. There are *lexical* ambiguities, e.g., when a homonym has multiple meanings (e.g., study, execute) and practical ambiguities when information must be inferred, e.g., *put the food on the table* does not specify exactly what edible items to bring, how to carry the food, e.g., in a pot and without turning it upside down during the transport.

Robot Software and Systems

This chapter provides an an introductory overview to standard industrial robot systems and programming, research robot software and finally, the software architecture used in our experiments. Robot systems consist of a heterogeneous mix of hardware and software components. The hardware can consist of robot manipulators, sensors, fixtures, grippers, tools and tool changers, and input devices such as teach pendants or tablets. The software can for example be image processing algorithms, control software, databases, and graphical programming user interfaces. The architecture is distributed and setting up the communication and data management of the full system while ensuring real-time requirements can be quite a challenge.

1 Standard Industrial Workflow and Tools

A standard industrial manipulator is programmed using a teach pendant or in a programming and virtual simulation environment. The YuMi comes with a programming app for a tablet as well as with *lead-through*. Each robot arm has a gripper that is controlled using *signals*, the YuMi grippers are also equipped with a camera and a suction tool. Programs are created by recording a sequence of points and replaying them interluded gripper and sensor commands. Typically, an industrial robot is programmed point-to-point, the path can be a series of close points specifying, e.g., a welding trajectory. Program logic and user interfaces for the operator can also be programmed into the system using, for example, the native robot language.

Many industrial robot vendors have created their own programming languages. These languages are designed with motion specification in mind, allowing debugging by stepping through instructions one by one, either forward or backwards. An example program written in ABB native code, RAPID (ABB Robotics, 2010), is displayed in Fig. 1. It is a small program where the robot arm moves to target positions (`target_3`, `target_5`), opens and closes the gripper (by setting the digital signal `DOutput`). Each instruction specifies motion types (`MoveL` is a linear move) and parameters (e.g., `v100` is speed 100 mm/s).

```
PROC main()
    SingArea\Wrist;

    MoveL target_3,v100,z50,tool0\WObj:=wobj0;
     IF DOutput(do1)=0 OR DOutput(do2)=1 THEN
        Reset do2;
        Set do1;
        WaitTime 0.5;
    ENDIF
    MoveL target_5,v100,fine,tool0\WObj:=wobj0;
    IF DOutput(do2)=0 OR DOutput(do1)=1 THEN
        Reset do1;
        Set do2;
        WaitTime 0.5;
    ENDIF
    MoveL target_6,v100,z10,tool0\WObj:=wobj0;

    SingArea\Off;
ENDPROC
```

Figure 1: An example program written in RAPID.

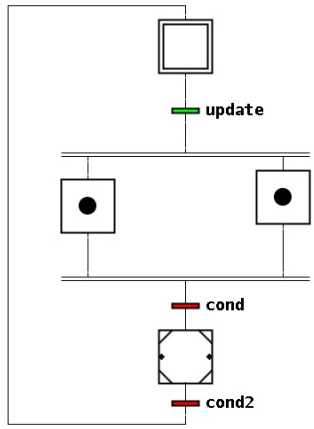


Figure 2: An example of an SFC.

Native robot languages are widespread but non-standard. There are five standard languages for industrial automation applications, defined in the IEC-61131-3 standard (IEC, 2003). Three of them are graphical: Sequential Function Charts (SFC), Ladder Diagram (LD) and Function Block Diagram (FBD) while Instruction List (IL) and Structured Text (ST) are textual. SFCs are used to program *programmable logic controllers* (PLCs). Each state (step) has an action that is executed periodically until a transition condition is true and the next states are activated. An example of a SFC with four states is shown in Fig. 2. In the example, the uppermost state is the initial state (with double-lined border), followed by parallel execution of two states (the running states are marked with a dot). The lowermost step is a nested state machine which can be expanded into a hierarchical structure of additional state machines.

A robot program can be debugged and optimized using graphical simulation environments. Typically, such simulation environments have a graphical representation of the robot and the workspace, and a virtual robot controller that can execute the instructions in a realistic manner, e.g., ABB robots can be simulated in RobotStudio (ABB RobotStudio, 2017), see Fig. 3. In a typical workflow, the program is created and tested in the simulation and programming environment. During deployment on the physical system only a few points are updated using the teach pendant.

2 Research Software Architectures

To abstract away the details of the low-level system components, and make the software development easier, the communication and data management can be handled by *middle-*

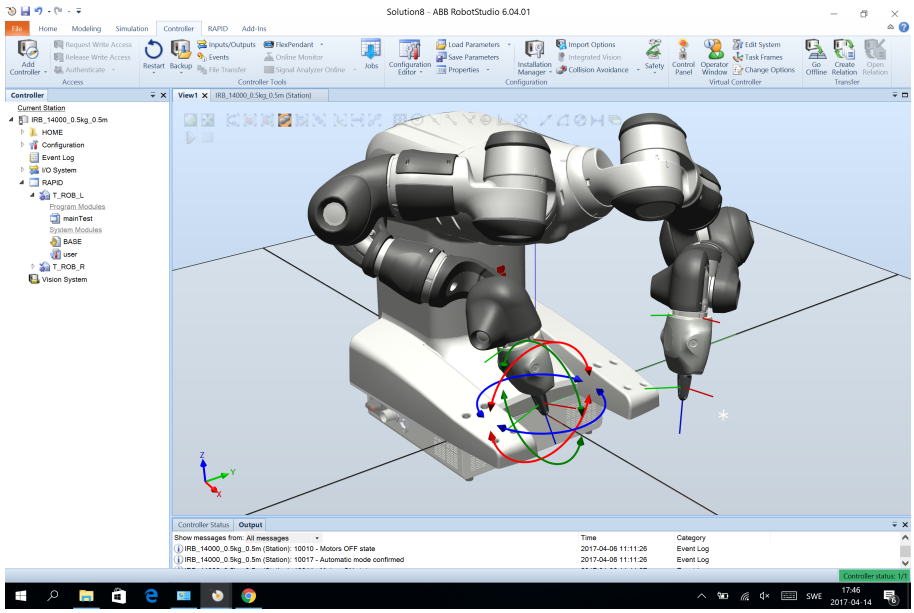


Figure 3: A screen capture of ABB RobotStudio.

ware. Middleware is an abstraction layer between software applications and the operating system and provides an interface for execution and communication between components. Hence, middleware can decrease development time and simplify code reuse. Surveys of current robotic middleware are presented by Elkady and Sobh (2012); Mohamed et al. (2008), a few are mentioned below.

The Robot Operating System, (ROS, 2014), is a robotic middleware that is tremendously popular in the research community. Code modules called *nodes* can be written in Python or C++. The nodes communicate using an asynchronous publisher-subscriber model or by calling blocking services on other nodes. In the publisher-subscriber model there are a set of *topics* that publisher nodes can write to and other nodes can subscribe to. A publisher node can be a sensor that publishes data messages, for example, a camera node with an image message. A Master node helps the nodes to set up the communication. The publisher node will advertise its topics to the Master, and a subscriber node, for example an image processing algorithm, connects with a subscribe call to the Master which sets up direct communication between the nodes. The topics are one-directional and asynchronous, but there are also synchronous *services* where one node sends a request and a response is returned. Because of the popularity of ROS, there is a large collection of open source packages for sensors, robots, navigation with varying levels of quality.

However, in the industry, the enthusiasm has been mild, since the flat architecture gives scaling issues and the system lacks real-time guarantees. One attempt to cater to the needs

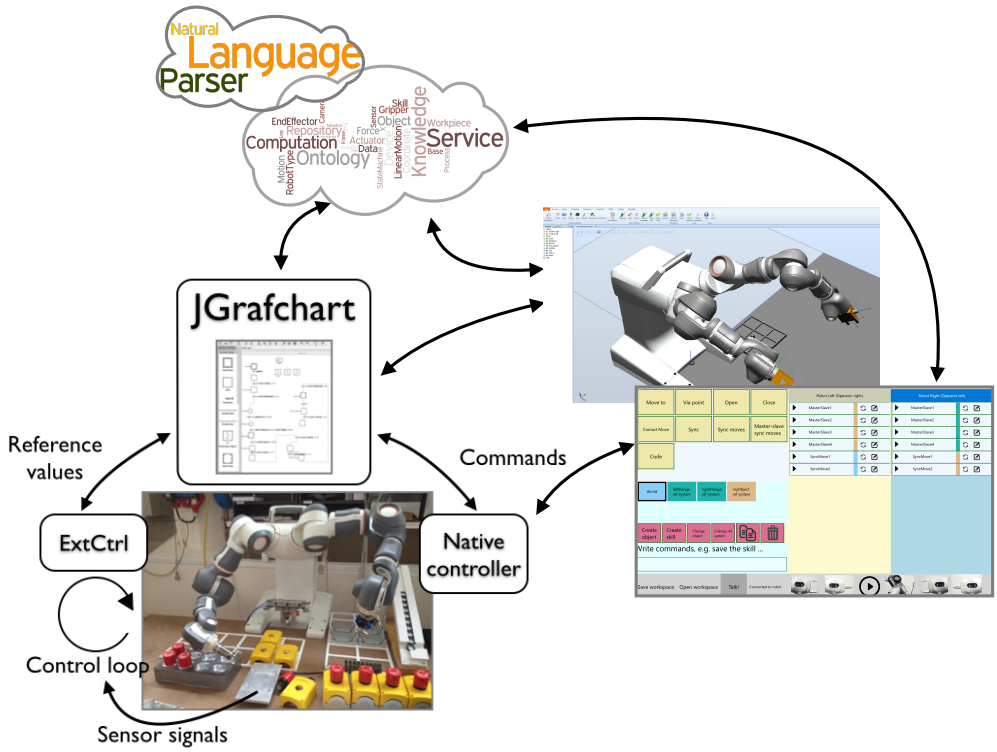


Figure 4: An overview of the system architecture.

of the industry is *ROS industrial* (ROS-I-Consortium), however the initiative has not yet taken off.

Another example of robotics middleware is the Open Robot Control Software, OROCOS. The Orocos Project, is a framework for real-time robot control, thus complementary to ROS. Like ROS, the software is organized in modules, here called *components*. However, the OROCOS Real-Time Toolkit is designed with hard real-time control in mind, letting the user to determine scheduling and periodicity of components and the component designers must enforce real-time behavior. Hence, making two independently written components work together can be difficult, a hardship that ROS users can ignore. Other frameworks, such as Rock (Rock Robotics, 2015), built on the OROCOS toolchain, provide additional features such as monitoring tools.

3 Overview of the Lund Software Architecture

An overview of the robot software architecture used in our experiments is shown in Fig. 4. The ontologies are stored in a Knowledge Integration Framework (KIF), represented by the cloud in the figure. On KIF, the services for code generation and the natural language program extractors are deployed. The user interacts with the robot either through the *Engineering System* implemented as a plugin in ABB RobotStudio, or via a Windows app that we developed for simplified user interaction. Sensor-based tasks are executed as SFCs in JGrafchart (Theorin, 2014), which sends reference values to the controllers using a data protocol called LabComm. The user interfaces communicate with the robot controller directly through ABB libraries, e.g., generated RAPID code is deployed directly to the native controller (even when the procedures are called from JGrafchart). The sensors and control algorithms are deployed on the external controller, *ExtCtrl* (Blomdell et al., 2010).

The external controller uses the iTasC framework (De Schutter et al., 2007). The framework separates the task specification given by constraints and the solver that fulfills the constraints during the execution. In the workspace, interesting points on objects or the robots are marked with local coordinate frames. The task is specified by a *closed kinematic chain*, a closed loop of connecting frames, as illustrated in Fig. 5. Each arrow is a transformation to a frame (marked with coordinate axes). The blue frame is a constant frame, the yellow

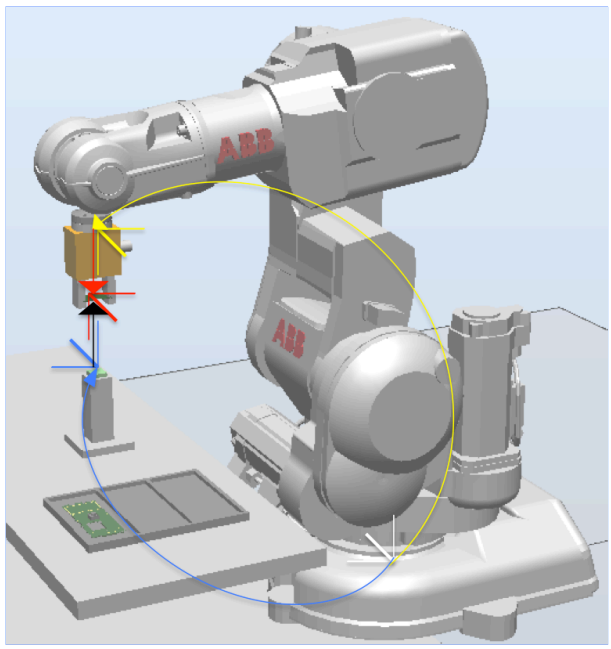


Figure 5: An example of a kinematic chain.

is the robot frame which will be determined by the kinematics of the robot, the red arrow is a tool frame and the black is a feature frame. When setting up a kinematic chain, the direction of the frames must be consistent, hence some frames will be inverted, e.g., the tool frame and the robot frame. The frames can either go through the robot (yellow arrow in the figure), the tool (red) or be constant (blue). The last frame in the loop (black in the figure) is called *feature frame*, and is used to constrain the execution. For example, it can be set to be constant relative to a moving frame, or the robot motion can be expressed in that frame. Each frame in the kinematic chain can be accompanied with an *uncertainty frame*, expressing the certainty of the coordinate values. The kinematic chain can go through more than one robot, thus expressing synchronized motions between arms. During execution, the solver implementation carries out the low-level control of the robot, hence the task specification can be expressed with high-level platform-independent constraints.

The robot architecture in Fig. 4 resembled other architectures by having abstraction layers separating the low-level hard real-time sensor-based control and the task execution that parameterize the skills and switches between the states, and high-level task sequencing provided by the knowledge-based services. This is related to the classic three-tier (3T) architecture presented by Gat (1998), where the robot software architecture is divided into a *skill layer*, where the low-level real-time control is executed, a *sequencer layer* that keeps a system state and selects which skill to execute at a particular time and sets the parameters to that skill, and on top are a *deliberation layer* where predictions and computationally heavy plans computed. However, in our system, the robot does not automatically replan its task during operation.

Different users interact with a robot system on different levels. For example, the experts in automatic control develop control algorithms, that are general enough to be reused task-independently. An application developer creates the state machine of the assembly, which can then be reused by robot operators that update the task parameters to new scenarios.

Related Work

Both in industry and in the research community, the problem of simplification of robot programming for non-experts has been addressed from several angles. Because of our industrial context, we will start with existing programming interfaces or prototypes for end-to-end programming. In the rest of the chapter, the disposition will roughly follow the three-tier architecture by Gat (1998), i.e, we will start with the low-level data-driven approaches, followed by the intermediate action representations and how these connect to the executable robot programs. The intermediate representations are in turn used in high-level knowledge engineering and reasoning architectures. Finally, we will look at how the representation can be extracted from natural language instructions, which is the highest level of abstraction considered in this work.

1 End-to-end Robot Programming

A survey of current programming methods for industrial robots are presented by Pan et al. (2010). For example, application specific tools (so-called *Power Packs*) are widely used, e.g., CAD models of parts are used to generate welding trajectories. Since then, several collaborative robots have entered the market with lead-through support and online programming interfaces, e.g., not only the YuMi, but Baxter and Sawyer from Rethink Robotics, Emika from Franka, Universal Robots' UR-series and Fanuc CR-35iA. These come with end-to-end programming interfaces and apps that allow quick and simple deployment, for example Baxter has easily configurable pick-and-place skills, Universal Robots comes with an iconic programming interface on the teach pendant and Emika has an expert made app library. Macros and apps let non-expert operators instruct the robot on a more user-centric and less detailed level, reducing the time to set up the tasks.

There are several examples of simplified end-user programming environments from multi-disciplinary fields, such as service robots in health care, where applications are developed in collaborative teams with both programmers and subject matter experts. RoboStudio (Datta et al., 2012) is a tool for the development of interaction behaviors in health care applications.

Interaction Composer (Glas et al., 2011, 2016) is an environment for creating user interaction as a state flow using high-level icons for C++ macros. Others are RoboFlow (Alexandrova et al., 2015), a flow-based visual programming tool for creating behaviors for a PR2, and ROSCo (Nguyen et al., 2013), a tool for creating behaviors for home robots as hierarchical finite state machines using a set of motion, gripper and perception primitives. The latter runs in ROS, hence programs are reusable on a platform with equivalent ROS-nodes, however, an expert was still needed to create the program. Also, Lourens (2004) wrap e.g., C++ macros and parameters in visual representations, thus creating an iconic programming interface that was used to recombine existing code blocks and was tested on a NAO robot (Lourens and Barakova, 2011).

Huang et al. (2016b); Huang and Cakmak (2017) evaluated a *Scratch*[1]-like programming language where non-expert users programmed a PR2 to grasp objects. Notably, they integrated a perception module and let the users define gripping points on objects (*landmarks*) through a GUI. They also noticed that the users deviated from the intended workflow where landmarks were created first and then used in the programming, which corroborate our observations that users, even experts, forget or want to change object references during the programming process.

As pointed out by Pan, one important drawback with online programming is that the robot cannot be in production. Therefore, although it can be intuitive for an operator, it is not always the preferred workflow, especially not in highly automated industries. We on the other hand, focus on enabling robot technologies for small and medium sized enterprises where a human worker otherwise would carry out the task manually. The setting of a small company resembles the scenarios tackled in service robotics in the sense that the operator can be less experienced in robotics and that instead of optimizing the execution time of the robot to minimize cost, the workload of the human operator should be reduced. In general, industrial tasks require high precision and low error rates, which are harder constraints than some house hold tasks such as setting the table.

To summarize, most existing solutions are still platform specific and it is challenging for non-experts to create a new robot skill from scratch.

2 Data-driven Approaches

In service robotics, the robots operate autonomously in unstructured environments such as homes, hospitals and shopping malls, with frequent interaction with non-experts and t he intended user is the home owner, hospital staff or shop worker. The users are not assumed to be proficient in programming and robotics and therefore high-level user-centric methods

[1]Based on a user interface called Blockly.

are needed where the user does not have to explicitly give the robot detailed instructions on how to carry out tasks. There are several approaches to learn skills from human demonstrations, so called *Imitation Learning* or *Learning from Demonstration* (LfD). An introduction to the field is given by Argall et al. (2010); Billard et al. (2008); Billard and Grollman (2013) and more recently, Billard et al. (2016). *Learning* implies generalizations from demonstrations, not only replaying the task (as in *Programming by Demonstration*). Demonstrations can take several forms, for example, by observing the human carrying out a task and transfer the actions to a robot. However, tasks often consist of multiple steps and during a demonstration, some motions, such as scratching one's head, are superfluous. Therefore, one of the problems that LfD addresses is *what to imitate*. That is, extracting the *goal* or evaluation metric of the tasks. Another problem is *how to imitate* the human when the robot has a different embodiment and perception capabilities, e.g., both with respect to mobility and dexterity and sensing. Therefore, the actions taken by the robot to achieve a goal can be different from the actions that the human demonstrated. This is referred to as the *correspondence problem* in the literature and solutions involve creating interfaces that reduce the mismatch, e.g., remote controls for teleoperation or by guiding the robot kinesthetically. This also makes it possible for the operator to correct the robot movements when it executes the learnt skill and refine the skill incrementally. However, when moving the robot kinesthetically, the user often needs to use both hands, which makes it challenging to demonstrate e.g., synchronized dual-arm motions. Also, when the user interacts with the robot, it is difficult to separate what sensor input comes from the user interaction and what forces to use to manipulate objects.

A task consisting of multiple steps is often more easily demonstrated fully and segmented into subskills or subgoals. For example, in the gift-wrapping application, the paper had to be wrapped around the box before the folding of the sides, which in turn depended on how tightly the paper was wrapped. Some of the related work focus on learning the sequence of partial ordering of subgoals or skills, some focus on learning the control policy for individual motions and some focus on extracting goals, e.g., spatial constraints between manipulated objects.

After collecting multiple demonstrations of a skill trajectory, the recorded (multidimensional) data (joint angles, Cartesian positions, forces, etc) can be used to train mixture models, e.g., *Gaussian Mixture Models* (GMMs) (see, e.g., Lee et al., 2012, 2013) where the motion is reproduced using *Gaussian Mixture Regression*, or *Hidden Markov Models* (HMMs) (see, e.g., Saveriano et al., 2015; Calinon et al., 2009, 2010). Ureche et al. (2015) demonstrated household tasks on a KUKA lightweight arm and automatically segmented the tasks into skills and extracted the relevant control parameters for the skills by studying the variance of the task variables. The variables that changed significantly over multiple demonstrations and during the demonstrations were considered relevant and were used for the segmentation and the controller parameters for each motion. Also, collaborative tasks

between a robot and a human can be encoded with GMMs and HMMs: see, e.g., Calinon et al. (2009); Rozo et al. (2014, 2016) where not only the position, but also the compliance and force interaction with the user were learned. Niekum et al. (2015) and Ekvall and Kragic (2008) used multiple demonstrations to learn partial ordering between subtasks. Ekvall and Kragic (2008) used the skill dependencies and combined high-level action planning with path planning to avoid object collisions.

Another widely used trajectory representation are *Dynamic Movement Primitives* (DMPs), developed by Ijspeert et al. (2002) (see ,e.g., Ude et al., 2010; Pastor et al., 2011; Kormushev et al., 2011). DMPs are stable nonlinear point attractor systems, where forcing terms[2] can be added to modify the trajectory. The forcing term consists of a set of weighted Gaussian basis functions that are activated over time. The weights can be learnt from a single demonstration, the target position is just a parameter to the function so the learnt trajectory can be used for different goals. Additional terms can be added to not only encode position-based trajectories but also forces, e.g., Kormushev et al. (2011) added a force term to the DMP through a haptic interface and Pastor et al. (2009) adapted the formulation to generalize robustly to new object positions and attached semantics to the trajectory to facilitate reuse. Later, Pastor et al. (2011) improved the policy using reinforcement learning where the success of the task was predicted from the sensor data.

In data-driven approaches, the user must provide multiple high-quality demonstrations that vary in the relevant parameters e.g., move objects in the scene between demonstrations to detect relative reference systems. In our context, even providing one demonstration is time consuming and challenging, hence one-shot programming methods with subsequent refinement are preferred or an unsupervised approach can be used. For example, Levine et al. (2016b) presented an approach where 14 robots were trained in two months to grasp objects producing 800 000 grasps that were used to train a *Convolutional Neural Network* (CNN) mapping vision input to motor commands. The perception and action can be coupled on a low-level, see, e.g., Lee et al. (2015) and several other methods from the research group from Berkeley: Levine et al. (2015) learned manipulation tasks with guided policy search where the cost function is specified as the desired goal position of the task. Levine et al. (2016a) used reinforcement learning and CNNs to map vision input to torque commands. In reinforcement learning, the challenge is to express a good cost function for the goal of the task that can be used for evaluation, this can either be hand-coded or learned, e.g., Yin et al. (2014) learned a cost function for letter trajectories and exploited it to encode the robot motions in a writing task.

These approaches learn the parameters to the low-level control and, depending on the variability in the training data, the skills can be generalized and reused in a slightly different setting. One major challenge is to annotate and semantically describe these learnt skills

[2] *Forcing* the trajectory to follow the demonstrated path, not meaning using force measurements.

with, e.g., partial ordering (which can be extracted from demonstrations, see, e.g., Niekum et al., 2015) and resource constraints so that an automatic planner or scheduler can reorder tasks, and with human understandable descriptions that help the operator to adapt and update the task when it fails. And the task will fail, both during deployment and regular execution. During deployment, the operator must be able to further adapt the task, e.g., by letting the user correct the robot trajectory (Ewerton et al., 2016), by incrementally updating the model with new demonstrations as described by Saveriano et al. (2015), where a forgetting factor is added to the previous learnt model.

3 Dual-arm Manipulation

In the gift-wrapping use case, dual-arm motions were needed to position the large package that was too heavy and bulky for a single arm. One arm was also used to fixate the package while the other folded the sides. In the emergency stop button box use case, some tasks were carried out using independent single arm skills and the arms were synchronized via rendezvous points because, e.g., the force sensor was a shared resource. In the dual-arm screwing skill, instead of using a fixture, one arm was used to hold the button while the other arm screwed the nut into place.

In a traditional industrial setup, the programming of dual-arm or multi-robot operations is more than twice as difficult as the programming of a single manipulation task because there is an overhead from synchronization and coordination. However, in a pure *master-slave* configuration, where one arm follows the other with a fixed offset, the programming time is only dependent on the master arm's program and the initialization of the synchronization. If the robots move synchronized but independently, the programming process can be decoupled and the synchronization added later, but this approach requires programming experience.

Smith et al. (2012) present a survey of dual-arm systems, applications and technical challenges from a control and planning perspective. Many approaches use remote control, either via joysticks or via human motion tracking. For example Kruse et al. (2015) present an application where the robot autonomously located and grasped a heavy object and then human operator took over and tele-operated the robot through skeleton tracking using Microsoft Kinect. Ramirez-Amaro et al. (2015) used video recordings of humans carrying out household tasks and transferred them to the iCub and the REEM-C humanoids. Ge (2013) used optical tracking to program a YuMi robot and although the YuMi arms have 7 DOFs so that the human arm movements could be mimicked and Tunstel et al. (2013) remote controlled terrain driving mobile dual-arm robots using a two-hand multi-DOF joystick.

An example of application specific user support is given by Makris et al. (2014), who let the user guide bi-manual pick-and-place tasks through a gesture interface. Zöllner et al. (2004) presented work in 2004 where human demonstrations were recorded with stereo cameras and sensor gloves and segmented and classified as manipulation primitives. The primitives were either symmetric or asymmetric coordinated actions depending on whether or not the arms manipulated the same or different objects. Similarly, Krüger et al. (2011) simplified the dual-arm programming by providing macros for bi-manual actions on an object, e.g., *bi-approach* or *bi-hinge*. Also, Reinhart and Zaidan (2009) used the motion of workpieces as the references for cooperating robots, so the user only had to specify the desired trajectory of the object using a 3D model. However, their work focused mostly on implementing a compliance control algorithm for the joint control of the robots. Muhlig et al. (2009) tracked the workpiece trajectories using a stereo vision system and learned the motions (using GMMs) for a bi-manual pouring task on an ASIMO robot. However, most related work is concerned with multi-robot planning (see, e.g., Vahrenkamp et al., 2011) or control (e.g., Sariyildiz and Temeltas, 2011; Sieber et al., 2013; Lee et al., 2014), for example, Park and Lee (2015, 2016) presents a control framework for a humanoid for different types of coordinated motions expressed in task space variables.

In a framework using LfD, kinesthetic teaching of bi-manual operations is challenging because the human operator must demonstrate two tasks simultaneously, but possible if the robot is for example small. Gribovskaya and Billard (2008) used kinesthetic demonstrations on a small humanoid to record trajectories and learn spatial constraints and synchronization points. For a larger robot, this approach is impractical. Instead, the trajectories can be extracted from observations of human dual-arm manipulations, e.g., Zhou et al. (2016) extract trajectories and create coordinated DMPs using tracking data from the KIT database (Mandery et al., 2015). They experiment with a wiping task, where movement of the arm and the hand are controlled by two different DMPs coupled in a leader-follower (or serial) manner so that the local movement of the hand is encoded in the coordinate system of the leader. The leader on the other hand can move relative to a plane, so that the entire wiping task can be translated.

4 Multiple Modalities

Kinesthetic teaching combined with graphical user interfaces are now standard interfaces for small collaborative robots. Additional modalities such as speech, pointing gestures and haptics are common in laboratory settings. Profanter et al. (2015) evaluated the user preferences for four different modalities in a Wizard-of-Oz user study where the experimenters interpreted the users' pointing gestures, speech input, 3D pen input as well as touch input on a screen. They found that gestures were preferred for selecting objects and specifying points on the object, while touch was the preferred for specifying a location. Speech was

considered the most difficult, e.g., because the users struggled to name the objects. These results correspond well to our assumptions that speech is suitable only when the user can name or display the object names and only for high-level tasks, e.g., not for specifying parameters. In subsequent work, Perzylo et al. (2015b) describe a natural language interface for high-level instructions, which parallel our work by connecting the utterances to an ontology of objects and tasks. Multiple modalities can be used to reduce the number of necessary demonstrations and can be used to communicate the knowledge and states of the robot system. Alexandrova et al. (2015) use action visualizations of a single demonstration to let users change reference frames (*landmarks*) of motions and e.g., reorder actions. This can allow more intuitive and natural means of communication, and, e.g., Mead (2017) provides a cloud-based software platform for robot and application developers called *Semio*, with drivers for multimodal interaction, e.g., speech recognition (including pitch, rate and volume) and body language (e.g., gaze).

5 Manipulation Primitives and Skills

To bridge the gap from low-level control to more abstract reasoning, the motor skills need a semantic representation. A review of research approaches up to 2007 were presented by Krüger et al. (2007). The problem can be approached either bottom-up from a machine perspective as the data-driven methods discussed in the previous section, or top-down, starting with human concepts of symbolic actions. The symbolic representation of robot skills, e.g., as *action primitives*, can be used in automated reasoning process or to generate action plans using standard AI planning and scheduling tools (see, e.g., Mosemann and Wahl, 2001).

Action primitives are predefined parameterized templates for executable robot instructions that can be combined into more complex skills (Kröger et al., 2010; Felip et al., 2013). These primitives can either be procedural or declarative, but correspond to an executable low-level instruction. In a declarative approach, Bruyninckx and Schutter (1996) and De Schutter et al. (2007) expressed the desired motion and sensor-values as constraints on a *kinematic chain* using coordinate reference frames of objects in the world or on the robot. This *Task Frame Formalism* (iTasC) was extended by Kröger et al. (2010) and implemented by, e.g., Finkemeyer et al. (2005) and Pedersen et al. (2014), to describe a *hybrid motion* expressed in a frame, a synchronously executed *tool command* and a terminating *stop command*. The motion primitives abstract low-level sensor-based constraints and motions and must be combined into more complex state machines to produce a robot skill. The implementation presented in Paper III is based on the same formalism and a comparable control architecture, however, the technical implementation details differ.

A procedural approach with parameterized action templates (so-called *Robotic Assembly Skills*) were presented by Wahrburg et al. (2015) where the actions were encoded as trajectories and the complete skill was represented as a finite state machine. Their application was similar to ours, with an expert-made parameterized *snapfit* that was implemented on a YuMi robot. An approach related to ours, where the task description had a platform independent reusable description, was presented by Perzylo et al. (2016). In their work, assembly tasks were described by defining spatial constraints between parts in a graphical view. Using an ontology, their system could then generate executable programs fulfilling the semantic spatial constraints (Somani et al., 2016), and demonstrated that a robot system with domain knowledge and domain specific user-centric tools reduced the programming times with around 70 - 80%. The bottleneck in such system is to model the knowledge about objects and robot skills which, in our experience, does not scale well to new domains.

Skills can also be based on code-reuse, e.g., the robot manipulation skills presented by Pedersen et al. (2014) encapsulate blocks of parameterized executable code with pre-condition, post-condition and continuous checks. The skills were initialized with a set of parameters and terminated with an evaluation of the post-conditions. Andersen et al. (2014) created an abstraction layer between an execution environment (called the *Robot Virtual Machine*) and parameterized skills for, e.g., pick-and-place and palletizing with a user interface with wizards for helping the operator specify the skill parameters. They, as well as Krüger et al. (2010), explored the concept that primitives should be encoded as actions on objects, analogous to human language.

6 The Grounding Problem

The concept of *affordances* stemming from cognitive science (Gibson, 1986), is used by Asfour et al. (2008); Wörgötter et al. (2009); Wächter et al. (2013), who introduced the *Action-Object-Complexes*. The objects in the Action-Object-Complexes have attributes, e.g., a cup can be empty or full and the actions that are offered by the object transform the attributes. Each action has pre-and postconditions to describe the transition and the implementation should evaluate whether or not it succeeded. The representation was grounded to actions learned from human demonstrations, e.g., Asfour et al. (2008) learned trajectories (encoded as HMMs) from observing humans, Kalkan et al. (2014) labeled actions on an iCub with effects and trained *support vector machine* classifiers to predict the outcome of a behavior, and Wächter et al. (2013) used a library of predefined complexes to classify segmented demonstrations of human tasks (see also Aksoy et al., 2016; Kaiser et al., 2016). The work developed further into *semantic event chains* presented by Aksoy et al. (2011). In their work, a sequence of (human) actions on objects were observed and used to compare manipulation scenarios. Aksoy et al. (2011) and (Asfour et al., 2008) made the analogy between primitive actions (such as *objects touching* and *not touching*) to an alphabet, hence, sequence com-

parisons are equivalent to substring matching and complex actions are compared to words, which they (Aksoy et al., 2015) later used to classify new actions.

Grounding the high-level symbols in low-level perception and action is a classic AI problem. Coradeschi et al. (2013) present a short survey of work in cognitive robotics up to 2012. The presentation is divided into two subtopics, *physical symbol grounding* where symbols are grounded to real world objects and perception, grounding words in action, and *social symbol grounding*, where the symbols are shared between multiple agents and therefore constrained, e.g., by communication. Especially in dynamical environment, the connection between the symbols describing entities and the sensor data must be maintained, *anchored*, which can be done through probabilistic approaches, see, e.g., Elfring et al. (2013).

7 Ontologies

In the context of robotics, ontologies are used to represent knowledge about robots, sensors, and tasks. The working group *Ontologies for Robotics and Automation* has developed a Core Ontology for Robotics and Automation, CORA, defining positions (Carbonera et al., 2013) and later extending it with environments (Fiorini et al., 2015). The group has also created an ontology for kit building (Balakirsky et al., 2012) which has been evaluated using human- and multi-robot interaction (Jorge et al., 2015). Lim et al. (2014) presented the RACE ontology for robot experiences and human-robot interaction, e.g., dialogue, and the W3C Semantic Sensor Network Incubator group developed an ontology for sensors and observations (Compton et al., 2009, 2012). Schlenoff and Messina (2005) presented an ontology for modeling robot requirements in urban search and rescue.

Ontologies for common household tasks and objects were developed in the RoboHow project (Tenorth and Beetz, 2013). The KnowRob knowledge processing system encoded the knowledge in OWL was adapted from the OpenCyc (Lenat, 1995) ontology for common sense reasoning. Early work included the *OpenRobots Ontology* for household tasks and their reasoning framework was implemented using an RDF triple store and OWL Description Logic, closely related to our approach. Tenorth and Beetz (2013) created a *Semantic Robot Description Language* to combine kinematic descriptions of a robot in the *Unified Robot Description Format* with actions and capabilities (Kunze et al., 2011). Their action representations include high-level concepts such as *PrepearingFoodOrDrink* and subclasses such as *Stirring* and include physical requirements of the system (e.g., sensors, or a mobile base). The system grounded the entities with a SLAM mapping system to create semantically described shared environments (Riazuelo et al., 2015) The knowledge is used to produce reactive action plans for household tasks (Beetz et al., 2012). These plans can be executed in CRAM (*Cognitive Robot Abstract Machine*), a toolkit for programming and executing high-level robot plans that will replan and recover from failures online (Beetz

et al., 2010; Winkler et al., 2012). The KnowRob knowledge-base is queried using Prolog and is open and extensible. For example, Muhayyuddin et al. (2015) used KnowRob to integrate ontological reasoning with motion planning by modeling objects as fixed and movable, thus, the generated motion plans could involve moving obstacles. In the aftermath of the RoboHow project, they developed `Open-EASE`, a web-based service for storing and analyzing robot experiments (Beetz et al., 2015, 2016).

8 Connecting Natural Language and Robot Actions

Kalkan et al. (2014); Andersen et al. (2014) and Krüger et al. (2010) compared robot actions with natural language instructions, but the idea of using natural language to instruct a machine is older than Unix time itself. A famous early attempt is SHRDLU (Winograd, 1971) developed by Terry Winogard. SHRDLU was a computer program that understood English and let a user describe how to move objects in a block world. This was in 1968 and the program could understand 50 words, such as "block", "cone", "blue", "place on" and tried to guess the user's intention from the word combination.

Modern day examples from the robotics community are used to, e.g., give mobile robots route instructions (Tellex et al., 2011; MacMahon et al., 2006; Shimizu and Haas, 2009). The representation for connecting language instructions (usually verbs) to actions differ. Perzylo et al. (2015a) generated grammars by explicitly annotating classes in the RoboEarth ontology with Wordnet synset. Spangenberg and Henrich (2015) presented a representation of *verbalized physical effects* (affordances) to manipulation primitives (Kröger et al., 2010). Each verbalized physical effect is described with a verb, an effect, input and output quantities and constraints for the execution of the movement primitive. Another related approach is the semantic frames used by Brian Thomas and distributed as a ROS package `roboframenet`[3], or the *semantic word* representation presented by Twiefel et al. (2016), and Fischer et al. whose system uses structured responses consisting of *utterances* (commands) and *slots* (arguments) that map to robot programs.

Natural language utterances can be grounded by narrating a demonstration (see, e.g., Stramandinoli et al., 2016), e.g., Misra et al. (2016) use the Stanford Lexical parser (Klein and Manning, 2003) to create in intermediate representation, *verb clauses*, consisting of verbs, objects and prepositional relationships that are mapped to sequences of instructions of (predefined) actions. Related methods, that used statistics to map semantic frames to a subset of actions carried out in a 2D virtual environment, were presented by Panzner et al. (2015), while Salvi et al. (2012) used a bag-of-words model to map speech utterances to a set of simple manipulation actions.

[3] `http://wiki.ros.org/roboframenet`

One of the drawbacks of approaches where the classification of language instructions to robot actions are trained from labeled examples is that the user cannot easily extend the vocabulary on their own. In our applications, we use the general purpose statistical parser and semantic role labeler described below.

Background note on the Lund statistical parser

An introduction to natural language processing (NLP) applications is given by Nugues (2016a). The first approaches were ruled-based, where hand-made grammatical rules where used to process text (Nugues, 2016b). However, for unrestricted natural language many rules are needed, especially for handling homophones, ambiguous interpretations and spoken language, and since 2000, when the performance and availability of processing power increased, most computational linguistics use statistical methods.

The general purpose statistical model running on a virtual machine at Lund University can process (parse) unstructured English sentences in about $10 - 50$ ms and is accessed from for example mobile devices.

When the meaning of a sentence is extracted the following questions are at least partially answered:

- What is going on? (Predicate)
- Who/what is doing it? (Actor)
- What objects are involved? (Arguments to the predicate)
- Where is this going on? (Location argument)
- When and how long is this going on? (Temporal argument)
- How is the action carried out? (Manner)
- Who is the beneficiary of the event? (Beneficiary)

Language is ambiguous, homophones, such as *press* in *news press* and *press down* belong to different part-of-speech and have different meaning. In a sentence, the words that answer the above questions are labeled with the *semantic role* listed in parentheses after the question. This is done using special purpose dictionaries such as WordNet (Princeton University, 2010), FrameNet (Ruppenhofer et al., 2010), or PropBank (Palmer et al., 2005), that list predicates and roles that can belong to the predicate. In the robotics context, the sentence *execute the program*, where *execute* means *enact* (the predicate *execute.02*), is perfectly

acceptable, but the command *execute the human*, where the homophone refers to killing (*execute.01*), certainly is not.

The model for the parser is trained using a *corpus*, which is a large text mass where the sentences are annotated with syntactic and semantic information. There are several corpora, for example the Penn Treebank (Marcus et al., 1994) which is created from *Wall Street Journal* articles, and the PropBank (Palmer et al., 2005) that added predicate-argument structures to the Penn TreeBank. The latter is used by the Lund parser. The parser uses three main steps to classify the sentence, further details are described in Björkelund et al. (2010). First the sentence is split into words (tokenized), and each word is assigned a part-of-speech tag and the canonical form (*lemmatization*). Next, it produces a *dependency graph*, which is a graph structure with the grammatical relations between the words. The dependency graph is finally used in a semantic role labeler to produce the predicate argument structures. The semantic role labeler uses binary or multiple logistic regression in a cascade of classifying steps.

- **Predicate Identification:** Each word is either classified as a predicate or not using binary logistic regression.
- **Predicate Disambiguation:** Determines the sense of the predicate if there are multiple senses. Lemmas that can be both verb and nouns have one classifier per part-of-speech.
- **Argument Identification:** First each word is either classified as an argument or not. Then a multi-class identifier determines the role of the word.

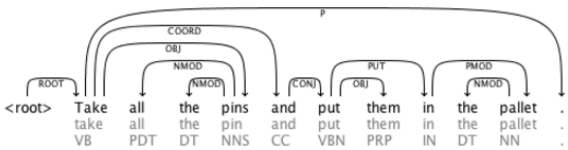
If the sentence is somewhat grammatically correct, the parser will produce a well-formed machine-readable table structure.

For example, the input sentence *Take all the pins and put them in the pallet* produces the output tables shown in Fig. 1. Two predicates were identified, *take.01* and *put.01*, these are visually presented in the first table. Because the sentence is formulated as a direct command, there is no actor (*A0*) and the first argument (*A1*) are the things being taken or put respectively. For the second predicate, *put.01*, a second argument, *in the pallet*, was identified answering the question where the *A1* should be put. In the middle figure, the dependency graph is visually displayed, it is a tree rooted in *take*. The same information is also presented in the CoNNL-format in the last table. In the part-of-speech (POS) column, e.g., the token *pins* was identified as a plural noun (*NNS*), *the* as a determiner (*DT*), and *and* as a conjunction[4].

