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Force Controlled Robotic Assembly without a Force Sensor

Andreas Stolt, Magnus Linderöth, Anders Robertsson, Rolf Johansson

Abstract—The traditional way of controlling an industrial robot is to program it to follow desired trajectories. This approach is sufficient as long as the accuracy of the robot and the calibration of the workcell is good enough. In robotic assembly these conditions are usually not fulfilled, because of uncertainties, *e.g.*, variability in involved parts and objects not gripped accurately. Using force control is one way to handle these difficulties. This paper presents a method of doing force control without a force sensor. The method is based on detuning of the low-level joint control loops, and the force is estimated from the control error. It is experimentally verified in a small part assembly task with a kinematically redundant robotic manipulator.

I. INTRODUCTION

Robotic assembly is a task that requires physical contact between the robot and its environment. Traditionally this has been solved using position control together with fixtures to achieve the desired accuracy. When the task contains uncertainties, however, additional sensing is needed to accomplish the assembly. One way to incorporate sensors and specify general tasks is to use the iTaSC framework [7] (instantaneous Task Specification using Constraints). In [16] it was described how this framework was used in an assembly of an emergency stop button.

Previous work in robotic assembly can *e.g.* be found in [4], where optimization of force control parameters with respect to cycle time was made in assembly of a clutch. An example from the automotive industry is [9], which describes powertrain assembly. In [19] synchronized Petri nets were used to model the assembly process and an experimental evaluation was made with a peg-in-hole assembly.

A. Robotic assembly strategies

There exist a few different strategies for performing robotic assembly, where different amounts of sensor information are used. One way is to use pure position control of the robot. To be able to do this one has to rely on that the accuracy of the robot, of the involved parts, and of the work cell are good enough. Usually task specific fixtures and toolings are needed. Further, one has to be certain that nothing unexpected will happen during the assembly operation, as this is hard to discover without an external

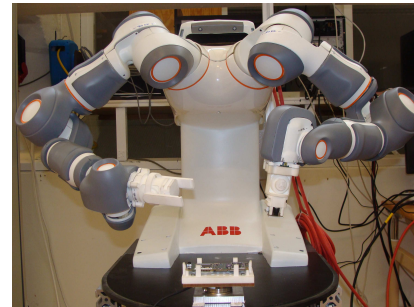


Fig. 1. The ABB FRIDA robot [12] used in the experiments.

sensor. It is possible to handle some degree of part variation by using a compliant tool.

A second strategy is to use binary information from sensors. This means that the assembly is divided into several steps, in which the information from the sensors is used to trigger transitions between the steps. This strategy can be used when there are a few uncertainties, *e.g.*, some variations in the parts. One example can be to use a sequence of search motions in order to find a certain feature of an object, and once this feature is found, it is possible to use pure position control to finish the assembly operation.

Yet another alternative is to use sensors for continuous feedback control. This strategy makes it possible to cope with large uncertainties, but it is also the strategy that is the most difficult to program for a robot operator. One example of this strategy is force controlled assembly, where force sensing can be used to identify contact formations, keep contacts and find new contacts during an assembly operation. If contacts only are detected in a binary fashion, as described in the previous paragraph, there is a risk of losing contact or getting very large contact forces during sliding motions. Hence, continuous sensing can make assembly possible when more uncertainties are involved, and also reduce the risk of damaging equipment.

The strategies described in the previous paragraphs can handle different amounts of uncertainties and the type of effort one has to spend to get them running are different. In the case of pure position control one has to assume that the position accuracy is very good and that everything will go as planned. These requirements can be relaxed when binary sensor information is used, but then one has to take care of the sensor signals in an appropriate way instead. Using continuous sensing demands even more sensor processing, and feedback control strategies, which may be hard to tune. The two last strategies also require a sensor, which may be expensive. The reusability and the increased robustness to

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uncertainties, however, are incitements to use the strategy based on continuous sensing.

