LUND UNIVERSITY

Force Controlled Knife-Grinding with Industrial Robot

Sörnmo, Olof; Robertsson, Anders; Wanner, Anders

Published in:
2012 IEEE Multi-Conference on Systems and Control

2012

Citation for published version (APA):
Sörnmo, O., Robertsson, A., & Wanner, A. (2012). Force Controlled Knife-Grinding with Industrial Robot. In *2012 IEEE Multi-Conference on Systems and Control* (pp. 1356-1361). IEEE - Institute of Electrical and Electronics Engineers Inc..

Total number of authors:
3

Force Controlled Knife-Grinding with Industrial Robot

Olof Sörnmo, Anders Robertsson and Anders Wanner

Abstract— **This paper investigates the application of sharpening knives using a force controlled industrial robot, for an arbitrary knife shape and orientation. The problem is divided into different parts: calibration of the knife by identifying its unknown orientation, identification of the knife blade contour and estimation of its position in the robot frame through force control, and grinding of the knife, following the path defined by the earlier identified shape, while applying the desired contact force to the revolving grinding wheels. The experimental results show that the knives can be sharpened satisfactorily. An industrial application has also been developed and tested, and it has produced a sharpening quality equal or greater to that achieved manually.**

I. INTRODUCTION

In many robot applications, the robot is required to come into physical contact with the work object in order to complete its task. Certain tasks, *e.g.*, drilling, require the robot to exert a specific force on the work object. If the force is too strong, the work object or the robot tool may break, and if the force is too weak, the task will not be executed properly. It is therefore crucial that the exerted force can be controlled in a well-behaved manner. In applications such as grinding, not only the force needs to be controlled precisely, but the motion of the robot as well.

The subject of force controlled grinding using industrial robots has been investigated in several papers. An extensive study on methods for force controlled weld bead grinding is presented in [1]. A method for controlling a robot during grinding applications using torque control is presented in [2], where the contact force is estimated using a torque observer. A stub grinding and deburring application using a high-bandwidth force-controlled industrial robot was developed in [3]. Methods for force control during two different grinding tasks, performed by an industrial robot were presented in [4]. The benefits of using force control for grinding applications are discussed in [5], where it was shown that it is possible to compensate for both the disturbances caused by low robot stiffness and robot path tracking errors during grinding.

This paper presents a method for automatic sharpening of knives as well as automatic calibration, using a force controlled industrial robot. The overall aim is to increase the number of knives sharpened each day, as well as to improve and guarantee a repeatable sharpening result.

This paper is organized as follows. A short motivation of the work is provided in Sec. II, Sec. III presents the simulation- and experimental setup, followed by a description of the simulations and experiments, as well as the grinding procedure experiments. An industrial implementation is described in Sec. IV. Experimental results from both the research lab and the industrial setting are presented in Sec. V, followed by discussion and conclusions.

II. MOTIVATION

There are several advantages of using an industrial robot for knife sharpening rather than using a traditional tool jig. First and foremost, the robot has a large workspace and is not limited to working with a single specific machine. This also makes the need for regripping the knife during a cycle obsolete. Since all machining operations in this study are force controlled, the tool jig for each operation would require a separate force/torque sensor. In addition, the force/torque-sensor on the robot can be used for identifying the knife shape as well as measuring the knife length. Further, an industrial robot has in general more degrees of freedom than a tool jig, which allows for more flexibility in the setup and calibration of the robot cell.

III. METHOD

A. Simulation- and experimental platform

In this paper, simulations were performed in MATLAB Simulink, using the predefined blocks from the *ExtCtrl*-library [6] developed at Lund University, describing the robot kinematics. Experiments are executed using an *ABB IRB-140B* 6-DOF robot with an IRC5-controller, using an open robot control extension called *ORCA* [7]. The Simulink models are translated then compiled to *C* using *Real-Time Workshop* [8] in order to run them on the robot system. A JR3 force/torque sensor is mounted on the robot flange, which measures forces and torques in the Cartesian directions, at a sampling rate of 8 kHz.