[4]The word *or* is also a grammatical conjunction, not to be confused with the *logical* conjunction AND and disjunction OR.

	Take	all	the	pins	and	put	them	in	the	pallet	.
take.01		A1									
put.01							A1	A2			

Parsing sentence required 26ms.



ID	Form	Lemma	PLemma	POS	PPOS	Feats	PFeats	Head	PHead	Deprel	PDeprel	IsPred	Pred	Args: take.01	Args: put.01
1	Take	_	take	_	VB	_	_	_	0	_	ROOT	Y	take.01	_	_
2	all	_	all	_	PDT	_	_	_	4	_	NMOD	_	_	_	_
3	the	_	the	_	DT	_	_	_	4	_	NMOD	_	_	_	_
4	pins	_	pin	_	NNS	_	_	_	1	_	OBJ	_	_	A1	_
5	and	_	and	_	CC	_	_	_	1	_	COORD	_	_	_	_
6	put	_	put	_	VBN	_	_	_	5	_	CONJ	Y	put.01	_	_
7	them	_	them	_	PRP	_	_	_	6	_	OBJ	_	_	_	A1
8	in	_	in	_	IN	_	_	_	6	_	PUT	_	_	_	A2
9	the	_	the	_	DT	_	_	_	10	_	NMOD	_	_	_	_
10	pallet	_	pallet	_	NN	_	_	_	8	_	PMOD	_	_	_	_
11	.	_	.	_	.	_	_	_	1	_	P	_	_	_	_

Figure 1: The semantic parser outputs predicate-argument structures in the CoNNL-format.

From this table, the output can be matched to robot instructions from the skill database and arguments can be mapped to objects in the world, as described in Papers VI and VII.

Approach

Robotics is an engineering research, where we build and evaluate artifacts. The methodological approach resembles design science, where an artifact is designed in an iterative process of problem identification, ideas, implementation and evaluation. The robotic system is thus designed in small incremental steps, where isolated features are implemented and tested separately. Fig. 1 presents an overview of the research work presented in this thesis. The work started with vague ideas about what abstractions we needed to reduce the programming workload for human operators but still be able to generate executable robot code. Because humans express their tasks using actions on objects, we wanted to apply these high-level concepts to instruct robots as well. Humans also use multiple modalities during communication, e.g., language to convey high-level goals of a task, and physical interaction to show positions or contact forces. The hypothesis was that a platform-independent representation of reusable robot programs would simplify task programming by bootstrapping the programming process and abstract away from the low-level details of the system. A reusable robot program is called *skill* which is the *capability of performing an action resulting in a meaningful outcome*. The work presented in this thesis describes and evaluates a skill representation where a robot program consists of a semantically annotated state machine, where each step is an action primitive that has a direct mapping to executable commands.

The work was thus carried out incrementally, first we created a skill representation and then we evaluated it from machine and user perspective and refined it further. The knowledge about objects, devices and tasks were modeled in OWL ontologies (Paper I). The ontologies were stored together with instances of work cell descriptions and skills in an online database repository that could be accessed by multiple robots. The ontology was a development from previous research projects (Paper II) into knowledge-based robot architectures.

The evaluations were prioritized from a pragmatical point of view, a representation that cannot be executed on a physical robot system has very little value in practice, hence the machine perspective was evaluated first (Paper III).

The skill acquisition bottleneck can also be addressed by simplified programming tools for non-experts and experts (Paper IV and Paper V). Based on experiences from the gift-

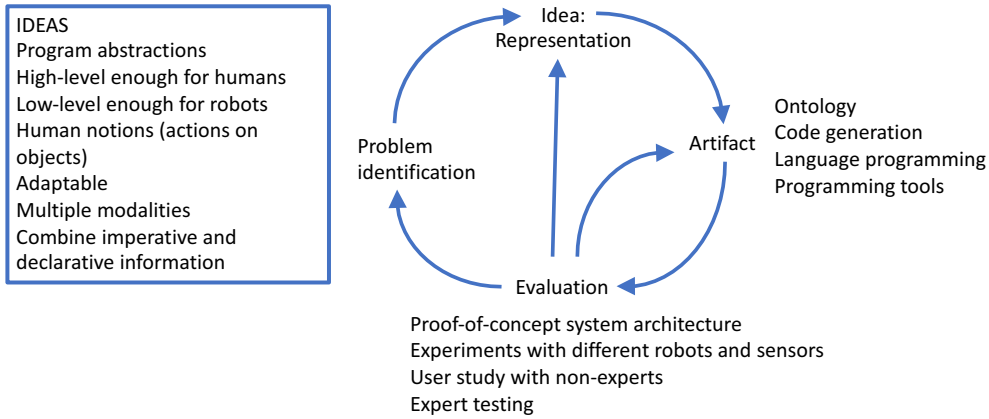


Figure 1: An overview of the methodological approach.

wrapping and emergency stop button case studies we developed a prototype for skill-based programming from scratch. To test the usability of our representation, we developed a simple user interface that allowed non-experts to program reusable robot skills, and verified in a user study that, not only could non-experts program new skills, they could also reuse and edit expert-made skills (Paper IV). When comparing programming methods we used time as a metric, because it corresponds to cost, but also because other metrics, such as for example number of steps, are not equivalent between different modalities (e.g., writing code and selecting buttons in an interface). There are two phases worth measuring, first, the time it takes for the operator to find a robust solution (*task prototyping*), and the time it takes to program a robot when a strategy is known (*programming time*). In the expert evaluations, we first let the users test different strategies using their preferred programming environment and debug their program on the robot, and then program it from scratch using both the prototype and traditional tools (Paper V).

One challenge when programming dual-arm robots using kinesthetic teaching in contact situations, is that the user is limited to a few modalities at once, that is, the user cannot simultaneously insert instructions on a touch screen and demonstrate the task on the robot. To overcome this issue, we have support for speech commands in unstructured natural language. Each object and skill has a parameter with a set of natural language names that are used to match programs and objects to predicates and arguments (Paper VI and Paper VII).

Implementation and Evaluation

This section describes the most relevant implementation details and metrics of our proof-of-concept system architecture.

1 Knowledge Integration and Services

We had identified the need for modeling knowledge about robots, devices and actions in an extendable way. An example of device properties is given below. The knowledge was expressed in modular OWL ontologies created using the ontology editor Protegé. These were stored together with the instances in an *RDF triple store*. RDF, short for Resource Description Framework, is a format where data is described as triples. Our implementation uses the Sesame Workbench (OpenRDF Sesame, 2015) with multiple data repositories. Each triple $\langle S, P, O \rangle$, has a *subject node* S, a *predicate* P and an *object node* O. Resources and properties in RDF are identified using unique Uniform Resource Identifier (URIs).

Example: Knowledge representation

The type of knowledge that was modeled was e.g., that both a `CartesianRobot` and a `MobileRobot` are different subtypes of a more abstract type `Robot`. A gripper with pincer fingers, `PincerGripper`, can be opened and closed, that is, this functionality is represented by the skill properties `Grasp` and `Release`. The reverse property is also true, that is, if we look up a `Grasp` skill in our knowledge base, the grippers that provide the functionality are listed. Each gripper has other properties, such as a `Mass` expressed in some unit, e.g., either *kg* or *g*, as well as conversion ratios between the units. Also, to guarantee that the information is correct, the gripper can only have one mass property. This meta-information about reverse properties, cardinality of properties and class hierarchies was represented in ontologies and stored in the knowledge base.

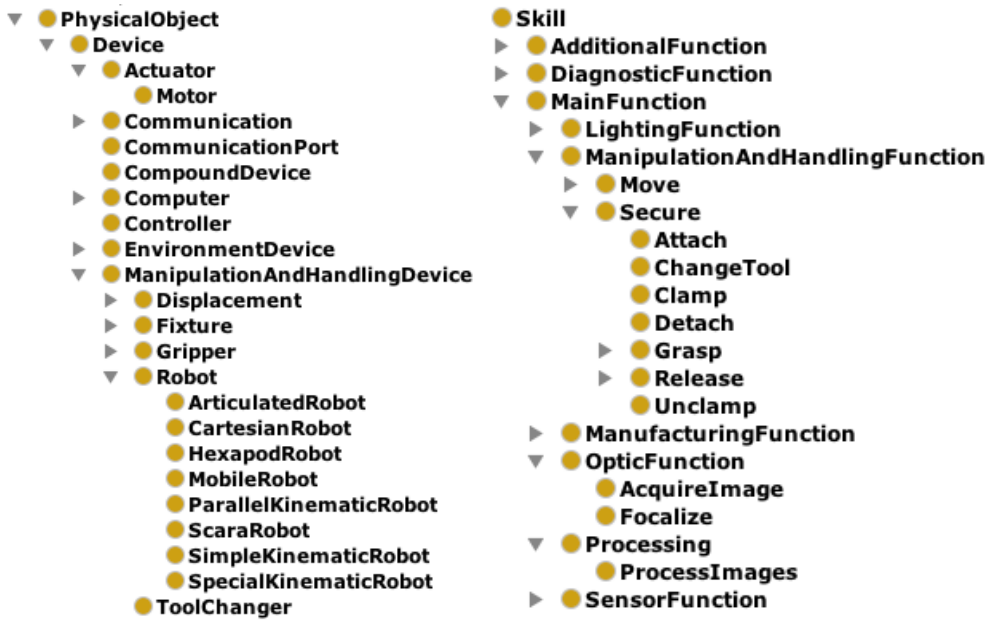


Figure 1: Snippets from the ontologies for objects and skill types.

The object node can also be a primitive data type such as string or a number, called a *literal*. Literals cannot point to any other nodes and unconnected edges are not allowed. Hence, a triple is equivalent to a directed edge in a graph and a node can have multiple outgoing and incoming edges. When a triple is added to the repository, a reasoner will infer new triples for the asserted information, e.g., if an instance of type `CartesianRobot` is added, the reasoner will infer that it is a `Robot` as well, so that when the repository is queried for objects of type `Robot`, the inserted instance will be presented as well.

The core ontology, `rosetta.owl`, consisted of a hierarchy of robots, devices and sensors. Primitive actions were separated into a smaller ontology, `primitives.owl`. Instances of skills were typed and could be expressed as hierarchical state machines or native code. Each state in the state machines could either be primitive actions or nested skills. Each primitive had a type (e.g., `Move`, `Guarded motion`, or `Gripper action`) and a set of typed parameters. The `configuration.owl` ontology contained base types for skill requirements, conditions and parameters modeled the parameter types and imported the unit ontologies, QUDT and OM to express quantities, units and conversions. For motions and positions, the parameters were relative coordinate frames on objects (e.g., a guarded motion moves along an axis of a coordinate frame of an object) in the work cell. The ontology `coordination.owl` contained the base types for state machines and graphs, e.g., contact and assembly graphs. The sizes of the ontologies are shown in Table 1.

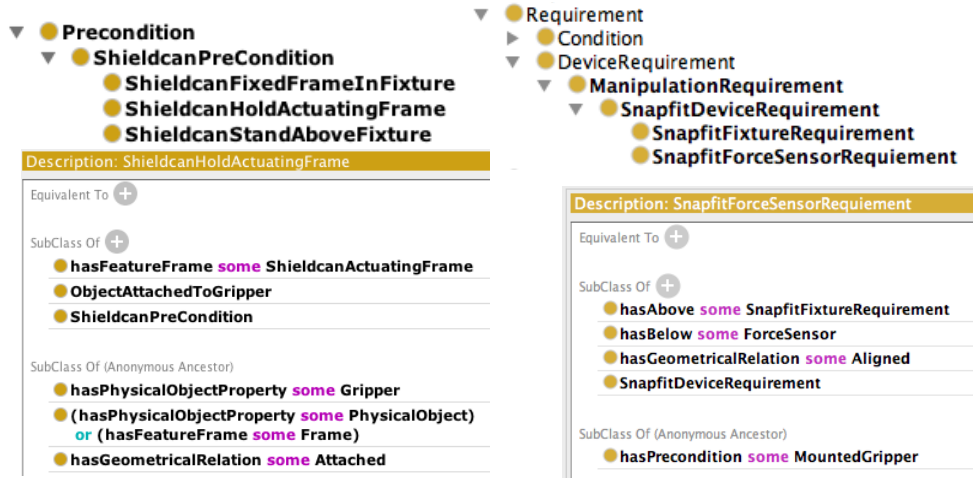


Figure 2: Snippets from the ontologies for preconditions and device requirements.

Snippets from the ontologies are displayed in Fig. 1, showing different robot types, different types of skills for manipulating objects and an example of a precondition for a shield can insertion skill. Each skill had a small ontology describing parameters, device requirements (e.g., force sensor or a fixture), pre-and postconditions and default values for each numeric parameter (e.g., velocities and forces). The devices listed their skills as capabilities, that is a skill had a `isSkillOf` property for each device that provided it. The users could create their own instances of skills with new parameter values and store them in an individual repository.

Each skill had preconditions for grippers and objects, e.g., the precondition for the *shieldcan insertion* shown in Fig. 2 is that the shieldcan is located in the robot gripper and the gripper is located above the fixture. The naming of the conditions, *fixed frame* and *actuating frame* were chosen to distinguish between the reference object and the robot flange, the frames that were used for setting up the closed kinematic chain in the code generation step. Device requirements were added in a similar fashion, e.g., the *snapfit* skill from the emergency stop button box assembly and discussed further below, needed a fixture and force sensing and this was modeled as a two requirements, `SnapfitFictureRequirement` and `SnapfitForceSensorRequirement` (snippet shown in Fig. 2), describing that that a force sensor should be placed below the fixture. The requirement is a subclass of a precondition describing the gripper requirement for the *snapfit*, because the nut and the switch were picked with different grippers during the assembly.

The initial user interface, the Engineering System (see Fig. 3), was implemented as a plugin to ABB RobotStudio, coded in C# and communicating with the KIF database using SPARQL queries or queries to the Java Servlet services, and with the robot using the stan-

Ontology	Nbr of classes
rosetta.owl	597
coordination.owl	73
configuration.owl	65
primitives.owl	53
snapfit.owl	81

Table 1: The size of the ontologies.

dard ABB controller APIs. In the Engineering System, the robot programs could be simulated virtually using a virtual robot controller and CAD models of the workpieces. Using the CAD models, relative coordinate frames (*feature frames*) were specified as points on the objects and spatial constraints between the objects such as grip positions or insertion points were specified geometrically as shown in Fig. 3.

The assembly was described using an assembly graph. Fig. 4 shows the assembly graph of the emergency stop button box assembly. The leaves represent the workpieces: the yellow box, stop button, nut, box bottom and switch, while inner nodes were subassemblies. The full assembly consisted of two partially ordered subassemblies, first the stop button was inserted into the yellow box top using a peg-in-hole skill, then the two parts were rotated and the nut was screwed onto the stop button joining the three parts. The switch was snapped to the bottom part of the box using a *snapfit* skill. In the user interface, the assembly graph was visually represented as a tree, partially ordered bottom-up. Although the tree was binary, three-part assemblies would be described as two ordered assemblies like the screwing. For each subassembly, the user could select a skill instance or skill type from the KIF skill database and from the selection, an assembly sequence was proposed including actions for fulfilling the preconditions such as movements for picking parts and moving into start positions (e.g., the start position for the *shieldcan* above the fixture). The user was also notified of missing device requirements. All positions were initialized using default values, e.g., *above* meant 100 mm in the positive z-direction of the object frame (located e.g., at the center of the top surface of the fixture).

2 Code Generation

To evaluate the reusability and platform independence of the skill representation, we developed a proof-of-concept architecture with a skill database and a code generation service. The skill state machine of the *snapfit* from the emergency box button were transferred between the dual-arm Frida and an IRB140 robot. The skill was instantiated with work cell specific object position parameters and robot specific velocities. The Frida robot used con-

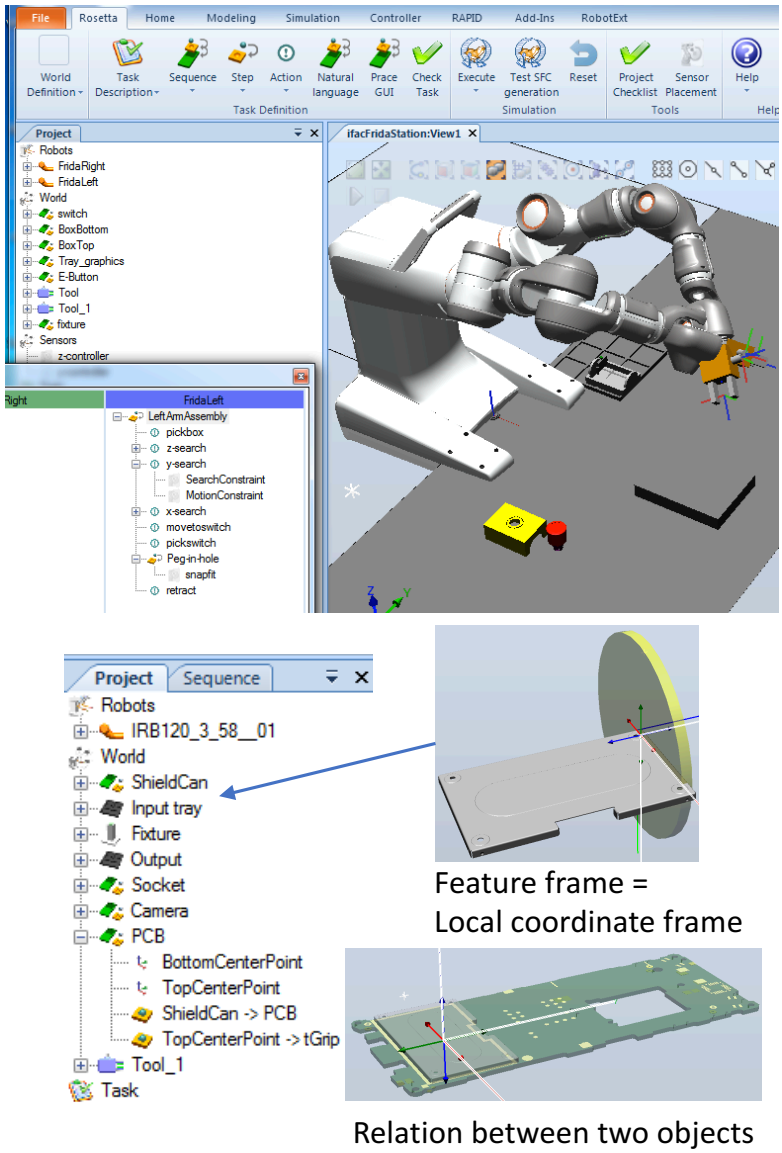


Figure 3: The graphical user interface in RobotStudio were used to specify spatial relations between CAD models of objects, e.g., the shieldcan and the PCB shown to the right.

tact force estimation while the IRB140 had an external force controller mounted on the wrist. From a high-level perspective, the setups were equivalent, but the sensing and the kinematics of the robots differed. The parameters for each instance of the skill were edited using the Engineering System, see Fig 5. The reusable description reduced the number of parameters that had to be specified by the operator significantly, and the parameters that

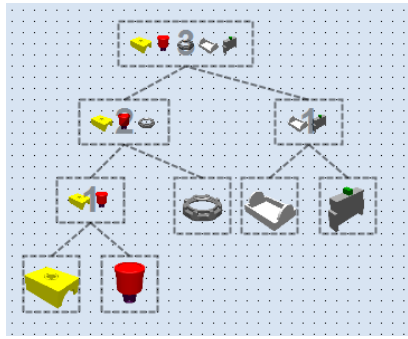


Figure 4: An assembly graph visually describing the partially ordered subassemblies of the emergency stop button box assembly.

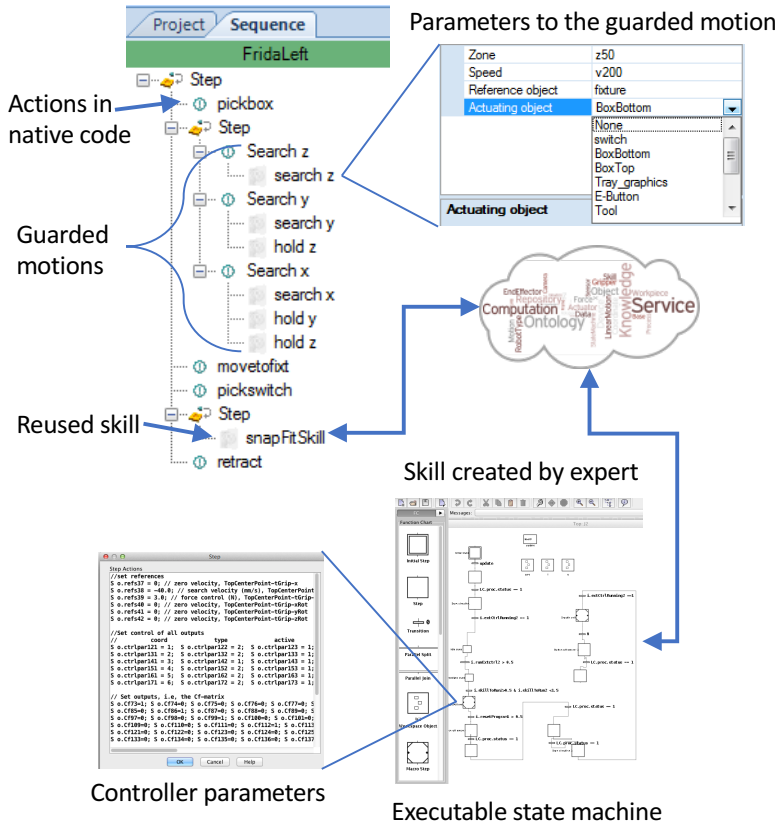


Figure 5: Example of task sequence for aligning a box and inserting a switch using a *snapfit* skill. The user edits high-level skill parameters such as points on objects, force thresholds and velocities.

had to be changed had a human readable format. The reference frames needed to set up the closed kinematic chain was extracted from the graphical interface directly, and the sensor signals were also generated to match the force sensor or estimation (converting units, adding offsets and orientations etc.). Further details are found in Paper III and an overview of the steps is displayed in Fig. 5 and 6. The example in Fig. 6 was part of the emergency stop button box, the user specified 67 parameters counting the default values for e.g., velocities, this corresponded to 393 parameters in the executable state machine.

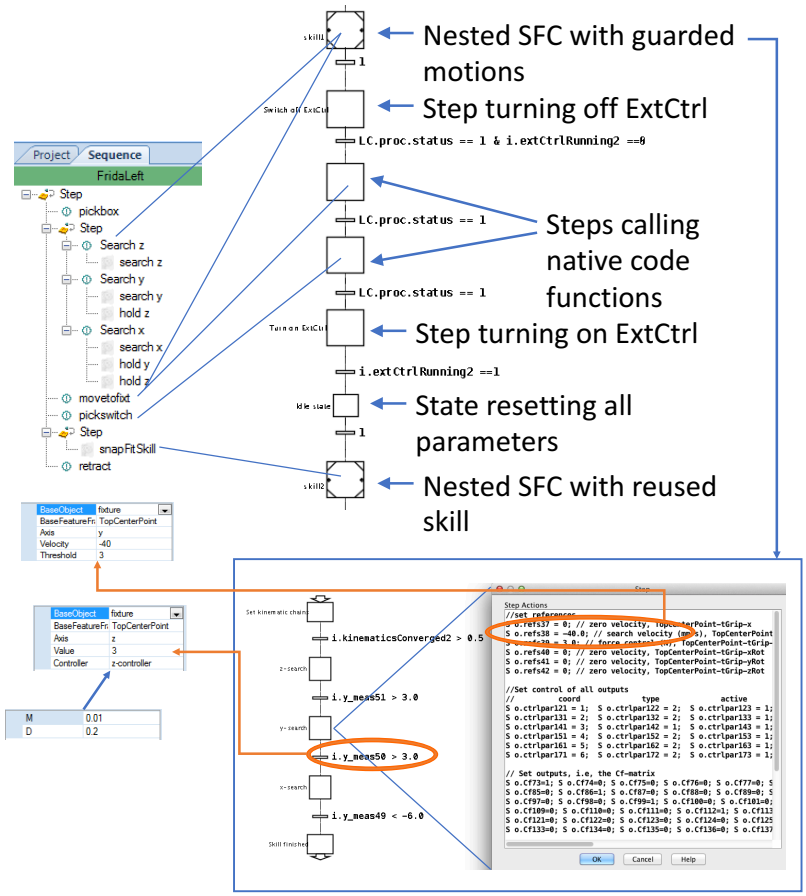


Figure 6: For each step in the sequence in the Engineering System, steps for the executable state machine were generated, as well as steps for switching between the controllers and initializing the kinematic chains. The low-level sensor and controller parameters were set automatically.

3 Human-robot Interaction

Although the user interface in the Engineering System reduced the programming effort for experts, it used the traditional offline programming workflow. After analyzing the use cases, we implemented a prototype for online programming that reduced the number of features and only generated native code. The prototype was implemented as a Windows app that ran on a Surface Pro tablet. The prototype was used to evaluate the skill representation from a usability and user perspective. The resulting iconic programming interface is shown in Fig. 7.

The implementation has shortcut buttons (to the top left) that generate macros for the most common instructions. Each instruction was represented as an icon in the program sequences to the right. For example, the `Contact Move` was a macro for contact force detection with reasonable default parameter values for velocity and torque. Synchronized motions and rendezvous points were added in pairs. The example sequence shown in Fig. 7 contains multiple synchronized motions, *master-slave* motions, where the right arm follows the left to move a lid bi-manually and insert it on a box (see Paper v). Testing and debugging was facilitated by for example automatic execution of synchronized actions during debugging, and through individual play buttons on each instruction for testing skills or actions and updating positions with a single click. The user could also select a subset of instructions to execute (`Run Selected`) or start the execution from an arbitrary point in

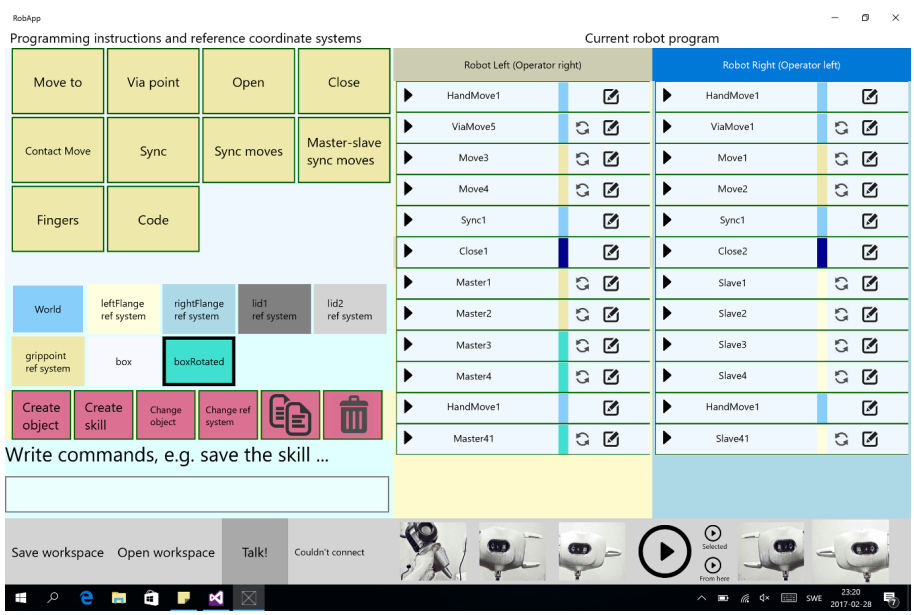


Figure 7: The graphical user interface for skill-based end-to-end programming.

the program (`Run from here`). The task was represented as a sequence and generated native code, which the operator could modify further. Any native code procedure could be called from the graphical interface directly using the `native code` instruction. The programs could be saved as skills and were then added in the same panel as the macros. When initializing an empty workspace, there were only reference systems for absolute coordinates (called `World` in the graphical user interface) and the respective flanges, and the user had to create new reference systems by pointing out `objects` using the robot arms.

The main difference compared to other tools was the support for iterative refinement and abstraction. This was facilitated by storing both the joint values, the absolute and, if a reference object was used, relative Cartesian position for each motion. The user could therefore switch back and forth between the reference systems, which allowed a workflow that started with testing in absolute coordinates, followed by the addition of suitable object coordinate systems (such as the desired grip positions).

As presented in Paper IV, we evaluated the prototype in a user study with 21 non-expert subjects for *task prototyping* and debugging of an application that they were familiar with (Duplo building). After a three-minute introduction to the tool, the subjects had 30 minutes to program the robot to pick LEGO pieces and insert them robustly on a tower. In subsequent steps, the users had to reuse either their own or an expert-made skill, and, as a control group, some had to reprogram everything. Out of the 21, 19 succeeded in developing a robust solution for the initial task and 14 managed to complete at least one additional step. We could also see that reuse simplified the programming significantly.

For expert programmers instructing single and dual-arm tasks, the programming time was reduced with 70-80%. Because synchronized skills were coupled and each action stored multiple target representations, the flange position of both arms were known when the synchronized motions started, and the reference frame of one arm could be changed to the other to reconfigure the coordination to master-slave mode. That is, the user could switch the master and the follower arms by changing reference frame of the master to the flange of the other arm. The graphical interface corrected automatically dubious combinations such as both arms moving relative to each other or one arm relative to itself. When dual-arm skills were swapped between the arms, the position of the slave arm was inverted. The synchronized motions could also be relative to objects, either the same or separate, and by changing the reference system the dual-arm motions could be rotated or mirrored as described in Paper V.

The design of the code behind the prototype is modular so that both the graphical view (e.g., with two robot arms) and the code generation and robot communication can be easily exchanged. The last version of the prototype also supported the natural language programming features for English.

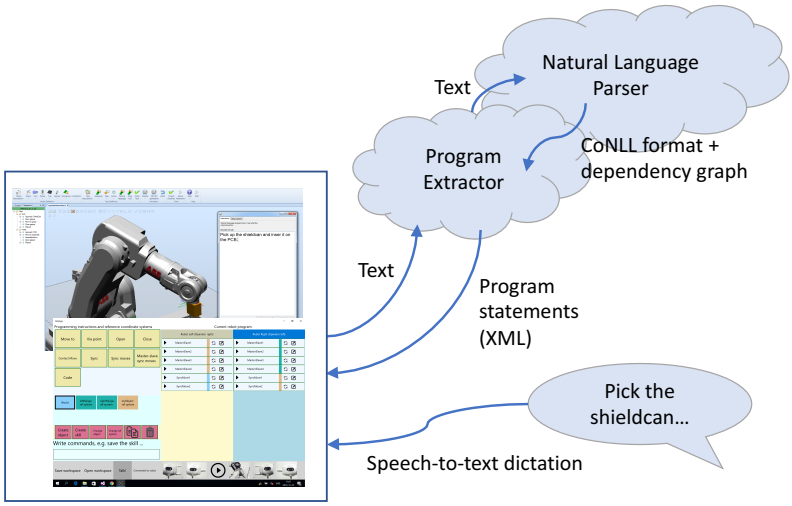


Figure 8: The user writes or dictates the instructions to the robot, the text is sent to the program extractor that in turn calls the semantic parser. The parse result is matched to program statements and the resulting sequence is returned to the user interface.

4 Natural Language Programming

The natural language programming interface that we developed consisted of a chain of speech-to-text dictation, semantic analysis of the text using the general-purpose Lund parser for semantic role labeling, a program statement extractor algorithm that matched the sentences to robot programs, and finally, an instantiation to robot programs using the knowledge in the system, as shown in Fig. 8. The user gave the instructions either by typing or using off-the-shelf dictation tools (Android speech-to-text API, Windows dictation or Google cloud services). The text was sent to the program extractor together with a description of the robot workspace including predefined commands, user created object and skills with names and types. The program extractor was implemented as a Java servlet and was deployed on the KIF server. The servlet separated the instructions into sentences and forwarded them one-by-one to the Lund parser. The output from the parser was then then matched to the existing robot programs by using the (nested) predicate-argument structures starting with the root predicate (Paper VI and VII).

Because of the general-purpose parser, the user could extend their own vocabulary on the fly (Paper IX), by naming objects and skills with arbitrary names without retraining the system. For the speech-to-text interface, we tested both the Android speech recognizer on a tablet and the Microsoft .Net API, with best results for the Android API, however, the free form dictation is the weakest point in the chain because it often failed in the noisy lab environment.

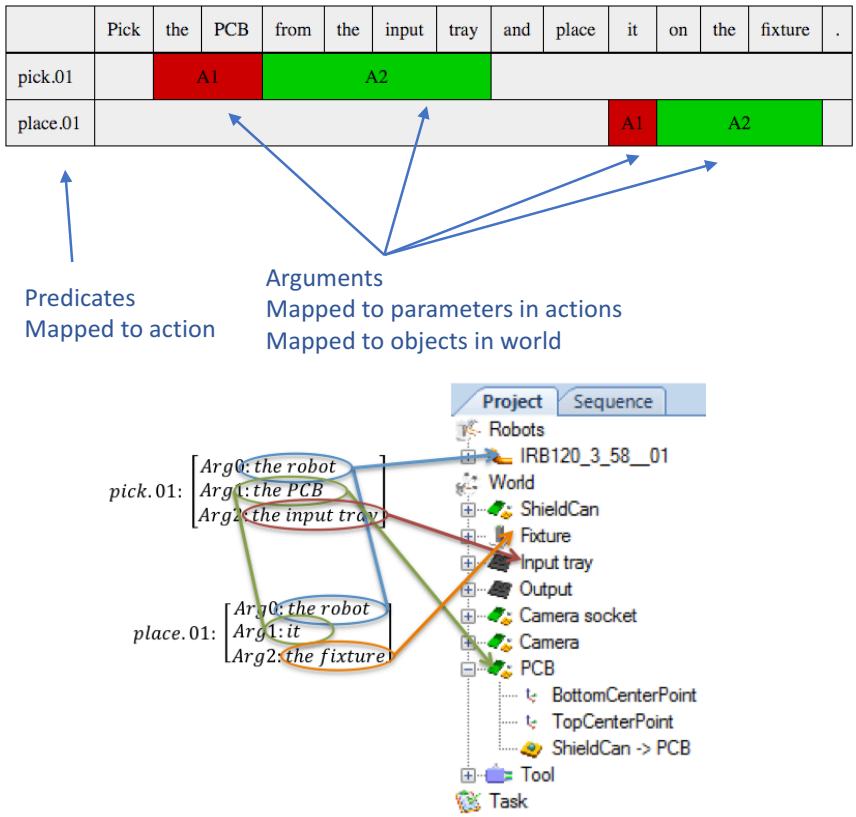


Figure 9: The semantic output is matched to skills and objects in the robot workspace.

An example is shown in Fig. 9, where the instruction *Pick the PCB from the input tray and place it on the fixture* was parsed into two predicates (*pick.01* and *place.01*) and each predicate had two arguments. If no other actor (*A0*) was mentioned, the robot was used as default. The predicates could either be mapped to robot skills or commands from the workspace description, or if the predicate was a *wildcard* (*do*, *use*, *assemble* and some types of *move*), the arguments determined the action type, that is, if the arguments included a skill name or a nested predicate argument structure (e.g., a condition) this would be used. The arguments could either refer to objects in the world, measurements or skills. The program statement extractor returned a sequence of program statements, `Statement`, with actions IDs from the robot workspace and object arguments (ignoring determiners etc.) with type and cardinality. Conditions were subtypes to `Statement`, either parallel (`AndStatement`), branching (`IfStatement`) or guard conditions (`UntilStatement`), which linked to the nested condition `Statements`, created from the nested predicate-argument structures in the sentence as described further in Paper VII.

In this example, the PCB is a named object in the workspace. When the argument is in plural form, e.g., *pick all PCBs* or *pick three PCBs*, the resulting match will identify the objects by type (*PCB*) and select all or three depending on cardinality. Coreferences (*it*) would naively be solved by using the last object(s). When the program sequence was returned to the user interface, it still had to be instantiated with correct parameters. E.g., by using the positions of the objects and spatial relations between the objects. Ambiguities were solved to match the object types as close as possible to the parameter types in the skills (e.g., *assemble the PCB and the shieldcan using shieldcan insertion* can be interpreted as inserting the *PCB* on the *shieldcan* or vice versa, but because the *shieldcan insertion* skill was created using an object of type *shieldcan* as a manipulated object (and *PCB* as a fixed frame), the best match would use the same types. Similarly, when instantiating loops over multiple objects, for example in the palletizing example in Fig. 1, where several pins were moved to a pallet, the pallet or tray properties were used to generate a grid of insertion positions.

Summary of the Included Papers

Paper I

A Knowledge-based robotic system architecture

The paper presents our knowledge-based software architecture with an online knowledge integration framework (KIF) containing ontologies for robots, devices, sensors and tasks. The knowledge is modeled in modular ontologies. The base ontology is the `rosetta.owl` which contains robots and devices. `frames.owl` describes relative coordinate frames that can be attached to objects and are used to specify a *kinematic chain*. Robot programs are described as sequential function charts in `sfc.owl`, and the action parameters are described in `params.owl`. KIF contains a database with semantically annotated expert-made skills that can be downloaded by the user interface (the Engineering System) and deployed on different types of robot systems. It also presents the reasoning services on KIF which provides program sequence verification, a natural language interface, and code generation that the user invokes from Engineering System.

Paper II

Cloud-based robot architectures

The paper presents experiences from four European projects (SIARAS, ROSETTA, PRACE and SMErobotics) and their software architecture. The SIARAS software system supported reconfiguration of the robot cell provided utility functions and interfaces to simulation tools in the cloud. The `siaras.owl` ontology was the embryo to what later would be ROSETTA ontology. The ROSETTA architecture was focused on knowledge-sharing for automatic robot program generation by skill reuse. In the PRACE project, the focus was to simplify the human-robot interaction by extracting task parameters from demonstrations. SMErobotics evaluated an architecture suitable for small and medium sized enterprises (SMEs) and formulated the requirements of a useful skill representation.

Paper III

Code generation for force-controlled skills

The paper presents the code generation process where high-level sequences of parameterized actions created in the Engineering System are transformed into executable force-controlled robot code for the external force controller. The steps in the sequence can either be position-based robot motions relative to object positions, reusable skill implementations downloaded from KIF, or created as guarded search motions using the coordinate frames specified on objects using CAD models in the virtual simulation environment. The guarded motions have a search direction along one of the axes on a coordinate frame, a stop condition (a force value) and possible force-constraints in other directions than the search. The executable code is a state machine in the Grafchart language where additional steps for switches between the position and the force controller are added, the kinematic chain is setup automatically using the robot type and the frame parameters. Each guarded search sets new reference values for force and velocities in different directions, as well as the transition conditions. The code generation works for four ABB robots.

Paper IV

Prototype evaluation for simplified programming of reusable robot skills

After two case studies, a programming prototype was developed to simplify the robot programming and debugging using a graphical user interface together with lead-through programming. The prototype was evaluated in a user study with 21 non-experts as well as an expert programming test. The users had to program a Duplo building task using a single-arm and macros for motions, gripper actions and primitives for vision and contact force estimation. The result showed that 19 out of 21 non-experts could program the task after a 3-minute introduction. The average time to finish the task was 20 minutes. Additional tasks were carried out to test skill reusability by dividing the test subjects into 3 groups: the first group reused their own skill, the second group received an expert-made skill and the third group had to program everything from scratch. The sample set was small, however, we could conclude that the expert-made skill was the easiest to reuse. Another interesting observation was that the correlation between success rate was very weakly correlated to the users' self-reported experience with programming and machinery. The programming time for the expert was reduced by 80%.

Paper v

Reusing and transforming synchronized dual-arm skills

The prototype from paper IV was further developed to support dual-arm synchronized motions, either in master-slave configuration or relative to object coordinate frames. Traditional dual-arm robot programming treats the robot arms as two separate tasks and synchronization adds a large overhead. In our prototype, the synchronized motions are treated as linked entities and automatically executed, deleted or moved in pairs. The linking lets the user swap the programs for each arm in master-slave configurations and the master arm will be switched and all relative positions updated to the inverse transformation for the (new) slave arm. The prototype was also evaluated for task transformations in a gift-wrapping application. When switching the arms the relative positions for the arms can either be rotated if a single point of reference is used. Using two reference pairs of opposite points, the task was mirrored after the switch.

Paper VI

Natural language programming of industrial robot tasks

A method for natural language programming was presented where the output from a general purpose statistical parser with semantic labeling was matched to high-level robot skills and objects in the robot's workspace. The semantic output from the parser, created by Björkelund et al. (2010) consists of a table of predicate-argument structures, where the predicates corresponds to the action or verb in the sentence and the arguments are the objects acted upon. The architecture had a small library of robot skills, each with natural language labels and position parameters relative to objects. Mapping the predicates to robot skills and the arguments to the object parameters, a skeleton of a task could rapidly be generated from written unstructured natural language descriptions. The functionality was demonstrated with pick-and-place tasks. The objects were matched to the arguments by name or type and coreferences (*it*) were solved naively by using the previously identified object. The knowledge from the system was used to set parameters for the generated action sequence, e.g., the skills for opening and closing the gripper were extracted from the device description and spatial constraints between objects were used as parameters for relative positions.