This paper will propose a method of how to perform force sensing without a force sensor, by instead estimating the forces from the joint position control errors. The method is experimentally verified in a real world small part assembly task using a redundant robotic manipulator, see Fig. 1.

II. ESTIMATING EXTERNAL FORCES

The simplest and most straightforward way of estimating the external force acting on the end-effector is to use a force sensor. One alternative is to use a wrist-mounted sensor, and by assuming that the end-effector is rigidly connected to the sensor, the external force acting on the robot can be calculated. Another option is to use torque sensors on each joint of the robot, *e.g.*, as done in the DLR lightweight arm [2]. If the individual joint torques are collected into the vector τ , the end effector force F can be calculated from $\tau = J^T F$, where J is the Jacobian of the robot.

If there is no force sensor available, one alternative is to use the motor torque in each joint. The problem with this approach is that it requires the measured torques to be compensated for disturbance forces—*e.g.*, gravity and friction—before the torque signals can be used. Further problems arise if there are gears in the robot, since a high gear ratio will amplify noise and model errors and make it hard to achieve an accurate estimate. If it is possible to extract the joint torques, the same approach as with individual torque sensors in the joints can be utilized. It is also possible to use the motor torques together with a dynamical model of the robot to estimate the forces. In [18] it is presented how this can be performed by using a filtered dynamic model and a recursive least-squares estimator.

A third approach is to use some kind of observer. One way is to use disturbance observers, *i.e.*, to use a dynamical model of the robot and consider deviations from this as disturbances caused by external forces, see *e.g.* [8] and [13] for examples of this approach. Direct force observers can also be used. In [14] an H^∞ force observer is used. In [10] and [3] the force is estimated by considering how position estimation errors behave as a damped spring-mass system.

Force estimation can also be performed by using adaptive methods. In [11] a method based on the Extended Kalman filter together with an adaptive law is presented. Another adaptive force estimation approach is given in [15]. Estimation of the robot joint velocities and accelerations together with a dynamic model are used to perform impedance control without a force sensor in [17].

A clear disadvantage with the proposed methods using observers and adaptive methods is that they usually require a dynamic model of the robot. Such a model is straightforward to derive in theory, but in practice you often do not know the values of all parameters involved. It is possible to perform identification experiments, but then one will probably run into problems with friction, which is hard to model in a good way. Even with all parameters known, for a manipulator with 6 or 7 joints the dynamic equations get very large and

complicated. They might therefore be hard to implement in a real-time controller.

Yet another approach is possible when each joint on the lowest level is individually controlled, which is a common solution in industrial robots. By disabling the integral action in the joint controllers, they will act as virtual springs, and the deviation of each joint angle from its reference will correspond to a joint torque. By using the same approach as with individual joint torque sensors, it is possible to calculate the external force. Due to friction and gravity, the joint errors may become large if the integral action is removed completely, leading to bad performance in the position control and bias in the force estimate. One remedy to this problem is to use a small integral part, which allows force transients to be detected, but over time the position errors will be removed. Estimation of forces based on joint errors, using small intergal action, acts as a high-pass filtered version of the forces. A similar concept is used in the ABB product SoftMove [1].

The joint torques τ and the end effector forces F are related by

$$\tau = J^T F + e \quad (1)$$

where $J = J(q)$ is the robot Jacobian, q is the robot joint coordinates, and e are disturbance joint torques with the assumption $\mathbb{E}[e] = 0$ and $\mathbb{E}[ee^T] = R_e$. The minimum variance estimate of the force is then given by $\hat{F} = (JR_e^{-1}J^T)^{-1}JR_e^{-1}\tau$, but if the disturbances are large, the estimate may be of very poor quality. By adopting a Bayesian approach and using prior knowledge about the particular assembly operation, it may be possible to improve the force estimates. Assume that the prior knowledge about F can be described by $\mathbb{E}[F] = \bar{F}$ and $\mathbb{E}[(F - \bar{F})(F - \bar{F})^T] = R_F$, and that the distribution of τ conditioned on F is given by (1), then the minimum variance unbiased estimate of F is

$$\hat{F} = (JR_e^{-1}J^T + R_F^{-1})^{-1}(JR_e^{-1}\tau + R_F^{-1}\bar{F}) \quad (2)$$

For example, it may be known that the contact torques on the end effector may be very small during an assembly operation. By reflecting this knowledge in R_F , the estimates of the contact forces can be improved.