B. Knife shape identification and knife calibration

Simulations. In order to identify the shape of the blade, the knife is assumed to be rigidly attached to the robot, with a known starting point and the cutting edge of the blade perfectly aligned facing the positive direction of the flange x-axis. The orientation of the robot flange coordinate system is displayed in Fig. 2. The knife blade is approximated by a two-dimensional contour, modeled as a third-order polynomial. The contact force is modeled as a spring: $F = k\Delta x$,

---

Olof Sörnmo and Anders Robertsson are with the Dept. of Automatic Control, LTH, Lund University, SE–221 00 Lund, Sweden. E–mail: {Olof.Sornmo,Anders.Robertsson} @control.lth.se.

Anders Wanner is with Robot Solutions Scandinavia AB, Hörby, Sweden. E–mail: anders@robotsolutions.se.

The research leading to these results has received funding from the Swedish Foundation for Strategic Research within the program ProViking, under grant ProFlexA PV08-0036.

where Δx is the distance from the undeformed contour, and k the spring constant. A tool, which the robot will achieve contact with, is defined as a stiff line situated below the knife blade. The knife position is defined so that it is not in contact with the tool initially. In this paper, *hybrid force control* [9] is utilized. As the name suggests, it is a controller that switches between motion and force control depending on if contact is present or not. The force controller acts on the force norm error, in the direction of the contact force. In this paper, the force controller is chosen as a PI controller, whose transfer function is given by

$$G_{PI}(s) = K_p\left(1 + \frac{K_i}{s}\right). \tag{1}$$

Since the force measurements contain high frequency noise, a derivative part is not adopted. The PI controller acts on the error between a given force norm reference and the measured force norm. The control signal from the force controller is multiplied with the normalized force measurement so that the control is exercised in the direction of the force.

In order to optimize control performance, the parameters K_p and K_i of the PI controller in (1) need to be tuned. To place the poles of the closed loop system, a model describing the robot Cartesian position is needed. A third-order model from position reference to position of each joint is given by [10]

$$G_{pos}(s) = \frac{560s + 200000}{s^3 + 140s^2 + 10560s + 200000}. \tag{2}$$

An approximate Cartesian model can be derived by assuming that the Cartesian position in one dimension, for small angles, can be described by the dynamics of a single joint. Following this assumption, the transfer function $G_{pos}(s)$ from position reference to position is given by (2), and K_p and K_i can be determined.

Once the knife is in contact with the tool, a new search direction is defined for every sample period, being described as a vector perpendicular to the force vector. Since the force vector is normal to the knife contour, the search direction will consequently be equal to the tangent of the unknown knife contour. By using this search direction combined with a force controller, the robot follows the contour without losing contact with the knife.

Experiments. In the experimental setup, the knife is not perfectly aligned, so the deviations from the desired knife orientation need to be determined before the shape can be identified. The unknown orientation around the flange y-axis will be taken into account during the shape identification, thus only the orientation deviations around x and z need to be determined. To do this, a zero-reference torque controller can be implemented, which acts on a given point on the knife blade against a surface with the desired orientation. The controller would strive to align the blade with the surface, and thus give the desired orientation. However, since the knife shape and orientation is still unknown it is not possible to define a point in which the torque controller can act. A different approach is therefore implemented. If the knife is rotated around the direction of the blade in the point of contact, the other end of the knife will eventually come into contact with the tool, and the rotation will revolve around that point instead. Once this happens, the torque will change abruptly because of the sudden change of contact point. The resulting discontinuity in the torque is detected, and the flange orientation is recorded at that point. To do this, the point of contact needs to be identified in order to rotate around it, but as mentioned before, this point is unknown. If the knife is instead rotated around the known flange frame, contact will be lost. The addition of a force controller to the rotation will keep the knife in contact while it is rotating, and the desired rotation will be achieved. A picture of the setup and the resulting torque is displayed in Fig. 1. With both unknown orientations identified, the experimental shape identification can take place. Although the identification can be performed in the same manner as in simulations, it is modified in order to prepare for the grinding procedure. The modification consists of reorienting the knife during the identification so that the knife surface in contact is parallel to the tool surface. In terms of force, this is equal to a contact force that only has a component in the tool frame z-axis. This is accomplished by adding a proportional orientation controller with torque as output that controls the normalized force measurements in the tool frame to only point in the z-direction. The reorientation is to be done without interfering with the identification trajectory. If the reorientation is done around one of the axes of the flange frame, the point on the knife in contact with the tool will move and contact may be lost. The reorientation should therefore be done around the actual point of contact, which is defined as the tool center point (TCP). In the simulations, the tool position was user-defined and was used to reorient the knife. In the experimental setup, the tool position is not known, and therefore an estimate of the TCP position is needed, which can be obtained based on the force and torque measurements. Since the knife is assumed to be perfectly aligned after the previous calibration, the problem can be reduced to a two-dimensional problem. The torque M_y around the flange y-