Paper VII

Extracting constraints from natural language instructions

The natural language programming interface from Paper VI was further developed to support the generation of force-controlled search motions, control structures such as loops, parallel constraints and skills as arguments. The output from the semantic parser can be ordered as a tree where the main activity is the root (or higher up in the tree). The tree and the semantic labels are matched to program structures using an algorithm that extracts conditionals for each predicate. That is, predicate-argument structures that are nested by *while*, *until*, *if* and *when*. The nested predicate-argument structures were labeled by the parser as temporal or locational arguments. The *until*-conditions were mapped to transition conditions in the guarded motions and the *while*-conditions were mapped to parallel constraints, for example a constant force during a search. The conditions could be nested using *and* or *or* and express sensor readings or by using keywords for default parameters (*contact* and *timeout*). When multiple objects are mentioned, e.g., *take three needles and put them in the pallet*, the cardinality is used to generate a loop over three objects with the type *needle* and, one-by-one, pick them and place them in a pallet. The ambiguity from the example sentence (whether to pick all three needles at once and then placing them one-by-one) was solved by using the knowledge about the gripper (if it could hold more than one object) and the pallet, which has a grid of potential positions. The conclusion of the paper was that the low number of robot skills available in the library was a limiting factor in the application.

Discussion

Before we reach the robotized society of tomorrow, with mechanical co-workers and delivery drones, where human labor is precious and pleasant, we have to find solutions to several challenges. To reiterate a few: present day robots are difficult to instruct and interact with, and the hard work results in tailored applications that are neither general, reusable nor robust. The robots have poor perception and situational awareness, and unforeseen situations end in failures. Even if failure is detected, they can hardly reason about why, or what to adjust or redo to complete the task. For the human operator, it can be cumbersome to resolve the issues and correct the program accordingly.

Researchers have addressed these issues for years. There are high-level planning approaches, low-level sensor control, and user experiments evaluating how people prefer to instruct robots. We have reviewed several intermediate action representations that support contrasting efforts, focusing on various aspects, from verbalizing actions, to solving collaborative dual-arm motions. However, we cannot find a useful representation by just looking at the question from one perspective, because the *problem* is the gap between how humans and machines describe actions and perceive objects, and the robot systems have both symbolic AI reasoning processes and robotic devices acting and sensing in the real world. Humans describe tasks in high-level unstructured language, while the reasoners work with high-level formal languages and the physical systems interpret and execute tasks in low-level platform-specific (structured) code. We needed to use a holistic approach, because the problem of simplification of robot programming is not about optimizing one single algorithm, it is about creating a system that functions efficiently as a whole.

In the skill representation that we developed, we attempted to take all these perspectives into account. We used a high-level ontological approach where we modeled symbolic knowledge, as well as code generation for the low-level platform-specific code. We evaluated it from a user perspective, to verify that the representation was useful and simplified the robot programming. We also presented a method for extracting program statements from unstructured natural language instructions. To be able to carry out our experiments, we developed a robotics software architecture with a knowledge base, reasoning services, programming interfaces and task execution.

The work was carried out iteratively. First a knowledge framework was developed where we modeled complex skills and evaluated the code generation and skill transfer. However, this required expert-made skills as well as detailed annotation, which was time consuming to create. To bootstrap the skill acquisition, we developed a (simplified) user interface where both non-experts and experts could program skills from scratch. The semantic annotations were extracted using natural language, which the user could then use to interact with the robot. In the following sections, we will discuss the implementation in more detail and compare with related work.

1 Knowledge Representation

First, we developed a knowledge-based architecture and the core ontological concepts. Previous work in the robotics domain used ontologies to model mostly positions and simple kitting applications. Only recently Perzylo et al. (2016) provided a model of geometrical knowledge and spatial constraints in a suitable ontology. Our work extended the state-of-the-art to include assembly skills, parameters, specification of kinematic chains and the description of devices and robots. The focus was industrial assembly operations. The ontologies are modular to avoid conflicts and let the user select only the dependencies they want.

We chose to implement the database as an RDF triple store to provide reasoning services because it was more flexible than a relational database with fixed tables and there existed multiple inference engines. One drawback with the approach is that queries to the repository can become very slow if not expressed in an effective manner, for example, by explicitly binding subgraphs to variables. Another option that we briefly investigated was to use a graph database, Neo4J, where the literal properties can be directly attached to the nodes so that the information is stored in a compact format, however, there was no inference engine that we could use.

The skills are shared in a cloud-based architecture where multiple robots can access the same skill database and knowledge-based AI services. Other architectures have explored functionality in other directions, e.g., were used to generate PDDL from action descriptions to automatically plan and replan tasks on a high level. While, e.g., RoboEarth (Waibel et al., 2011) populated their skill database from natural language text of, e.g., cooking instructions, such approach assumes that there exist executable skills for each instruction, an assumption we could not make because our domain focuses on assemblies of novel products.

Our approach is philosophically different from the Action-Object-Complexes, in that it is not the object that affords skills, the objects are mere parameters to the skills, rather, it is the devices that have skills as capabilities. In this way, we do not have to model the human

as an *object* during user interaction, and, e.g., dancing and waving are simply non-object relative actions. Otherwise, the concept of pre- and postconditions are similar, however, they ground the actions using trajectories extracted from human demonstrations encoded as HMMs, while we focused on providing programming tools that let the user manipulate the representation directly.

2 Code Generation

During the initial evaluation presented in Paper III, we focused on the low-level code generation functionality, therefore ignoring the complexity of the system setup from a usability perspective. It had required experts from automatic control to create the force-controlled skill and experts in knowledge representation to create the ontology descriptions. The assumption that a robot system would have access to a library of robust expert-made skills did not scale, because the acquisition of expert-made general-purpose skills was a bottleneck in the system. Worse yet, just because the generated programs were syntactically *correct* and *executable*, did not mean that the program worked well on the new robot, e.g., the velocity and force parameters had to be adapted depending on the robot and sensor type. The latter is a focus of the related field of *parameter learning*, where automatic adaption and exploration of parameters can be used to optimize assemblies. Learning can also be used to detect errors, e.g., by learning a nominal force profile and then detecting deviations from it. The work to automatically adapt parameters during deployment was out of scope of this thesis. However, the reason the skills and the parameters were typed was to simplify the use and integration of existing algorithms for low-level parameters optimization.

3 Human-robot Interaction

High-level approaches are limited by the small number of executable robot skills in the library, where the knowledge must be modeled and added into the system by an expert in knowledge engineering or in robotics. Hence, we had to bootstrap the knowledge acquisition by developing a simple programming prototype that non-expert operators could use, which was evaluated in Paper IV and V. It limited the usage to object specification and sequential skill programming of dual-arm robot programs. For practical reasons, specifically the high implementation effort to integrate functionality in an experimental lab setup, we limited what type of features we evaluated in the user study, e.g., we left out speech, trajectories and the teaching of force-controlled policies and vision calibration. Also, the functionality described in the chronologically earlier papers was not evaluated, that is, the users did not try more complex guarded motions or reuse skills between different types of robots, which were discussed in for example Paper III. This is a very relevant direction

of future work and the user interaction for instructing and refining trajectories and force-controlled tasks is an active research area in the robotics community.

In the gift-wrapping application, the collaborative aspects of the task had to be reduced to preparation work (putting the paper and the box in front of the robot), starting the process through a graphical user interface and manually resume the program after the user gave a ribbon to the robot. This interaction had to be programmed in native code and the current user interface does not aid the non-expert user in creating collaborative tasks. In related work, multi-disciplinary teams with both robot programmers and interaction experts developed interfaces for programming of interactive tasks using high-level modules. Non-expert programming of collaborative human-robot tasks from scratch is an exciting area of future work.

4 Skill Creation

For a skill library to be useful, the intended users must be able to understand, adapt and modify the downloaded skills. Also, it must be easy to create and add new skills to the library for both experts and non-experts. While other approaches use multiple demonstrations to train skill models, in our context this approach is intractable for two main reasons: even a single demonstration is time consuming to carry out sufficiently well, and a black-box model with implicit (hyper-)parameters that the operator cannot interpret is undesirable. When using demonstrations, it must be clear what and how the user should demonstrate, e.g., the operator can use a haptic device to input a specific parameter value for a force-controlled task. We developed a prototype interface for one-shot instructions where non-experts could program reusable skills from scratch.

5 Dual-arm Manipulation

The programming of dual-arm motions poses a challenge from both a programming and a control point of view. The position- and force-based control of coupled arms can be handled by, e.g., coordinated DMPs (Zhou et al., 2016) or by setting up a closed kinematic chain using the iTasC formulation (Stolt et al., 2011). Instructing multiple robot arms to carry out coordinated tasks adds a potentially large overhead for the operator, hence related work has investigated specifying the movements of multi-robot systems as trajectories on the workpiece or by extracting trajectories from human demonstrations. Synchronized tasks are difficult to extract from for example kinesthetic demonstrations using the robot, because the user has to physically move both arms simultaneously which is only feasible on small robots. Other approaches track human demonstrations using vision, which then must be mapped to the robot.

However, in our gift-wrapping use case, we used the full arms to move and hold the package and these full arm motions are not easily extracted from observations of humans or expressed as end-effector trajectories relative to the object. Instead, we focused on reducing the workload during the programming process for expert users. By simple means such as debugging actions in pairs and setting up the master-slave configuration with default values, we could significantly decrease the programming time for the dual-arm tasks in our experiment. While programming dual-arm motions, especially in contact, the need for robust speech commands became evident.

6 Natural Language Interfaces

The system used general purpose components to analyze the language commands, and especially the speech-to-text dictation was a weak link in the chain because of noisy laboratory environments, non-native English speakers and application-specific user specified vocabulary (e.g., *PCB*, *snapfitskill*). In further experiments, components of the system were replaced, e.g., the different dictation APIs were evaluated, the semantic parser was switched to Swedish and mapped to English program descriptions using dictionaries and synonyms. The arguments to the actions can be sensor values, however, the examples using force parameters were somewhat artificial, because it is more suitable to input the forces using other means, e.g., haptic devices or external force measurements. Other applications that use natural language programming in robotics extract, e.g., spatial information from the sentences for direction following for mobile robots. They learn their models from examples and the resulting application can effectively run locally on a battery-driven mobile system, instead of using a cloud-based solution. One drawback with such an approach is that if the user wants to extend the vocabulary, it requires multiple examples and retraining. This can be mitigated with generated grammars as presented by Perzylo et al. (2015a) resulting in a structured language interface. The related work that used intermediate representations, such as the verbalized effects, was verb-centric, mapping the verbs to robot actions. While the predicate-argument structures that we use are verb-centric as well, the skills can be the *argument* if the predicate is a *wildcard* in sentences such as *Do a snapfit* and *Assemble the shieldcan and the PCB using the shieldcan insertion skill*. The use of conditions and parallel action extractions is to our knowledge not well investigated in the robotics community.

The modular architecture allowed the components to be switched, e.g., both the Engineering System and the Windows app called the same program extractor that was deployed as a Java servlet on the KIF server. We created an English version as well as Swedish version of the servlet, the first was presented in Paper VI and VII, the bilingual program extractor was presented in Paper XIII. The Swedish statement extractor implemented the same algorithm as presented in Paper VII, but a few language adaptions had to be made because the Swedish semantic parser was less robust and it used automatic translation to find skills with originally English natural language names.

7 Future Work

Future work can be extended in several directions, here I will only mention the ones that I personally am interested in investigating. One of the programming features that has been discussed in the literature but that was out of scope of this work, was the programming of fully collaborative tasks, where non-experts create a task involving dialogues and physical interaction with humans. Also, psychological aspects in human-robot interaction, such as trust (see, e.g., Sadrfaridpour et al., 2016) are out of scope.

While the presented user interface supports some simple debugging and automatic transformations of the program and high-level features such as natural language support, many interesting areas of research have been left out. For example, the dialog system for user interaction is very rudimentary, so potential future work includes a robot system that asks questions to resolve ambiguities and collect user data to provide helpful suggestions, e.g., by presenting suitable skills from the database depending on what types of objects the user adds. Also, the semantic extraction is limited to skill and object types (and parameter types), and pre- and postconditions still need more advanced users.

Last words

There are people who look towards a robotized future with dread, regarding automation as a threat to jobs and society. Others look forward to a life in leisure in a post-scarcity economy. Some think robots will take over the world, either out of malice or ignorance. If the present is a book, it is open-ended. I am aware that I cannot make any assumptions about the *unknown*, but I *believe*, that to make robots helpful, they need to be able to comprehend what we *want* and not just obediently follow their programming. They need to be able to understand the meaning of their actions and goals, and the reason behind them. They need to know when to follow a human command and when to refuse. They need knowledge.

Scientific publications

Included papers

Co-authors are abbreviated as follows:
Jacek Malec (JM), Elin A. Topp (ET), Mathias Haage (MH), Klas Nilsson (KN), Anders Robertsson (AR), Andreas Stolt (AS), and Pierre Nugues (PN).

Paper I: Knowledge-Based Instruction of Manipulation Tasks for Industrial Robotics

I did the implementation of the knowledge-based services for sequence generation from language, assembly graphs, scheduling and task checking as well as the corresponding implementation in the Engineering System. JM did the implementation of the knowledge integration framework and the original ontologies from SIARAS and RoSta and SFCs. I added ontologies for frames and parameters and added pre- and postconditions to the ROSETTA ontology.

Paper II: On Distributed Knowledge Bases for Small-Batch Assembly

The paper presents the experiences of cloud-based robotics architectures from several research projects. I did the implementation of the Engineering System and reasoning services presented in the sections regarding ROSETTA and PRACE. JM did most of the work related to knowledge integration. KN contributed with the SME perspective and AR contributed collecting and discussing the experiences from the different types of cloud-based architectures.

Paper III: From High-Level Task Descriptions to Executable Robot Code

I did the high-level implementation of the graphical user interface where, e.g., parameters and coordinate frames were specified by the user. I implemented the code generation service that generated the task level state machine, that, e.g., switched between position and force-controlled skills. JM was responsible for the knowledge integration framework. AS implemented the code generation for the guarded motions where the kinematic chain was

setup and reference values specified to the controller. AS also implemented the low-level control algorithms.

Paper IV: Simplified Programming of Re-usable Skills on a Safe Industrial Robot – Prototype and Evaluation

I did and ET did the analysis of the case studies, I did the implementation of the prototype and MH did code review and minor feature additions. The study design to evaluate reuse was done in cooperation between me and ET, I was responsible for the task design and pilot testing, she was responsible the setup with video and consent. During the study we share the task of monitoring the subject. I carried out the expert evaluations. The data presented in the paper was measured by ET from the collected video material.

Paper V: The Art of Synchronized Dual-Arm Robot Programming

I did the implementation of the dual-arm programming interface and I and MH carried out the expert evaluations. I and ET developed the ideas behind the user interaction from Paper IV further to include dual-arm motions. The representation of the synchronization and task transformations relative to objects is based upon long standing discussions between all co–authors.

Paper VI: Natural Language Programming of Industrial Robots

I developed and implemented the method of mapping predicates to robot programs and arguments to objects, PN did the parser interface and semantic parsing that he and others had developed in previous work.

Paper VII: Describing Constraint-Based Assembly Tasks in Unstructured Natural Language

I did the development of the additional natural language features and the implementation in the Engineering System. The resulting task is generated using knowledge about the world and object relations using ideas developed by JM.

Other contributions

viii **Making Robotic Sense of Incomplete Human Instructions in High-level Programming for Industrial Robotic Assembly**

M. Stenmark, M. Haage, EA. Topp, J. Malec
AAAI-17 Workshop on Human-Machine Collaborative Learning, 2017, AAAI Press.

ix **Supporting Semantic Capture during Kinesthetic Teaching of Collaborative Industrial Robots**

M. Stenmark, M. Haage, EA. Topp, J. Malec
Proc. of the 2017 IEEE 11th International Conference on Semantic Computing, 366-371, 2017. DOI: 10.1109/ICSC.2017.40

x **From Demonstrations to Skills for High-level Programming of Industrial Robots**

M. Stenmark, EA. Topp
AAAI Fall Symposium 2016. Technical Report FS-16, 2016, 75–78, AAAI Press.

xi **Robotic Gift Wrapping or a Glance at the Present State in Santa's Workshop**

A. Stolt, **M. Stenmark**, A. Robertsson, K. Nilsson
Paper presented at Reglermöte 2016, Gothenburg, Sweden.

xii **The GiftWrapper: Programming a Dual-Arm Robot With Lead-through**

M. Stenmark, A. Stolt, EA. Topp, M. Haage, A. Robertsson, K. Nilsson, R. Johansson
ICRA Workshop on Human-Robot Interfaces for Enhanced Physical Interactions, 2016, available at http://robotics.ozyegin.edu.tr/icra16workshop/papers/

xiii **Bilingual robots: Extracting robot program statements from Swedish natural language instructions**

M. Stenmark
Frontiers in Artificial Intelligence and Applications. Vol. 278: 13th Scandinavian Conference on Artificial Intelligence, 2015, 137–146, IOS Press, DOI: 10.3233/978-1-61499-589-0-137

xiv **Connecting natural language to task demonstrations and low-level control of industrial robots**

M. Stenmark, J. Malec
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Abstract, Robotics: Science and Systems, Workshop on Programming with Constraints, 2013, available at https://robohow.eu/meetings/rss-2013-constraints-workshop

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Part II

Included Papers

Paper 1

Paper I

Knowledge-Based Instruction of Manipulation Tasks for Industrial Robotics

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ABSTRACT

When robots are working in dynamic environments, close to humans lacking extensive knowledge of robotics, there is a strong need to simplify the user interaction and make the system execute as autonomously as possible, as long as it is feasible. For industrial robots working side-by-side with humans in manufacturing industry, AI systems are necessary to lower the demand on programming time and system integration expertise. Only by building a system with appropriate knowledge and reasoning services can one simplify the robot programming sufficiently to meet those demands while still getting a robust and efficient task execution.

In this paper, we present a system we have realized that aims at fulfilling the above demands. The paper focuses on the knowledge put into ontologies created for robotic devices and manufacturing tasks, and presents examples of AI-related services that use the semantic descriptions of skills to help users instruct the robot adequately.

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DOI: 10.1016/j.rcim.2014.07.004.

1 Introduction

The availability of efficient and cheap computing and storage hardware, together with intensive research on big data and appropriate processing algorithms on one hand, and on semantic web and reasoning algorithms on the other hand, makes the existing results of artificial intelligence studies attractive in many application areas.

The pace of adoption of the knowledge-based paradigm depends not only on the complexity of the domain, but also on the economic models used and the perspective taken by the leading actors. It may be quite well illustrated by opposing the service robotics area (mostly research-oriented, mostly publicly funded, using open source solutions, acting in non-standardized and not-yet-legally codified domain) with industrial robotics (application-oriented, privately funded, using normally closed software, enforcing repeatability and reliability of the solutions in legally hard-controlled setting).

When robots are working in dynamic environments, close to humans lacking extensive knowledge of robot programming, there is a strong need to simplify the user interaction and make the system execute as autonomously as possible (but only as long as it is reasonable). This also motivates the integration of AI techniques into robotics systems. For industrial robots working side-by-side with humans in manufacturing industry, AI-based systems are necessary to lower the programming cost with respect to the required time and expertise. We believe that only by building a system with appropriate knowledge and reasoning services, we can simplify the robot programming sufficiently to meet those demands and still get a robust and efficient task execution.

In this paper, we present a knowledge-based system aimed at fulfilling the above demands. The paper is focusing on the knowledge and ontologies we have created for the robotized manufacturing domain and is presenting examples of AI-related services that are using the semantic descriptions of skills to help the user instruct the robot adequately. In particular, the adopted semantic approach allows us to treat skills as compositional pieces of declarative, portable and directly applicable knowledge on robotized manufacturing.

The paper is organized as follows: first we introduce the robot skill, then we describe the system architecture. Next section introduces our robot skill ontology and other relevant ontologies available in the knowledge base, as well as some services provided by the system. Next we introduce the interface towards the user, i.e. the Engineering System, and briefly describe the program execution environment exploiting the knowledge in a non-trivial way, then we describe the related research. We conclude by suggesting future work.

2 Robot Skills

Our approach is anchored on the concept of a *robot skill*. As it may be understood in many different ways, both by humans and machines, it needs to be properly defined and made usable in the context of our domain of applications. The presentation in this section adopts a historical perspective, showing how our understanding of skills pushed forward the capacities of systems we have created.

Our earliest deployed system has been developed in the context of the EU project SIARAS: *Skill-Based Inspection and Assembly for Reconfigurable Automation Systems*. Its main goal was to build fundamentals of an intelligent system, named *the skill server*, capable of supporting automatic and semi-automatic reconfiguration of the existing manufacturing processes. Even though the concept of skill was central, we have assumed *devices* as the origin of our ontology. Our idea then has been that skills are just capabilities of devices: without them no (manufacturing) skill can exist. A device can offer one or more skills and a skill may be offered by one or more devices. We have not introduced any granularity of such distinction; all the skills were, in a sense, primitive, and corresponded to operators as understood by AI planning systems (models of operations on the world, described using preconditions, postconditions, sometimes together with maintenance conditions). This understanding laid ground to the development of a robotic skill ontology, `siaras.owl`, that has been used to verify the configurability of particular tasks given current robotic cell program expressed as a (linear) sequential function chart (SFC). This approach has been proven to be valid, but the ontology grew quite fast and became problematic to maintain, given dozens of robots with a number of variants each, thus multiplying the number of devices. The details of SIARAS approach have been described in Haage et al. (2011). Fig. 1 and Fig. 2 illustrate the basic hierarchy of skills available in the `siaras.owl` ontology.

The dual hierarchy, that of devices, has been illustrated in Fig. 3 and Fig. 4, while Fig. 5 shows some of the properties that can be attributed to devices.

The deficiencies of the SIARAS ontology, that is, atomicity of skills and devices, fixed parameterizations and scalability issues, have led us to reconsider the idea. These time devices did not play a central role any longer, but rather skills have been put in the center. In the ROSETTA project[1] the definition of skills has been based on the so-called production (PPR) triangle: *product*, *process*, *resources* (Cutting-Decelle et al., 2007) (see Fig. 6). The *workpieces* being manufactured are maintained in the product-centered view. The manufacturing itself (i.e., the process) is described using concepts corresponding to different levels of abstraction, namely *tasks*, *steps*, and *actions*. Finally, the resources are materialized in *devices* (capable of sensing or manufacturing). The central notion of *skill* links all three views and is one of the founding elements of the representation.

In case of a robot-based production system, skills may be defined as *coordination of parameterized motions*. This coordination may happen on several levels, both sequencing (expressed, e.g., via a finite state machine or a similar formalism), configuring (via appropriate parameterization of motion) and adapting (by sensor estimation). On top of this approach, based in our case on *feature frame* concept (De Schutter et al., 2007), we have built a set of reasoning methods related to task-level description, like, e.g., task planning. The details are presented in the following sections

3 Architecture

The generic setup describing the intended usage of our approach is illustrated in Fig. 7. The system architecture is very roughly depicted in Fig. 8. The Knowledge Integration Framework (KIF) is a

[1] RObot control for Skilled ExecuTion of Tasks in natural interaction with humans; based on Autonomy, cumulative knowledge and learning, EU FP7 project No. 230902, `http://www.fp7rosetta.org/`.

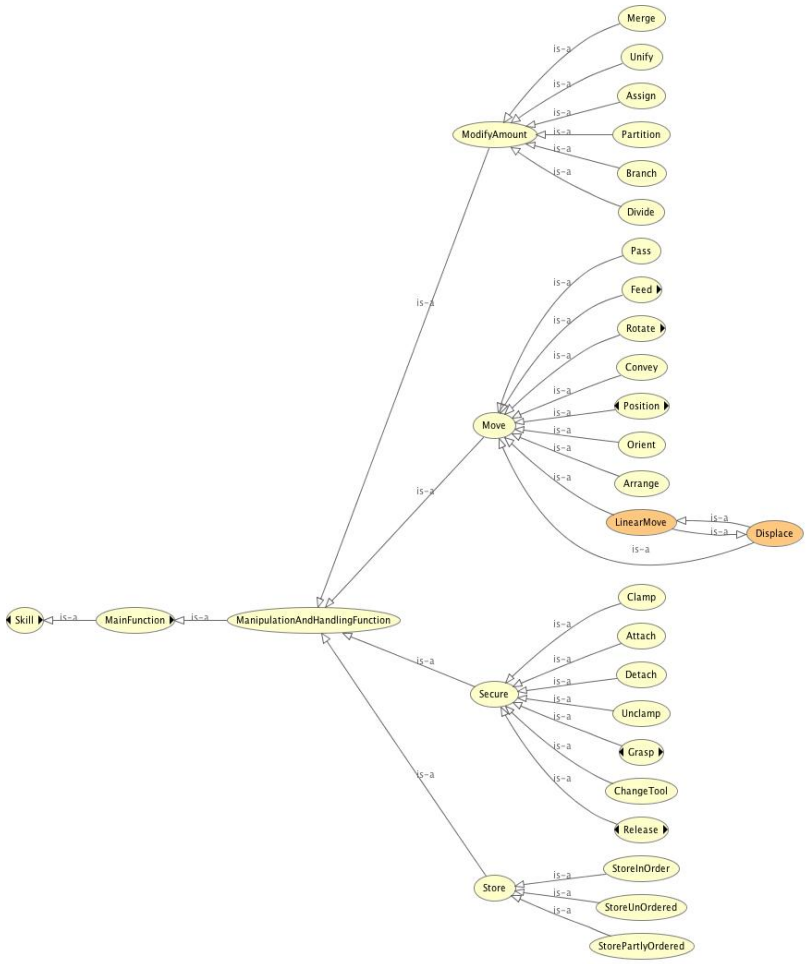

Figure 1: Manipulation and handling skills, as defined by SIARAS ontology.

server that contains data repositories and ontologies. It provides computing and reasoning services. There are two main types of clients of the KIF server, the Engineering System, which is a robot programming environment, and the robot task execution system.

The task execution system is a layer built on top of the native robot controller. Given the task, the execution system generates the run-time code files utilizing online code generation (see Section 5), then compiles and executes the code.

The Engineering System uses the ontologies provided by KIF to model the workspace objects and downloads skills and tasks from the skill libraries. Similarly, new objects and skills can be added to the knowledge base by the Engineering System. Skills that are created using classical programming

Figure 2: Top skill classification, as defined by SIARAS ontology.

tools such as various state machine editors (like, e.g., JGrafchart[2]), can be parsed, automatically annotated with semantic data and stored in the skill libraries.

The services, described later in the paper, are mainly used by the Engineering System to program, plan and schedule the tasks.

[2] `http://www.control.lth.se/grafchart/`

Figure 3: Manipulation and handling devices, as defined by SIARAS ontology.

4 Knowledge Integration Framework

The Knowledge Integration Framework, KIF[3] is a module containing a set of robotics ontologies, a set of dynamic data repositories and hosting a number of services provided for the stored knowledge and data. Its main storage structure is a Sesame[4] triple store and a set of services stored in Apache Tomcat[5] servlet container.[6]

The ontologies we use in our system come from several sources and are used for different purposes.

[3]We realize the name coincidence with Knowledge Interchange Format (Genesereth and Fikes, 1992), but as this name has been used for more than six years by now, we have decided to keep it.

[4]`http://www.openrdf.org`

[5]`http://tomcat.apache.org`

[6]Technically speaking, the triple store is also a servlet.

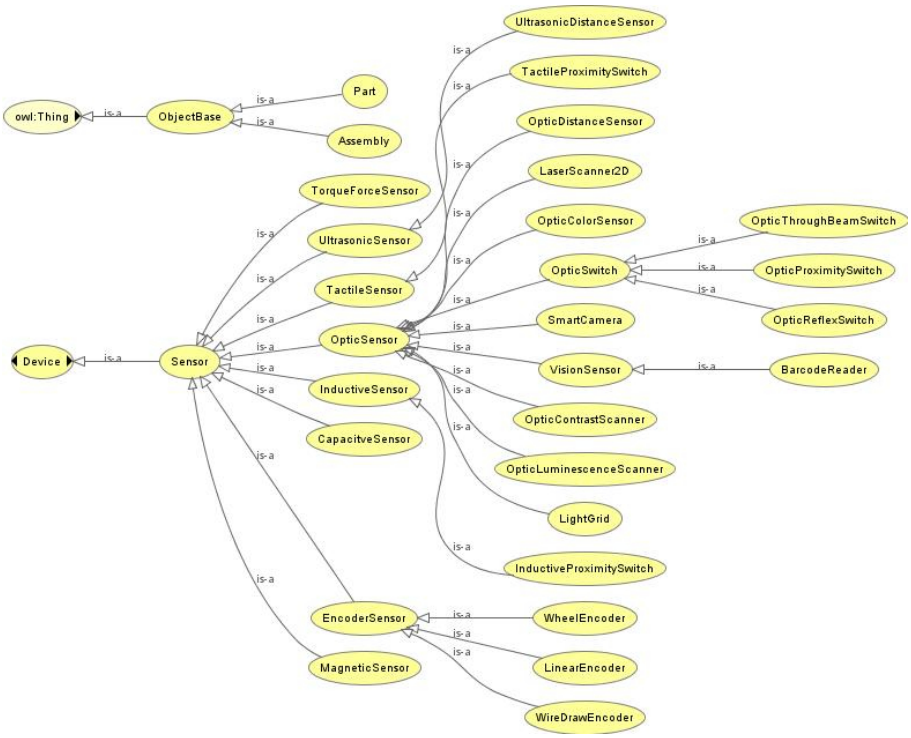

Figure 4: Sensor devices, as defined by SIARAS ontology.

The main, core ontology, `rosetta.owl`, is a continuous development aimed at creating a generic ontology for industrial robotics. Its origins is the FP6 EU project SIARAS described earlier in Section 2. It has been further modified within the FP6 EU project RoSta, (Robot Standards and reference architectures, http://www.robot-standards.eu/, see Nilsson et al., 2009). Within the FP7 EU Rosetta project this ontology has been extended, refactored and made available online on the public KIF ontology server `http://kif.cs.lth.se/ontologies/rosetta.owl`. However, this is just the first of a set of ontologies available on KIF and useful for reasoning about robotic tasks.

The ontology hierarchy is depicted in Fig. 9, where arrows denote the ontology import operations. We used extensively the QUDT ontologies and vocabularies (Quantities, Units, Dimensions and Types, initiated by NASA and available at `http://www.qudt.org`) in order to express physical units and dimensions. This ontology has been slightly modified to suit the needs of our reasoner. However, as QUDT ontologies led to inconsistencies, we have introduced the possibility to base the quantities, units and dimensions on the alternative OM ontology[7] (Rijgersberg et al., 2013).

The core Rosetta ontology (as its predecessors) is focusing mostly on robotic devices and skills. According to it, every device can offer one or more skills, and every skill is offered by one or more devices. Production processes are divided into tasks (which may be considered specifications), each

[7] `http://www.wurvoc.org/vocabularies/om-1.6/`

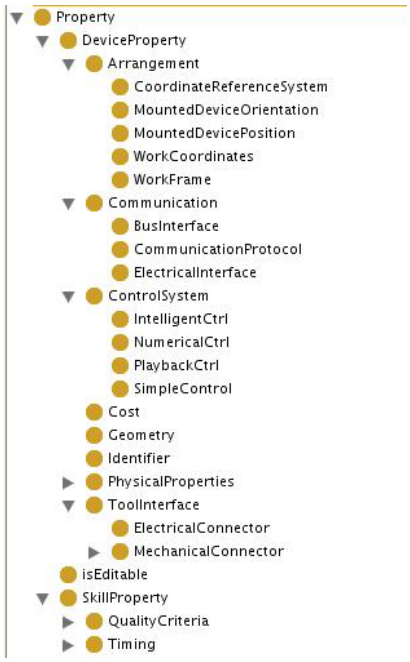

Figure 5: Device properties, as defined by SIARAS ontology.

realized by some skill (implementation). Skills are compositional items: there are primitive skills (non-divisible) and compound ones. Skills may be executed in parallel, if the hardware resources and constraints allow it.

On top of the core ontology we have created a number of "pluggable" ontologies, serving several purposes:

Frames The `frames.owl` ontology deals with feature frames and object frames of physical objects, normally workpieces involved in a task. In particular, the feature frames are related to geometrical locations and therefore the representation of location is of major importance here. The constraints among feature frames are expressed using *kinematic chains* (De Schutter et al., 2007), also introduced by this ontology.

Injury The `injury.owl` ontology deals with the levels of injury risks when humans and robots cooperate, or at least share common space. The ontology specifies the possible injury kinds, while the associated data, either extracted from earlier work (Deutsche Gezetzliche Unfallversicherung, 2011), or gathered during the Rosetta project (Matthias et al., 2012), are provided as the upper limit values that may be used in computations of injury risks or of evasive trajectories for a robot.

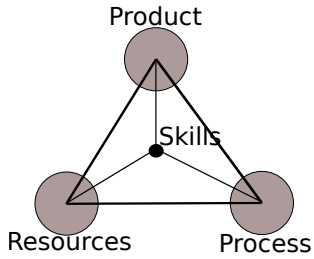

Figure 6: The PPR model, with skills as common coordinating points for the three views.

Params Each skill may be parameterized in a number of ways, depending on the granularity level of control, available information or the demands posed on the skill. In order to provide knowledge about skill parameterization for knowledge services (like, e.g., task consistency checking), the `params.owl` ontology describes skills and their mandatory and optional parameters, their units and constraints.

SFC The `sfc.owl` ontology characterizes various behavior representations using variants of executable state machines (Sequential Function Charts are one of them; the others included are OpenPLC, Statecharts, rFSMs and IML). It also contains the semantic description of several graph-based representations of assembly, like assembly graphs, constraint graphs or task graphs (Malec et al., 2013), that may also be considered to be behavior specification, although at a rather high level of abstraction.

This solution illustrates two important principles of *compositionality* and *incrementality*: every non-trivial knowledge base needs to be composable out of simpler elements, possible to be created by a single designer or team without the need to align it with all the other elements. The alignment, or conflict resolution (e.g., inconsistency), should be performed (semi-)automatically, after plugging the element into the system. So, every "top" ontology should only be forced to adhere to QUDT (or OM) and ROSETTA ontologies, possibly neglecting other elements existing in parallel.

The incrementality principle ensures that every "top" ontology should be amenable to incremental change without the risk of breaking the whole system. Thus, changes to, e.g., Params ontology should not affect the consistency and utility of, e.g., SFC ontology. On the other hand, one can imagine situations where changes in one module (e.g., introduction of a new constraint type between feature frames, described in `frames.owl`) might facilitate improvements in another (e.g., easier specification of parameters for a given skill, described in `params.owl`).

Besides storing the ontologies, the triple store of KIF provides also a dynamic semantic storage used by Engineering System to update, modify and reload scene graphs and task definitions. Depending on the kind of repository used, some reasoning support may be provided for the storage functionality. More advanced reasoning, and a generic storage of arbitrary kind of data, is provided by KIF services, described below.

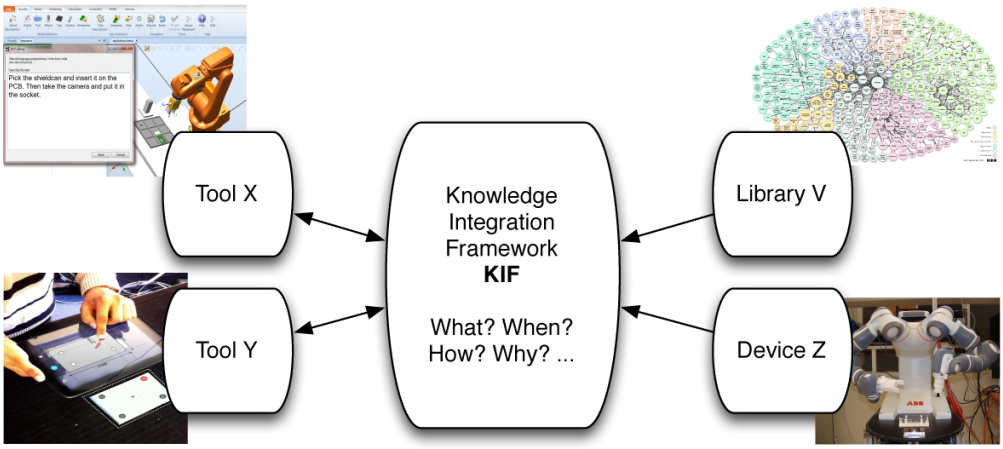

Figure 7: The Knowledge Integration Framework provides services to the Engineering System and the Task Execution. The latter two communicate during deployment and execution of tasks. The Task Execution uses sensor input to control the robot and tools.

5 Knowledge-Based Services

The knowledge base provides storage and reasoning services to its clients. The most basic service it offers is access to libraries with objects and skills, where the user can upload and download object descriptions and task specifications. Some of them are stored with semantic annotations, as triples, e.g., workpieces, scene graphs or skill definitions. Others are stored as uniform chunks of data without semantically visible structure (e.g., RAPID programs or COLLADA files), although other tools may access and meaningfully manipulate them for various purposes.

The services are mostly user-oriented, providing programming aid, and can be used step-by-step to create a workspace and then to refine a task sequence from a high-level specification to low level code. The workspace is created by adding a robot, tools, sensors and workpieces to the scene, giving the object properties relevant values and defining relations between objects (see Section **??**).

The user specifies a task using the workpieces and their relations. On the highest level, the task is represented by an assembly graph (Malec et al., 2013). An example assembly graph of a cell phone is shown in Fig. 10. The assembly graph is normally a tree (not necessarily binary). The leaves are the original workpieces which are joined into subassemblies represented by parent nodes and the full assembly is represented by the root. Each subassembly can be annotated by more information, such as geometrical relations between the objects, or what type of joining mechanism to use (e.g., glueing, snapping, screwing). The tree imposes a partial order on the operations, where child assemblies have to be carried out first. When going from the task specification given by the assembly graph to an executable program, the task has to be sequentialized. Depending on the robot, or on the number of collaborating robots, the sequence can be realized in several ways, hence, an assembly graph specification can be shared by several robot systems, even though the sequences realizing it will differ.

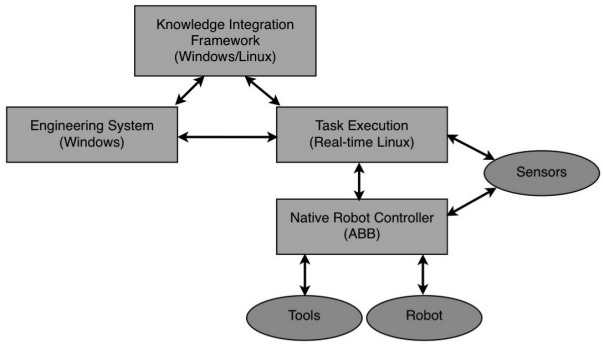

Figure 8: The Knowledge Integration Framework provides services to the Engineering System and the Task Execution. The latter two communicate during deployment and execution of tasks. The Task Execution uses sensor input to control the robot and tools.

KIF provides a planning service that transforms an assembly graph to a sequence of operations using preconditions and postconditions of the skills. Initially the service verifies the device requirements of a skill. Fig. 11 displays the device requirements of an implementation of the skill that inserts a shieldcan onto a printed circuit board (PCB). This skill has only three device requirements: a mounted tool (which is a manipulation requirement), a fixture and a force sensor, which (though it is not displayed in the figure) must be aligned vertically. When planning the sequence, the planner adds actions that fulfill the preconditions (see the example in Fig. 12), such as moving objects into place.

However, the sequence can also be created directly by the user, either manually or by using a natural language instruction interface. Later, the same planner can be used to verify that the sequence fulfills the preconditions of each action (Fig. 13).

The natural language interface is described in more detail elsewhere (Stenmark and Nugues, 2013; Stenmark and Malec, 2014b). The user either dictates or types English instructions in a text field (see an example in Fig. 14). The input text is sent to a natural language service on KIF where the sentences are parsed into predicates (verbs) and their corresponding arguments. Each verb has several different *senses* depending on the context and meaning, e.g., the predicate *take* in *take off the shoes* has sense *take.01*, but in the sentence *Take on the competition* it has sense *take.09*. *The shoes* and *(on) the competition* are arguments to the predicates. Each sense has a number of predefined arguments for, e.g., the actor doing the deed, the object being manipulated, the source or the destination. These arguments are labelled as *A0*, *A1*, etc. Both the sense of the verbs and the arguments are determined using statistical methods described in Björkelund et al. (2010).

The natural language service outputs a preliminary form of program statements derived from the sentences. However, the matching to actions and objects existing in the world is done in the Engineering System. In the simplest form a program statement contains an action (the predicate) and a few arguments (objects). The action is then mapped to a robot program template while the arguments are mapped to the physical objects in the workspace, using their names and types. Actions described this way can be picking, placing, moving and locating objects. More complicated

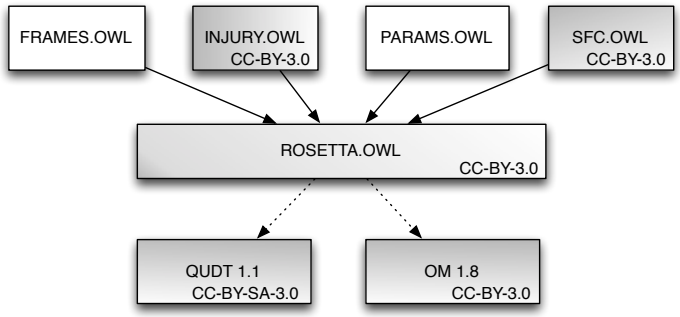

Figure 9: The KIF ontologies used by the Rosetta project. In case an ontology is openly available, the type of license is quoted.