III. ASSEMBLY SCENARIO

The assembly scenario considered is a subassembly of a mobile phone. A 'shield can' should be assembled onto a printed circuit board (PCB). The shield can should be pressed onto a socket on the PCB. There are no tolerances between the shield can and the socket, and the shield can will therefore have to be deformed to fit. The parts involved are small and fragile, and the assembly therefore has to be performed with care not to break anything.

A. Robot system

The robot system used in the assembly scenario is FRIDA, the new concept robot from ABB [12]. It is a dual-arm



Fig. 2. The vacuum gripper used in the experiments.

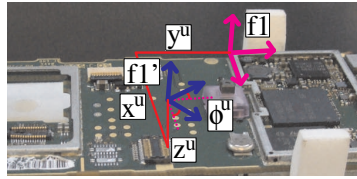


Fig. 3. Illustration of the uncertainties in the assembly task. The magnitude of the uncertainty is scaled up to make room for the frames and the labels.

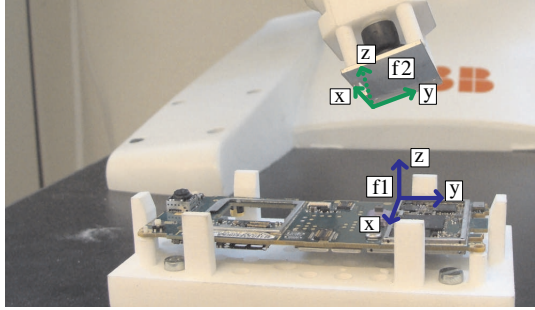


Fig. 4. Illustration of the frames used in the assembly task.

manipulator developed for automation of assembly operations. Each of the two arms is redundant with 7 degrees of freedom. The robot is controlled with the ABB IRC5 robot control system. This system has been extended with an open control system [5], [6], which makes it possible to modify the references for the low-level joint control loops.

To make it possible to perform the mobile phone assembly, special tooling has been produced. A fixture has been designed for keeping the PCB in position. A suction tool is used to grasp the shield can, see Fig. 2. The maneuverability in contact is good in the vertical direction (the $f2$ z -direction in Fig. 4), but worse orthogonal to this direction ($f2$ x - and y -direction in Fig. 4), since the shield can may slide.

A 6 degrees-of-freedom ATI Mini40 force/torque sensor has been placed beneath the PCB fixture (see Fig. 1) to make it possible to both perform the assembly using force sensor feedback and make a comparison with it when the external forces are estimated from the joint errors.

IV. TASK MODELING

The task was modeled with the iTaSC framework. A thorough explanation of this is given in [7]. The iTaSC framework is suitable to handle both over- and under-constrained tasks, as well as manipulators with redundant degrees of freedom. For instance, in the velocity based control scheme of iTaSC the redundancy can be used to optimize some criterion of the joint velocities. In the case of an over-constrained task, weighting or prioritizing of the constraints can be used to calculate the desired motion.

The assembly operation is described using two frames, shown in Fig. 4.

- Frame $f1$ is attached to a corner of the socket on the PCB.
- Frame $f2$ is attached to a corner on the shield can.

A. Uncertainties

Uncertainties in the task include the exact location and orientation of the fixture holding the PCB, and also how the shield can has been grasped. The first one can be modeled by introducing an uncertainty frame $f1'$. This frame represents the modeled position of the socket corner on the PCB, while $f1$ gives the real position. It is assumed that the fixture is mounted such that the PCB is placed in the horizontal plane, but the exact location and orientation in this plane is uncertain. This is modeled by introducing three uncertain translations and one uncertain reorientation angle (around the $f1$ z -axis), see Fig. 3. Similarly, in the grasp the orientation around the z -axis and the translations along the x - and y -axes in frame $f2$ are uncertain.