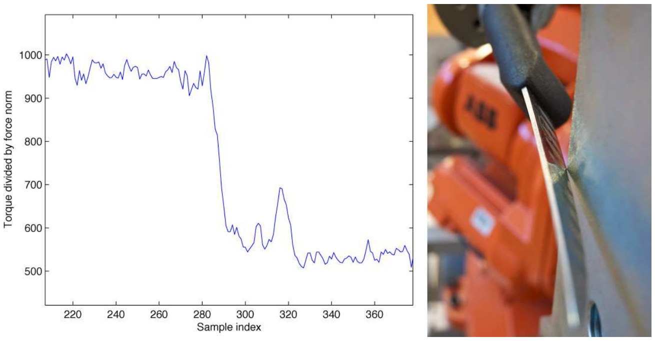

Fig. 1. The setup for orientation calibration (right), and the change in torque that appears during the calibration (left).

axis at time t and $t+1$ is given by

$$M_y(t) = f_x(t)z_0 + f_z(t)x_0 \tag{3}$$

$$\begin{aligned} M_y(t+1) =& f_x(t+1)(z_0 + \Delta z(t+1)) \\ &+ f_z(t+1)(x_0 + \Delta x(t+1)). \end{aligned} \tag{4}$$

Introducing

$$\begin{aligned} \tilde{M}_y(t+1) =& M_y(t+1) - f_x(t+1)\Delta z(t+1) \\ &- f_z(t+1)\Delta x(t+1), \end{aligned} \tag{5}$$

the expression in (4) can be rewritten to

$$\tilde{M}_y(t+1) = f_x(t+1)z_0 + f_z(t+1)x_0. \tag{6}$$

where x_0 and z_0 are the contact point coordinates, f_x and f_z the reaction forces in the respective directions. In order to estimate the values of x_0 and z_0, the recursive least squares (RLS) algorithm is utilized. This algorithm adaptively estimates the model parameters in a linear model by recursively minimizing the least squares error. A linear model is given by

$$y(t) = \boldsymbol{\phi}^T(t)\boldsymbol{\theta}(t) + v(t), \tag{7}$$

where $\boldsymbol{\phi}(t)$ is the input vector, $\boldsymbol{\theta}(t)$ the filter coefficients, $y(t)$ the measured output and $v(t)$ an unknown noise source. The RLS algorithm is defined by [11]:

$$\hat{\boldsymbol{\theta}}(t) = \hat{\boldsymbol{\theta}}(t-1) + \boldsymbol{K}(t)(y(t) - \boldsymbol{\phi}^T(t)\hat{\boldsymbol{\theta}}(t-1)) \tag{8}$$

$$\boldsymbol{K}(t) = \boldsymbol{P}(t-1)\boldsymbol{\phi}(t)(I + \boldsymbol{\phi}^T(t)\boldsymbol{P}(t-1)\boldsymbol{\phi}(t))^{-1} \tag{9}$$