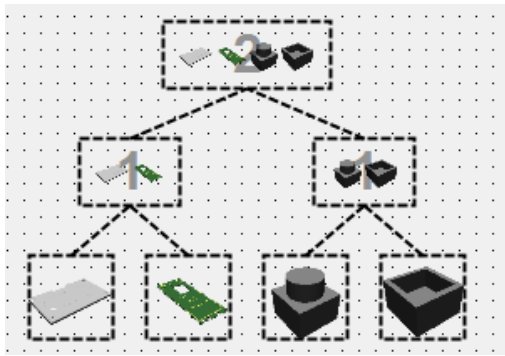

Figure 10: An assembly graph for a partial assembly of a cell phone. A metal plate, a *shield can*, is pressed onto a printed circuit board (PCB) and a cell phone camera is inserted into a socket. The camera socket is then fastened on the PCB.

program structures can be expressed using conditions that have to be maintained during the action or for stopping it, as in the sentence *Search in the x-direction until contact while keeping 5 N in the z-direction*. The example sentence *Assemble the shieldcan to the PCB using ShieldCanInsertion* given in Fig. 14 has a skill, *ShieldCanInsertion*, as argument to *use* (which in turn is a nested argument to *assemble*, see bottom of Fig. 15). *Use* is not mapped to a robot action, but rather prompts a search for a corresponding skill in the KIF libraries. The skill is instantiated with the arguments as parameters or, when no matching parameter can be found, with default values. For example, the *ShieldCanInsertion* is described in the ontology with an actuated object and a fixated object, which are mapped to *A1 – the shieldcan* and *A2 – the PCB*. These programs can be further edited or directly executed on a physical robot or in the virtual environment of the Engineering System.

There exists also a scheduling service that helps the user to assign actions to a system with limited resources. The current implementation of the service is based on the list-scheduling. The manipulation skills require different end effectors, e.g., for gripping and for screwing. By adding a tool changer to the cell, the robot can change end effectors during the task. The time it takes to change

Figure 11: The device requirements of the skill ShieldCanInsertion are modelled in an ontology. The **ManipulationRequirement** which several skills inherit from, is that a gripper has to be mounted on the robot. The **ShieldcanFixtureRequirement** and the **ShieldcanForceSensorRequirement** list that there must exist a fixture and a force sensor that have to be vertically aligned (not shown in the picture).

Figure 12: There are three preconditions to the ShieldCanInsertion skill. The skill has two *feature frames* (relative coordinate frames) as input parameters, where one is a reference object frame and the other is attached to the object in the gripper, i.e., an actuating frame. The first precondition is that the object with the reference frame has to be on the fixture. Secondly, the object with the actuating frame should be attached to the gripper, see Fig. 13, and finally, the position of the actuating object should be above the fixture. Imprecise geometrical relations such as "Above" are given concrete values by the Engineering System.

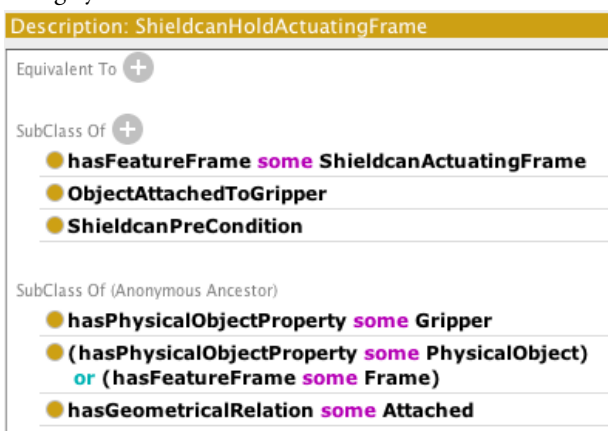

Figure 13: The ontology description of the precondition **ShieldcanHoldActuatingFrame** which is a subclass of **ObjectAttachedToGripper**.

tools is added as penalty on the priority of the actions. When there are multiple arms, one arm can of course change a tool while waiting for the other arm to finish its operation during a two-arm manipulation skill. A typical input to the service can be to schedule a partially ordered task on a two-armed robot with three tools and one force sensor. Each action lists its estimated time and the

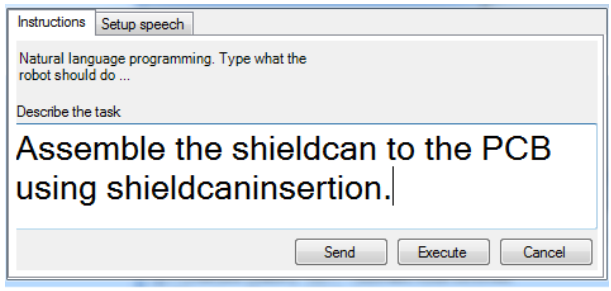

Figure 14: The user can describe the task using English sentences.

	Assemble	the	shieldcan	to	the	PCB	using	shieldcaninsertion	.
assemble.02		A1		A2			AM-ADV		
use.01								A1	

Parsing sentence required 22ms.

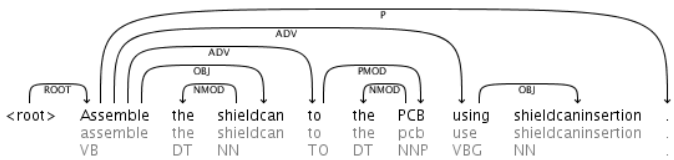

Figure 15: The result given by the parser of the sentence from Fig. 14. At the top, each line displays a found predicate with its arguments. Assemble was evaluated to *assemble.02* with the arguments *the shieldcan (A1)*, *to the PCB (A2)* and a manner *using shieldcaninsertion.* The bottom of the picture displays the dependency graph (actually a tree). The arrows point, beginning from the root of the sentence, from parents to children. Each arrow is labelled with the grammatical function of the child. Under each word the corresponding part-of-speech tag (determiner - DT; noun - NN, etc) can be found.

resource requirements, required tool(s) and resources. Given the estimated time to change tools and the number of cycles, the service will output a suggested schedule that minimizes the total time.

The last service named here is a code generation service used by the task execution system. It is described below in Section 7.

6 Engineering System

The Engineering System is a high level programming interface implemented as a plugin to the programming and simulation IDE *ABB RobotStudio* [8], shown in Fig. 16. When creating a station, objects such as the robot, workpieces, sensors, trays and fixtures can be manually generated in the station or downloaded from KIF together with the corresponding ontologies. A physical object is characterized by its local coordinate frames, the *object frame* and a number of relative coordinate frames called the *feature frames*, see Fig. 17. Geometrical constraints are expressed as relations between feature frames, and may be visualized as in Fig. 18. An example program sequence is shown in Fig. 19. The program has a nested hierarchy, where steps (such as pick or place) may contain atomic motions and gripper actions.

7 Execution

The sequence from Fig. 19 is sent to the execution system, which in turn calls the code generation service that returns a complete state machine (serialized in an XML file), which is visualized, compiled and executed using JGrafchart tool (Lund University, 2013). It creates a task state machine, where each state is either a call to primitive functions on the robot, or a nested skill. Fig. 20 shows a small part of a generated state machine. Each skill is either retrieved from KIF and instantiated with the new parameters, or generated from scratch by creating a closed kinematic chain for a given robot and the objects. The vendor-specific code is executed using the native robot controller, while the more complex sensor-based skills are executed using an external control system (Blomdell et al., 2010) and the state machine switches between these two controllers when necessary.

To guarantee a safe execution, the injury risk for different velocities is evaluated using the data stored in KIF and the final robot speed is appropriately adjusted.

8 Related Work

Task representation has been an important area for the domain of robotics, in particular for autonomous robots research. The very first approaches were based on logic as a universal language for representation. A good overview of the early work can be found in Brachman and Levesque (1985). The first autonomous robot, Shakey, exploited this approach to the extreme: its planning system STRIPS, its plan execution and monitoring system PLANEX and its learning component (Triangle tables) were all based on the first order logic and deduction (Nilsson, 1984). This way of thought continued, leading to such efforts as "Naive physics" by Patrick Hayes Brachman and Levesque (1985), or "Physics for Robots" (Schmolze, 1986). This development stopped because of the insufficient computing power available at that time, but has recently received much attention in the wider context of semantic web. The planning techniques (Ghallab et al., 2004) have also advanced much and may be used nowadays for cases of substantial complexity, although generic automation problems are usually still beyond this limit.

[8] `http://new.abb.com/products/robotics/robotstudio`

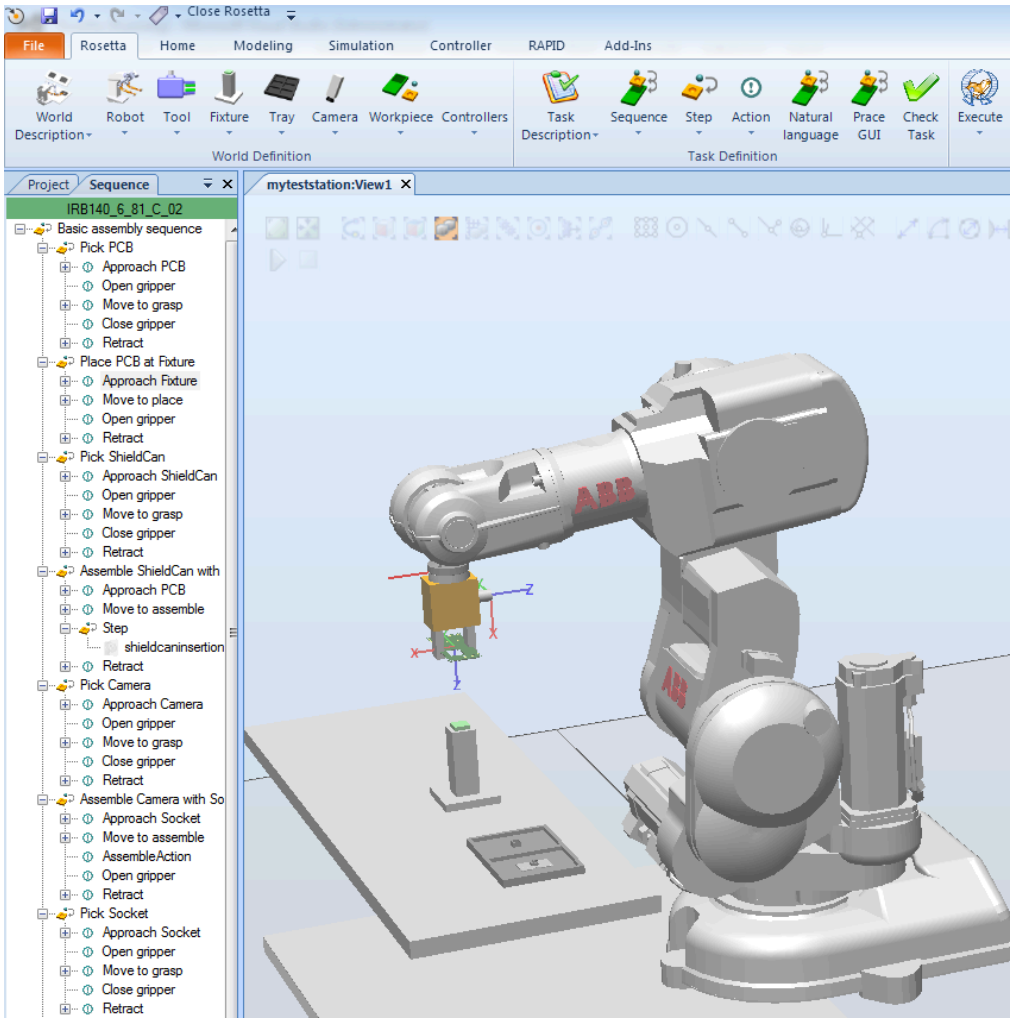

Figure 16: The engineering system is a plug-in the programming environment ABB RobotStudio.

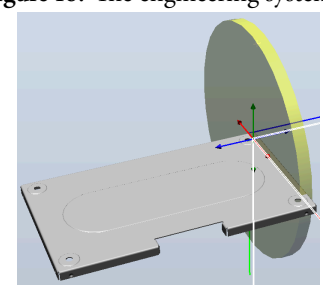

Figure 17: A *feature frame*.

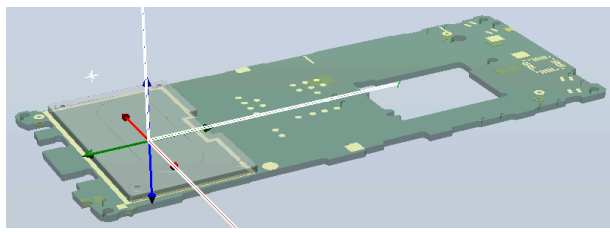

Figure 18: A geometrical relation between two objects.

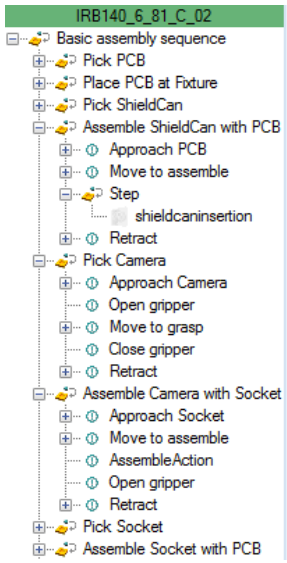

Figure 19: An example sequence of the cell phone assembly. First, the PCB is moved to the fixture. Then, the shield-can is picked and inserted on the PCB using a sensor-based skill called *shield-caninsertion*. The cell phone camera is assembled with the socket, and then the socket is inserted on the PCB.

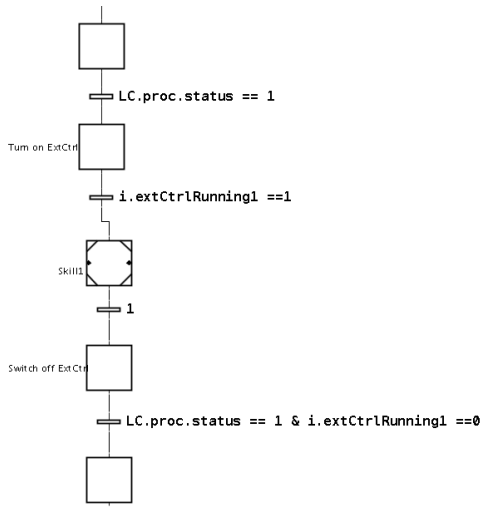

Figure 20: Each box is a state in the task state machine. The state called *Skill 1* with marked corners is a nested state machine containing a (dynamically generated) sensor-based skill. Before and after the sensor-based skill the external controller is started and turned off, respectively.

Later, mixed architectures begun to emerge, with a reasoning layer on the top, reactive layer in the bottom, and some synchronization mechanism, realized in various disguises, in the middle. This approach to building autonomous robots is prevalent nowadays (Bekey, 2005), where researchers try to find an appropriate interface between abstract, declarative description needed for any kind of reasoning, and procedural one needed for control. The problem remains open until today, only its complexity (or the complexity of solutions) grows with time and available computing power.

Task description in industrial robotics setting comes also in the form of hierarchical representation and control, but the languages used are much more limited (and thus more amenable to effective implementation). There exist a number of standardized approaches, based, e.g., on the IEC 61131 standards (IEC, 2003) devised for programmable logic controllers, or proprietary solutions provided by robot manufacturers, however, to a large extent the solutions are incompatible with each other. EU projects like RoSta[9] are attempts to change this situation.

At the theory level all the approaches combining continuous and discrete formalisms may be considered as variants or extensions of hybrid systems (Goebel et al., 2012), possibly hierarchical. Hybrid control architectures allow us to some extent separation of concerns, where the continuous and

[9] `www.robot-standards.org`

real-time phenomena are handled in their part of the system, while the discrete aspects are treated by appropriate discrete tools. Our earlier work attempted at declaratively specifying such hybrid systems, but was limited to knowledge-based configuration (Haage et al., 2011).

Robotics systems are usually build from a number of distributed heterogenous hardware and software components that have to seamlessly interact during execution phase. In order to simplify configuration, communication and hide the complexity of the system, as well as to promote portability and modularity, there exist several frameworks for robotics middleware (see comprehensive surveys Elkady and Sobh, 2012; Mohamed et al., 2008). Module functionality can be provided as nodes in the ROS 10 environment, or as standardized components in RT-components (Noriaki et al., 2005), where the modules can provide blackbox-type computations with well-specified interfaces.

Task descriptions come in different disguises, depending on the context, application domain, level of abstraction considered, tools available, etc. Usually tasks are composed out of skills, understood as capabilities of available devices (Björkelund et al., 2011), but the way of finding appropriate composition varies heavily, from manual sequencing in many workflows, via AI-influenced task planning (Ghallab et al., 2004), hybrid automata development tools (Goebel et al., 2012), Statecharts (Harel, 1987) and Sequential Function Charts (SFCs) (IEC, 2003), iTaSC specifications (De Schutter et al., 2007), to development of monolithic programs in concrete robot programming languages, like, e.g., ABB RAPID.

There have been several attempts to codify and standardize the vocabulary of robotics. There exists an old ISO standard 8373 requiring however a major revision to suit the demands of contemporary robotics. IEEE Robotics and Automation Society is leading some work towards standardization of robotic ontologies. In particular, there are first drafts of robotic core ontology (Carbonera et al., 2013), although not as developed as the ROSETTA ontology described in this paper. Regarding industrial robotics, the work on kitting ontologies, originated at NIST (Balakirsky et al., 2012), may be considered as an early attempt to address the problem.

In the area of service robotics there are several systems exploiting the knowledge-based approach, and relying on an underlying ontology, like KnowRob (Tenorth and Beetz, 2013) (based on the generic OpenCyC ontology by Matuszek et al., 2006), used in RoboHow project[10] or several participants in the RoboEarth project[11] (Waibel et al., 2011). However, they do not attempt to standardize the domain, as the variance of tasks and skills in the service robotics is very large. On the other hand, the KnowRob ontology became a de-facto standard used in several experimental robot systems.

9 Conclusions

We have shown a generic knowledge-based system architecture and its possible use in industrial robotic systems. In particular, we have employed the approach for representing and realizing force-controlled tasks realized by one- and two-armed ABB robots in an industrial setting. The presented generic ontologies are either novel, or a derivative of our earlier research. The use of semantic tools

[10] `http://robohow.eu`

[11] `http://roboearth.org/`

and explicit knowledge in industrial robotics is in its early stage, with only a few other published examples (Balakirsky et al., 2012). The ideas have been experimentally verified and work well in the currently ongoing EU-projects PRACE[12] and SMErobotics[13]. The implemented system is just a proof of concept, and systems that are derived from this work must undergo usability, security and performance testing, before they might be considered to be ready for industrial practice. But already now it can be stressed that the knowledge-based approach allowed us to create composable representations of non-trivial assembly skills, shown to be reusable among different models of ABB robots, but also portable to other vendors and control architectures (like the one reported in Klotzbücher and Bruyninckx, 2012) and running on a Kuka LWR4 robot.

The already ongoing continuation of the work presented above involves integration of a heterogeneous system consisting of a mobile robot platform (Rob@Work) running a ROS-based control system, and a real-time-enabled ABB-manipulator running the ABB-specific control software, so that the two parts can operate seamlessly together as an integrated, knowledge-based, productive robotic system. This work includes deploying knowledge-based services in the context of chosen robotic middleware.

Future work involves contribution to the IEEE standardization efforts, and aligning and sharing robotic ontologies with other research groups. An online documentation of the core ROSETTA ontology is also expected. The number of knowledge-based services should be extended with, e.g., online reasoning during execution, geometrical reasoning and integrated path planning and optimization. We are also verifying this approach in other domains of manufacturing, like woodworking and machining, expecting to extend the ontologies appropriately.

We have found out during the work described in this paper that skills are much more than just a potential to execute coordinated motions. This line of thought has been already present in Nilsson et al. (2013), where business aspects of skills have been pointed to. We plan to explore this topic in the nearest future.

Acknowledgments

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The work described in this paper has been done in tight collaboration with many people from the project consortia. The authors are indebted for many fruitful discussions.

An early version of this paper has been presented during the 12th Scandinavian Conference on Artificial Intelligence, Aalborg, Denmark, October 2013.

[12] `http://prace-fp7.eu/`

[13] `http://www.smerobotics.org/`

Paper II

Paper II

On Distributed Knowledge Bases for Small-Batch Assembly

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ABSTRACT

This paper presents ongoing research involving design and evaluation of different architectures for providing knowledge-based solutions in industrial robotized automation systems. The conclusions are that distributed, cloud-based approaches offer many possibilities, in particular for knowledge exchange and reuse, and facilitate new business models for industrial solutions. However, there are many unresolved questions yet, e.g., those related to reliability, consistency, or legal responsibility. There is a definite need for further research and better infrastructure before this approach would become attractive for industrial actors.

Note to Practitioners:

It is possible to extend the capabilities of a robot system by providing online services. An example of such service is an online library of robot applications, an app store, where robot programs can be downloaded and installed on the system with little effort from the user. Another is text analysis, that requires heavy computations but can provide a more natural user interaction. In this paper we discuss technical solutions and challenges that we have experiences during several European projects, that aimed at simplifying the robot programming by providing such libraries with knowledge and computational services. Since robot programming is time consuming and requires expertise, and thus is expensive, there is need for good services that simplifies this process. However, at the moment, there is no working market place for the distribution of existing solutions.

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DOI: 10.1109/TASE.2015.2408264.

1 Introduction

Traditionally, the use of industrial robots as in large-scale manufacturing is based on well-structured data reflecting the semi-structured environment of the robots and the detailed engineering of the system and application processes. With long product series it is well worth to have expert system integrators and robot programmers: during production any problem is solved by further engineering (Rossano et al., 2013). However, the efficiency of the resulting system depends on skilled production personnel. From a software point of view, established solutions with product data management, CAD/CAM, production planning, and so on are suitable, and they can build on relational databases that are hosted locally. While such system might benefit from a cloud-computing approach, it is not strictly necessary. In the following we will, however, take a closer look into the future of manufacturing and discover the actual needs for a cloud-based approach, which we after some further introduction will approach in a step-wise manner.

The paper is divided as follows: after the introduction we present the evolution of our approach from a local blackboard system, to a local knowledge-base-based one, to a distributed knowledge-based one, to a system involving human interaction, and finally to a cognitive one. Then related works are presented, followed by a discussion of the adopted solutions. The paper ends with conclusions and suggestions for future work.

1.1 Manufacturing

In modern (and future) manufacturing, shorter series of customized products imply an increased demand on flexibility (EURON, 2006). Flexible and user-oriented systems are also needed by small and medium sized enterprises (SMEs) that cannot afford to have the technical experts on robot programming and system integration (Pan et al., 2010). Moreover, equipment (including robots) will be purchased from a variety of technology providers, which cannot be enforced to follow pre-defined standards, so significant knowledge is needed for system integration. During programming, the situation is similar since the environment is less structured and variability of the involved processes is difficult to cope with as product variants imply frequent change-overs.

Hence, the needs for software support in future flexible manufacturing include:

- Knowledge needs to be represented and structured in a more flexible ways, i.e. in terms of changeable graphs rather than rigid tables.
- Knowledge needs to be grounded and semantically well defined such that it can be utilized (and updated) by both the human (via easy to use interfaces) and by the machine (to manage errors and unforeseen situations).
- Distributed production sites should be enabled to share knowledge.
- Due to maintenance, licensing and security issues, related software functions (e.g., for motion planning and process optimization) better be provided externally as software services.

Thus, high productivity for manufacturing of customized products causes a for need knowledge-based systems, and it creates an interest for cloud computing as a mean for providing the requested services.

1.2 Cloud computing

Cloud computing is normally understood as an infrastructure offering remote computing as a service to demanding clients. It may also involve distributed on-line resources, shared among interested clients. It becomes an opportunity in the robotized automation as it offers possibility of knowledge expansion and sharing among installations, knowledge transfer between different users and runs, better customer support from system integrators, simpler system installation and bootstrap, and new services based on creation and maintenance of specific knowledge-bases.

Whereas some software engineers think about a web service in terms of a remote procedure like in RPC, it is important to understand that a service, as in software as a service or as in SOA (service-oriented architectures), is an entity that is based on a business value (Belmans and Lambrette, 2012). Just like in hardware where it is the business aspect that creates the market for components in terms of reusable entities, software services provide function of value and thereby they contribute to reuse. Robots, representing the most flexible machine in manufacturing, are also programmed (or instructed such that there is a resulting robot program), so what about reuse of (valuable parts of) robot programs?

1.3 Robot programming

Robot programs (or task definitions) have meaning in terms of the application context. The need for short change-over times implies a need for code reuse. That reused code represents the task-related configuration. Machine learning can be performed on the motion level, in terms of adaptation, or can take the form of structured learning on a task/error specification level. The reused code should support machine learning functions as needed for optimizing performance. The data resulting form learning needs to be grounded in application terms, and it needs to be reusable to avoid learning the same thing over and over again, which in turn means reuse of how coordination is done as part of robot capabilities. Putting the configuration and coordination together, grounded in human terms and packaged considering business value, leads to the notion of skills. That is, skills comprise the reusable robot capabilities, which we claim is an enabler for the SME-like flexible manufacturing, which in turn is facilitated by robot cloud services.

2 A first local utility-based approach

The first approach was the SIARAS (Skill-Based Inspection and Assembly for Reconfigurable Automation Systems) project[1]. The main interest from an AI perspective was knowledge-based auto-

[1] `http://cordis.europa.eu/search/index.cfm?fuseaction=result.document&RS_RCN=12197834A`

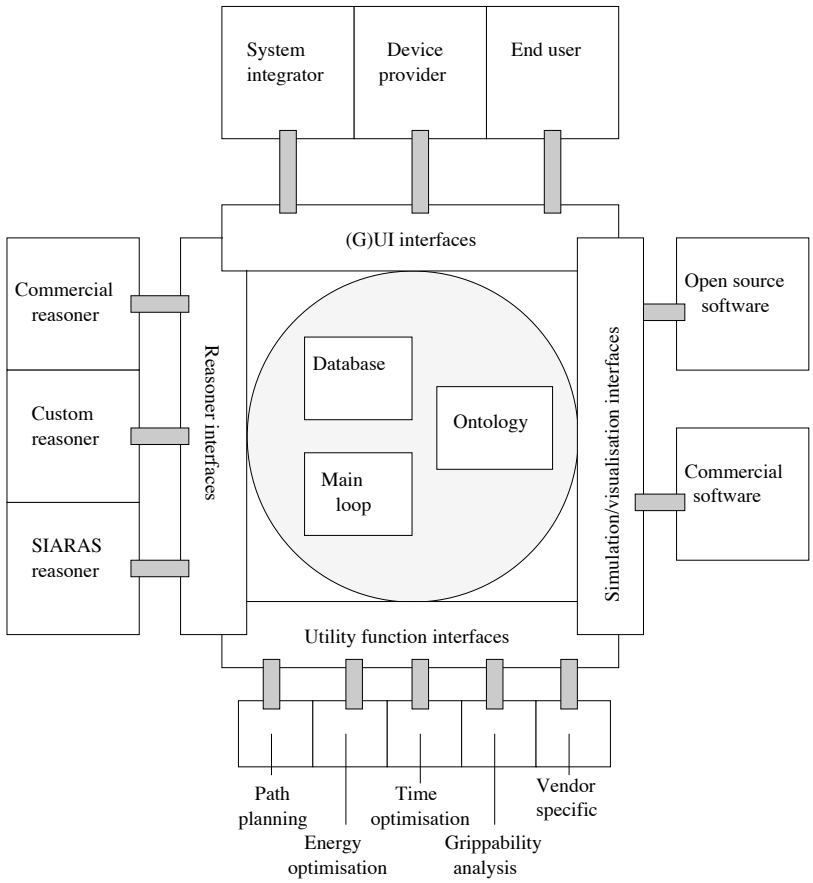

Figure 1: The SIARAS blackboard architecture

matic reconfiguration of automation systems. The results of this work have been presented in Stenmark and Malec (2014a). The outcome was an intelligent support system for reconfiguration and adaptation of robot-based manufacturing cells. Declarative knowledge was represented first of all in an ontology expressed in OWL, for a generic taxonomical reasoning, and in a number of special-purpose reasoning modules, specific for the application domain. The domain-dependent modules were organized in a blackboard-like architecture.

An overview of the adopted architectural solution is shown in Fig. 1. The main focus has been put on generic interfaces, allowing independent service, data or knowledge providers to adapt to the system expectations. In particular, some experiments have been made using several simulation/vizualisation tools, providing independent user interfaces suited for different needs and, last but not least, exploiting external "utility functions" (knowledge sources in blackboard architecture terms) provided by robot manufacturers, sensor manufacturers and system integrators.

The SIARAS system demonstrator used several machines communication using Ethernet (simulation software required different operating systems), but only locally within the engineered system.

Some further experiments were done with distributing device database (shown in the central module in the Figure), allowing several device manufacturers to provide their data independently of each other, using their own computer systems connected to Internet (Lidén, 2009). However, the ontology used was single and centralized, available locally on the SIARAS system.

3 Knowledge integration

The ROSETTA project[2] (RObot control for Skilled ExecuTion of Tasks in natural interaction with humans; based on Autonomy, cumulative knowledge and learning) focused on simplifying interaction between the user and the robotized automation system, and on ensuring human safety in all circumstances. The former goal in particular demanded knowledge-based solutions, although the latter one also exploited some explicit knowledge encoded in a specific injury ontology.

The concrete system built around this idea has been designed with assembly tasks as the main domain of application. This has limited the set of skills necessary to specify, kinds of sensors used as well as the end effectors that robots need for fulfilling their objectives and made creation of the test system possible. The architecture, depicted in Fig. 2, is an instantiation of the previous one, assuming a concrete simulation and visualization environment, here called Engineering Station, and concrete brands and models of robots for which the Task Execution system generates code, executable by the Native Controller. The architecture assumes a number, possibly geographically separated, engineering stations, and a number of independent robot system installations, connected to a common knowledge server.

During the ROSETTA project we have built KIF server and made it available for testing by all project partners. The server provides access to semantic storage with skill descriptions, task specifications and station (robot installation) definitions. It also contains a set of ontologies expressed in the OWL language. Besides, it provides a set of knowledge-based services like task consistency checks, rudimentary planning and scheduling, natural-language-based task definition, or process parameter learning. The engineering system has been realized as a plug-in to the ABB RobotStudio software, as we used ABB robots in our experiments.

The KIF concept can also be used in a hierarchical way with local servers. By setting up a local server in a factory or a lab, it is possible to address some of the problems of a distributed system. The server

[2] `http://www.fp7rosetta.org`

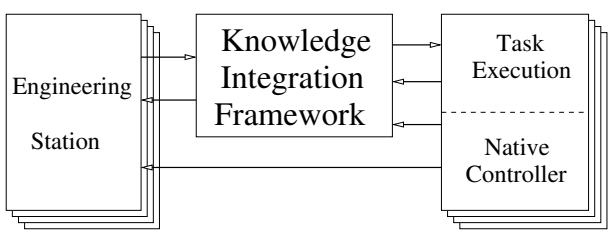

Figure 2: The ROSETTA architecture

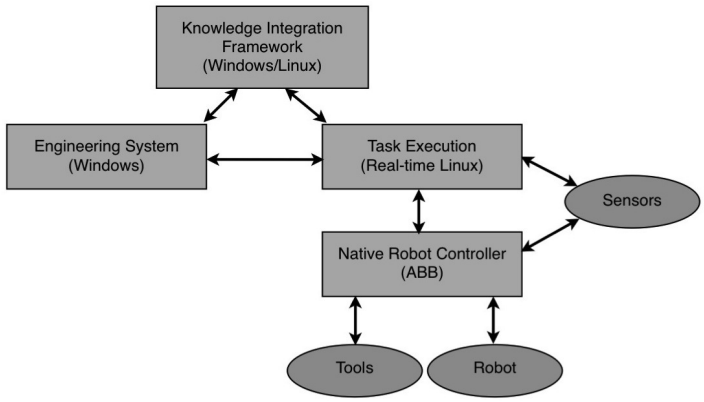

Figure 3: A concrete ROSETTA system

can be complementary to the global KIF by storing additional, perhaps non-public, ontologies and storing shared cell and task information only relevant for the factory or lab. From these local servers, generic concepts can be uploaded to the global server.

4 Knowledge representation

The main idea behind the ROSETTA solution is illustrated in Fig. 4 (Björkelund et al., 2011). A central knowledge broker, called Knowledge Integration Framework (KIF[3]), is organizing access to knowledge and data sources, provides information about available devices and their capabilities, and serves a number of tools enabling human users of various kinds (factory floor operators, system integrators, device manufacturers, skill designers, system maintainers) to perform their tasks in the simplest possible way. The solution is generic in the sense that no particular data formats are mandated, only the tool APIs are specified in order to ensure interoperability.

Based on the assumptions of a shared work-cell information scenario, the local KIF may "automatically propagate" e.g, the status of a local tool or fixture calibration also between task realizations for individual robots whereas 'generic functionality' such as descriptions for different standard operation such as a 'peg-in-the-hole' or a 'snapfit' functionality may be retrieved from a higher level in the hierarchy. The instantiation and realization of a peg-in-the-hole operation is of course strongly dependent on local configuration and access to sensor information. Although this may be considered as a reference implementation, it is worth to point out that a common high-level task description was evaluated not only between the different ABB robots, but also in two completely different laboratory setups: at the setup of RobotLab, Lund, shown in Fig. 8 and at the lab of our project partners at KU Leuven, where not only the robot manipulators were of very different nature (ABB Frida and the KUKA LWR, respectively), but also the robot system software from the very low-level control up to the high-level of state machines/SFCs and robot programming languages differed substantially.

[3]We are aware of the acronym conflict with Knowledge Interchange Formalism, but chose to stay with this name anyway.

More details about this system may be found in Malec et al. (2013), and Stenmark and Malec (2014a) and the constraint-based task specifications and the combination of high-level action specification and low-level motion execution is described in Stenmark et al. (2014).

One of the core insights of the project was that the robotic ontology used for supporting all connected subsystems cannot be monolithic, as it used to be in our previous work. There are too many agents with too many overlapping demands: e.g., engineering stations requesting data about physical objects in the station environment or demanding knowledge about skills available for a particular brand of robot equipped with a specific force/torque sensor; dialogue managers demanding a translation of text with constraints imposed by a concrete production environment; error management systems requesting specifics of a concrete skill; or, a safety controller interested in limit values for maximum robot speed given a human body part close to the end effector, etc. We have investigated the possibility of ontology modularization and reached a preliminary and rather ad-hoc solution, presented in Fig. 5. We import the QUDT[4] ontology (quantities, units, dimensions and types) into the core robotic skill ontology centered around devices (`rosetta.owl`). This ontology in turn serves as a basis for defining feature frames substantially simplifying task definition (`frames.owl`), providing limit values for robot-human contact (`injury.owl`), specifying several methods for describing behaviour using graphical representation of transition systems (`sfc.owl`) or concretizing parameters of robot skills (`params.owl`).

Since productive robots in SME manufacturing need to efficiently interact with human operators, the use of formal knowledge and ontologies is not primarily for making the robot 'intelligent' or fully autonomous, but rather enabling it to respond properly to human input. Thus the Human-Robot Interaction is both a goal and a source of knowledge to be incorporated.

[4] `http://www.qudt.org`

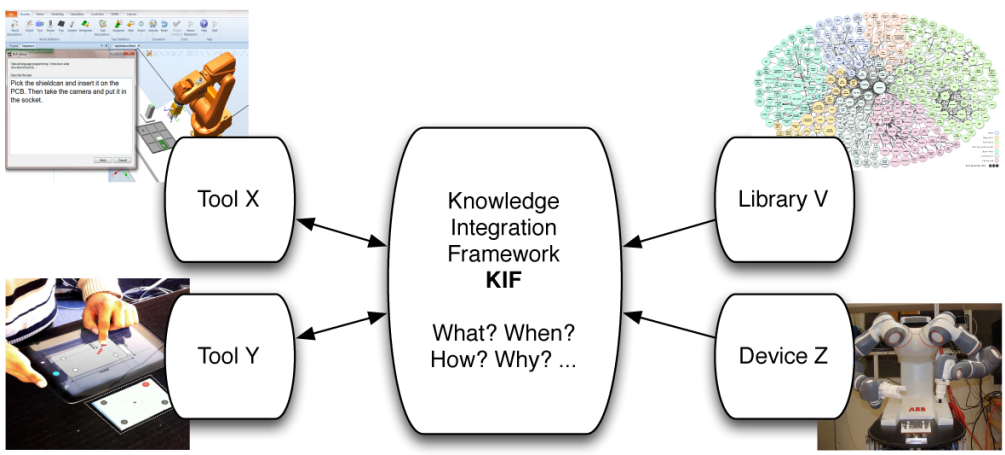

Figure 4: The KIF idea

5 Human-robot interaction

The developed above architectures for distributed robotics systems have knowledge bases and ontologies for knowledge representation of robot cells and skills, as well as reasoning services. In the ROSETTA project we have created a system for high-level programming, where the user can combine preprogrammed skills into a new task and adapt the skill parameters to the new station. Executable code is then generated for the task. The skill representations and services are further developed in the ongoing PRACE project. The goal of the Productive Robot ApprentiCE project[5] is development of highly adaptable two-handed mobile robot systems for automation of small batch assembly operations.

The focus is on fast and intuitive training of the robot task by using programming-by-demonstration techniques to synthesize a task solution. The learnt task is to be stored in a central knowledge base. The knowledge base also contains knowledge about mapping operator demonstrations into assembly operations.

The architecture is built from knowledge-based web services interacting with a legacy ABB controller and a ROS system. At the moment, we are working on a demonstrator where a two-armed robot is mounted on a mobile base and the system is programmed using a tablet. The system uses ROS-based components for high-level computations, while the low-level sensor control uses realtime protocols. Both the tablet and the mobile robot have limited local computing power and battery time. Thus, we use a distributed system for code generation, planning, trajectory generation and control, where computationally heavy, non-realtime services are located on more powerful machines and accessed remotely.

The modular approach of promotes reuse the online services for planning and scheduling and natural language programming, see Fig. 6, thus extending the system capabilities with very little effort.

[5] `http://prace-fp7.eu`

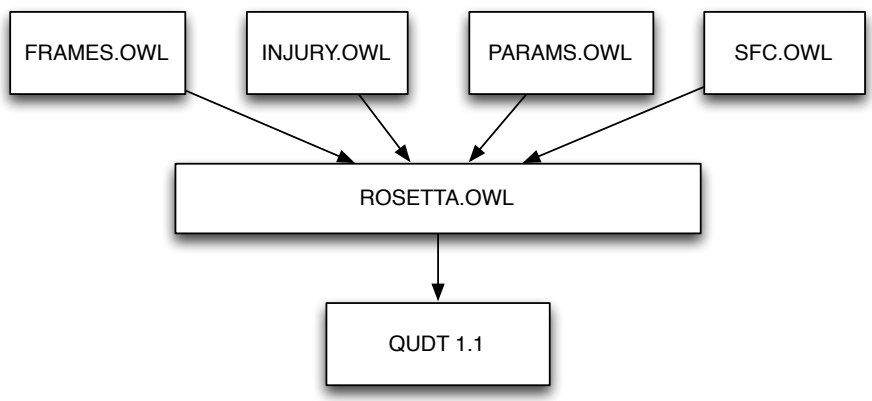

Figure 5: The ROSETTA ontologies

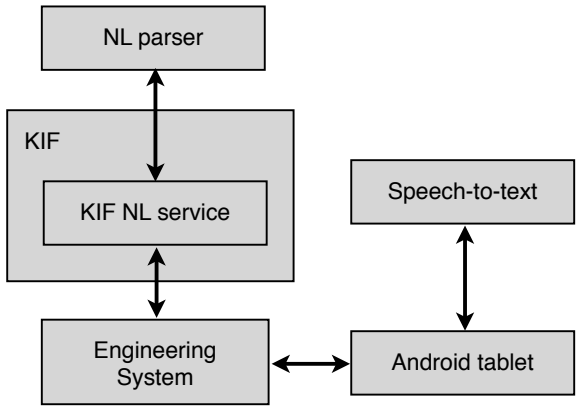

Figure 6: The service architecture for the natural language programming interface. The NL service on KIF receives text, sends it to a general natural language parser (NL parser) and outputs a sequence of robot actions. These actions are generated into executable code using the architecture displayed in Fig. 3. The Android tablet can use its own speech-to-text cloud service and send the text to the Engineering System, thus extending the user interface to a portable platform.

6 SME-suitable cognition

In the SMErobotics[6] initiative one of the main foci is on applicable robot solutions for small and medium sized enterprises (SMEs). In a typical SME-scenario, short production series call for less use of expensive fixture-based production for economical reasons, but then require easily reconfigurable setups which need to cope with and compensate for large structural uncertainties. The higher level of uncertainty can be handled by advanced sensor-based systems, but today even the conventional industrial robot programming, without the above mentioned extensions, is still a bottleneck with respect to both time and expertise. Based on high-level task descriptions and intuitive interaction where the worker's process knowledge (not the knowledge of robotics) can be fully utilized, the goal is not to reach a fully automated system, but a system with high productivity due to the interaction of an operator with the robot system, giving flexibility in production changes, and short error recoveries.

Cognition is needed both on the robot side and on the human side, symbiotically, and must be integrated with learning. Although newly learnt functionality on the robot side may be immediately distributed, locally or globally, this does of course not count for the human operators where each individual will have a different level of experience and expertise and thereby different abilities and preferences on how to interact and instruct. A personalized interface and dialogue system that the individual operator can access remotely, may be beneficial in this human-robot-collaboration. Concepts and symbols used in dialogues need to have a grounding that is shared by the human and the machine, e.g., to support the user in error situations.

[6] `http://www.smerobotics.org`

In this scenario the possibility to extend the available services with online reasoning and policy generation of error handling procedures opens also for efficient individual operator dialogues. In the SMErobotics project this topic is investigated in the context of modular knowledge and distributed reasoning systems.

The modularity of knowledge is also crucial for reuse of robot tasks or subtasks, representing partial solutions to production problems. Without being able to reuse solutions, the SME user will find the robot overly dumb and not productive in the common case of frequent changeovers. To accomplish such reuse it was found that stored knowledge must be in a compositional form, and the definition of skills need to be enhanced such that it maps to the notions and practices of the SME end user. More specifically, a useful skill representation should fulfill the following requirements:

- It has a business value, meaning that it carries out a non-trivial computation or motion sequence.
- It encapsulates the configuration and coordination information of the system.
- It describes parameters that can be adapted and automatically optimized by the robot system.
- The motions and actions are semantically described so that the system can reason about the skill.
- The semantics and taxonomy of the machine readable representation should relate to the human notions i natural language.