The prior distribution of the uncertainty coordinates is assumed to have a standard deviation of a few millimeters and a few degrees respectively. The only sensor information available is the contact force.

B. Assembly strategy

The assembly strategy is designed such that the uncertainties are resolved in a robust way. A suitable strategy is to first find a corner of the socket with the shield can in a tilted position, see *e.g.* Fig. 4, by executing a sequence of guarded search motions, *i.e.*, the search motions are stopped once the corresponding contact force is sensed. Once the corner is found, rotate the shield can to what is believed to be the correct orientation and press it onto the socket. When a certain force and torque are applied the shield can can be considered to be assembled.

By inspecting the PCB a suitable corner to try to find is the one where frame $f1$ is placed, see Fig. 3. The area in front of this corner is almost free of small edges that can lead to problems during the assembly. It is further large enough to be possible to find, considering the variance of the modeled uncertainties. A detailed assembly sequence is given below:

- 1) Pick up shield can from tray
- 2) Goto start position
- 3) Search for contact in negative $f1$ z -direction
- 4) Search for contact in positive $f1$ y -direction
- 5) Search for contact in negative $f1$ x -direction
- 6) Find corner of socket by yet another search in positive $f1$ y -direction (force control in x -direction)
- 7) Make a rotational search around the $f2$ x -axis and the $f2$ y -axis
- 8) Press shield can into position
- 9) Release shield can and move away with robot

An illustration of how the corner of the socket is found is given in Fig. 5.

V. EXPERIMENTAL RESULTS

A. Force estimation

The force estimation is affected by how the detuning of the joint controllers has been performed. If the integral part is completely removed there will be problems with offsets, because of gravity and friction forces. Keeping the integral

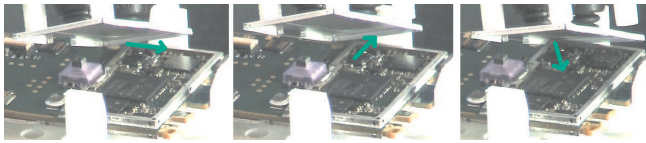


Fig. 5. Snapshots from the assembly sequence to illustrate how the corner is found. The arrows indicate in which direction the shield can is in contact. In the leftmost photo the robot is in state 5 and has sensed contact in the y -direction, in the middle photo the robot is in state 6 and has sensed contact in the x -direction, and in the rightmost photo the robot has found the corner.

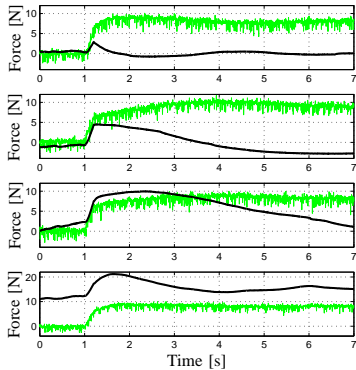


Fig. 6. Estimated force (black) and measured force (green) in one direction for some different values of the integral gain in the joint controllers. The nominal controllers have the integral gain K_i . The topmost diagram has integral gain K_i , the second diagram $0.1K_i$, the third diagram $0.01K_i$, and the lowermost no integral action at all.

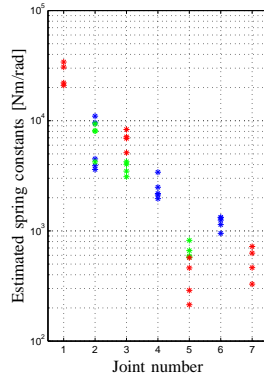


Fig. 7. Experimentally determined spring constants for the different joints. The joints are numbered from shoulder to wrist. The different colors denote values obtained from different arm configurations.

part, however, makes it impossible to estimate a constant force, as this would require the joint controllers to have a stationary error. Keeping the integral action will act as a high-pass filter on the estimated forces, which means that only transients can be detected. The behavior for different detunings is shown in Fig. 6, where the force sensor has been used to find contact in one direction and control the contact force to a constant value. It can be seen in the diagrams that a high integral gain gives a transient with a short duration, which may be hard to detect. Removing the integral action completely, however, introduces a bias in the estimate. The final controller detuning chosen to be used in the assembly task was with $0.03K_i$ as integral gain, where K_i is the integral gain in the nominal joint controllers.

A large disturbance acting on the force estimates is friction in the joints. Experiments were performed to estimate the friction magnitude in each joint, which mostly consisted of Coulomb friction. These values were used to choose the diagonal elements of R_e , the variance of the disturbance forces in Eq. (1). The effect of gravity was assumed to vary slowly, such that the integral part in the joint controllers could compensate for it.

According to the identified joint friction torques, they will lead to force estimation errors with an order of magnitude of 1 [N]. Estimation errors of this size were measured for the experimental execution of the assembly task, see Fig. 8.

To determine the spring constants of the joints, forces

or torques were applied to the tool of the robot, and the amplitude of the resulting joint error transients were recorded. Doing this for three different arm configurations, it was possible to determine the stiffness of all joints. Approximately 5 experiments were performed for each arm configuration, and the results can be seen in Fig 7. For each joint the mean value of the experiments was later used for force estimation.

Torques in the assembly sequence were measured in frame $f2$. The major part of the assembly sequence is therefore performed with only a point contact, which means that the torques should be zero around this point. Modeling errors will of course contribute to some torques, but they should be small. This insight can be used as prior information, *i.e.*, it can be used to choose \bar{F} and R_F . No bias force is expected, which gives $\bar{F} = 0$. The variance R_F is chosen to be large for the forces and small for the torques. The estimate that utilizes this prior information is compared to an estimate without this information in Section V-C.

B. Assembly scenario with force sensor

The assembly sequence described in Sec. IV-B was implemented using a force sensor. The results are similar to those presented in [16]. Major differences are that the involved parts are smaller here, and also the magnitude of the measured forces. The sliding search motions cause large disturbance forces that make it hard for the force controllers to keep contacts in other directions. This makes it difficult to increase the overall assembly speed. The small force magnitudes also require care when choosing triggers for the state transitions in the controlling state machine.

C. Assembly scenario without force sensor

The assembly strategy had to be modified when the estimated force was used. The high-pass character of the force estimates made it impossible to control constant forces. Instead, once a search motion made contact the position was controlled instead of the force. This changed strategy made the assembly less robust, but the effect was small concerning the uncertainties in this particular task. As the contact torque estimates were found out to be unreliable, the rotational search in state 7 was replaced with a position control to the believed final position of the shield can. To be able to do this maneuver successfully it had to be assumed that the mounting plane of the PCB was known with good accuracy, which is a reasonable assumption to make, as the PCB is placed in a fixture. Gripping uncertainties, corresponding to small rotations around the $f2$ z -axis, were not expected to be a problem, as the gripper is compliant in this direction and because the shield can was rotated down when in contact with a corner of the socket, such that the shield can was forced onto the socket by its edges. To be certain that the shield can was assembled correctly once the rotating motion was finished, the robot pressed the shield can with a large force towards the socket, kept the position of making contact for some time and then the assembly was assumed to be finished.