There is to our knowledge no such skill definition developed yet, but this is the current core topic in our ongoing research, with the aim of supporting reuse/portability of motions (see Nilsson et al., 2013) for a motivation of the the business and natural language aspects).

In order to semantically anchor the term SKILL we use an appropriate ontology including all the above mentioned aspects. Figure 7 shows a fragment of this ontology that extends our earlier work presented in Nilsson et al. (2013) and Stenmark and Malec (2014a). The full insight regarding the implication of 6D motions and uncertainties (in both processes, equipment and specifications), and why that results in a fundamentally different problem than reuse of computer code, is outside the scope of this paper.

7 Related work

The rapid growth of network services and the latest development of cloud solutions in a very general form has definitely had its impact also in automation and robotics (in industrial as well as in service robotics).

Although the concept of network distributed control and functionality in not new, see e.g., Inaba et al. (2000), the term "cloud robotics" has spread tremendously since James Kuffner has introduced it in 2010; it has attained a large interest in the robotics community reflected in a number of publications, it is appearing in research calls and has led to important development in open-source and

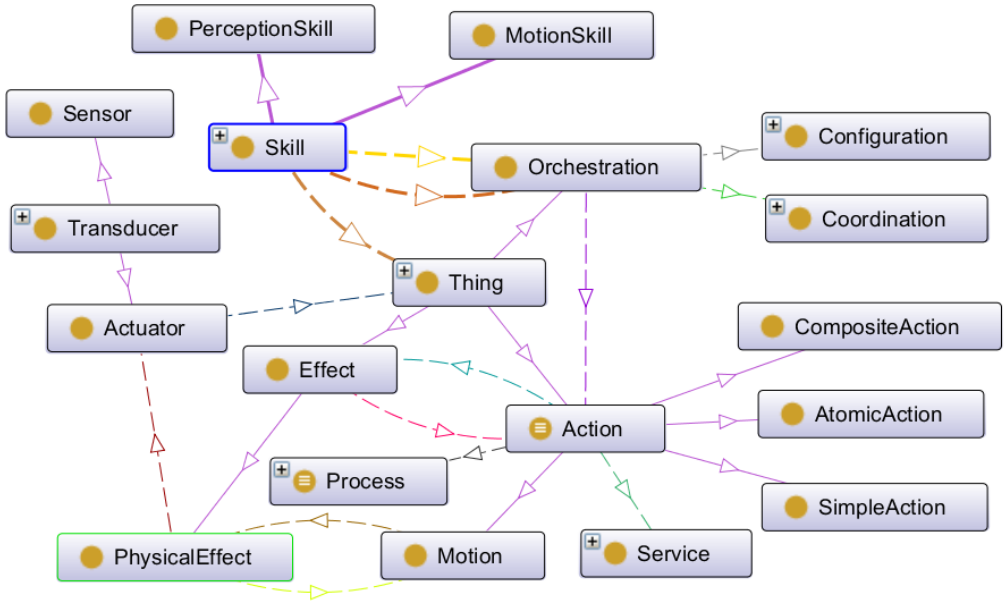

Figure 7: Central part of ongoing skill definition.

open-access projects[7] during the last couple of years. An important European project addressing the topic of knowledge sharing online, is RoboEarth[8] (Waibel et al., 2011), that aims at creating a World Wide Web for robots. Their knowledge base contains ontologies, tasks and environmental data (Beetz and Tenorth, 2012), which are shared by robots. The RoboEarth infrastructure, named Rapyuta, has recently become available publicly (Hunziker et al., 2013; Mohanarajah et al., 2014a) in its alpha version. Rapyuta is a system for distributed robot control of multiple agents. Each agent has an endpoint (or a *clone*) in the system and a Master task that handles the configuration of the communication. A use case is presented in (Mohanarajah et al., 2014b), where mobile robots collectively build a 3D map. The robots carry out very little processing, instead each device has a *robot clone* deployed in Rapyuta. The clone is a ROS environment that controls the robot remotely and propagates the image messages to another process that builds the map. The RoboEarth knowledge-base, which is equivalent to KIF with ontologies and services, can be accessed from Rapyuta. The communication within Rapyuta is handled similarly to ROS, with the addition of process-IDs to the (ROS) messages, hence, it is a system that integrates multiple ROS environments. It is a system suitable for, e.g., service robotics, where the latency of the system does not impact the performance. This architecture is not suitable for industrial applications where: 1) the system has real-time requirements, 2) the software is proprietary, that is, it might not be an option to deploy software within the system, but instead services and software might run remotely on company servers, hence, the configuration cannot be done by a Master task.

[7] See e.g., `http://code.google.com/p/rosjava/`

[8] `http://www.roboearth.org`

Departing from network research, and in particular, networked robotics systems, Hu and coworkers analyze the opportunities offered by cloud robotics infrastructure (Hu et al., 2012). Their applications focus though on the typical mobile robotics domains, like SLAM, navigation and grasping, leaving manufacturing outside the scope of interest.

Another popular cloud service, also in and for robotics, is natural language interpretation, such as speech-to-text techniques which we also see commonly appearing in e.g., smartphones. Thomas and Jenkins (2012) describe a system for commanding a robot using natural language. Stenmark and Nugues (2013) describe a more advanced solution to this problem.

An recent survey of work related to cloud robotics and automation was made by Goldberg and Kehoe (2013). Kehoe et al. (2013) have also presented a concrete application of cloud computing for robot grasping using Google's object recognition infrastructure. However, it is not available publicly, making it less attractive for the cloud robotics community.

8 Implementations

The architecture in Fig 2 is implemented in an experimental setup at Lund University. The main research platform in the ROSETTA and PRACE projects was the two-armed concept robot (with Christian name Frida) from ABB Robotics, seen to the left in Fig 8. To the right we have a conventional industrial robot (ABB IRB120) extended with an open robot control interface Blomdell et al. (2010). Thus, the workcell contains two different manipulators and different hardware configurations with respect to sensor information (e.g., force/torque measurements) are used.

The Engineering System is implemented as an extension to ABB RobotStudio[9], and displayed in Fig 9. In the Engineering System the task is realized as a sequence of actions, which in turn can be generated from a partially ordered assembly graph or by using online services provided by KIF. The ontologies, architecture and services provided in the system are described in more detail in Stenmark and Malec (2014a).

9 Discussion

The research done so far allows us to make the following observations. However, we would like to stress that their scope is limited by the context in which our research has been done: industrial robotized manufacturing systems, mostly relevant for assembly.

Online knowledge bases Their simplest possible advantage is to make deployment of a knowledge base and its associated services to every single system installation unnecessary. Instead, one central copy (or several mirrored ones) of the knowledge server needs to be created and maintained. In particular, the knowledge update and system upgrade can be made instantaneous, making fresh services immediately available to all users worldwide.

[9]http://new.abb.com/products/robotics/robotstudio/downloads

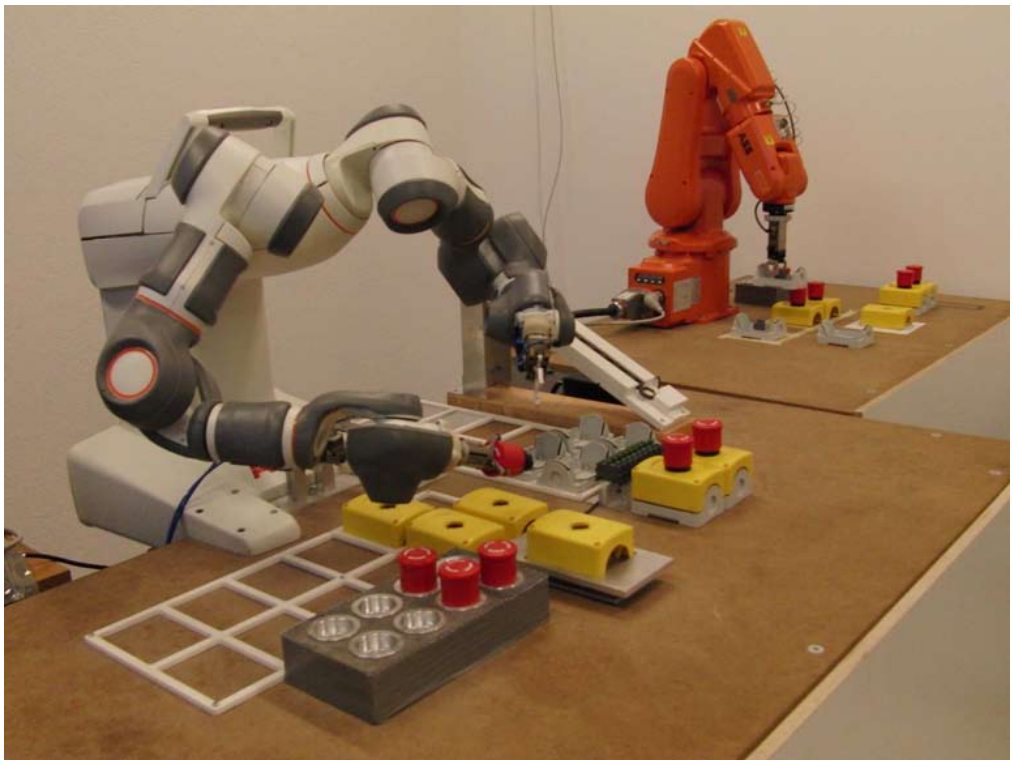

Figure 8: A setup of two different robots, the two-armed concept robot Frida and the ABB IRB120, for individual or coordinated assembly of emergency buttons within the ROSETTA project.

Depending on the model adopted for the knowledge base (monolithic or distributed, federated or governed by a single body) the chances of getting more knowledge provided to the system increase dramatically. However, this introduces also a whole set of issues that need careful attention, like e.g., reliability of knowledge coming from different, possibly unknown sources, guarantees of access to the (or a) knowledge base in all circumstances, depending on the business model adopted, consistency of knowledge provided by different actors, completeness of available resources with respect to a given set of tasks, knowledge overlap and possibility of choosing particular services based on experience, trust, or other criteria, just to name a few.

In particular, such federated model would allow many stakeholders like robot producers, system integrators, sensor providers, software deployers, to cooperate and contribute to a rich market of knowledge-based solutions, in a manner similar to what happens now in the ROS community regarding lower-level solutions for robotics.

One of the greatest challenges during the implementation of the knowledge-base was to handle several different formats of knowledge. The ontology is created in OWL, however, knowledge is provided in several standards, such as Automation ML, Collada, PLCOpen and it has to be possible to read to and from and convert between different formats.

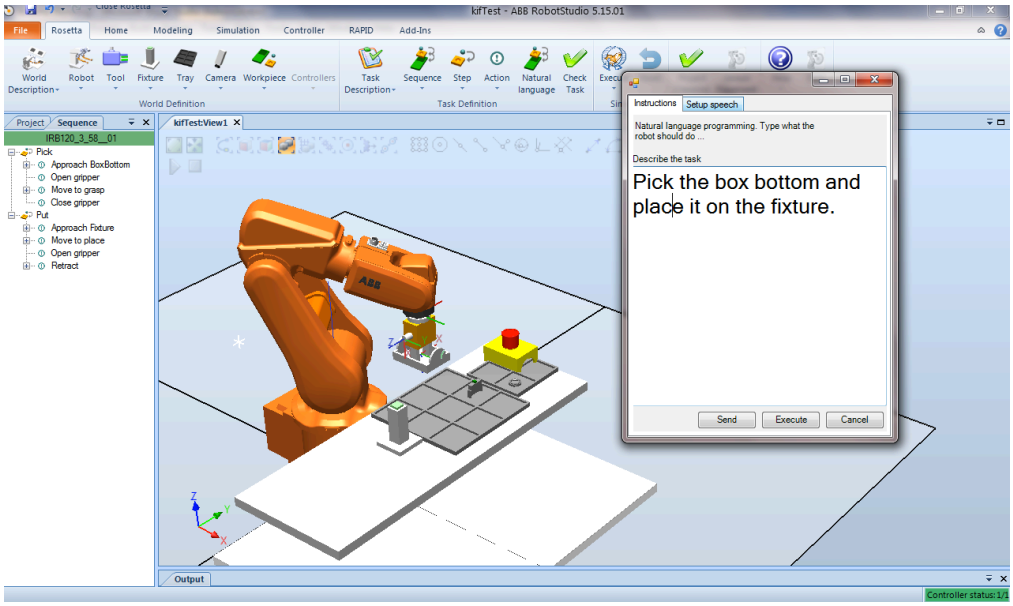

Figure 9: The user can program the robot using a visual programming tool developed in ROSETTA, where the task is represented by a sequence of actions that are refined into executable code using the online services for e.g., code generation.

Reuse of knowledge As it has been shown in our investigations, such approach allows reuse of knowledge introduced by one stakeholder by others. This applies to skill definitions as well as concrete parameter modifications or adaptations, or fault detection routines inserted after a skill has been deployed in a concrete task. The experience gathered during deployment of a system may be made available to others without unnecessary delay or update burden.

On the other hand, the question of relevance of such experience is unclear and needs to be raised here. How can one judge whether parameters adapted at site A are useful for site B? How can one realize whether a user of a particular robot C possibly wants to deceive other users by uploading incorrect values? Being able to generalize, evaluate the relevance and reason about the collected data from several setups is a challenge that service providers have to overcome in order to improve their solutions for e.g., parameter adaption and error handling.

Web services for robots Web services are an attractive computational model, making it possible to request specific (possibly knowledge-based) services, without knowing any particular details about their implementation, residence, ownership, etc. With a thoroughly defined API it makes it possible to separate concerns between the installed system: specific, task-related, hardware-specific computations, and the service provider: generic, task-independent, hardware-independent, portable computations.

As in the cases above, the questions of reliability, responsibility of service providers, portability and generality need to be raised here. However, the responsibility question is clearer, as it seems

rather straightforward how to make service providers accountable. In this manner, given sufficiently large market, robot system capabilities may increase substantially in a very short time. This is an opportunity for the robot manufacturers that seems to be very attractive.

It has to be made clear here that industrial players are rather conservative with that respect and that a lot of effort needs to be put into issues of security, reliability and dependability. Both on the side of manufacturers, be it robot, sensory equipment, or end effectors, as well as system integrators and end users, everyone is interested in keeping their know-how well protected as this is the main source of their profit. Sharing it freely, or just making it vulnerable to cyberattacks, is a risk that needs to be seriously considered and resolved. Without addressing those questions there is a risk that research activities will have only very modest influence on industrial practices.

On the other hand, there are solutions available, known from computer networking area and used in business-to-business communication, that address those issues. They are currently being extended to the context of cloud-based services (see e.g., Yoshinori et al., 2013). What needs to be done is porting them or adapting to a domain involving both software and heterogenous hardware subsystems, tightly interacting with each other. It is definitely a challenging task, but e.g., the automotive industry shows[10] that these questions may be answered in a manner satisfying to all market participants.

10 Conclusions

Cloud robotics is a key enabling factor for automation in SMEs. First, it can provide an ecosystem for distribution of solutions, similar to an app store. The applications can collect data and store it online in order to improve the skills and learn parameters, thus improving the capabilities of the robot over time. Also, user-interaction (such as natural language or image processing) and learning algorithms can use data and/or computationally heavy procedures during the setup and adaption. The applications cannot guarantee safety, this certification has to be done independently. Market forces will affect the quality of the services, solutions with better performance/features can have a higher price or license fee and, more importantly, solutions that are too difficult to understand or configure will be outcompeted.

This vision of a robot app store and shared knowledge-bases is ambitious and the efforts described in this paper are just the very first steps towards the goal. The main challenge for cloud robotics to take off in industrial robotics is not the lack of possible technical solutions, but it it trapped in its startup phase: in order to provide services with business value, the knowledge bases, services and solution distribution system(s) (the market place) have to be in place, but these in turn need knowledge and solutions to distribute to get started.

[10] `www.autosar.org`

Acknowledgments

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Paper III

Paper III

From High-Level Task Descriptions to Executable Robot Code

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ABSTRACT

For robots to be productive co-workers in the manufacturing industry, it is necessary that their human colleagues can interact with them and instruct them in a simple manner. The goal of our research is to lower the threshold for humans to instruct manipulation tasks, especially sensor-controlled assembly. In our previous work we have presented tools for high-level task instruction, while in this paper we present how these symbolic descriptions of object manipulation are translated into executable code for our hybrid industrial robot controllers.

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1 Introduction

Deployment of a robot-based manufacturing system involves a substantial amount of programming work, requiring background knowledge and experience about the application domain as well as advanced programming skills. To set up even a straightforward assembly system often demands many days of work of skilled system integrators.

Introducing sensor-based skills, like positioning based on visual information or force-feedback-based movements, adds yet another level of complexity to this problem. Lack of appropriate models and necessity to adapt to complexity of the real world multiplies the time needed to program a robotic task involving continuous sensor feedback. The standard robot programming environments available on the market do not normally provide sufficient sensing simulation facility together with the code development for specific industrial applications. There are some generic robot simulators used in research context that allow simulating various complex sensors like lidars, sonars or cameras, but the leap from such simulation to an executable robot code is still very long and not appropriately supported by robot programming tools.

The goal of our research is to provide an environment for robot task programming which would be easy and natural to use, even for plain users. If possible, that would allow simulation and visualization of the programmed task before the deployment phase, and that would offer code generation for a number of predefined robot control system architectures. We aim in particular at ROS-based systems and ABB industrial manipulators, but also other systems are considered.

In our work we have developed a system for translation from a high-level, task-oriented language into either the robot native code, or calls at the level of a common API like, e.g., ROS, or both, and capable to handle complex, sensor-based actions, likewise the usual movement primitives.

This paper focuses on the code generation aspect of this solution, while our earlier publications described the task-level programming process in much more detail (Björkelund et al., 2011; Malec et al., 2013; Stenmark and Malec, 2013, 2014b).

Below we begin by describing the system architecture and the involved, already existing components. Then we proceed to the presentation of the actual contribution, namely the code generation process. In the next section we describe the experiments that have been performed in order to validate this approach. Finally we present a number of related works. The paper ends with conclusions and suggestions for future work.

2 System Overview

The principles of knowledge-based task synthesis developed earlier by our group (Björkelund et al., 2011; Björkelund et al., 2012) may be considered in light of the Model-Driven Engineering principles (Kent, 2002). In particular, the system described in the rest of this paper realizes the principles of separation of concerns, and separation of user roles, as spelled out recently in robotic context in Vanthienen et al. (2014). It consists of the following components:

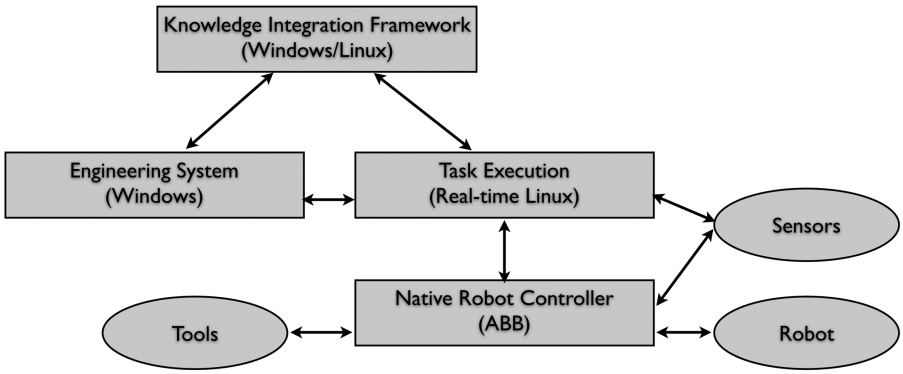


Figure 1: The Knowledge Integration Framework provides services to the Engineering System and the Task Execution. The latter two communicate during deployment and execution of tasks. See also Fig. 5.

- An intuitive task-definition tool that allows the user to specify the task using graphical menys and downloading assembly skills from a knowledge base, or by using a natural-language interface (Stenmark and Malec, 2014b; Stenmark and Nugues, 2013);
- An advanced graphical simulation and visualization tool for ABB robots, extended with additional capabilities taking care of other hardware used in our experiments;
- Software services transforming the task specification into a combination of a transition system (a sequential function chart) and low level code executable natively on the robot controller;
- Controllers specific for the hardware used: IRC5 and custom `ExtCtrl` (Blomdell et al., 2010) for the ABB industrial robots, and ROS-based[1] for the Rob@Work mobile platform;
- ABB robots: a dual-arm concept robot, IRB120 and IRB140, Rob@Work platform from Fraunhofer IPA[2], Force/Torque sensors from ATI Industrial Automation[3] used in the experiments mentioned in this paper, as well as vision sensors (Kinect and Raspberry Pi cameras) used for localization.

The functional dependencies in the system are illustrated in Fig. 1.

The knowledge base, called Knowledge Integration Framework (KIF), is a server containing robotic ontologies, data repositories and reasoning services, all three supporting the task definition functionality (Björkelund et al., 2012; Malec et al., 2013; Stenmark and Malec, 2013). It is realized as an OpenRDF Sesame (`http://www.openrdf.org`) triple store running on an Apache Tomcat servlet container (`http://tomcat.apache.org`). The Engineering System (ABB RobotStudio (ABB RobotStudio, 2017)) is a graphical user interface for high-level robot instruction that uses the data and services provided by KIF for user support. The Engineering System uses the ontologies provided

[1] `www.ros.org`
[2] `http://www.care-o-bot.de/en/rob-work.html`
[3] `http://www.ati-ia.com`

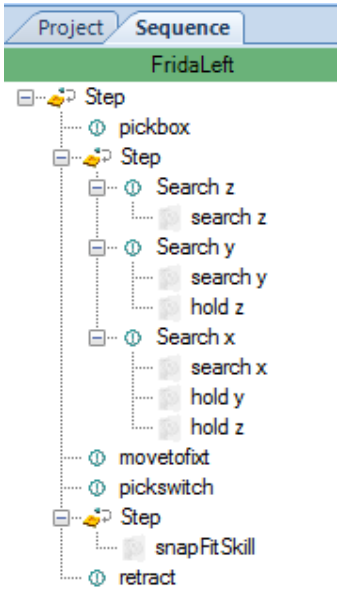
by KIF to model the workspace objects and downloads known skills and tasks from the skill libraries. Similarly, new objects and skills can be added to the knowledge base via the Engineering System. Skills that are created using classical programming tools, such as various state machine editors (like, e.g., JGrafchart (Theorin, 2014), used both as a sequential function chart (IEC, 2003)—a variant of Statecharts (Harel, 1987)—editor, and its execution environment), can be parsed, automatically or manually annotated with semantic data, and stored in the skill libraries.

The Task Execution module is built on top of the native robot controller and sensor hardware. It compiles, with the help of KIF, a symbolic task specification (like the one shown in Fig. 2) into generic executable files and, when needed, hardware-specific code, before executing it. It is implemented on a real-time-enabled Linux machine, linking the external control coming from JGrafchart (a simple example is shown in Fig. 2b) or possibly other software, with the native controller of the robot. Depending on the system state (execution or teaching mode) or the action being carried out, the control is switched between the `ExtCtrl` system for sensor control and the native controller, allowing smooth integration of the low-level robot code with the high-level instructions expressed using the SFC formalism. It also runs adaption and error detection algorithms. The native robot controller is in our case an ABB IRC5 system running code written in the language RAPID, but any (accessible) robot controller might be used here. The Engineering System uses among other tools a sensor-based-motion compiler (Stenmark and Stolt, 2013) translating a symbolic, constraint-based (De Schutter et al., 2007) motion specification into an appropriately parametrized corresponding SFC and the native controller code.

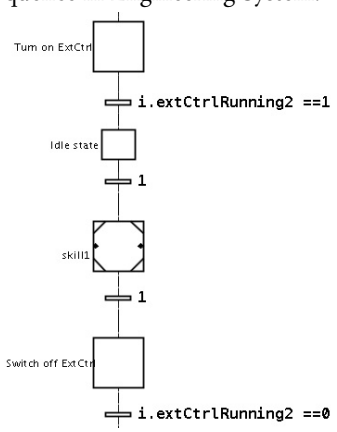
In addition to the benefit of providing modular exchangeable components, the rationale behind KIF as a separate entity is that the knowledge-providing services can be treated as black boxes. Robot and system-integration vendors can offer their customers computationally expensive or data-heavy cloud-based services (Stenmark et al., 2013) instead of deploying them on every site and each installation.

3 Code Generation

In order to illustrate the process of code generation, we will use an example task where a switch is assembled into the bottom of an emergency stop box. Both parts are displayed in Fig. 3a. The task is described in the Engineering System as a sequence, shown earlier in Fig. 2a. First the box is picked and aligned to a fixture with a force sensor. Then the switch is picked and assembled with the box using a snap-fit skill. The sequence is mixing actions (`pickbox`, `movetofixt`, `pickswitch` and `retract`) that are written in native robot controller code (ordinary blind moves), guarded search motions which are actions that are force-controlled (alignment to the fixture), and it also reuses a sensor-based skill (`snapFitSkill`. In this section we present how we generate and execute code for tasks containing these three types of actions. As an example we will use the sequence shown in Fig. 2a that, when executed, requires switching between the native robot controller and the external, sensor-based control (`ExtCtrl`).



(a) The task is shown as a sequence in Engineering System.

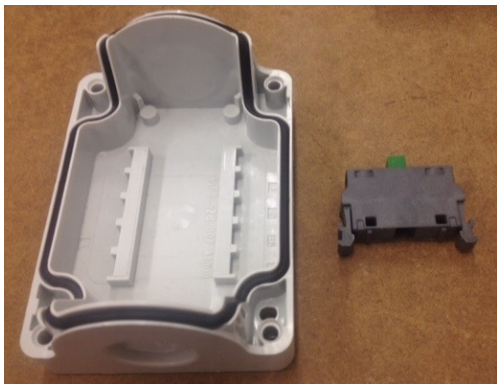


(b) A small part of the state chart generated from the sequence in Fig. 2a.

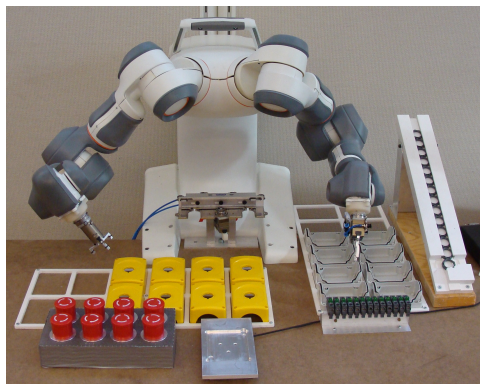
```
<SkillSpecification>
  <Frame id="f1">
    <origin>[ 490 , 6 , 43 ]</origin>
        <quaternion>[ 1 , 0 , 0 , 0]</quaternion>
  </Frame>
  <ToolTransform id="tool1">
    <trans>[0,0,87]</trans>
        <quaternion>[0,-0.707106781,0.707106781,0]</quaternion>
  </ToolTransform>
  <ImpedanceControlParams id="z-controller">
    <M>0.01</M>
    <D>0.2</D>
  </ImpedanceControlParams>
  <ImpedanceControlParams id="y-controller">
    <M>0.02</M>
    <D>0.6</D>
  </ImpedanceControlParams>
  <Action id="z-search" tool="tool1">
    <Direction>
      <searchVelocity unit="mm/s">-30</searchVelocity>
      <motionframe>f1</motionframe>
      <motiondir>z</motiondir>
      <threshold unit="N">3</threshold>
    </Direction>
  </Action>
  <Action id="y-search" tool="tool1">
    <Direction>
      <searchVelocity unit="mm/s">-40</searchVelocity>
      <motionframe>f1</motionframe>
      <motiondir>y</motiondir>
      <threshold unit="N">3</threshold>
    </Direction>
    <Constraint>
      <type>forcecontrolled</type>
      <controllerId>z-controller</controllerId>
      <motionframe>f1</motionframe>
      <motiondir>z</motiondir>
      <value unit="N">3</value>
    </Constraint>
  </Action>
```

(c) A sample XML description corresponding to the guarded motion skill from Fig. 2a that is sent to the code generation service by Engineering System. The parameter values are either set automatically or by the user in the Engineering System. If a guarded motion is generated, e.g., from text and one of the parameters is an impedance controller, the controller is selected among the controller objects in the station. All mandatory parameters must be specified before the code generation step.

Figure 2: A task can be created using the graphical interface of the Engineering System or by services for automatic sequence generation. The sequence shown is part of an assembly of an emergency stop button (see next section), consisting of a synthesized guarded motion, a complex *snapFitSkill* and three position-based primitives, see Fig. 2a. In Fig. 2b the step named *skill1* is a macro step containing the synthesized guarded motion skill. Before and after the actual skill the steps for starting and turning off `ExtCtrl` are inserted. The idle state resets all reference values of the controller. Finally, Fig. 2c presents the corresponding input to the code generation service.



(**a**) The parts that are used in the process: the bottom of an emergency stop box (later "box") and a switch that will be inserted into the box.



(**b**) The two-armed ABB robot and the workspace setup.

Figure 3: The example setup for the assembly experiments.

The task sequence is translated into executable code in two steps. First, the native code for each primitive action is deployed on the robot controller. In this case RAPID procedures and data declarations are added to the main module and synchronized to the ABB controller from the Engineering System. In the second step a KIF service generates the task state machine (encoded as an SFC). Thus, KIF acts both as a service provider and a database, where the service builds a complete SFC, which can include steps synthesized from skills that are stored in the KIF databases. The final SFC is executed in JGrafchart, which, when necessary, calls the RAPID procedures on the native controller. The data flow between the modules is illustrated in Fig. 4.

3.1 Execution System Architecture

The execution system architecture is depicted in Fig. 5. The task is executed in JGrafchart, which in turn invokes functions on different controllers. The external controller (`ExtCtrl`) is implemented using Matlab/Simulink Real Time Workshop. It sends position and velocity references to the robot while measurements from the sensors are used to control the motion. Motions are specified using a symbolic framework based on iTaSC (De Schutter et al., 2007), by constraining variables such as positions, velocities or forces in a closed *kinematic chain* that also contains the robot. The communication between the modules is done using a two-way protocol called LabComm (`http://wiki.cs.lth.se/moin/LabComm`). LabComm packages data in self-describing samples and the encoders and decoders may be generated for multiple languages (C, Java, RAPID, C#). The `ExtCtrl` interface divides the samples into four categories: inputs, outputs, parameters and log signals. Hence, JGrafchart can set output signals and read inputs from the underlying controller.

LabComm is also used to send commands (strings and acknowledgements) to the native controller. In that sense, the protocol aligns well with ROS messages, and two-way LabComm-ROS bridges have also been created. This is important since a few of our robot systems are ROS-hybrids, where an ABB manipulator is mounted on top of a ROS-based mobile platform, each having a separate LabComm channel to JGrafchart.

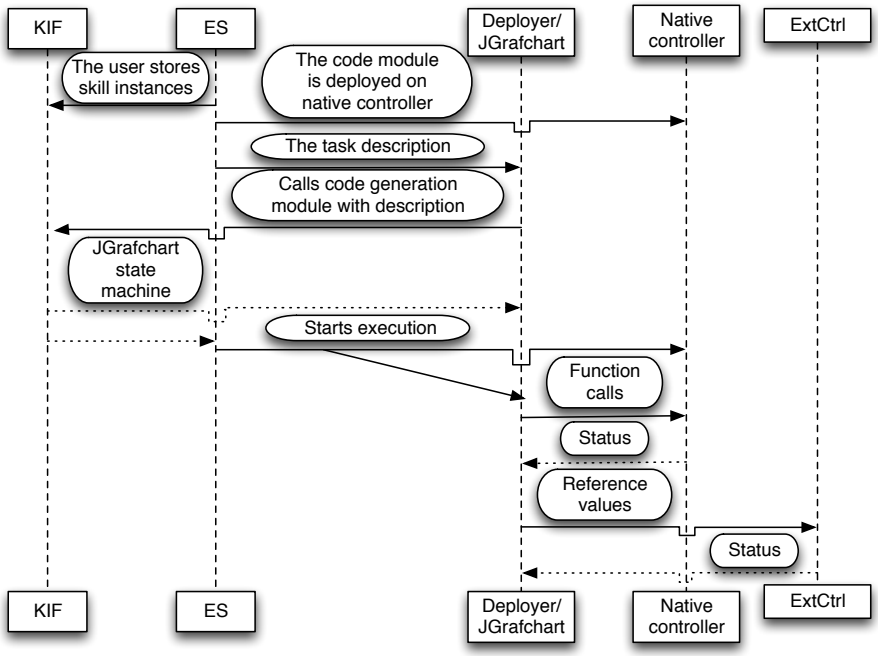


Figure 4: The Engineering System (ES) sends the task description to a small helper program called Deployer which in turn calls the code generation service on KIF, loads the returned file and starts JGrafchart.

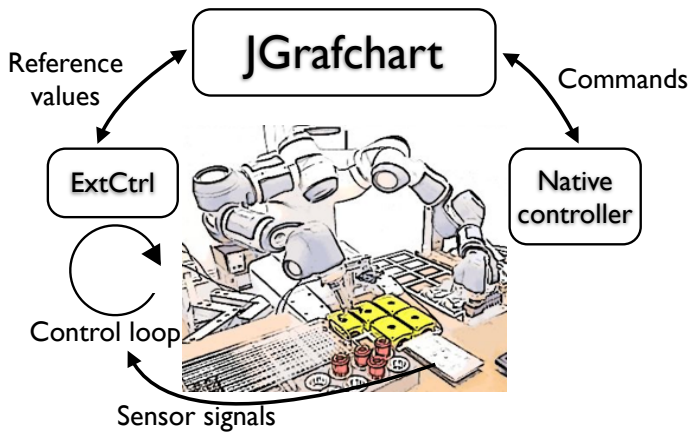


Figure 5: A schematic image of the execution architecture. The task state machine is executed in JGrafchart, which in turn sets and reads reference values to `ExtCtrl` and sends commands to the native controller.

3.2 Sequential function charts in JGrafchart

JGrafchart is a tool for graphical editing and execution of state charts (Theorin, 2014). JGrafchart is used for programming sensor-based skills and has a hierarchical structure where state machines can be nested. For each robot, the generated state machine will be a sequence. Each primitive or sensor-based skill is represented by a state (step), and transitions are triggered when the primitive action or skill has finished. Each state can either contain a few simple commands or be a nested state machine, put into a so called macro step (in Fig. 2b shown by a square with marked corners). The generated and reused skills are put into these macro steps while primitive actions becomes simple steps with function calls.

When alternating between sensor-based external control and the native controller, the controllers are turned on and off during the execution, so these steps need to be added as well during the generation phase. The switching between controllers is handled by the state machine in JGrafchart. When `ExtCtrl` is turned on or off, the robot has to stand still to avoid inconsistent position and velocity values. When a controller is turned on it starts by updating its position, velocity and acceleration values to the current values on the robot.

The state machine can have parallel activities and multiple communication channels at the same time. Hence, code can be generated for multiple tasks and executed in parallel. Although the state machine allows synchronization between the tasks, we do not have a high-level representation of synchronized motions yet.

Finally, the sequence IDs and graphical elements, such as positions of the blocks, have to be added in order to provide an editable view. We generate very simple layout, however, much more could be done with respect to the legibility of the generated SFCs.

3.3 Code generation service

The code generation is implemented as an online service which is called by the Engineering System. It takes an XML description with the sequence as input and outputs the XML-encoding of the sequential function chart understood by JGrafchart. An example of the input is shown in Fig. 2c. Each robot has its own task, which needs to specify what LabComm port it will connect to. A primitive is specified by its procedure name and parameters to the procedure. Reusable skills are referenced by their URI, which is the unique identifier that is stored in the KIF repositories.

3.4 Reusing skills

A skill that is created in JGrafchart as a macro step, can be uploaded to KIF and reused. During the upload, it is translated into RDF triples. The skills are annotated with types, e.g., SnapFit, and skill parameters that are exposed to the users are also annotated with types and descriptions. The RDF representation is a simple transformation, where each state in the state machine is an RDF node annotated as a *State*, together with parameters belonging to the state, the commands, a description of the state (e.g. *Search x*) and is linked to transitions (which similarly are annotated with type and values). In this way, the parameters can be retrieved and updated externally using the graphical view

in the engineering system. When a skill is updated in the engineering system, the new instance is also stored in KIF with the new parameter values. The URI in the input XML file refers to the updated skill, that is retrieved during the code generation process and translated back from triples to XML describing a macro step. The macro step is then parameterized and added as a step in the task sequence XML.

3.5 Guarded motions

One drawback of using the reusable skills is that there are implicit assumptions of the robot kinematics built into them, and thus the skill can only be used for the same (type of) robot. This limitation can be avoided by using a symbolic skill description and regenerating the code for each specific robot. This is what we do for the guarded motions. In this case, the skill specification is larger, as shown in Fig. 2c, where three actions are described. First, a search in the negative z-direction of the force sensor frame (f1) is performed. When the surface is hit, the motion continues in negative y-direction of the same frame while holding 3 N in the z-direction, pushing the piece to the side of the sensor. The last motion is in the x-direction while both pressing down and to the side, until the piece is lodged into the corner. In order to setup the kinematic chain, the coordinate frames that are used to express the motions have to be set, as well as the tool transform, that is, the transformation from the point where the tool is attached on the robot flange to the tip of the tool. Each constraint is specified along an axis of a chosen frame. There can be one motion constraint (using the <Direction> tag) which specifies the motion direction, speed and the threshold value for stopping. The other rotational and translational axes can also be constrained. The constraint should also specify what set of impedance controller parameters to use. Knowing what robot the code is generated for, the control parameters for the kinematic chain are set to the values of the frames and each motion sets reference values on corresponding parameters. Simply put, it is a mapping, where several hundred output signals have to get a value, where most are just dependent on the robot type, while some represent the coordinates of the frames in the kinematic chain and other reference values during execution. During the code generation the right value has to be set to the corresponding reference output signal and this is calculated depending on what frame is used.

3.6 RAPID code generation

The actions that have native controller code are called primitives. There are several different primitives and, in fact, they do not have to be simple. The most used are simple linear motions, move primitives for translation and rotation, and actions for opening and closing the gripper. The gripper primitives are downloaded together with the tool. The simplest form of a primitive is pure native code, a RAPID primitive, which does not have any semantically described parameters but where the user can add arbitrary lines of code which will be called as a function in the program. This is an exception though, since most primitives are specified by their parameters. E.g., the properties of a linear move are shown in Fig. 6. The target positions will be calculated from the objects' CAD-models and the objects' relative frames and positions in the virtual environment. The code for each primitive type and target values are synchronized to the controller as RAPID procedures and data declarations.

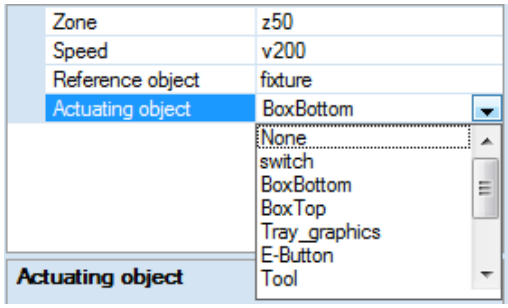


Figure 6: The properties of a move primitive: zone data for specifying maximal allowed deviation from the target point, velocity in mm/s, the position(s) of the motion specified by a relative position of the actuated object to a (frame of a) reference object. A motion can have a list of positions added to it.

Hence, JGrafchart will invoke a primitive function with a string consisting of the procedure name followed by comma-separated parameters, e.g, "MoveL target_1, v1000, z50". The string value of the procedure name can be invoked directly with late binding, however, due to the execution model of the native controller the optional parameters have to be translated into corresponding data types, the target name must be mapped to a robtarget data object and, e.g., the speed data has to be parsed using native functions.

4 Experiments

In order to verify that the code generation works as expected, we tested it using the sequence from the Engineering System depicted in Fig. 2a which resulted in an executable state machine, the same that is partly shown in Fig. 2b. The state machine is the nominal task execution, without any task-level error handling procedures. We have generated code for a two-armed ABB concept robot (see Fig. 3b) and the generation for guarded motions is working for both the left and the right arm, as well as for ABB IRB120 and IRB140 manipulators.

5 Related Work

The complexity of robot programming is a commonly discussed problem (Pan et al., 2010; Rossano et al., 2013). By abstracting away the underlying details of the system, high-level programming can make robot instruction accessible to non-expert users. However, the workload for the experienced programmer can also be reduced by automatic generation of low-level control. Service robotics and industrial robotics have taken somewhat different but not completely orthogonal paths regarding high-level programming interfaces. In service robotics, where the users are inexperienced and the robot systems are uniform with integrated sensors and software, programming by demonstration and automatic skill extraction is popular. A survey of programming-by-demonstration models is presented by Billard et al. (2008).

Task description in industrial robotics setting comes also in the form of hierarchical representation and control, but the languages used are much more limited (and thus more amenable to effective implementation). There exist a number of standardized approaches, based e.g., on IEC (2003) devised for programmable logic controllers, or proprietary solutions provided by robot manufacturers, however, to a large extent incompatible with each other. EU projects like RoSta (Nilsson et al., 2009) (`www.robot-standards.org`) are attempting to change this situation.