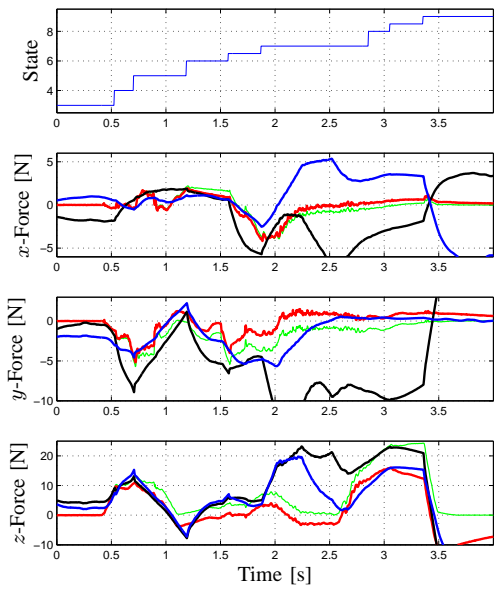


Fig. 8. Measured and estimated forces from the assembly sequence without force sensor together with the state sequence. Forces estimated with a priori information about the low torques are shown in blue, and forces estimated without a priori information in black. For reference, raw force data from the force sensor is shown in green, and high-pass filtered force data in red. The data from the force sensor has not been used for control in this execution.

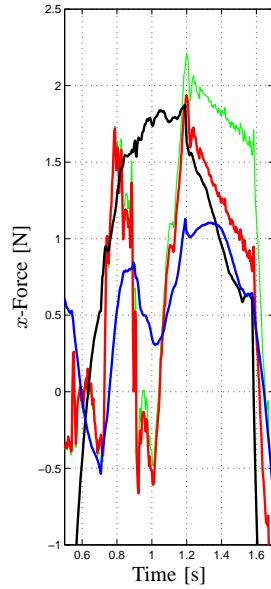


Fig. 9. Selected part of the measured and estimated x -force around the transition from state 5 to 6.

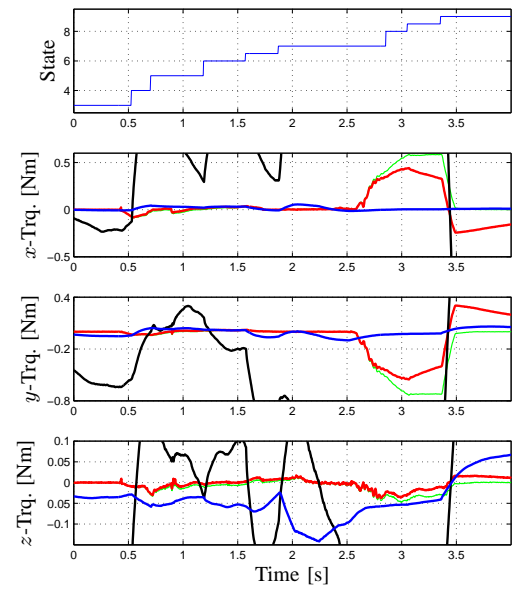


Fig. 10. Measured and estimated torques from the assembly sequence without force sensor together with the state sequence. Torques estimated with a priori information about the low torques are shown in blue, and torques estimated without a priori information in black. For reference, raw torque data from the force sensor is shown in green, and high-pass filtered torque data is shown in red. Some data has been cut away to show what happens in the measured torque. This shows that the black curve is a bad estimate.

Force data from an experimental execution is given in Fig. 8. The high-pass character of the estimated force is verified by including a high-pass filtered version of the measured force. Two versions of the estimated force are shown, with and without a priori information about the low torques. The first state shown is the search for contact in the $f1$ z -direction. The transition condition, a large positive z -force can be seen in all force curves at $t = 0.5$ [s]. The following state is the search in the positive y -direction and it makes contact at $t = 0.7$ [s], which is seen by a large negative y -force. State 5 is then a search in the x -direction. The search motion is made with contact in both the z - and the y -direction, and this initially causes a friction peak in the x -force (at $t = 0.8$ [s]), the relevant part of the x -force is displayed in Fig. 9. The force then disappears and the contact is made at $t = 1.1$ [s]. The estimated force with a priori information shows the same behavior as the measured force, but the force estimate without a priori information does not. The transition to the next state is finally made at $t = 1.2$ [s]. The final search for the corner of the socket is then made in two steps; first a y -search in state 6 and then an x -search in a new state, here called 6.5. The transition condition for the y -search can be seen at $t = 1.6$ [s] and the transition condition for the x -search at $t = 1.9$ [s]. The transitions can be seen in both estimated forces, but the resemblance with the measured force is better for the estimate with a priori information. State 7 is the position control of the orientation, such that the shield can is rotated down onto the socket. The rotation is made around the origin of frame $f2$. Modeling errors in the position of this frame is the reason for the large