In industrial robotics, programming and demonstration techniques are used to record trajectories and target positions e.g., for painting or grinding robots. However, it is desirable to minimize downtime for the robot, therefore, much programming and simulation is done offline whereas only the fine tuning is done online (Mitsi et al., 2005; Bottazzi and Fonseca, 2006; Hägele et al., 2008). This has resulted in a plethora of tools for robot programming, where several of them attempt to make the programming simpler, e.g., by using visual programming languages. The graphics can give meaning and overview, while still allowing a more advanced user to modify details, such as tolerances. In robotics, standardized graphical programming languages include Ladder Diagrams, Function Block Diagrams and Sequential Function Charts. Other well known languages are LabView, UML, MATLAB/Simulink and RCX. Using a touch screen as input device, icon-based programming languages such as in Bischoff et al. (2002) can also lower the threshold to robot programming. There are also experimental systems using human programmer's gestures as a tool for pointing the intended robot locations (Neto et al., 2010). However, all the systems named above offer monolithic compilation to the native code of the robot controller. Besides, all the attempts are done at the level of robot motions, focusing on determining locations. Experiences show (Stolt et al., 2011) that even relatively simple sensor-based tasks, extending beyond the "drag and drop" visual programming using those tools, require a lot of time and expertise for proper implementation in mixed architecture like ours.

Reusable skill or manipulation primitives are a convenient way of hiding the detailed control structures (Kröger et al., 2010). The approach closest to ours is presented in the works of M. Beetz and his group, where high-level actions are translated, using knowledge-based techniques, into robot programs (Beetz et al., 2010). However, the resulting code is normally at the level of ROS primitives, acceptable in case of service robots, but without providing any real-time guarantees needed in industrial setting. In this context, they also present an approach to map high-level constraints to control parameters in order to flip a pancake (Kresse and Beetz, 2012).

6 Conclusions and Future Work

In this paper we have described how we generate executable code for real-time sensor-based control from symbolic task descriptions. Previous work in code generation is limited to position-based approaches. The challenge to go from high-level instructions to robust executable low-level code is an open-ended research problem, and we wanted to share our approach in high technical detail. Naturally, different levels of abstraction have different power of expression. Thus, generating code for different robots from the same symbolic description is much easier than reusing code written for one platform by extracting its semantic meaning and regenerating the skill for another platform. Hence, it is important to find suitable levels of abstraction, and in our case we have chosen to express the guarded motions using a set of symbolic constraints. The modular system simplifies the code generation, where the user interface only exposes a subset of parameters to the user, while the

JGrafchart state machine contains the calculated reference values to the controllers and coordinates the high-level execution. The external controller is responsible for the real-time sensor control which is necessary for achieving the necessary performance for assembly operations.

In future work we plan to experiment using a mobile platform running ROS together with our dual-arm robot and thus evaluate how easy it is to extend the code generation to simultaneously support other platforms. The sequence can express control structures, such as loops and if-statements, ongoing work involves adding these control structures to the task state machine as well as describing and generating the synchronization between robots.

The robustness of the generated skills depends on the user input. One direction of future work is to couple the graphical user interface with haptic demonstrations and learning algorithms in order to extract e.g., force thresholds and impedance controller parameters. Another direction is to add knowledge and reasoning to the system to automatically generate error handling states to the task state machine.

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Paper IV

Paper IV

Simplified Programming of Re-usable Skills on a Safe Industrial Robot – Prototype and Evaluation

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ABSTRACT

This paper presents a study on iconic programming support for mainly position-based lead-through programming of an ABB YuMi collaborative robot. A prototype tool supporting a hybrid programming and execution mode was developed and evaluated with 21 non-expert users with varying programming and robotics experience. We also present a comparison of the programming times for an expert robot programmer using traditional tools versus the new tool. The expert programmed the same tasks in 1/5 of the time compared to traditional tools and the non-experts were able to program and debug a LEGO building task using the robot within 30 minutes.

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1 Introduction

In recent years, we have had a renaissance in industrial robotics: a new segment of robot models (e.g., UR5, ABB YuMi, Rethink Robotics' Baxter and KUKA's LBR iiwa) intended for safe human–robot collaboration and simpler robot programming have emerged. The application areas for these robot models are typically assembly of consumer electronics or repackaging of (small) products. One difference between these robots and previous models is the *lead–through* programming, or kinesthetic teaching, mode. In this mode, the user can guide the robot arm into the desired positions and thus record and replay a robot program.

Kinesthetic teaching using force-guided motions (Massa et al., 2015), gravity compensation and variable stiffness (Wrede et al., 2013; Tykal et al., 2016) support also non-expert operators to program and configure tasks (Rodamilans et al., 2016), however, dynamic environments, uncertainty and the use of noisy sensor feedback are still challenges for the operator (Stenmark et al., 2016), and so far, experts are still needed to program the robots on the necessary levels of robustness and precision.

Programming by demonstration, PbD, or learning from demonstration, LfD (Billard et al., 2016), is a well-established concept in service robotics, however, these methods often require multiple demonstrations which we consider less suitable in an industrial setting where rapid instruction and evaluation is needed. The desired approach in an industrial context is rather a one–shot demonstration, from which enough parameters for an executable representation can be extracted.

Orthogonal to the PbD approach is the use of high–level instructions to simplify robot programming for industrial tasks, e.g., using natural language (Stenmark and Nugues, 2013) and semantically defined parameterized motion primitives (Felip et al., 2013), often called *skills* (Pedersen et al., 2014, 2016). Such semantic descriptions are desirable because they enable the automatic generation of, e.g., standard PDDL[1]–descriptions for planning and scheduling of tasks or path planning and generation from virtual models (Perzylo et al., 2016).

We propose to aim for a middle ground by combining programming by demonstration and parametrized skill representations to simplify robot programming, i.e., *it must be possible for non-expert users to create their own skills from scratch* and specify object references that can later be used as basic building blocks in high–level approaches.

In this paper we present a prototype of a programming tool for industrial robots, which enables non–expert users to program and edit simple industrial tasks using one–shot demonstrations, i.e., kinesthetic teaching, and also reduces the programming and debugging time for an expert programmer. We extracted initial requirements regarding functionality and behavior for the design of this tool from two case studies and evaluated it in two experiments with an expert user and in a study with 21 non–experts.

The remainder of the paper is organized as follows. In Section 2 we present the background and related work for our efforts. We present the case studies for extraction of requirements in Section 3 and our resulting prototype implementation in Section 4. In Section 5 we report on the evaluation of the tool through a user study with 21 subjects and by two expert experiments. We conclude the paper in Section 6 with a discussion of our findings and suggestions for future work.

[1]Planning Domain Definition Language

2 Related Work

The research into intuitive human-robot interaction and programming is so far more active in the field of service robotics, since service robots act in dynamic non-structured environments and are intended to interact with non-expert operators. Some of the following approaches are nonetheless relevant also for work in intuitive programming of industrial robots.

For instance, robots can learn from humans by observing the human carrying out a task and extract action parameters and objects involved in this process. Billard et al. (2016) use objects and locations as task parameters and can extract these in a new workspace from human demonstrations. Feniello et al. (2014) synthesize the program specification for repositioning tasks from examples, e.g., their system can learn a program sequence that sorts objects by color. *Visuospatial skill learning* is also used by Ahmadzadeh et al. (2015) to extract the geometric constraints of the objects in a task and to learn the sequence of push and pull skills in a task. Using *Gaussian mixture regression*, trajectories can be generated from the learning results (Huang et al., 2016a). From multiple demonstrations, high-level semantics such as intentions (Fonooni et al., 2016), transition conditions (Kober et al., 2015) and precedence constraints for sequencing of manipulation primitives (Kramberger et al., 2016; Manschitz et al., 2014) can be extracted. Niekum et al. (2015) segment demonstrations automatically using (beta process autoregressive) *Hidden Markov Models*, learn the reference coordinates for each trajectory from clustering the demonstrations in different coordinate frames and iteratively refine the resulting finite state machine based on new demonstrations.

Low-level skills can be encoded as *dynamic movement primitives* (DMPs) (Ijspeert et al., 2002) demonstrated using, e.g., *Imitation Learning* and further optimized using *Reinforcement Learning*. Examples of research in imitation learning methods for robot skill learning are given by Kormushev et al. (2011), who combine kinesthetic learning of positional trajectories with force profiles demonstrated using a haptic input device to demonstrate ironing skills. Steinmetz et al. (2015) use an external force/torque sensor mounted on the robot arm to record force and position simultaneously and learn the force profiles for a PID-controller. Abu-Dakka et al. (2014) redeploy peg-in-hole skills in new settings by adding exception strategies that randomly search for the hole to improve robustness. Nemec et al. (2013) use a priori knowledge and reinforcement learning to reduce the number of demonstrations needed to teach a flip task to a robot and Pastor et al. (2011) use reinforcement learning to optimize a pool strike. All these methods, however, focus on one specific type of movement or task, each of which requiring a specific setup. Additionally, data driven approaches require multiple demonstrations with enough feature variation to extract task parameters and specifically for reinforcement learning based approaches it is a challenging problem to design a good cost function (which needs to be either taught or manually tuned).

Multiple demonstrations are time consuming, hence a one-shot approach is desired. Also, industrial tasks often require high precision, which can be difficult to achieve from generalizations between multiple demonstrations and the underlying representation of instructions must support adaption and debugging. Ko et al. (2015) list and motivate the main qualitative aspects of a programming (by demonstration) system that have to be evaluated, namely: accuracy and repeatability, adaptability and generality, learning fatigue, system complexity and production speed .

Tsarouchi et al. (2016) identify various challenges in the human-robot interaction for industrial robots, and while e.g., multimodal communication and learning by demonstration have received

significant research attention also in this field, the user interfaces are often too complex for non-expert users. The learning curve can be leveled by using visual programming environments, e.g., Huang et al. (2016b) showed that a *Scratch*-like programming language reduced the programming effort and Glas et al. (2016) have developed *Composer* for designing social robot behavior. An increasing number of industrial robots provide template skills for common applications, e.g., the UR-series from Universal Robots as well as Baxter and Sawyer from Rethink Robotics come with template pick-and-place skills, and the Franka robot from Emika lets the user download expert made *apps* (i.e., skills) and combine these into more complex task using visual programming. Apps that can be used out-of-the box with little effort make these types of robots attractive, e.g., for small companies, however, programming new re-usable skills from scratch is still a challenge, which we try to handle with the interface proposed in this paper.

In order to bootstrap the instruction process, the interaction can be improved by systems that ask leading questions (Cakmak and Thomaz, 2012; Mohseni-Kabir et al., 2015), or by using other modalities such as speech, see, e.g., Pardowitz et al. (2007) or a graphical user interface so that the task constraints generated from a single demonstration can be understood and edited by the operators (Alexandrova et al., 2014; Kurenkov et al., 2015). We plan to enhance our system with the necessary reasoning capabilities so that such an approach to supporting the user can be integrated.

3 Case Studies

We analyzed the programming process and required motion types and primitives from two rather complex applications that we had previously built for the dual-arm ABB robot YuMi. One is an emergency stop button assembly that uses force-based motions for snapping and screwing together switches and nuts (Stolt et al., 2011; Stolt and Linderoth, 2013). The second case is a position-based gift-wrapping application, which was developed as part of a commercial campaign in Sweden during the fall of 2015 and toured consumer electronic retail stores wrapping gifts all over Sweden (Stolt and Stenmark, 2015; Stenmark et al., 2016; Stolt et al., 2016).

Both applications rely on synchronized motion between the two arms of the ABB YuMi dual-arm robot. The robot is designed for safe human-robot collaboration and each arm has seven degrees of freedom. These features are used in the gift-wrapping application since the wrapping process uses a collaborative step and multiple contact points on the arm. Videos of both applications are available through YouTube (Stolt and Linderoth, 2013; Stolt and Stenmark, 2015).

We identified several issues during the programming process, which are mostly related to the traditional programming interfaces and assumed workflow for the YuMi (Stenmark et al., 2016; Stolt et al., 2016). From those issues, we derived requirements for the development of a programming interface that supports (and is supported by) our underlying architecture for skill representation and robot code generation (Stenmark et al., 2014).

3.1 Traditional interfaces and interaction

The ABB robot can be programmed in the ABB programming language RAPID either using an engineering tool called RobotStudio, a Windows Universal App (YuMi Online) or by using the teach pendant (an integrated joystick and touch display interface for direct robot control, a standard piece of equipment usually accompanying industrial robots, see Figure 1), directly. RobotStudio and the app can run on the same Windows device and are connected to the robot through a local network. Each of the tools has different features. RobotStudio is intended for editing RAPID programs and for simulation. The app has an online programming interface supporting a few commands (motions and gripper actions) and has a limited debugging support. It has however a kinesthetic programming mode, lead-through, which makes it easy to teach positions in free space. Contact situations are more suitable to teach with the joystick on the teach pendant since contact forces will move the arms out of position if lead-through is enabled. The teach pendant can also be used for debugging, for example by moving the program pointer and executing instructions one-by-one.

The traditional workflow starts with offline programming and simulation before deploying a program on the physical robot. First, the program can be written and executed in the virtual environment in RobotStudio. When the user is satisfied, the program is deployed on the physical system and testing in the real environment can begin. User interaction can be added into the RAPID program by inserting dialogue prompts into the program. Then the resulting program can be deployed in the factory and the robot operator will only interact with the robot using the dialogues. All error handling procedures need to be added beforehand by the programmer.

It is not trivial to include (contact) forces and deformable material into simulations, hence, our applications required *online* programming, i.e., testing and updating using the physical robot system including the lead-through functionality for kinesthetic teaching of poses, which was non-trivial with the given interfaces due to their different features. Specifically, in the gift-wrapping application the programmers were required to sometimes circumvent the safety mechanisms originally designed for unsafe robots, but still deployed on the inherently safe YuMi.

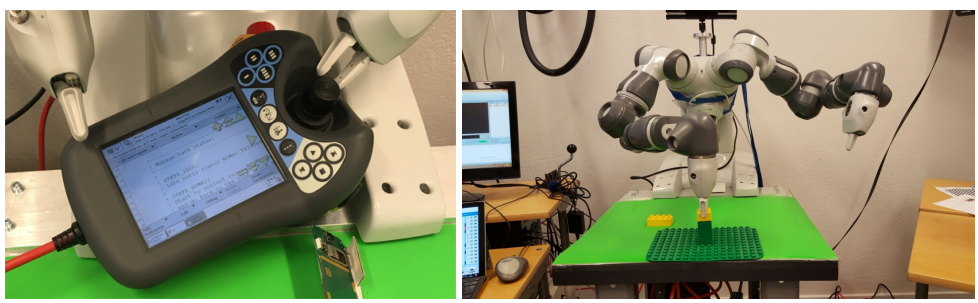

Figure 1: ABB's (YuMi's) teach pendant (left) and YuMi in the LEGO building task (right).

3.2 Analysis

Our observations from programming the two applications provided an initial list of system requirements regarding which basic instructions should be possible to rapidly include and update in a program and some hypotheses about better user interaction and support, which we explain briefly in the following.

Actions: The applications required mostly motions specified through gripper target positions in Cartesian space (both relative specified objects or in world coordinated). Secondly, joint configurations were often used in the gift-wrapping application for specifying the position of other parts of the arm than the gripper. Also, both applications relied on contact motions (i.e., motions that stop when a force threshold is reached) for robust task execution. Other actions identified as common are gripper commands (open and close), movement to synchronization points for both arms, and synchronized motions of both arms.

Reuse, refinement and update: In order to be able to reuse a task, i.e., a program sequence with small changes, e.g., in object positions, it must be possible to specify work objects so that motion primitives can be programmed using relative reference coordinate systems. Also, it must be possible to easily change and adapt reference coordinate systems for existing work pieces, as it must be assumed that even expert users occasionally forget to specify the correct reference immediately.

User interaction: In the two applications, user interaction *a*s part of the normal operation was limited to handling discrete events in the program flow. For stopping or pausing the execution, the operator touched the robot and simply triggered the safety system break, but that also required manual restart of the robot and required rather long cycles to update and test specific instructions. Here, we assume that a rapid cycle of stopping the execution, changing and updating instructions where necessary and testing (executing again) is desirable.

Compatibility: Since we initially assume only a subset of instructions (actions as described above) to be available in our graphical user interface, the interface should generate an editable program file that an expert user can refine further by using the traditional tools and interfaces.

Based on this list of observations and assumed requirements, we designed a prototype interface supporting users in quickly creating basic programs (skills) through kinesthetic teaching and iconic programming (Stenmark and Topp, 2016). These skills can then later be refined and form the basis for more complex programs, which can be generated using even more high-level approaches to robot programming, as proposed earlier (Stenmark and Nugues, 2013).

4 Implementation

In the following we describe the graphical user interface, which we developed based on the previously described findings from our case studies. The interface was also meant to be a tool for investigating, how our underlying ideas, mainly the skill representation and the reuse of skills through parameterization, would support non-expert users in programming an industrial robot.

A screen capture of the implemented programming tool is shown in Fig. 2. It is implemented as a touch-enabled Windows app running on a Surface Pro with 8 GB RAM and a wireless connection to the robot controller. The implementation is programmed in C# and uses ABB robot controller libraries for network communication and math calculations.

4.1 Features

The graphical interface divides the screen into an instruction panel to the left and a program panel to the right. In the upper left corner, the built-in basic actions are displayed in yellow, while the user-created skills (sequences and combinations of such primitives or other skills) are added to the list in purple. The default actions are the following:

`Move`: a fine-point slow move. When this instruction is added to the robot program sequence, it takes the current position of the active arm and saves it as precise goal position (trajectories between specified points are generated by the robot controller so far). The target is saved with three positions: the exact joint position for the robot arm, the Cartesian position relative to the world (or robot base) system and, if an object is selected, the position relative to the object. Thus, the user can switch coordinate systems between objects or to absolute positions, or between Cartesian and joint space motions without updating the position.

`Via`: a fast motion with zone parameter 5 mm as default, i.e., getting close to the specified pose within this zone is considered sufficient. Analogously to the fine-point move, the position is saved in absolute and relative coordinates as well as in joint space.

`Open` and `Close` for fully opening and closing the gripper. The gripper action will execute when added to the program.

`Contact Move`: a movement towards a contact point which will stop when detecting an estimated contact force. The current position of the robot will be used to set a contact position, but the motion will continue beyond that point.

`Sync`: adds synchronization points, i.e., points in the program sequence where both arms should reach the specified pose at the same time.

`Fingers`: an action for setting the finger positions exactly and changing the gripping force of the fingers.

`Locate objects`: will call a local procedure on the robot controller for detecting objects using the built-in cameras on the robot's hands. For the time being, the camera calibration, image settings and detection algorithms must be provided by an expert and reloaded into the controller. The detected object's reference system will, however, be updated each time the procedure is executed hence the user can use the object references to program the robot without considering the underlying code.

Under the actions, the user can add coordinate frames related to objects by pointing with the robot. These can be updated when the object is moved.

The current robot programs for respective arms are displayed to the right. Each action has a line with an individual play arrow, an editable name, a color label for the relative coordinate system, a button for updating the position, editing and a picture. The order of the sequence can be edited by dragging and dropping.

Additional buttons provide functionality for opening and closing the grippers without adding program instructions, executing, toggling the lead-through functionality of the robot and saving/loading a complete workspace consisting of skills, objects and current robot program.

4.2 Reuse of skills

Action (sub)sequences can be selected and stored as skills, these will show up in the action list as purple buttons. In the sequences the skills can be expanded and edited further.

The user can add skills with single instructions but with application-specific parameters such as speed, zone (precision parameter for movement), and object data, and thus have for example multiple types of parameterized motions. E.g., in the gift-wrapping application, the speed was different for motions manipulating the paper and pushing the box, hence, each time an instruction was added the speed parameter had to be set to the correct value.

The actions and skills are robot agnostic and can be switched between the arms. The `Sync` actions can of course cause problems if not moved in pairs. If a skill was programmed using one arm, the joint positions cannot be reused for the other arm, so the default execution will use the Cartesian positions either relative to the object or in absolute coordinates. By selecting multiple actions, the relative object can be changed and updated to another by one button click, recalculating the relative offset to the new object using the absolute coordinates system.

Once the user requests a sequence to be executed (played), the high-level representation of the program is used to generate low-level instructions (RAPID code) for the robot controller currently connected to the user interface.

Our current prototype implementation does not (yet) support more advanced (and natural) force-based motions or logging and executing trajectories, however, a respective extension is subject to ongoing work.

4.3 User interaction and interference

The programming and debugging modes are merged into one hybrid mode, where the speed can be reduced during debugging and the safety system stops the robot in case of collisions with objects or the user, or predicted self-collisions.

The programming interface is designed to be forgiving towards the user. The user can program the entire sequence in absolute coordinates and then later add objects to the workspace and change the reference of the motion without reprogramming. The actions can be tested, refined, and updated individually, and any type of sequence can be saved as a skill.

Debugging is not a separate part of the execution process; however, the current implementation only supports running of individual actions and skills, or the entire sequence. Future work includes additional running and debugging options, e.g., running only a selected subset of actions, starting the execution at arbitrary points in the program and toggling debugging *break points*. The existing tools for jogging the robot using a joy stick or editing the generated RAPID program in a text editor are still available.

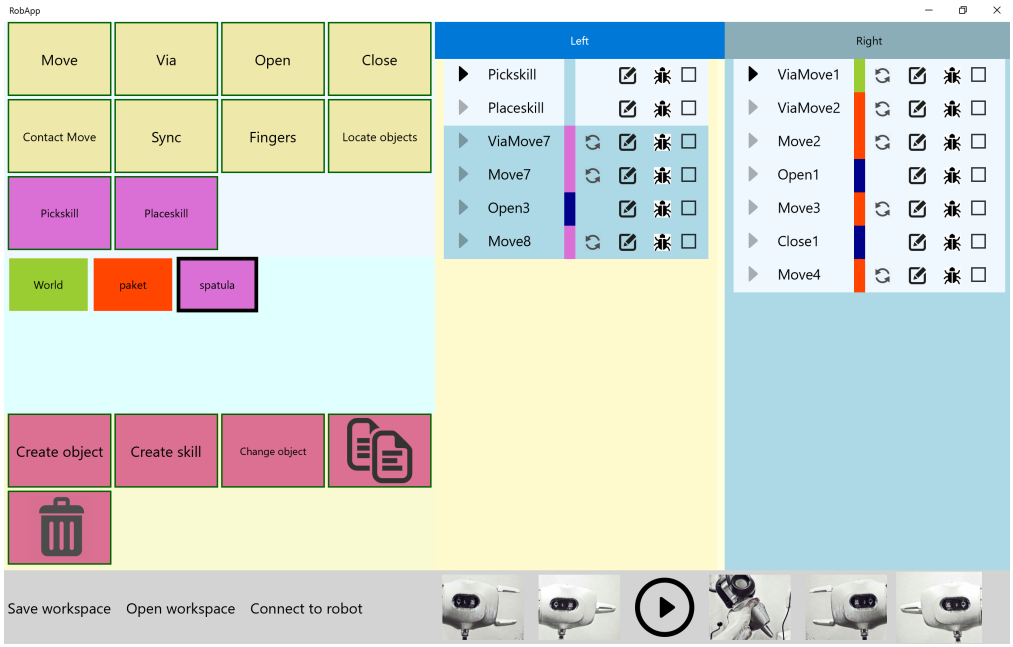

Figure 2: The graphical user interface.

5 Evaluation and User Study

The programming interface was evaluated by comparing programming times for one expert who programmed two robot tasks using both the new interface and traditional programming methods and through a user study with 21 non-expert, although technically or mathematically interested and experienced, users in a LEGO building task.

We see this study as an opportunity to observe potential users interacting with an industrial robot in a realistic setting, as the LEGO building task, although seemingly a child's play, has quite some challenges similar to those of assembling smaller products like, e.g., mobile phones. In the following paragraphs, we describe the study setup which had the original background of testing the effects of skill re-use and parameterization for non-expert programming of assembly tasks for industrial robots (Stenmark and Topp, 2016). We will thus in the following explain the different conditions for testing our hypotheses on the re-use of skills and break down our results by these conditions, but we had to realize that the study turned out to be as much an evaluation of the interface's general applicability as it was a tool for testing our original hypotheses. Thus, we focus on the rather general results about the overall benefits of our approach for non-expert programming of industrial robots and on the results we could achieve in the experiments carried out by the expert.

5.1 Study setup

We recruited our subjects mainly from an undergraduate (introductory) course on robotics and through advertising at the departments of Computer Science and Automatic Control at our university to ensure a somewhat technical or software oriented background. Here, we assume that this would be the case also for prospective users (instructors) of this type of robots in industrial contexts. However, we had the subjects fill in a questionnaire to also collect data about how they ranked their own experience with programming and technical equipment, to get a more accurate understanding regarding their background.

Our subjects were asked to program one arm on a dual-arm ABB YuMi with standard grippers to assemble different types of LEGO Duplo bricks using the robot's lead-through mechanism for kinesthetic teaching of poses in combination with our graphical interface for iconic programming. Figure 1 shows the setup for the study with the robot just finishing one step of the overall task. Routines for locating two specific types of LEGO bricks with the help of the built-in camera of the robot gripper were already provided by the experiment leaders as functionalities to be invoked by inserting a respective instruction in the program sequence. This was done for convenience as the camera calibration procedure is quite tedious and time consuming and should not be part of the study. The LEGO piece localization procedures had the arm move to a predefined position, from where the pieces could be localized robustly, given that they were placed within a coarsely sketched area. This allowed to specify pick-up poses relative to the work piece. We are aware that this is quite sophisticated knowledge about robotic systems to be handled for non-experts, however, it gave us the opportunity to observe how our subjects could be supported by our interface in switching between reference coordinate frames for the different objects involved in the task.

Conditions and specific tasks

The overall task was carried out in two phases: The first phase was the same for all participants while the second phase divided the users evenly into three groups corresponding to the three different test conditions. During the first phase, the instructions were to program the robot arm to pick up a LEGO Duplo "2x2" piece (referred to as "small LEGO") and insert it on top of another small piece, which was already the top of a little "tower" (task step 1). This program should then be used to create a skill, i.e., a re-usable representation of a sequence of motion primitives. For the second phase, the participants were asked to program the robot arm to carry out the same task another three times, but with a "2x4" piece ("large LEGO"), which should be placed first "centered" (step 2), then "hanging over on the left" (step 3), and finally "hanging over on the right" (step 4) with respect to the "tower top". For these three steps, the different conditions defined the programming paradigm, i.e., the first group, Group A, was to re-use and refine their own previously created skills, Group B was to re-use an expert-made skill and Group C was a control group in which participants should program each step from scratch without re-use of previously created and saved skills.

The instructions were given in written form, for each phase separately. After reading the instructions for step 1 the participants were introduced to the robot and the programming interface by one of the experiment leaders for a couple of minutes and then started to work on their tasks. The experiment leader observed the process, both to be able to resolve technical problems (the robot stops and needs

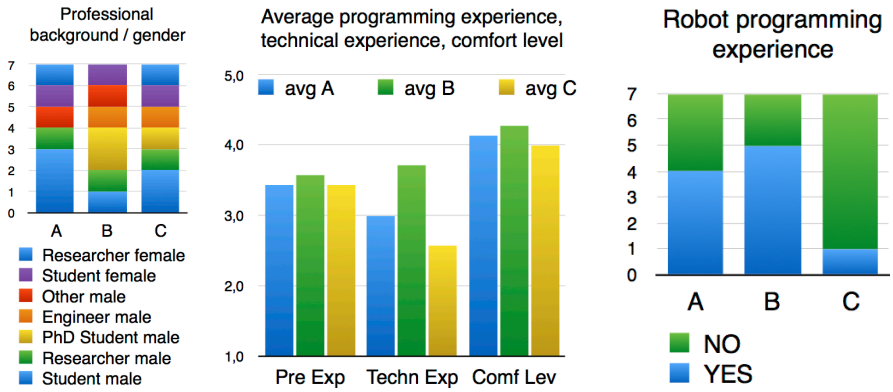

Figure 3: Participants' background and gender (left), experience and comfort level ratings (middle), and experience in programming a robot (right).

to be reset when it collides with any obstacle) and to assist the subjects with the handling of the programming tool in case they needed help (the tool has no built-in "help" functionality so far). Upon completion of step 1 and if the time frame allowed, the participants received the instructions for steps 2–4.

From pilot testing with involved researchers we had estimated that roughly 30 minutes for the actual programming was a suitable time limitation for each participant, however, this had the effect that in quite some cases the participants would not reach far enough into the second phase to complete all four programming steps. In this paper, we will thus focus on rather general evaluation criteria like success rate and time needed for completion in the first phase, and how many further steps the subjects managed to complete before running out of time. A more thorough analysis regarding the effect of the different methods and the subjects' individual ways of handling the task steps of the second phase is planned as future work.

After either completing all four steps or running out of time, we asked our subjects to fill in a questionnaire with both demographic questions (gender, occupation) and several five–level scale questions ranging from "not at all" to "absolutely" about their previous experiences with robots or programming, and the level of comfort they felt when handling the robot. Additionally, there was one yes/no question on whether they had ever programmed a physical robot before. We also gave them the opportunity to explain in free text what they found most difficult and what they would suggest to be changed in the programming interface.

Analysis

We had 21 participants (five female, 16 male), seven in each of the condition groups A, B, and C respectively. Figure 3 shows the distribution of professional background and gender as well as whether they had any previous experience of robot programming. The two participants with a non-technical professional background registered as communicator and nurse / kindergarten teacher respectively.

Table 1: Success (overall rating average) and time (minutes average)

	Success	Time Step 1	Time Step 2	Time Step 3	Time Step 4
All	6.0	20.6	8.1	5.0	3.5
Group A	5.0	20.4	14.5	1.5	-
Group B	9.0	18.4	3.0	5.5	2.0
Group C	4.14	22.9	9.5	9.0	8.0

We evaluated the trials for each participant according to the following criteria:

time step *n*: the time spent on completing step *n* after completing the previous step.

success rate: the sum of the success ratings for each step *n* according to the following criteria *full (3)* – the LEGO piece was fully attached on top of the "tower" robustly by the robot in step *n*; *partial (2)* – the LEGO piece was placed correctly but not (entirely) attached; *fail (1)* – the step was not carried out fully, i.e., the LEGO piece was not placed correctly; *n/a (0)* – the step was not carried out at all.

Table 1 summarizes the (average) results according to these criteria, broken down by the different groups, while Table 2 shows the number of subjects managing the respective step with at least partial success.

We can state that almost all participants managed to handle the first step with at least partial success. The two participants (group C) who failed completing the first step had difficulties in understanding how the robot would move (directly between specified poses) after their instructions.

One of them stated also to have felt rather uncomfortable (2) when handling the robot, despite marking rather high levels of programming (5) and technical (4) experience, and mentioned the two coordinate systems as difficult to understand. This low comfort rating was in fact the only one below the "neutral" rating of 3 for all 21 participants. Worth noting is also that all three participants reaching full success in step 4 belonged to group B, i.e., the condition with the task to re-use an expert-made skill for the last three steps. As step 2 for this group was mainly to analyze and understand the provided skill, this obviously saved them a lot of time compared to the other groups. Overall we can state, that 14 of 21 participants managed to understand the tool, the robot's movements, and the LEGO bricks' properties (including the challenge of robustly attaching them to each other) sufficiently well to complete two steps of the overall tasks within 30 minutes.

As we noted a somewhat uneven distribution of programming and technical experiences over the different groups, we checked for correlation effects between experience ratings and success rates or

Table 2: The number of subjects reaching success rating 3-2-1 respectively in the different steps.

	Step 1 3-2-1	Step 2 3-2-1	Step 3 3-2-1	Step 4 3-2-1
All	13-6-2	11-3-0	7-2-0	3-0-1
Group A	5-2-0	3-1-0	1-1-0	0-0-0
Group B	5-2-0	6-0-0	5-1-0	3-0-0
Group C	3-2-2	2-2-0	1-0-0	0-0-1

time needed for the different steps respectively, but we could not find any obvious connections; programming experience, technical experience and robot programming experience had all a very low negative correlation (-0.18, -0.18, and -0.23) with time for completion of step 1 and a slightly stronger, but still very low, positive correlation (0.24, 0.22, and 0.33) with the overall success rate. Thus, we consider the different outcomes for the groups as an indication for an effect of the different conditions, i.e., being able to reuse previously programmed or even provided skill representations simplifies the programming process significantly, as the subjects in the control group (C) needed roughly the same amount of time for each step in the second phase, when programming from scratch.

In group A, who should re-use their own previously created step1 skill for the following steps, the subjects needed some time to handle the updating and parametrization of the skill in step 2, but once they had understood how to do this, the following steps were handled within rather short time frames, which were even shorter than those for group B, who otherwise had very high success rates, but had to understand and update a program that they were not familiar with from the beginning. However, sample sizes are small and became even smaller over the different steps, hence, these results should be seen with some caution and treated as trend indications rather than definite findings.

Specific challenges and observations

As indicated above, all participants but one felt at least neutral, if not comfortable, when handling and programming the robot. We consider this a confirmation for the overall idea of combining kinesthetic teaching with iconic programming in an interactive way, i.e., allowing for frequent switches between execution, testing / debugging and further instruction, is a good starting point for further development of the tool. However, we also have to see the comments (and observations) regarding the challenges the subjects experienced, which we summarize in the following, according to how often they were mentioned (high frequency first).

Precise positioning and fixating of the LEGO piece Many subjects mentioned the placement of the piece as a challenge. In fact, attaching two LEGO bricks to each other robustly with slippery robot grippers is tricky, and the success seems to depend a lot on whether the respective subject could determine a good strategy from the LEGO properties (the piece clicks best into place when being "folded" and then pressed, rather than through hovering over the target and moving straight down at once). The expert–made skill provided for group B followed this strategy, and worked very robustly (it merely took the expert—one of the researchers involved in the study setup—roughly two minutes to create this skill). Here, we plan to equip a future high–level interface for programming with the capability of providing suggestions based on previously known skills for similar work pieces to find the optimal strategy for a given work piece.

Different reference coordinate frames and switching between them As mentioned before, we are aware that selecting relevant coordinate frames is quite a challenge for any non–expert user, however, we can now, based on our observations of how the subjects managed to solve the problem and how exactly they could be supported, design further support based on reasoning and mixed–initiative interaction into future tools. We also observed, that many subjects simply forgot to assign the correct coordinate system, even though they understood how relative motions work. This was anticipated in the design of the tool, allowing the user to switch reference frames for an already existing movement, which made it very easy to correct the program after an issue with the reference frames was discovered.

Understanding all functionalities of the tool in the limited time frame, handling the interface This suggests that we might even have had better results, had the subjects been given more time to "play" with the tool. Some stated also informally after finishing, that "now, it would be great to start over, now I have understood this!".

Pose recording vs trajectory recording, understanding robot movement Some of the subjects, as also mentioned above, struggled to understand the concept of specifying positions to move to rather than trajectories to move along. In particular, the "contact move" posed a challenge as it results in a movement towards a virtual projection of a desired pose beyond the contact point. Further development of respective tools to include trajectory and contact force profile teaching is ongoing work.

Robustness, compensating for the LEGO piece sometimes slipping from the gripper As we did not make use of specifically designed grippers for LEGO-bricks, this was obviously a problem in some cases. It could be compensated for only through a good picking and placing strategy that would be robust to the slipping. Using more appropriate tools on the robot for grasping specific work pieces is obviously a good strategy, and is subject to investigations within the project work for the ongoing SARAFun project (SARAFun).

We see quite some of the challenges pointed out by our subjects as concrete confirmation of assumptions we had regarding obvious points to work with in the future.

In addition to not finding a strong correlation between experience and success rates, we observed that the one person with the least technical background not only felt very comfortable (4) when programming the robot, but also managed to complete all four steps of both phases within 21 minutes with full success. On the other hand, we observed highly experienced PhD students in Automatic Control struggling with the task for significantly longer periods of time and had one participant with high experience ratings failing in the first step already.

Figure 4: Paper folding (left). When rotating the box, only two positions must be updated (right).

In a sideline of the study, we had one nine-year old child test the interface in the study setup. The child, while certainly an expert in LEGO building, was not a proper study participant due to a lack of English reading capabilities, but managed with only a little help regarding the switch of reference coordinate frames and the use of the contact move to program the first step (picking up and inserting the 2x2-piece on top of the "tower") within 20 minutes.

Boldly speaking, these observations seem to suggest that understanding of the task and assuming the robot to follow kinesthetic instructions as precisely as a (fellow, smaller) child, rather than assuming it being capable of understanding complex instructions, made it easier for the subjects to solve the task. In the following we will present the evaluation of the programming tool carried out by an expert user, before drawing conclusions from our findings.

5.2 Expert evaluation

One of the case studies we presented in section 3, the gift-wrapping task, formed the basis for the evaluation of the programming tool by an expert who is quite familiar both with programming YuMi in the traditional way using a teach pendant and coding directly in RAPID as well as with the specifics of the gift-wrapping process. For the evaluation, a folding task was chosen, where the right arm fixated a gift box with the elbow while the left straightened the corners using nine positions (fine and via), as illustrated in Figure 4. The operator used the programming tool presented in this paper to add a *packet object* to the world and programmed the actions for the left arm relative to this *packet object*. Then the box was moved to a different position and the packet and right arm positions were updated accordingly. After that the left-hand program executed without change. The entire programming, involving one test execution for each position took slightly below two minutes. The same process was then programmed using traditional tools which took slightly more than 11 minutes.

We also evaluated the interface in another context. Here, the overall task was to create two skills, one for picking a tool from a fixture and one for placing it back into the fixture. Creating a *tool object* and storing the positions for the picking and placing and saving these as skills took 70 seconds with our interface and more than 5 minutes with traditional programming methods, hence, the initial programming time was reduced by 80% using our interface compared to the traditionally provided methods. A more realistic scenario would then certainly involve multiple adjustments and parameter

tuning, if required using the advanced settings in the traditional tools, however, executing and updating single instructions requires two button presses in our tool, while the traditional approach requires at least five steps, twice that if more than one coordinate system is used in the task.

We can thus state, that for an initial online programming process of applications that are difficult to test in a simulator (e.g., paper folding), our interface speeds up the programming process significantly. As it allows for debugging, executing, as well as updating and even reordering single steps in the robot program, we would expect our programming interface to be quite suitable (and faster than the traditional methods) also for more complex procedures.

6 Conclusion

In this paper we discussed our approach to high–level, intuitive programming of industrial robots for assembly tasks. We presented findings from an analysis of two case studies regarding the desired capabilities and functionalities of a programming interface for online programming in settings where the traditional work flow is not suitable, due to, e.g., simulation for testing not being an option. Based on these findings we developed a programming interface that supports a hybrid instruction and evaluation (execution) process and thus quick implementation and test cycles through a graphical interface for iconic programming. The interface supports also the specification of objects and their positions in the work cell of the robot, as well as updating these at any time. It is also possible to reorder instructions graphically and sequences of instructions can be saved as a skill for later re-use and refinement. We evaluated both with experts and 21 non–expert users in a user study and can state the following regarding the improvements and simplifications we assumed our tool to yield.

Already the basic support of a rapid instruction, test, and execution cycle with the possibility to reorder and update single instructions for refinement reduced the programming time for an expert by 80% compared to using the traditional programming tools and interfaces. This was specifically supported by the possibility to easily specify and refine object positions and reference frames and assigning them to certain instructions, so that re-use of program parts (skills) was enabled or even (as evaluated) a full program for one robot arm could be run without modifications, when the pose of the object the respective instructions referred to was updated. The possibility to change the frame of reference for already existing instructions is an additional convenience, as it is easy to forget to always set the correct one from the beginning, even for experts.

Our evaluation with 21 non–experts showed that the programming tool provides an interface sufficiently easy to handle, so that 19 of 21 participants could construct a satisfying solution to a LEGO–building task within 30 minutes, and 14 of them even managed to complete one or several follow–up steps. We can also state, that the reuse of previously created (own) skills and even more so of provided, expert–made skills, simplifies the programming process significantly. Our subjects struggled mainly with the precise positioning of the LEGO–bricks so that they would click into place firmly and (as we previously assumed) with the different object reference frames needed to handle picking up the pieces from arbitrary poses. For the first issue, we assume that process knowledge (how to best approach one work piece with the other to attach them correctly) was here of more significance than knowledge about the robot system, as we could not find an obvious correlation between

success rate and experience. For the reference coordinate system issue we can state that although the users—even if they had understood the problem with the frames—would frequently forget to assign the correct one to their instructions, they managed to correct their mistakes quickly with the functionality for changing reference frames.

Other tools for high-level programming often assume an existing library of robot skills, e.g., tools supporting natural language instructions as for example presented by Stenmark et al. (2014) need basic knowledge of objects (and their coordinate frames) and that it is possible to update and refine solutions suggested by a learning and reasoning system to industrially adequate robustness and precision. Hence, we see our interface as appropriate to support even non–expert users in handling the construction of such basic knowledge items as well as in updating and refining existing solutions.

Overall, we see our implementation as a successful prototype, which we can now use as a basis for further development and studies and software distribution within the research community. The integration of high-level (natural language) instruction capabilities with the interface as well as functionalities for teaching force profiles and trajectories as basic movement primitives, or skills are subject to ongoing work. This would presumably support the user even more in teaching contact moves and specific operations like snap–fit assembly. As the reference coordinate problem is difficult for users to both understand and then also to remember in the programming process, we plan to integrate mixed–initiative support based on reasoning about possible options regarding the assignment of reference frames to instructions.

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Paper v

Paper V

The Art of Synchronized Dual-Arm Robot Programming

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Abstract

In this paper, we present our successful efforts to improve intuitive programming of synchronized dual-arm operations in industrial robotic assembly tasks. To this end we extend an earlier proposed programming interface to integrate options for the specification, adaptation and refinement of synchronization points, synchronized motions and master-slave relations during program parts. Our approach supports the user by handling motion constraints and geometrical transformations necessary for refinement and transfer of program sequences between arms implicitly, hence, the user can express desired modifications by updating (high-level) instructions in a graphical interface. We report on two experiments confirming the applicability and efficiency of our approach.