z -forces around $t = 2.7$ [s], as the rotation is not made exactly around the origin of $f2$. These forces are detected and the reference position in the z -direction is adjusted. The shield can is pressed onto the socket with a large force in state 8, which can be seen in the z -force at $t = 3.0$ [s]. Finally, the robot waits 0.3 seconds in state 8.5 and then moves away in state 9.

Measured and estimated torques from the experimental execution are given in Fig. 10. It can be seen from the sensor measurements that torques significantly different from zero only are present during the last stage of the assembly, *i.e.*, during state 7 and 8. The estimate with no a priori information really bad, neither the magnitude nor the shape show any resemblance with measured data. Using the a priori information gives a reasonable magnitude on the estimate, but it does not react to the applied torques in state 7 and 8 and the estimate is therefore unreliable.

The estimated forces are reasonably correct when in contact, but the performance is worse when no contact is present, see, e.g., after $t = 3.4$ [s] in Fig. 8. The use of a priori information about the size of the external torques gives better force estimates, and they are in fact crucial for performing the assembly task considered, as one of the transition conditions only can be found using this estimate. The similarity between the high-pass filtered force data and the force estimate, at least in the case when a priori information is used, verifies the high-pass character of the estimate. Most of the discrepancy between the measured and the estimated force is because of friction, as was described in Sec. V-A.

VI. DISCUSSION

Estimating forces from the joint errors instead of using a force sensor introduces some difficulties in the implementation of the assembly operation, compared to using a force sensor. Doing it the way presented in this paper requires you to choose an appropriate detuning of the joint controllers. Since the disturbances in the estimates may be quite large, special care must be taken when choosing force thresholds in the design of the assembly sequence.

When the robot is not moving, the Coulomb friction in the joints makes it particularly hard to estimate the forces, since the contribution from gravity and other disturbance forces is unknown, and it is very difficult to predict how much additional torque is needed in the different directions to overcome the friction and make the joint move. When the robot is moving, however, the Coulomb friction torque is constant and even a small external force (*e.g.*, caused by a collision) can affect the motion and be seen as a transient in the joint errors. Since the disturbances from the friction are very similar between different executions of the same motion, the situation becomes even better and it is possible to robustly detect forces with the same order of magnitude as the friction disturbances. Since the disturbances are velocity dependent, there may, however, be a need to retune the force thresholds if the speed of motion is changed.

When moving at high speeds, dynamic effects and lag in the position tracking may cause large errors in the force estimation, but sometimes increasing the speed of motion makes the sensing easier, since transients caused by collisions then become easier to detect in the high-pass filtered data.

The fact that the disturbances to a large extent are systematic, indicates that adaptation or learning techniques could be successful in improving the performance. By further on considering the entire signal instead of its instantaneous value it is probably possible to find more robust transition conditions. Another set of parameters that possibly can be adapted is the detuning of the joint controllers.

In the assembly scenario described in this paper, the sensing problem is very hard, since the contact forces are in the same order of magnitude as the disturbances caused by friction in the joints. To get useful estimates of the forces, the contact torques had to be assumed to be very small. If both arms of FRIDA would be used to perform two-handed assembly, there would be 14 joint errors available to estimate the forces and torques, as compared to 7 joint errors in the single-armed case. Possibly this could lead to improved estimates. In a different scenario, where contact forces are much bigger than the friction disturbances, it should be possible to perform assembly with a single arm, without assuming that the contact torques are small.

VII. CONCLUSIONS

A method for estimating the external forces acting on the end-effector of a robot has been described. It was based on the control errors for the low-level joint control loops. The

method was experimentally verified in a small part assembly task using a kinematically redundant robotic manipulator.

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