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1 Introduction

Over the recent years a new type of inherently safe industrial manipulators intended for direct collaboration with human shop floor workers has entered the market, examples of which are Universal Robots' UR5, ABB's YuMi, Rethink Robotics' Baxter and KUKA's LBR iiwa. These, as well as some traditional manipulators can be set up in a dual-arm configuration (in the case of ABB's YuMi or Rethink Robotics' Baxter this is the default solution) to handle bi-manual tasks, e.g., in product assembly.

A common property of these robot models is the *lead–through* programming, or kinesthetic teaching, mode which enables the user to physically guide the robot manipulator into desired positions instead of using e.g., a joystick. Still, the robot program has to be created as a sequence of motions and control logic, e.g., by adding instructions one by one using a *teach pendant* (shown in fig. 1), a textual program editor installed on a PC or simplified programming interfaces such as the YuMi Online Windows app.

Such kinesthetic teaching using force-guided motions (Massa et al., 2015), gravity compensation and variable stiffness (Wrede et al., 2013; Tykal et al., 2016) supports also non-expert operators to program and configure tasks (Rodamilans et al., 2016), however, dynamic environments, uncertainty and the use of noisy sensor feedback are still challenges for the operator (Stolt et al., 2016), and so far, experts are still needed to program the robots on the necessary levels of robustness and precision. Specifically, dual-arm operations like synchronized motions or master-slave configurations, where one arm's movements are specified in relation to the other one's, are quite complex to program, as often (even in originally dual-arm configurations like the ABB YuMi) the two arms are controlled as two independent robots for which the synchronization for bi-manual manipulation must be handled explicitly, and the programming of dual-arm programs needs user support, e.g., *both* by letting the user fine tune the positions of a single arm separately, and debugging synchronized motions in pairs (Stenmark et al., 2016). Re-use and adaptation of parts of the robot program that require essentially the same operations, but from a different arm's or even switched master-slave perspective, are rather complex.

Another approach to making the programming of complex robot instructions more available to non-expert users is the use of high–level instructions to simplify robot programming for industrial tasks, e.g., using natural language (Stenmark and Nugues, 2013) and semantically defined parameterized motion primitives (Felip et al., 2013), often called *skills* (Pedersen et al., 2014, 2016).

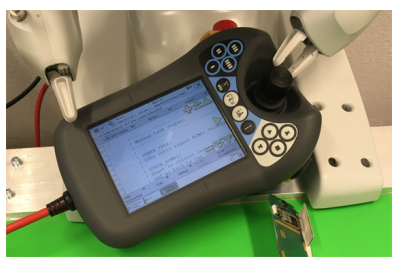


Figure 1: A teach pendant.

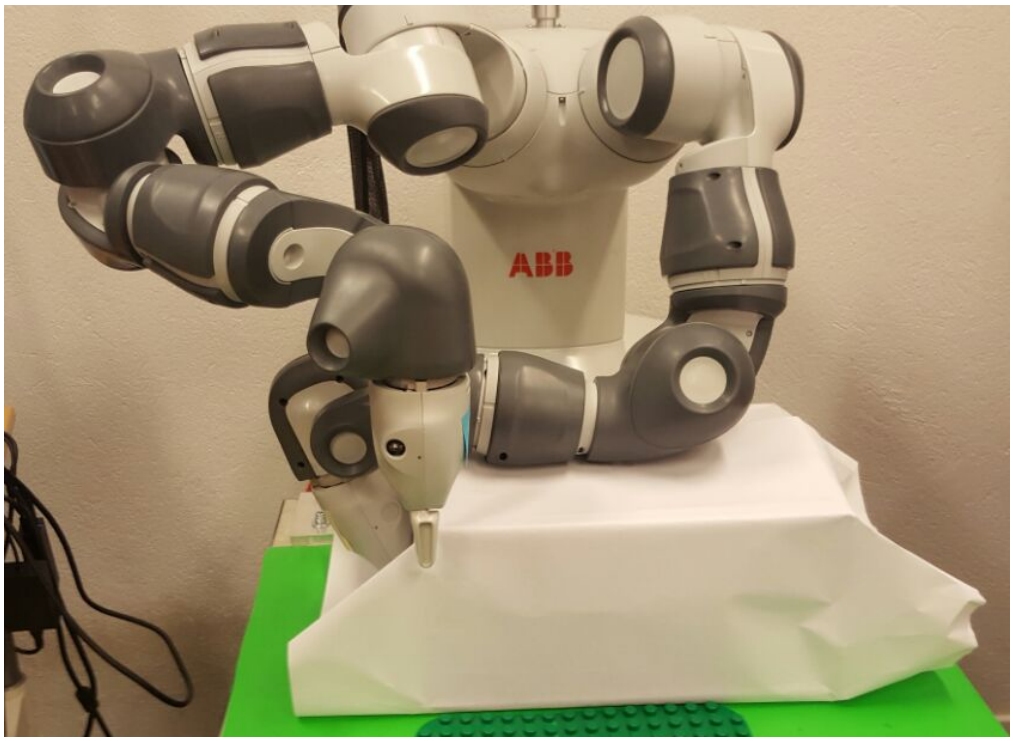


Figure 2: YuMi packing a parcel.

Such semantic descriptions are desirable because they enable the automatic generation of standard PDDL[1]–descriptions for planning and scheduling of tasks or path planning and generation from virtual models (Perzylo et al., 2016). However, in most cases these abstractions assume a library of skills or motion primitives that can be represented in executable robot controller code sequences, which can be applied in the high-level task description. Unfortunately, this assumption does not necessarily hold for highly specialized motions and configurations that might be needed in a specific assembly task.

We have earlier reported on our work that establishes a middle ground of these two approaches by combining kinesthetic teaching and a multimodal user interface with parametrized skill representations to simplify robot programming, which allows also non-expert users to specify and semantically annotate their own skills (motion primitives and also more complex program sequences), which can then be re-used and adapted on a higher level of abstraction into more complex task descriptions (Stenmark et al., 2017a,c,b), also allowing for certain operations to be specified relative to (adaptable) object reference frames. Although the reported experiments and user study were conducted on the dual-arm robot YuMi shown in fig. 2, they did not cover extensive handling of synchronized motions for genuine dual-arm operations.

In this paper, we can report on our successful and to our knowledge novel efforts to integrate also options for the specification of synchronization points, synchronized motions and master-slave re-

[1]Planning Domain Definition Language

lations during program parts, which can then, based on our parameterizable skill representation, be re-used and adapted into high-level instructions. This adaptation includes also the transfer of a skill (motion primitive) from one arm to the other, adaptation of synchronized motions to new object reference frames, and the switch of the master-slave relationship. Our approach supports the user by handling the necessary geometrical transformations implicitly based on the high-level instruction transfers expressed by the programmer through the graphical interface.

The remainder of the paper is organized as follows. We will refer to related work in the area of dual-arm robot programming in section 2. In section 3 we describe our skill representation and the conceptual framework for handling the re-use and parameterization of synchronized motions. We explain our implementation and experiments in sections 4 and 5, respectively, and discuss our results and conclusions in section 6.

2 Related Work

Dual-arm or bi-manual task handling has been investigated under different paradigms or points of views. An overview of dual-arm manipulation approaches considering among others the control and planning perspective is given by Smith et al. (2012). An early approach to programming by demonstration of bi-manual, tasks was reported by Zöllner et al. (2004), however, they consider mainly household related tasks, while we assume that a pure programming by demonstration approach is not sufficient for an industrial assembly context. This assumption is shared by Krüger et al. (2011), who report on an approach quite similar to ours for intuitive programming of industrial manipulators based on a combination of task representations and human demonstration (Makris et al., 2014). Their focus, however, is more on the observation of human movement demonstrations and transfer of these movements into robot control sequences for direct imitation, while we focus rather on the programming of re-usable synchronized motion sequences based on a representation that supports the robot operator by abstracting the low-level control primitives for synchronization of the two arms into intuitively understandable skill descriptions.

3 Objects, Primitives and Skills

The knowledge in the system is centered around objects (workpieces), devices such as manipulators, grippers and sensors and assembly processes describing the robot program. In this experimental setup, objects are created as abstract entities with a unique name, a type, and positions describing points on the object as relative reference coordinate systems. For example, the gift box used in the experiments described in Section 5 has multiple points defined, one for each side and two corners. Robot motions can then be specified using the reference coordinate frames and the positions can be updated e.g., using cameras. The robot manipulators have a reference frame attached to the wrist, the *flange*. The gripper is attached to the flange and has in turn one or more reference points, e.g., the tips of the fingers. For our experiments, we use a dual-arm robot where motions of one arm are specified in the other arm's flange reference system. The low-level implementation in this setup does not allow arbitrary reference points along the robot arms, thus, contact situations where the so-called elbow or lower arm are used are specified using joint angles.

3.1 Primitives

Each primitive has a set of semantically annotated parameter types with (system dependent) default values. The following primitives are implemented in the interface described in Section 4:

- **Motion types: Motion** has subtypes **Free Motion** and **Contact Motion**. **Free Motion** has subtype **AbsJointMove** (where the target is expressed in joint angles), **Linear Move**, **Circular Move** and **Joint Move** where the target is expressed in Cartesian space relative to a point on an object and the path will be linear, circular or by moving all joints simultaneously. The **Contact Motion** is a simple *G*uarded Search, which moves towards a specified point until the desired (estimated) contact force is reached, or, if no contact occurs, an error is thrown.
- **Gripper Actions** of the subtypes **Open**, **Close** and **Finger Position**. The first two actions open and close the fingers fully or until the current value of the gripping force is reached. The **Finger** action is used to set the gripping force and finger positions to the specified parameter values. It also has a `Wait/NoWait` flag indicating whether or not the gripper action is executed while the robot is moving.
- **Synchronization:** there are two types of synchronization in the system, either a *synchronization point* or *synchronized motions*. By default, the two arms execute independently as two separate robots, but a **s**ynchronization point is a rendez-vous between the robot programs that will force one arm to wait until the other reaches the corresponding point in its program. Similarly, the synchronized motions have references to each other.
- **Synchronized motions:** the two arms will start and finish motions at the same time, that is, the longest motion determines the execution time of all the motions. The motions can be specified in absolute joint (or Cartesian) coordinates or relative to objects in the workspace. They can also be specified relative to the position of the other arm, in a so-called **Master-Slave** configuration. The *master-slave* motions are used to lock a specific offset between the arms, e.g., when moving an object bimanually.
- **Native Code**: the (advanced) user can add any native robot code in plain text as a snippet that will be included inline at a given point of a program. Only object references are analyzed semantically. This action is used by the system integrator or an expert to create skill macros for sensor communication, e.g., by creating a function that uses cameras to locate an object. For example, if the user added an object named `screw` and the expert created a procedure that locates a screw called *screwLocatingFunction*, the position of the screw is updated with the native code line `screw := screwLocatingFunction`. Since the variable names are unique and typed both in native code and in the user interface, object references can be changed using the interface, hence, non-expert users do not have to edit the native code to update the object positions of other (similar) screws.

3.2 Re-use and transformation of skills

Motions relative to object reference coordinate systems can be transformed by either by changing the coordinate system or updating it. Using only one reference point (translation and rotation), whether it is the flange of the robot or a point placed on an object, is enough to *r*otate the skill. To

mirror the task in a plane, two pairs of points are needed, one point for each arm that is used during the programming phase, and then one new point for each arm respectively to allow the skills for each arm to be rotated and translated arbitrarily in the space.

3.3 Programming synchronized motions

While related work, e.g., the app provided with the YuMi robot, lets the user create a pair of motions for both arms with one click, the motions are not semantically or syntactically connected. With our representation, where synchronized points and motions have a reference to the other member in the pair, they can be created, deleted, executed, moved in the program sequence and copied in pairs. Hence, when moving a synchronized motion from one arm to the other, the other motion in the pair has to swap places with it in order to preserve a correct program.

Synchronized skills can also be re-used bi-manually and moved between the arms. When re-using dual-arm skills containing master-slave motions, when the skills for each arm are swapped, i.e., the original skill had the left arm as a master and the master moved in the reference coordinate system of object *objX* and the right arm, the slave, had an offset to the left *offsY*, then (when the skills are swapped) the right arm will become the master, moving to the same positions in the reference coordinate system of object *objX* and the position of the left arm, now the slave, will be updated to the inverse of *offsY*.

A special case is the refactoring of reference frames for synchronized motions. Since the synchronization is an alignment in time, the reference frame of one arm can be changed to the flange of the other if the original positions are known, thus synchronized motions can be refactored into master-slave configurations. All these programming concepts are implemented in the prototype described in the following section.

4 Implementation

The prototype design was developed after several case studies where the authors developed assembly applications on the ABB dual-arm robot YuMi. The user interaction is intended to simplify agile online robot programming. Mistakes should be easily corrected, with *programming* and *debug* modes merged into a single screen to facilitate a quick program modification and execution loop. All available information about the program is retained even though it may not be used immediately. As an example, a target position is saved with data for the current joint values, the Cartesian tool position and, if a reference object is selected, the relative position, which makes it easy to switch between representations. This allows the operator to quickly create a program and later work on creating and applying abstractions such as object references to make the program easier to re-use and adapt. The current graphical user interface is shown in fig. 3.

4.1 Code generation

Writing and debugging native controller code for synchronized motions is time consuming, even for experts. To simplify the user interaction during programming, the creation, reordering, deletion and execution of synchronized motions is done in pairs.

Below is an example of the generated RAPID code (edited for clarity) for the right arm in the example shown in the user interface screen capture in fig. 3. The example is a dual-arm pick and place of the lid on the toy box described in sec. 5. First, the arms move unsynchronized, open the grippers and move into gripping positions, after closing the fingers, four master-slave motions are used to move the lid and place it on top of the toy box. Finally, the lid is released (also synchronized). First, all variable names are declared and given values, these declarations are generated from the user specified objects and added automatically for synchronization points.

The main procedure corresponds to the actions of the right arm. After an initial via move in absolute joint space, the two following motions are relative to the grippoint and after closing the gripper the following four motions are relative to the flange of the left arm. Each slave move has an ID that must match a corresponding master move on the left arm. The synchronized motions are surrounded by commands for turning on and off the synchronization (SyncMoveOn/SyncMoveOff). The parameters such as speed (v200), precision (fine), tool offset (GripperR) and reference coordinate system (e.g., grippoint) are generated from the (default) parameter values or reference positions of the actions.

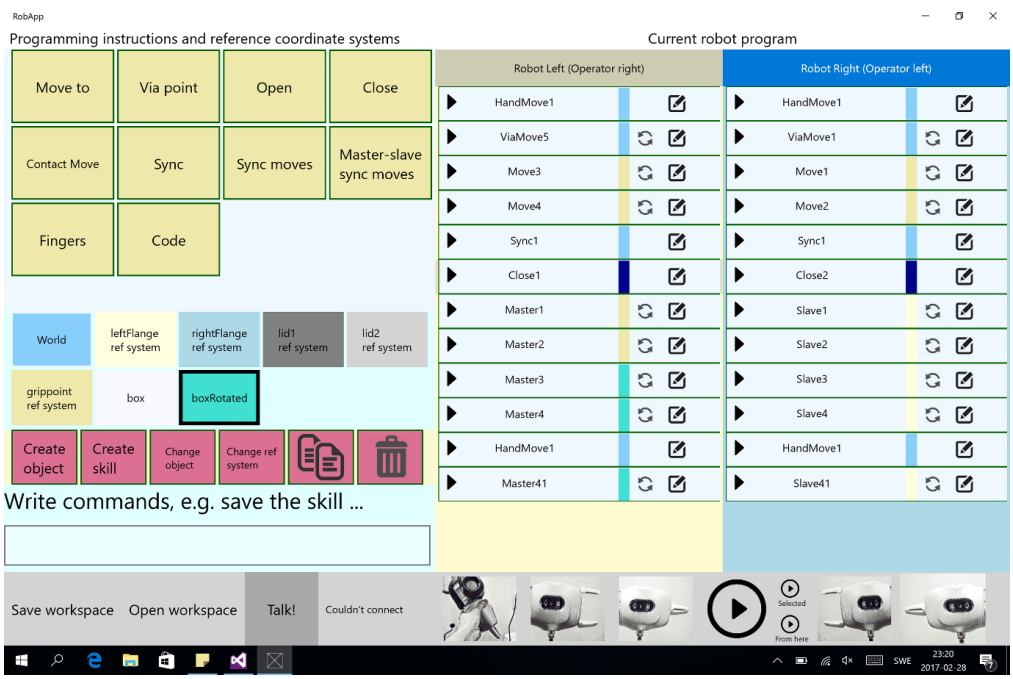


Figure 3: A screen capture of the GUI.

```
PERS tasks taskList {2} := [["T_ROB_L"], ["T_ROB_R"]];
VAR syncident syncMoveStart;
VAR syncident syncMoveStop;

VAR jointtarget ViaMove5 := ...
VAR robtarget Move1 :=...
VAR robtarget Slave1 :=...
[...]
PERS wobjdata grippoint :=...
[...]
TASK PERS wobjdata flangeRobL := ...
TASK PERS wobjdata flangeRobR := ...

PROC main()

Hand_SetHoldForce 15;
Hand_MoveTo 18\NoWait;
MoveAbsJ ViaMove5,v500,z5, GripperR;
MoveL Move1,v200,fine, GripperR\WObj:=grippoint;
MoveL Move2,v200,fine, GripperR\WObj:=grippoint;
WaitSyncTask Sync1, taskList;
CloseHand;
SyncMoveOn syncMoveStart, tasklist;
MoveL Slave1\ID:=1,v200,fine, GripperR\WObj:=flangeRobL;
MoveL Slave2\ID:=2,v200,fine, GripperR\WObj:=flangeRobL;
MoveL Slave3\ID:=3,v200,fine, GripperR\WObj:=flangeRobL;
MoveL Slave4\ID:=4,v200,fine, GripperR\WObj:=flangeRobL;
SyncMoveOff syncMoveStop;
Hand_SetHoldForce 15;
Hand_MoveTo 18\NoWait;
SyncMoveOn syncMoveStart, tasklist;
MoveL Slave41\ID:=41,v200,fine, GripperR\WObj:=flangeRobL;
SyncMoveOff syncMoveStop;
```

5 Experiments

Two programming experiments were conducted on the YuMi robot. The first was a bi-manual pick and place of a lid of a toy box, the second was a sub-procedure of a gift-wrapping application.

5.1 Bi-manual object manipulation

The first setup is depicted in fig. 4 and the robot was programmed to carry out a bimanual pick and place where a lid of the toy box was picked up and inserted on the box. To solve the task the grippers had to be placed in the holes of the lid using half-opened fingers, then a sequence of four *master-slave* motions were used to lift the lid and place it on top of the box. The program is shown in fig. 3. A robot programmer who had never used the tool prototype for synchronized motions and was presented with the task for the first time, needed 32 minutes to solve and debug the task fully. This involved finding a robust gripping strategy with half-opened grippers that did not subject the lid for high forces.

When a strategy was known, two experts (two of the authors of this paper) needed 5 and 10 minutes, respectively, to program the task but 21 and 32 minutes, respectively, using traditional tools (text editor and teach pendant). Prototyping from scratch using traditional tools was not tested.

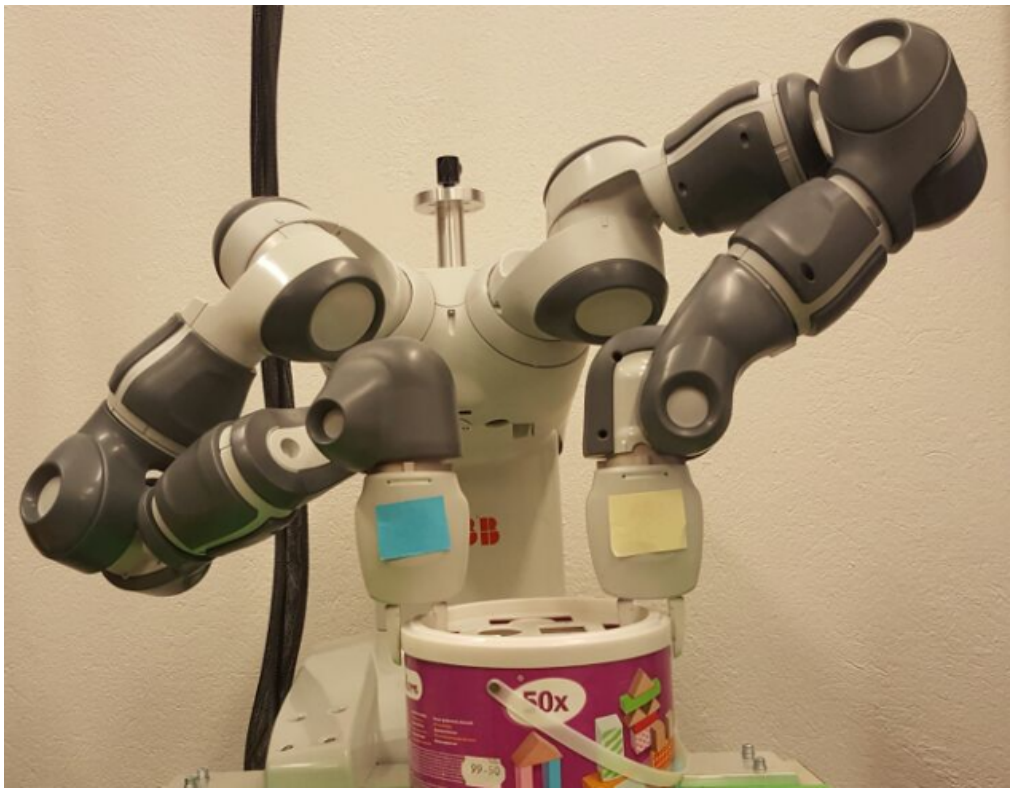
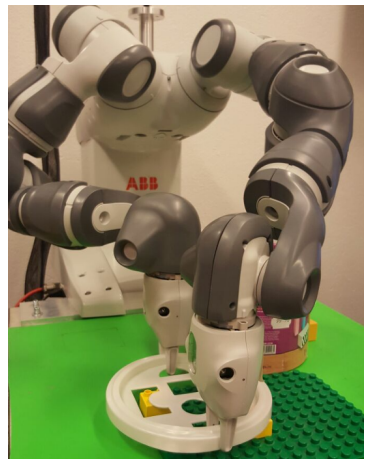


Figure 4: The task was to insert a lid on a toy box.

Further experiments were used to test the representation. The lid was rotated 90 degrees as depicted in fig. 5a, which caused the robot arms to collide during the pickup. The programs for the arms were swapped, resulting in a collision free pickup shown in fig. 5b.

However, attempting to attach the lid on the box also caused a self-collision. The insertion position was rotated 180 degrees by adding and changing references of the original program that used absolute coordinates for the insertion. Two new object references were added by pointing at the center of the insertion point using the gripper as shown in fig. 7, one rotated 180 degrees around the z-axis. Using the two options for *recalculating the reference system* and *c*hanging the object of the task, the reference system was changed from absolute coordinates to relative positions of the first position. After changing of the object reference, the resulting program carried out the same task but rotated and with interchanged master-slave motions, as shown in fig. 6.

(a) Colliding arms.



(b) Collision free gripping.

Figure 5: Swapping of the programs.

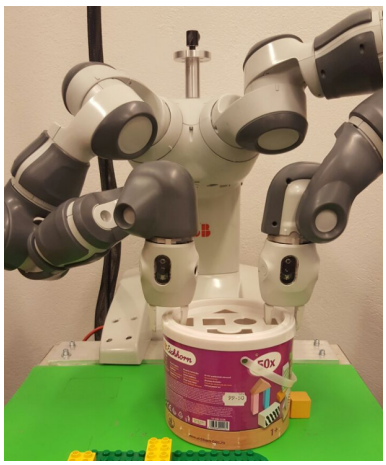


Figure 6: Collision free insertion.

Figure 7: Pointing out a new reference coordinate.

5.2 Mirroring tasks

In the second experiment, part of a gift-wrapping application (previously described in Stenmark et al., 2016)) were re-implemented, see fig. 2. The folding of the sides of the gift paper around the box are symmetric tasks: first the left robot arm holds the box while the right arm folds the paper around the corners to make a straight fold. The complete process involves flattening of the paper and taping, but to test the skills we will only look at the straightening of the corners.

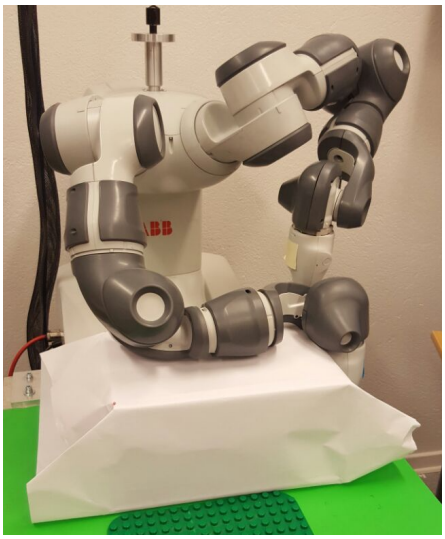


Figure 8: The rotated position.

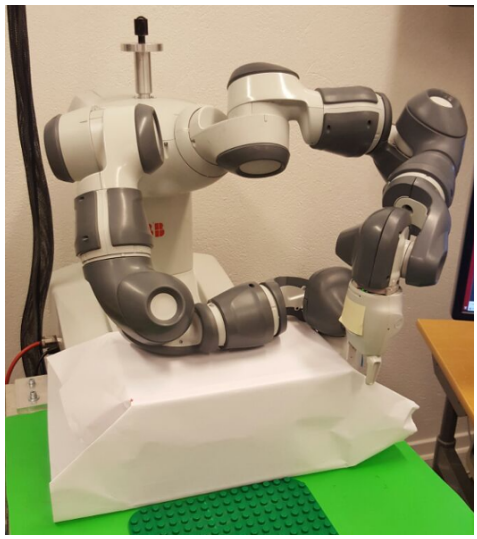


Figure 9: The mirrored position.

First, one reference point was added on the right (for the robot) side of the robot. The task was first programmed using the side point as reference point. A second reference point was added, this time on the left side pointing outward. The robot programs for the arms were swapped and a new reference object for the right arm changed to the new side point, resulting in a rotation of the task as shown in fig. 8.

The original task was mirrored from one side to the other by adding a point on the corner where the right arm is pointing in fig. 2 as well as a point in the mirrored corner (fig. 9) using the left arm. The programs for the arms were swapped but this time the folding hand used the (robot) left corner point as reference while the holding hand used the side point, which resulted in a mirrored task execution.

6 Conclusions

In this paper, we discussed our efforts to improve intuitive dual-arm programming of collaborative industrial robots. Our programming model allows for primitive dual-arm motion constructs with associated motion constraints to capture specification of synchronization points, synchronized motions and master-slave relations during program parts. We also present a taxonomy of our programming constructs as a starting point for a dual-arm ontology of programming constructs. This is combined with a programming interface that supports a hybrid instruction and evaluation (execution) process and thus quick implementation and test cycles through a graphical interface for iconic programming. The interface

supports also the specification of objects and their positions in the work cell of the robot, as well as updating these at any time. It is also possible to reorder instructions graphically and sequences of instructions can be saved as a skill for later re-use and refinement.

We have identified several program transformations, including rotations and mirror operations, that are useful for dual-arm programming relating to the inherent relationship between the arms. These transformations are exemplified in this paper through two transformation constructs, the mirroring transformation which allows a program written for a left-right arm configuration to be transformed into a program to be executed on a right-left arm configuration, and the master-slave switching transformation which allows a change of arm leadership role during ”follow me” operations.

Experiments confirming the applicability and efficiency of our approach were conducted on two small part assembly scenarios, collaborative placing of a lid on a box, testing dual-arm programming with motion constraints, and gift wrapping, testing dual-arm program transformations. We could observe a significant reduction (by two thirds) of programming time compared to applying traditional approaches and tools to the programming, particularly when the solution to the task at hand was known, i.e., the programmer knew how the robot arms should move and ”only” had to program them to do that.

However, our experience from the experiments indicates that further work on modes for dual-arm lead-through taking into account motion constraints might be a fruitful direction of investigation, perhaps in combination with work in the force-domain to allow expression of dual-arm constraints including torque and/or force conditions, i.e., applying a certain press on the sides of a box while picking it up. Standard functionality packaged with the industrial controller today includes only independent single-arm lead-through in the position domain. We also believe that investigation of guidance of non-experts / process experts in efficient robot programming techniques during the programming process would further improve programming efficiency, perhaps with robot-induced operator teaching as part of a robotic skill set.

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Paper VI

Paper VI

Natural Language Programming of Industrial Robots

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ABSTRACT

In this paper, we introduce a method to use written natural language instructions to program assembly tasks for industrial robots. In our application, we used a state-of-the-art semantic and syntactic parser together with semantically rich world and skill descriptions to create high-level symbolic task sequences. From these sequences, we generated executable code for both virtual and physical robot systems. Our focus lays on the applicability of these methods in an industrial setting with real-time constraints.

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1 Introduction

Robot programming is time consuming, complex, error-prone, and requires expertise both of the task and the platform. Within industrial robotics, there are numerous vendor-specific programming languages and tools, which require certain proficiency. However, to increase the level of automation in industry, as well as to extend the use of robots in other domains, such as service robotics and disaster management, it has to be possible for non-experts to instruct the robots.

Since humans communicate with natural language (NL), it is appealing to use speech or text as instruction means for robots as well. This is complicated for two main reasons: First, NL can be ambiguous and its expressivity is richer than that of a typical programming language. Secondly, tasks can be expressed as goals as well as imperative statements, hence, even if the instructions are correctly parsed, the description itself is often not enough to create a successful execution. There has to be a substantial amount of knowledge in the system to translate the high-level language instructions to executable robot programs.

In this paper, we introduce a method for using natural language to program robotized assembly tasks and we describe a prototype of it. The core idea of the method is to use a generic semantic parser to produce a set of predicate-argument structures from the input sentences. Such predicate-argument structures reflect common semantic situations described through language and at the same time use a logical representation. Using the predicate-argument structures, we can extract the orders embedded in a user's sentences and map them more easily onto robot instructions.

2 Related Work

Natural language programming for robots has been investigated for both service and navigational robots from the early 1970's. SHRLDU (Winograd, 1971) is an oft-cited example of the first attempts to give robots conversational competences. To interpret and convert a user's sentences into instructions, robotic system often make use of an intermediate representation. Examples include Tellex et al. (2011); MacMahon et al. (2006); Shimizu and Haas (2009), where the authors have developed their own domain specific semantic representation for navigational robots.

Tenorth et al. (2010) parse pancake recipes in English from the World Wide Web and generate programs for their household robots. They use the WordNet lexical graph (Princeton University, 2010) with a constituent parser and they map WordNet's *synsets* to concepts in the Cyc (Matuszek et al., 2006) ontology. Finally, they add mappings to common household objects.

In order to bridge the sentence to the robot actions, all the examples mentioned above seem to use ad-hoc intermediate formalisms that are difficult to adapt to other domains, languages, or environments. Frame semantics (Fillmore, 1976) is an attempt to provide generic models of logical representations of sentences. Frame semantics starts from prototypical situations shared by a language community, English for instance, and abstracts them into frames. While frame semantics is only a theory, FrameNet (FrameNet, 2013; Ruppenhofer et al., 2010) is a comprehensive dictionary that provides a list of lexical models of the conceptual structures. Commercial situations like selling are represented with the Commerce_sell predicate-argument structure, where the arguments

include a buyer, a seller, and goods. Given a sentence and a verb belonging to this frame, like *vend*, *sell*, or *retail*, a semantic parser will identify the predicate and its arguments.

As of today, FrameNet has not a complete coverage of English verbs and nouns. Propbank (Palmer et al., 2005) and Nombank (Meyers et al., 2004) are subsequent projects related to FrameNet that both developed comprehensive databases of predicate-argument structures for respectively verbs and nouns and annotated large volumes of text with it. As training data is essential to the development of statistical semantic parsers, most of the current parsers use the Propbank nomenclature, as they are easier to train.

To the best of our knowledge, few robotics systems use existing predicate-argument nomenclatures. An exception is RoboFrameNet (Thomas and Jenkins, 2012), a language-enabled robotic system that adopts frame semantics. However, the authors wrote their own frames inspired from FrameNet. Their model includes a decomposition of the frames into a sequence of primitives. They built a semantic parser that consists of a dependency parser and rules to map the grammatical functions to the arguments. Such techniques have been used from the early Absity system (Hirst, 1987) and are known to have a limited coverage.

In the project, we describe below, we used a multilingual high-performance statistical semantic parser (Björkelund et al., 2009, 2010) trained on the Penn Treebank and using the Propbank and Nombank lexicons. In contrast to RoboFrameNet, the parser we adopted can accept any kind of sentence.

3 System Overview

Architecture

The central part of the system architecture (Björkelund et al., 2011) is the *knowledge integration framework* (KIF). KIF consists of a client-server architecture where the server hosts ontologies, provides services, and object and skill libraries. The ontologies represent the world objects, such as robots, sensors, work-pieces and their properties, as well as robot skills. The skills are semantically annotated, platform-independent state machines, which are parameterized for reuse and executed using Lund University (2013).

KIF interacts with the *engineering system* (ES), which is the high-level programming interface, and the robot controller. The ES is implemented as an extension to the programming and simulation environment ABB RobotStudio (2017). When creating the robot cell, the objects, such as sensors, work-pieces, and trays, can be generated or downloaded from KIF together with the ontology. Every physical object has an *object frame*, and a number of *feature frames* related to its object frame. These frames are used to express geometrical constraints; see Fig. 1.

A program consists of a sequence of steps, which in turn consists of actions, motions, skills, or nested steps. The sequence is created using the graphical interface of the ES. The steps for picking a printed circuit board (PCB) and placing it on a fixture are shown in Fig. 2. To execute the sequence, platform specific code (robot code or the XML file used by the state machine executor) is generated

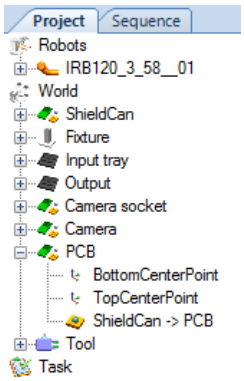

Figure 1: In the object browser, the robots are listed under robots; all physical objects are listed under world and each object lists its own frames and relations.

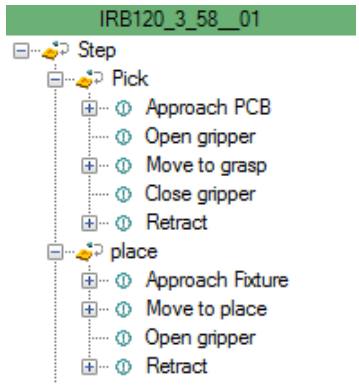

Figure 2: The visual rendering of a program for picking and placing a PCB.

for the motions, actions and skills, and deployed on the target platform. To help the user quickly setup a skeleton sequence of a task, we provide a natural-language parsing service on KIF; see Fig. 3. The service reads the text input, parses the text in search of predicate-arguments structures, and returns those containing predicates that match the task vocabulary.

On the client side, the predicates are mapped to programs; the arguments representing station objects and the other parameters are filled with default values or geometrical relations taken from the station. The programmer can then check the sequence, possibly alter it, and finally execute it.

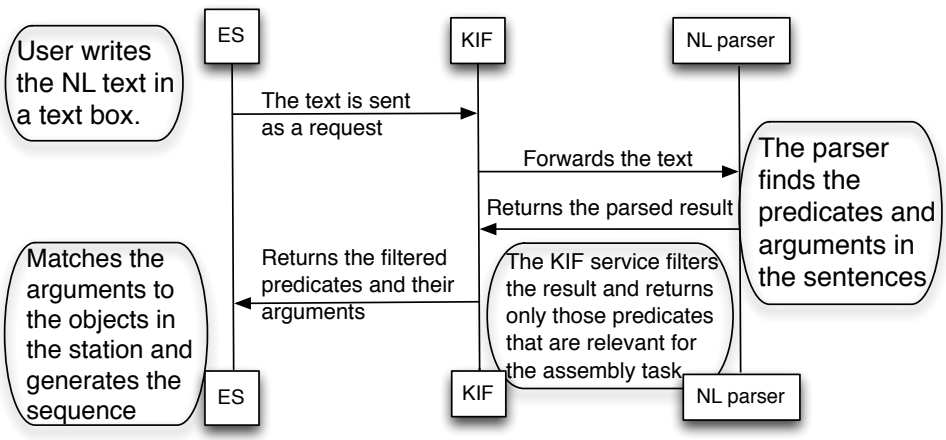

Figure 3: The data flow between the user, the KIF service and the semantic parser.

	Pick	the	PCB	from	the	input	tray	and	place	it	on	the	fixture	.
pick.01		A1		A2										
place.01										A1	A2			

Figure 4: Parsing result from the first sentence. The parser identified two predicates, *pick* and *place*, and two arguments for each predicate.

Predicate-Argument Structures

An assembly task can be defined as e.g.: *Pick the PCB from the input tray and place it on the fixture. Then take a shield can and insert it on the PCB*. These sentences are parsed to extract the predicates-argument structures *pick(PCB, input tray)* and *place(it, fixture)*, while the agent parameter, *robot*, is implicit.

The parser is trained on the Penn Treebank that uses the Propbank lexicon (Johansson and Nugues, 2008). Propbank labels each English verb with a sense and defines a set of arguments that is specific to each verb. In the sentence: *Pick the PCB from the input tray and place it on the fixture*, both *pick* and *place* have sense 1 (pick.01 and place.01):

- Pick.01 has three possible arguments; *arg0*: agent, entity acquiring something, *arg1*: thing acquired and *arg2*: seller.
- Place.01 has *arg0*: putter, *arg1*: thing put, and *arg2*: where put.

The parsing output is shown in Fig. 4. As shown in this figure, the *arg1* and *arg2* arguments to pick.01 are matched to *the PCB* and *the input tray* respectively, while the robot (*arg0*) is implicit. Before mapping the identified arguments to the station objects, the arguments corresponding to the same entity have to be gathered into *coreference chains*; see Fig. 5. The last step links the coreference chains to the entities in the station using the object name or type.

Task Vocabulary

The vocabulary is currently rather limited. We only considered predicates matching programs that the robot could generate. Each program has arbitrary language tags such as take, insert, put, calibrate, either predefined or edited by the user. Possible arguments to the programs are the objects in the station, which is a well-defined, finite world.

4 High-level Programming Prototype

On the highest level, the task is represented by an assembly graph (Malec et al., 2013), which is a partially ordered tree of assembly operations; see Fig. 6. The graph describes the assembly of an emergency stop button box.

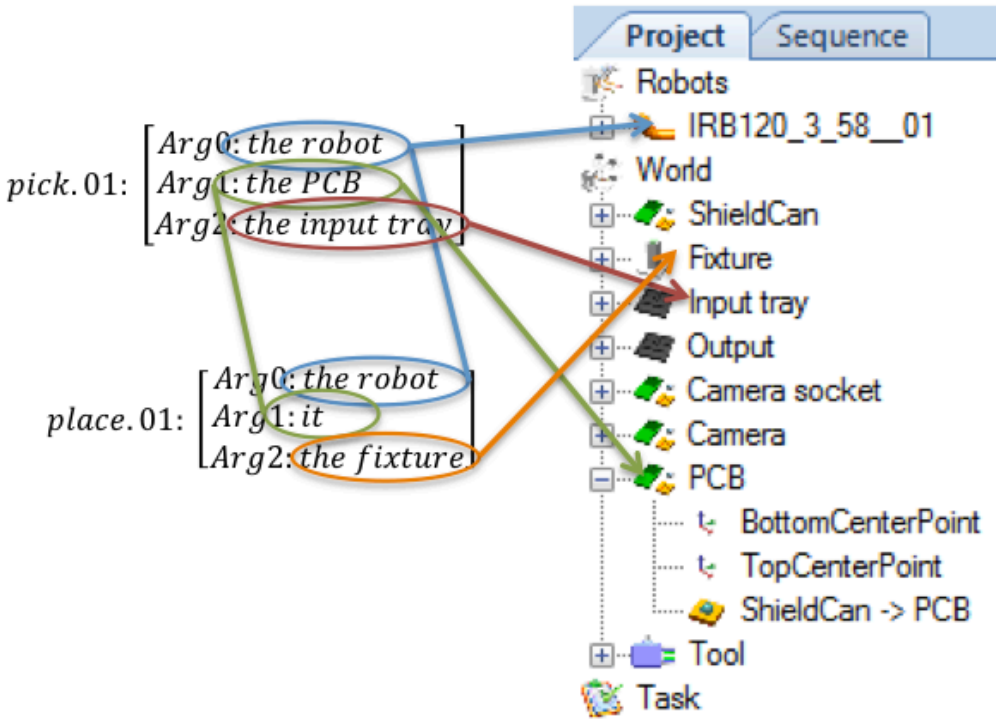

Figure 5: Coreference solving of entities in the first sentence. Mentions corresponding to the same entity are gathered into coreference chains.

Each operation specifies the desired geometrical relations of the involved objects and the skill type for the assembly. Examples of skill types in the ontology are *screw*, *glue* and *peg-in-hole*, where each type can have several different implementations. The assembly operations are subgoals, and the root node represents the final goal of the task. The motivation for the assembly graph is to have a platform independent task description, so that different implementations can be compared and reasoned about.

The assembly graph is realized by sequences of actions and motions for each robot. The sequence can be: 1) created manually by adding actions and motions one by one and editing their properties, 2) generated from the assembly graph or 3) created by using a natural language interface. An example of the latter is shown in Fig. 7: two assembly steps of a stop button box assembly are described by natural language. Fig. 8 shows the parsed result from Fig. 7.

Each predicate is mapped to a type of skill. For example, a *pick* or *take* consist of a sequence of primitive actions: approaching the object to be picked, opening the gripper, moving slowly to a grasp position, closing the gripper, and then retracting. The mapping of the objects are rudimentary: by name (ignoring space and case) or, if this is unsuccessful, by the ontology type (e.g. fixture, tray or pin). When generating the motions for picking and placing the objects, the application uses the existing grasp positions and relations between the work-pieces as default values. If no relations exist,

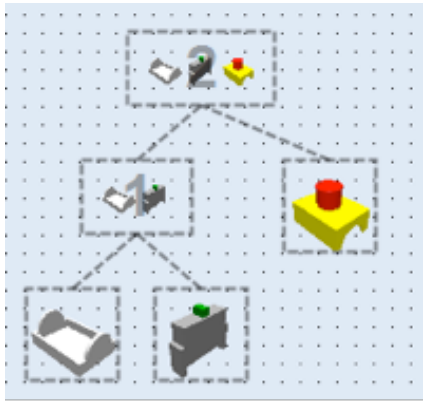

Figure 6: The assembly graph is created by dragging and dropping icons of the objects. Here, the first assembly operation involves the base of the emergency button (left) and the switch (right). In the second operation the lid is added to the subassembly.

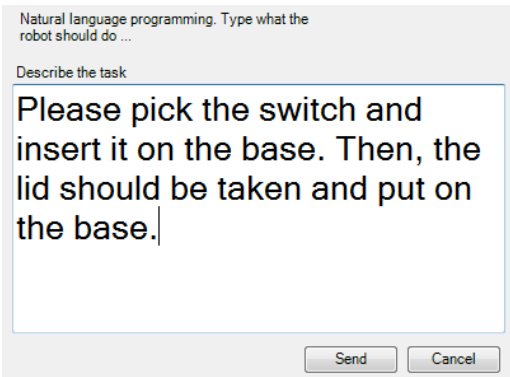

Figure 7: The commands are written into a simple text field, the narrative is then sent to the KIF service that facilitates semantic parsing.

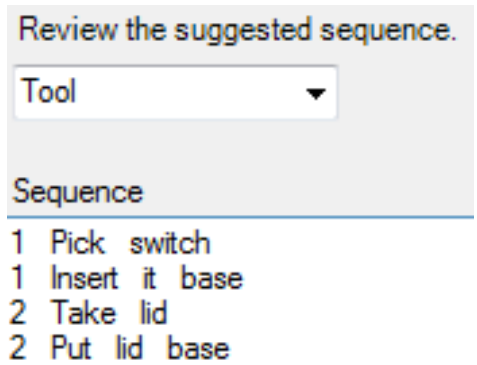

Figure 8: The result the parsed predicates along with their arguments.

a new one is created with zero offset. The actions for opening and closing the gripper are taken from the selected tool, since each tool describes its own procedures. The resulting sequence is shown in Fig. 9. Using reasoning services available from KIF, the generated sequence can then be checked for inconsistencies and additional skills are suggested to solve missing constraints (e.g. an object has to be placed in a fixture before an assembly or a tool needs to be exchanged between drilling and picking). The code generated from the sequence is executable on both virtual and physical robots; see Fig. 10. To expand the vocabulary, the user can add natural language tags to existing steps and upload them to KIF.

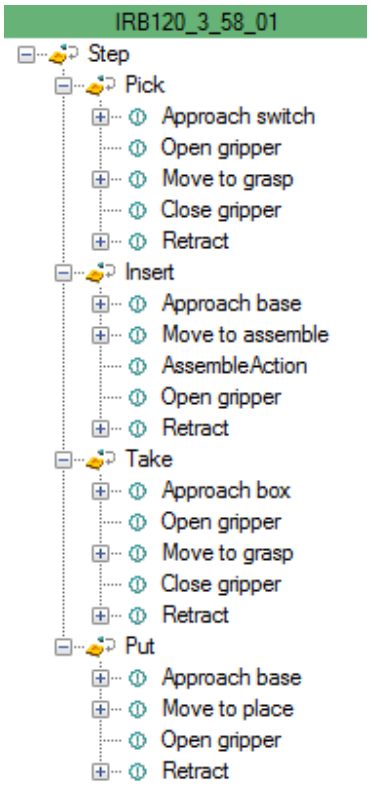

Figure 9: The generated sequence for inserting a switch on the base of a stop bottom and putting the top of the box on the base.

Figure 10: The sequence from Fig. 8 executed on a physical robot.

5 Conclusions

In this paper, we have presented a system to describe robot assembly tasks in the RobotStudio environment using natural language. From an input sentence, the processing pipeline applies a sequence of operations that parses the sentence and produces a set of predicate-argument structures. The semantic module uses statistical techniques to extract automatically these structures from the grammatical functions.

The NLP pipeline is designed so that it reaches high accuracies and has short response times required for user interaction. Parsing a sentence takes from 10 to 100 milliseconds. Drawing from the frame semantics theory, the semantic parser uses a standardized inventory of structures and can be applied to unrestricted text. This makes the pipeline more easily adaptable to new tasks and new environments.

As second step, the system maps the predicate and the arguments extracted from the sentence to robot actions and objects of the simulated world. These objects and actions are stored in a unified

architecture, the *knowledge integration framework* that represents and manages the entities, services, and skill libraries accessible to the robot.

Making the application part of a tool already used by industry is a conscious choice: high-level natural language programming is convenient to get an application up and running quickly. However, when tuning the parameters of a task, the programmer can still use the traditional tools, e.g. to edit the generated code directly. Also, because of the industrial focus, we have real-time performance on the underlying sensor and control systems, which is necessary for many manipulation tasks in assembly operations.

Unlike previously reported results, our approach supports both a command-like interface and parsing of longer texts, yielding multistep programs.

6 Future Work

The obvious drawback of this implementation is the lack of speech as an input modality. However, since many smartphones have sufficient speech recognition for our purposes, this was not our main scientific concern. Rather, we wanted to extend the skill library with relevant and generic assembly skills. We plan to extend our application with tools that make it simple to extract the natural language predicate-argument structures given a skill, its parameters (objects, velocities, forces), and a textual description of the skill. Another extension is to automatically search after suitable implementations that are tagged with synonyms to the used words.

7 Acknowledgments

The research leading to these results has received funding from the European Union's seventh framework program (FP7/2007-2013) under grant agreements N° 230902 (ROSETTA) and N° 285380 (PRACE) and from the Swedish Research Council grant N° 2010-4800 (SEMANTICA).

Paper VII

Paper VII

Describing Constraint-Based Assembly Tasks in Unstructured Natural Language

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ABSTRACT

Task-level industrial robot programming is a mundane, error-prone activity requiring expertise and skill. Since humans easily communicate with natural language (NL), it may be attractive to use speech or text as instruction means for robots. However, there has to be a substantial amount of knowledge in the system to translate the high-level language instructions to executable robot programs.

In this paper, the method of (Stenmark and Nugues, 2013) for natural language programming of robotized assembly tasks is extended. The core idea of the method is to use a generic semantic parser to produce a set of predicate-argument structures from the input sentences. The algorithm presented here facilitates extraction of more complicated, advanced task instructions involving cardinalities, conditionals, parallelism and constraint-bounded programs, besides plain sequences of commands.

The bottleneck of this approach is the availability of easily parametrizable robotic skills and functionalities in the system, rather than the natural language understanding by itself.

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1 Introduction

Programming of a traditional robot cell requires considerable expertise and effort. The new generation of robots, that work in an unstructured environment, that might have more degrees of freedom and two arms, introduces an increased level of complexity in user interaction and instruction. Therefore, methods of robot instruction that are accessible to non-experts would lead to greater usability of industrial robotics. Yet another aspect of the problem lies in vendor-specific solutions, available for each brand of robots. Different tools of varying complexity, different robot programming languages and different abstraction levels of task descriptions make them inaccessible for a plain user.

Since humans communicate with natural language (NL), it may be attractive to use speech or text as instruction means for robots. This is non-trivial for two main reasons: First, NL is often ambiguous and its expressivity is richer than that of a typical programming language. Secondly, tasks can be expressed as goals as well as imperative statements, hence, even if the instructions are correctly interpreted, the description itself is often not enough to create a successful execution. There has to be a substantial amount of knowledge in the system to translate the high-level language instructions to executable robot programs.

In this paper, the simple method from (Stenmark and Nugues, 2013) for natural language programming of assembly tasks is extended. The core idea of the method is to use a generic semantic parser to produce a set of predicate-argument structures from the input sentences. The original algorithm allows extraction of only plain sequences of commands. Here we show that using the predicate-argument structures together with the dependency graphs facilitates also extraction of more complicated task instructions, which involve cardinalities (e.g., pick *two* bolts and *two* nuts), conditionals (e.g., if...then...else) and constraint-characterized programs (e.g., do...until...)

2 Related Work

By abstracting away the underlying details of the system, e.g., by demonstration, high-level programming can make robot instruction accessible to non-expert users and reduce the workload for an experienced programmer. A survey of programming-by-demonstration models in robotics is presented by Billard et al. (2008).

In industrial robotics, programming and demonstration techniques are normally used to record trajectories and positions. As it is desirable to minimize downtime for the robot, much programming and simulation is done offline whereas only the fine tuning is done online (Hägele et al., 2008). There is a plethora of tools, often visual, for robot programming. In robotics, standardized graphical programming languages include Ladder Diagrams, Function Block Diagrams and Sequential Function Charts (IEC, 2003). Using a touch screen as an input device, icon-based programming languages such as in Bischoff et al. (2002) can also lower the threshold to robot programming.

Natural language programming for robots has been investigated since the early 1970's. SHRLDU (Winograd, 1971) is an example of the first attempts to give robots conversational competences. To interpret and convert a user's sentences into instructions, robotic system often make use of an

intermediate representation. Examples include MacMahon et al. (2006) and Tellex et al. (2011), where the authors have developed their own domain-specific semantic representations for robot navigation.

Tenorth et al. (2010) parse pancake recipes in English from the World Wide Web and generate programs for their household robots. They use the WordNet lexical database (Princeton University, 2010) with a constituent parser and they map entries in the WordNet dictionary to concepts in the Cyc ontology (Matuszek et al., 2006). Finally, they add mappings to common household objects.

In order to bridge the sentence to robot actions, all the examples above use ad-hoc formalisms. FrameNet (Ruppenhofer et al., 2010), based on frame semantics, is a comprehensive dictionary that provides a list of lexical models of the conceptual structures. Propbank (Palmer et al., 2005) has developed a extensive database of predicate-argument structures for verbs and nouns, and annotated large volumes of text. The Propbank nomenclature is used by most current statistical parsers, including ours.

Only few robotics systems use existing predicate-argument nomenclatures. An exception is RoboFrameNet (Thomas and Jenkins, 2012). However, the authors wrote their own frames inspired by FrameNet. They built a semantic parser that consists of a dependency parser and rules to map the grammatical functions to the arguments. Such techniques are known to have a limited coverage.

In the project described below we have used a multilingual high-performance statistical semantic parser (Björkelund et al., 2009, 2010) using the Propbank and Nombank lexicons. In contrast to RoboFrameNet, the parser we adopted can accept any kind of sentence. The NL processing module is a knowledge-based service in a larger programming environment (Stenmark and Malec, 2013). In particular, it allows one to create constraint-based task descriptions based on the iTaSC formalism, a property exploited here.

3 Background

The system has been described in detail in our previous work (Stenmark and Nugues, 2013; Stenmark and Malec, 2013); a simplified view of its components is shown in Fig. 1. It is a cloud-based system for knowledge sharing and distributed AI reasoning. The knowledge and reasoning services are stored on a server called Knowledge Integration Framework (KIF), which contains data repositories and ontologies modeling objects and actions. KIF also provides servlets for planning, scheduling and code generation, as well as the NL-programming servlet described in this paper. These services are used for offline programming by the Engineering System (ES), which is a user-interface implemented as a plug-in to ABB RobotStudio (2017) visual IDE.

Objects in the World The core ontology, **rosetta.owl** (Stenmark and Malec, 2013), contains devices such as sensors and robots. The ES also uses a separate ontology to describe parts, such as trays and workpieces. The ontologies describe object types and properties, while the data repositories contain instances of the types. E.g., a **ForceSensor** is a subtype of **Sensor** and of **PhysicalObject**, has property **measures** with value **Force**, and it also inherits properties such as **weight** from **PhysicalObject**. The object types and their property types are later used by the natural language programming system to link arguments to real world objects. Objects are displayed by ES using their CAD models. Each object has a number of relative coordinate frames called *feature frames*, attached to its main object

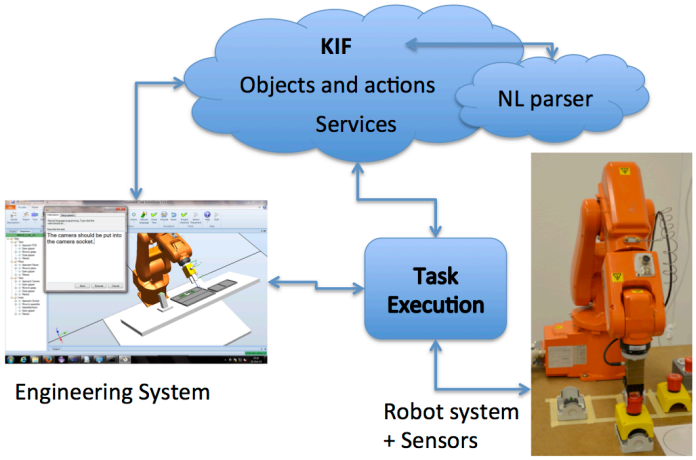

Figure 1: A view of the system architecture.

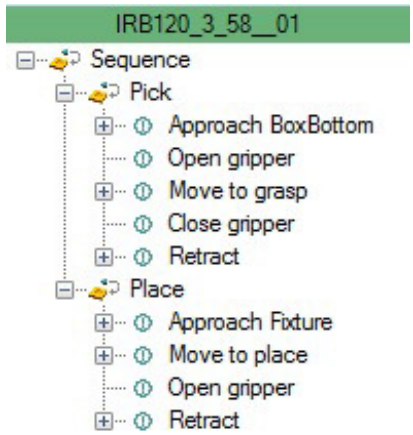

Figure 2: A sequence of skills.

frame. The feature frames are used to express relations between objects. A typical case is a gripping pose described as a relation between a gripper frame and an object feature frame.

Task Vocabulary The task vocabulary is limited to existing robot capabilities. In the KIF repositories, robot actions are stored as program templates, called *skills*. There are primitive actions, such as *search*, *locate* and *move* which can be combined into more complex skills such as *pick* and *place*. Each skill has parameters, e.g., velocities, other objects, their feature frames, or relations. Each skill has also a set of device requirements, pre - and post-conditions as well as optional properties such as natural language labels. The skills are downloaded from the KIF libraries into the ES and added to a task sequence, see Fig. 2. This sequence can be edited by drag-and-dropping objects and by editing parameters of each action or skill. As an additional modality, we have extended the system with

natural language support for sequence generation. Using language to express a task is faster than downloading or selecting each skill separately; besides, speech allows hands-free instruction of the robot.

Natural Language Programming The task is expressed in unstructured English, either by typing it in a text box directly in the user interface, or by connecting an Android app to the ES and using its speech-to-text conversion. The text is sent to a servlet on KIF, which in turn calls a general purpose statistical parser[1] (Björkelund et al., 2010) that outputs predicate-argument structures in standard format (cf. Fig. 3).

Predicate-Argument (PA) Structures As an example we use an assembly where a printed circuit board, a *PCB*, is covered with a metal plate, a *shieldcan*. First the PCB should be fixated, which can be expressed in English as *Take the PCB from the input tray and place it on the fixture.* The PA structures are *take(PCB, input tray)* and *place(it, fixture)*. The parser labels verbs with different *senses* depending on the context in which they are used. For example, take off (like a plane) is *take.19* and take down is *take.22*.

The parsing pipeline uses logistic regression to produce the PA structures, see Fig. 4. First, the dependency graph is extracted. The dependency graph connects the words in the sentence using their grammatical functions. It is technically a tree, where the root is the *dominant* word in the sentence, most often a verb describing an action, and the arrows (see for example bottom part of Fig. 6) point from the *parent* or *head* to its *children*. Then the predicates are identified, labelled with a sense and finally the arguments are identified and labelled. *Take* in our example has sense 1. The predicate *take.01* has three arguments named *A0-A2*, the actor (*A0*), the thing being taken (*A1*) and the source (*A2*). In this case, the robot is not explicitly mentioned, hence there is no *A0*. Pronouns, such as *it* or *them* are linked to their antecedents in the sentence.

[1]The parser is available as open source software, freely accessible at `http://barbar.cs.lth.se:8081/`.

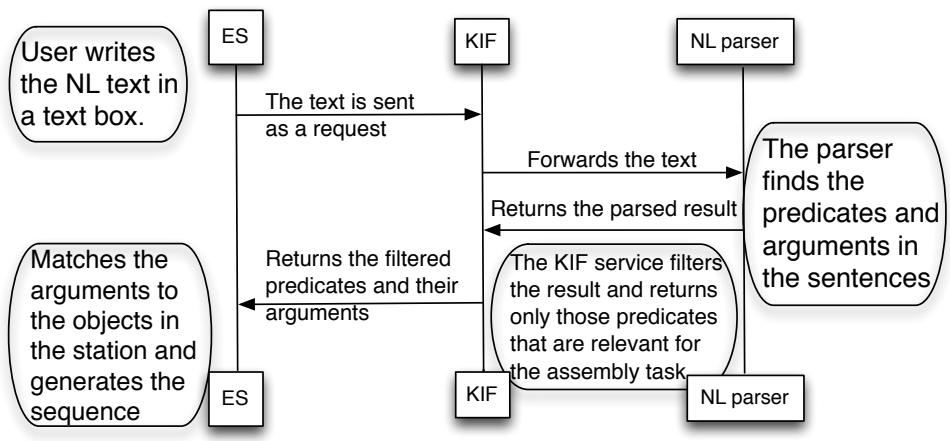

Figure 3: The NL parsing sequence.

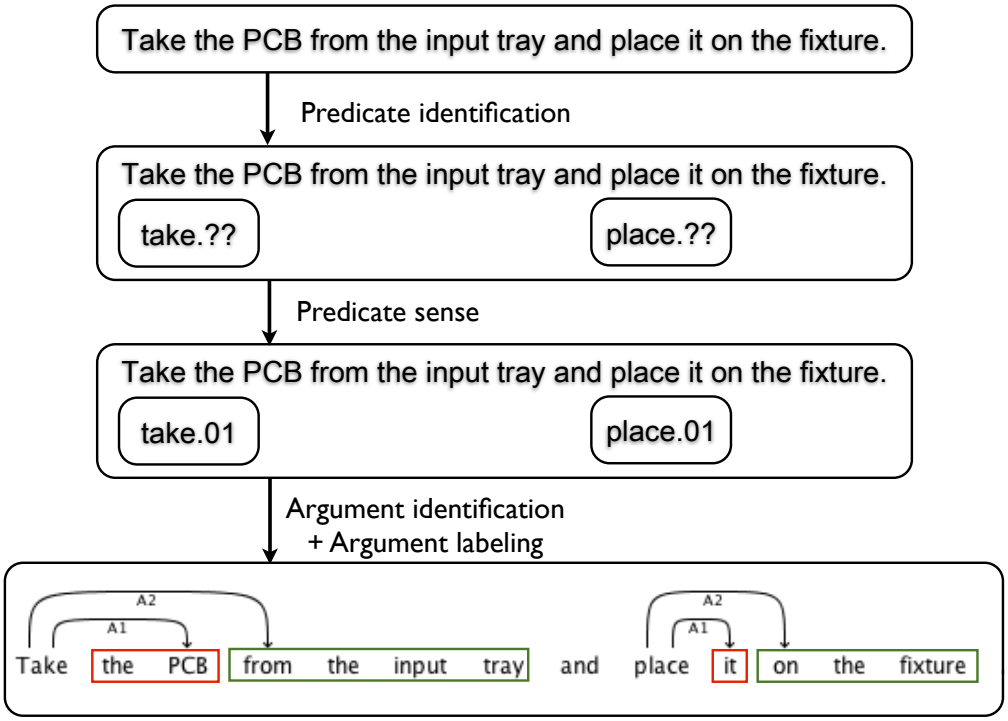

Figure 4: The parsing pipeline.

Previous work (Stenmark and Nugues, 2013) defined an algorithm describing how predicates can be mapped to robot skills, and arguments linked to specific world objects in order to create an executable sequence of the task, as displayed in Fig. 2. However, the supported programming features were limited, excluding e.g., such control structures as conditionals, temporal constraints, control parameters, parallel execution and references to program features. The contributions of this work are that predicate-argument pairs can be mapped to complex skills and the novel methods we are using to extract constraints and control structures from NL instructions.

Code Generation and Execution The executable code for primitive actions is generated in native controller language (RAPID). E.g., each gripper can have a predefined native code to open and close it. On the other hand, the sensor-controlled skills use a framework based on iTaSC (De Schutter et al., 2007), together with external force/torque sensors. These skills are specified by state machines using Lund University (2013) language, where states are simple motions and transition conditions are, e.g., timeouts or force and torque thresholds. A motion is specified by constraining outputs (e.g., positions or force values) from a *kinematic chain*. The kinematic chain is a specification of the relation between task variables and the robot, which are represented by a list of transformations. The state machine is generated by ES for all skills and all constrained motions (Stenmark and Stolt, 2013).

4 Pattern-Matching Algorithm

In this section, we present our method of extracting motion constraints and control structures from unstructured English in more detail. At the moment, the system supports cardinality, parallel execution, conditionals and program references. The algorithm that runs on KIF server is presented in Algorithm 1. It matches the output from the semantic parser to program statements, using the semantic labels, the part of speech (POS) tags and dependency relations between the words. The following examples illustrate how the matching of the different statements is carried out.

Cardinality refers to the number of elements. In the sentence *Take all needles and put them in the pallet*, the cardinality of the needles is *all*. *Take three of the needles ...* has cardinality three. The cardinality is easily extracted from the arguments. In these examples, the arguments A1 to *take.01* are *all needles,* and *three of the needles*, respectively. In the first case, the verb is labelled as plural (NNS) and the determiner *all* is used. In the second case, where there is an explicit numbering (CD) in the argument, it is used as cardinality. Personal pronouns, such as *them* or *it*, are assumed to refer to all the objects in the previous argument (this is done in the ES). There is a subtle difference between *Take the needle* and *Take a needle*, which is expressed in the use of determiner. In the first case, a specific needle is referenced, while in the second, it is only the object type that is mentioned and any needle can be chosen. When linking entities to specific objects in the world, the system will look for a specific object where the name matches the argument value in the first case, but in the second case, the argument value is an object type and the system will return objects of the given type instead. When the cardinality of an argument is larger than one, the resulting program structure is a loop, the sentence number is used to determine its scope, where actions in the same sentence are in the same loop. *"Take all needles. Put them in the pallet."* will thus be two loops, and in a single robot system the planning service will complain about such instructions.

Until is a keyword for extracting the exit condition. *Until* is used to express guarded motions such as *Search in the z-direction until contact.* The conditions can be nested PA structures as well, for example: *Move in the z-direction until you measure 5 N*. The results from the parsing of the two example sentences are displayed in Figs 5 and 6. In order to extract the program statements, the analysis starts with the root in case the root is a predicate. If the predicate belongs to the set of *understood predicates*, it is added as a program statement, together with its arguments. In the first example, the direction was identified as argument *A1* to *search.01*, however, in the second sentence, the direction is considered a location argument to *move.01*. In the case of missing object arguments, the location arguments are used instead, since these are valid parameters to motions. The default frame of the direction is the tool frame.

If the predicate has any temporal constraints, expressed by for example *until* and *while*, these are labelled *TMP* in the dependency graphs. The temporal constraints can be either a noun describing an event, or nested PA structures such as *measure* (pred) *5 N* (*A1*). The temporal constraints are added as a condition to the main program statement (*Move - z-direction*) and will later be used to create transition conditions and thresholds for the guarded motion. Conditions will be discussed in more detail later.

Algorithm 1: Pattern-matching algorithm. Non-trivial functions are described separately.

```
Data: Input text text, set of predicates that have an action-mapping, understoodPredicates
Result: list of program statements, list of unknown statements
Let sentences be a list of sentences in text split by ".", "!" and "?"
Let actions be an empty list
Let unknownStatements be an empty list
sentenceNbr ← 0
foreach sentence s in sentences do
    Increase sentenceNbr
    semOutput ← semParse(s)
    q ← sortPredicates(semOutput)
    while q is not empty do
        p ← poll first element in q
        if not(p is negated or an auxiliary verb) then
            if understoodPredicates does not contain p then
                stm ← createArgs(p,q)
                Add stm to unknownStatements
                wildcard ← getWildcard(p)
                if wildcard found then
                    Add wildcard to unknownStatements
                end
            end
            else
                stm ← createArgs(p, p)
                Add stm to actions with sentenceNbr
                wildcard ← getWildcard(p)
                if wildcard found then
                    Add wildcard to actions with sentenceNbr
                end
            end
            Remove nested predicates in stm from q
        end
    end
end
return actions and unknownStatements
```

Function sortPredicates(*semOutput*)

```
if semOutput has a root element then
    Let q be an empty queue
    root ← get root predicate from semOutput
    if root is a predicate then
        Add root to q
        Parse the tree breath first adding all predicates to q
    end
end
else
    predicates ← all predicates from semOutput in input order
    Add all predicates to q
end
return q
```

Function createArgs(*p*)

```
args ← findArgs(p)
stm ← (p, args)
if hasIfCondition(p) then
    word ← the child of p of form "if" or "when"
    condition ← recursiveSearch(word)
    stm ← if-statement with condtion and stm
end
if hasBreakCondition(p) then
    word ← the child of p of form "until"
    condition ← recursiveSearch(word)
    stm ← break-statement with condtion and stm
end
if hasParallellActivity(p) then
    word ← the child of p of form "while"
    condition ← recursiveSearch(word)
    stm ← while-statement with a and stm
end
return stm
```

Function findArgs(p)

```
a1 ← argument "A1" of p
if a1 does not exist then
    a1 ← search for an argument labelled "TMP", "IN", "AM-LOC"
    if a1 is not found then
        a1 ← search among children to p labelled "LOC"
    end
end
a2 ← argument "A2" in p
if a2 is not found then
    a2 ← search for an argument labelled "TMP", "IN", "AM-LOC"
end
if a1 is not found and a2 is found then
    a1 ← a2
    a2 ← void
end
return (a1, a2)
```

Function recursiveSearch(w)

```
foreach child c of word do
    if c is predicate then
        cond ← createArgs(c)
        if any child cc to c has POS-tag "CC" then
            nestedStm ← recursiveSearch(cc) (cc is "and" or "or")
            Add nestedStm to cond
        end
    end
end
return cond
```

Function getWildcard(p)

```
manner ← get argument from p with tag "AM-MNR"
if manner found then
    word ← recursively search all descendants of manner for a word labelled "NN", "NNS"
      or "NNP"
    if word found then
        stm ← new statement("use", word)
        return stm
    end
end
return empty statement
```

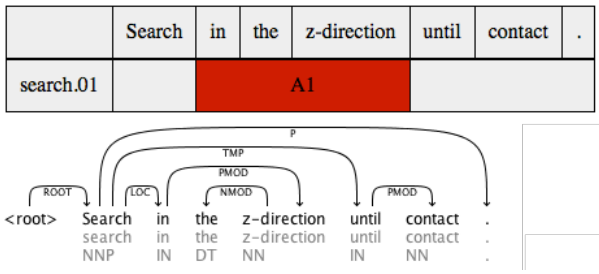

Figure 5: The parse result of *"Search in the z-direction until contact"*, together with the dependency graph.

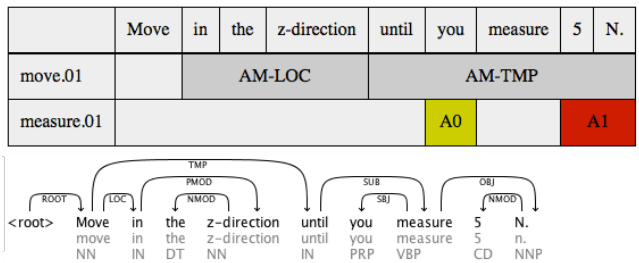

Figure 6: The parse result of *"Move in the z-direction until you measure 5 N"*.

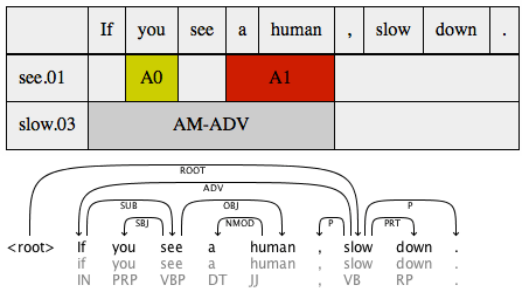

Figure 7: Result for an if-sentence.

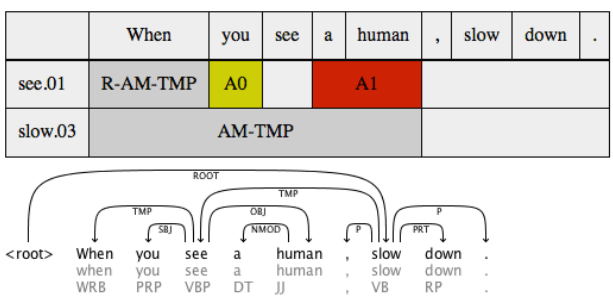

Figure 8: Result for a when-sentence.

While. In most programming languages *while* statements are equivalent to *until*, however, in natural language they also express parallelism. For example *"While holding 5 N in z-direction, search in x-direction until contact"* is a guarded motion along one axis, while adding a constraint in another direction. The result is translated into program statements similarly to *until*-statements. This sentence results in a *while*-statement describing the parallell actions of searching and holding, while the search is a nested until-statement with the transition condition.

Conditions. Conditions can be events or PA structures. In our system, the events that can be used are *contact*, *collision* and *timeout*. The predicates that are allowed are limited to *measure*, *reach*, *sense*, thus limiting the expressions to sensor values. The system also supports nested conditions using AND and OR, such as *contact or timeout*, because *and* and *or* are tagged as coordination conjunctions (*CC*) by the dependency parser.

If and **when.** In our system, these are considered equivalent, however, in the if-sentence the condition is considered an adverbial while in the when-sentence it is a temporal, see Fig. 7 and Fig. 8. This difference is ignored and the PA structure is used as a condition in both cases.

Keywords. All robot skills are not suited to be mapped to predicates, e.g., in a *Snapfit* skill two plastic pieces are snapped into position. Hence, the predicate *use* is dedicated as a keyword, where the argument is either another program or a device that is not part of the assembled parts, such as sensors or tools. That allows sentences such as *"Assemble the shieldcan and the PCB using myskill"*, see Fig. **??**. Here *myskill* can be *snapfit* or *peg-in-hole*, or be replaced with tool such as *gripper2*. When a *use*-predicate is evaluated by the system, it first searches among the sensors and tools for devices that the skill can use, and then online for a skill which can be used to replace the generic *assemble* action.

Another way to express similar commands is by using the word *with*. This will naturally not be parsed into a predicate, but rather be an argument to *assemble.2* called *manner* which is labelled *AM-MNR* in the result shown in Fig. **??**. Adverbs typically describe the manner of a predicate, such as *Carefully assemble...*. In case the manner contains *with* and a noun it is simply interpreted as a *use* with the noun as its argument.

Program references. A small set of predicates and PA structures are used to describe the program itself. For example *Repeat the task*. The predicates are *pause*, *stop*, *start*, *repeat*, and *restart*, while the arguments can be skills or general references such as *the task* and *the program*.

Negation. Predicates with negation are ignored. Although it is possible to imagine commands such as *Don't go close to the human*, we have chosen to require usage of an active command such as *Avoid the human*. For a negation to be meaningful, both an action and its negation have to be mapped to different skills, since the complement of an action is not a well defined concept.

When the program statements have been extracted from English sentences, the predicates are mapped into programs and functions, and the arguments are linked to objects in the world or to skills that are downloaded to the station. Thresholds for sensor values and parallell constraints are added to the guarded motions. Executable robot code for the task is generated from the guarded motions and skills. The resulting code has been verified by virtual robot execution in the Engineering System.

5 Discussion

Using the standard predicate argument-structures together with the dependency graphs, it is possible to extract the semantic meaning of complicated assembly task descriptions from unstructured English. The bottleneck is rather the availability of robotic skills and functionalities in the system, not the natural language understanding by itself.

In a virtual world, control parameters and sensor thresholds can be set to default values. In order to carry out robust task execution on a physical platform though, the damping and stiffness factors of the impedance controller and force signatures should be learnt for the task. The parameters to the impedance control can be learnt by experimentation, as shown by Stolt et al. (2012).

The approach and algorithms presented in this paper are not limited to just assembly tasks, or just to industrial robot task descriptions. After having completed experiments involving skill parameter learning, we plan to extend this approach to other manufacturing domains.

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Appendix

Appendix: Conference posters

Poster 1: On Distributed Knowledge Bases for Small-Batch Assembly

Poster 2: From Demonstrations to Skills for High-level Programming of Industrial Robots

Poster 3: The GiftWrapper: Programming a Dual-Arm Robot With Lead-through

On Distributed Knowledge Bases for Small-Batch Assembly

Maj Stenmark, Jacek Malec, Klas Nilsson, Anders Robertsson

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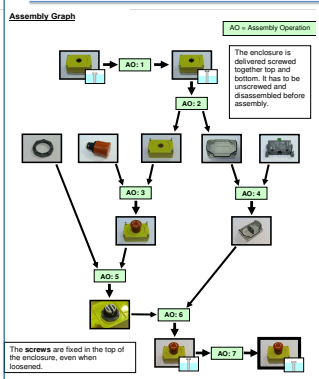
LUND UNIVERSITY

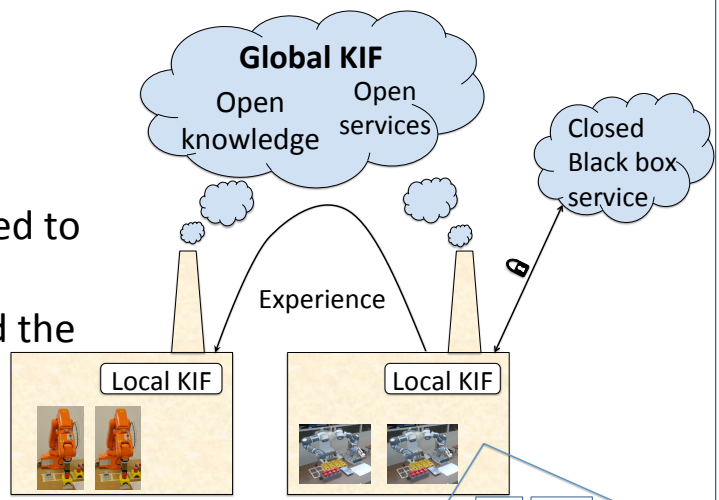


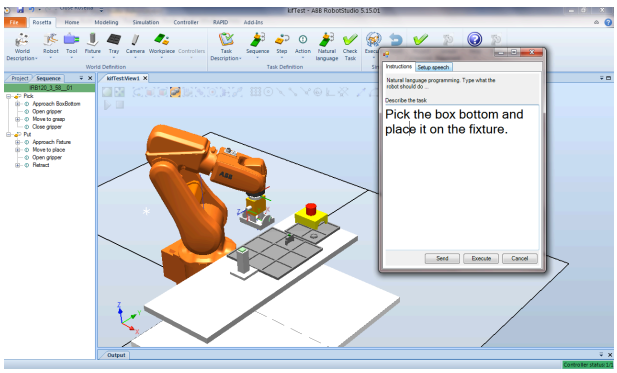
We propose *federated architectures*

- Easier knowledge *sharing* and *reuse*;
- *Security*: verify identity of client/server and protect communication;
- *Local* cache;
- For *non-critical* services.

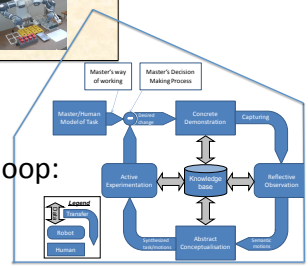
Problems with *knowledge reuse*

- How to evaluate the knowledge when applied to a new situation?
- Can the knowledge and the sources be trusted?
- Business case?
- Legal responsibilities?





PRACE loop:



Web services for robots

- Black box model;
- Industry: conservative and closed;
- Extend robot capabilities.

rosetta

PRACE

SME robotics

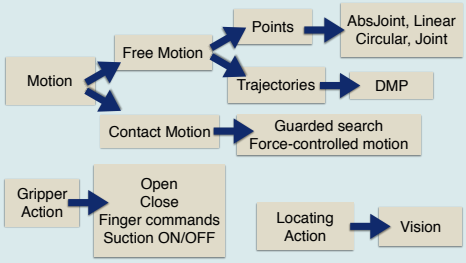
From Demonstrations to Skills for High-level Programming of Industrial Robots

Maj Stenmark and Elin Anna Topp
Department of Computer Science, Lund University, Sweden

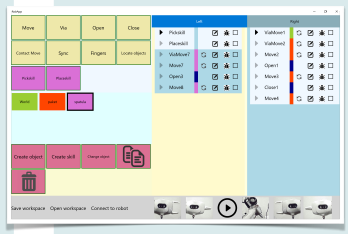
Can non-experts create reusable robot programs from scratch?
Can parameterized skills simplify and speed up robot programming?

In a user study with 21 subjects divided into 3 groups we tested different weather a parameterized skill representation was 1) understandable by a non-expert and 2) helpful when programming a similar task. One group reused their own skill, one group used an expert-made skill and one group reprogrammed every step from scratch.

Action representation



Prototype programming tool



The initial design specification was made from analysis of two case studies

The tool has object and skill abstractions and simple debugging and execution

The tool is intended to work together with lead-through to provide rapid online programming and testing

Skill reuse

The user can **create program abstractions from scratch,** so-called skills e.g. **Pick** and **Place**
Parameterization, e.g., positions relative to objects can be modified easily

Study

21 Participants

30 minutes each with the robot

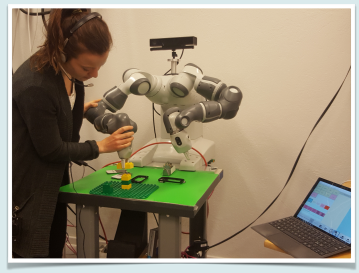
ABB YuMi — an inherently safe robot

Program a LEGO building task using lead-through and GUI

Step 1: insert small LEGO on tower

Step 2: reuse skill to insert large piece

Video for later analysis

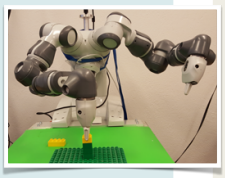


Programming task: pick LEGO pieces and insert them on a tower

Understand robot motion, use gripper cameras to locate LEGO (predefined robot action) and contact force estimation to insert the pieces

Switch from the LEGO's reference coordinate system and tower coordinates

Reuse own or expert made skill to repeat the task with a large LEGO in three positions



Preliminary results

- 19 out of 21 could program the first step.
- 14 out of 21 managed to steps.
- Reusing expert-made skill had best results, but the group was more experienced with machines.
- Difficult: finding a good insertion strategy for robust attachment.
- Understanding and using different reference systems.
- Very limited time to learn the tool and how the robot moved.
- Pose vs. trajectory recording.
- *Robot should suggest actions based on previous skills!*

Yes, robot programming is for (almost) everyone!
Yes, parameterization bootstraps the programming process!

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The GiftWrapper: Programming a Dual-Arm Robot with Lead-Through[1]

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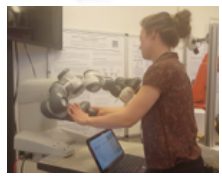
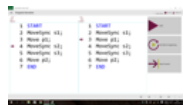
The application: customers at electronic retail stores in Sweden got their Christmas presents wrapped by a robot.

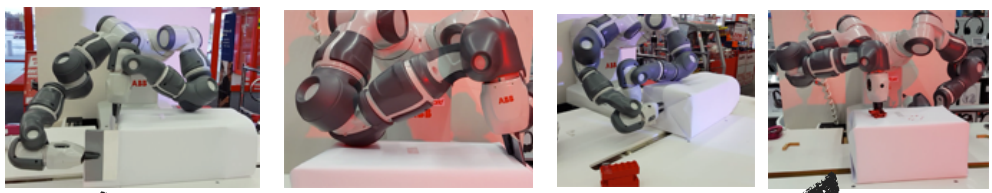
Robustness to uncertainty. No sensors were available and using only position-based execution is error-prone. Hence, the robot had to adjust the position of the box repeatedly during the wrapping to address uncertainty.



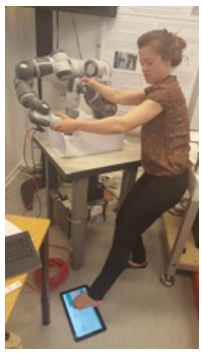


While lead-through can be useful for teaching positions, even simple robot programs need a graphical interface to add logic and control grippers, e.g., by setting the gripping force to avoid tearing.

Example



Inherently safe user interaction both during programming and during the gift wrapping.



Multiple contact points and **synchronized motions** require the programmer to teach positions while using other means to interact with the application.

Conclusions: It works!

We handled complex contact situations for soft objects with significant uncertainties by using clever combinations of position-based motions. These were achieved and tested using lead-through programming.

See the full process online

1. Finalist for the 2016 euRobotics TechTransfer Award http://www.erf2016.eu