$$\boldsymbol{P}(t) = (I - \boldsymbol{K}(t)\boldsymbol{\phi}^T(t))\boldsymbol{P}(t-1) \tag{10}$$

where $\hat{\boldsymbol{\theta}}(t)$ is a vector containing the estimates of the model parameters, $\boldsymbol{P}(t)$ the covariance matrix and $\boldsymbol{K}(t)$ a gain matrix. The RLS algorithm requires excitation to work properly, which is achieved by increasing the force until it reaches a given threshold. The estimate is used to calculate the location of the tool in the robot base frame, which will give the desired TCP coordinates after the required frame transformations. Since the TCP is fixed in the base frame, the estimate is used to reorient the knife throughout the whole identification. As soon as the estimate from the RLS is available, the TCP position in the flange frame is logged in order to be used as reference to the grinding procedure.

C. *Grinding procedure*

When sharpening a knife manually, the knife is pressed with a constant force between two rapidly rotating grinding stones. The knife is then moved along its contour, while striving to keep the knife surface normal to the force, until the blade ends. This procedure is either repeated, or the force is increased, until the knife is considered sharp.

The grinding procedure is to be done automatically using the robot, with the identified knife shape from the identification experiments used as reference. In order to make the robot follow the knife contour, the first set of coordinates from the recorded knife shape and the fix coordinates of the grinding stones are input to the robot inverse kinematics. The difference between the joint angles output from the kinematics forms the error for a controller that controls each joint separately, moving the robot to the desired position.

In addition to following the knife shape, the knife must be reoriented in order to maintain the contact force normal to the knife surface. By differentiating the recorded knife shape, the angle of the knife is obtained and used to define the desired orientation of the TCP, in each point of the motion. To make sure that the knife remains in contact with the grinding stones and that the force is kept constant, a force controller acting in the tool frame z-direction is added. Since the force controller sends its control signal directly to the robot system, the path-following controller will try to counteract the force control, since it is under the impression that the robot has deviated from the path. The desired z-component of the path is therefore continuously modified by adding the integral of the velocity reference that is sent to the robot system from the force controller.

The described experiments were performed to great success, and thus the setup was determined to proceed to an industrial application, which is described in the subsequent section.

IV. INDUSTRIAL APPLICATION

A. *Implementation strategy*

An industrial application has been implemented using the ABB RAPID platform with the *Machining FC* and *Assembly FC* add-ons, and runs on an IRC5 system coupled with an ABB IRB-140B robot and an ATI force sensor. Since the calibration and shape identification described earlier are time-consuming, it is neither cost- nor time-efficient to do this for every knife. In this application, it is only done once for every new knife type, and therefore it is assumed that the knife gripper (Figure 2) can grip all knife types identically each time. To achieve such an accuracy, the gripper on the robot needs to exert a large gripping force in order to avoid letting the knife slip when pressure is applied on the blade. Further, the knives that are fed to the gripper have to be perfectly oriented before the gripper is closed in order to obtain the same knife orientation each time. An external reorientation station is therefore designed, see Fig. 2, which grips a knife in an arbitrary pose, ideally reorienting it to exactly the same orientation each time. Instead of using an RLS estimator, the starting point of the knife is determined by performing a 4-point calibration. This strategy increases the time effectiveness considerably, but lacks the ability to detect errors and deviations in the knife shape for each individual knife. As a knife becomes increasingly worn out and resharpened over and over again, its contour will change. This change is assumed to be a direct displacement of the original contour, and any deviation is to be handled by the force control. In order to infer about the state of the knife that is to be grinded, the knife length is to be measured by detecting contact against a stiff surface. If the length measurement is below a fixed threshold, the knife is considered to be ready for trashing. Another possibility could be that the robot is actually not holding a knife, *e.g.*, if a knife is missing in the cartridge. Further, when a knife gets

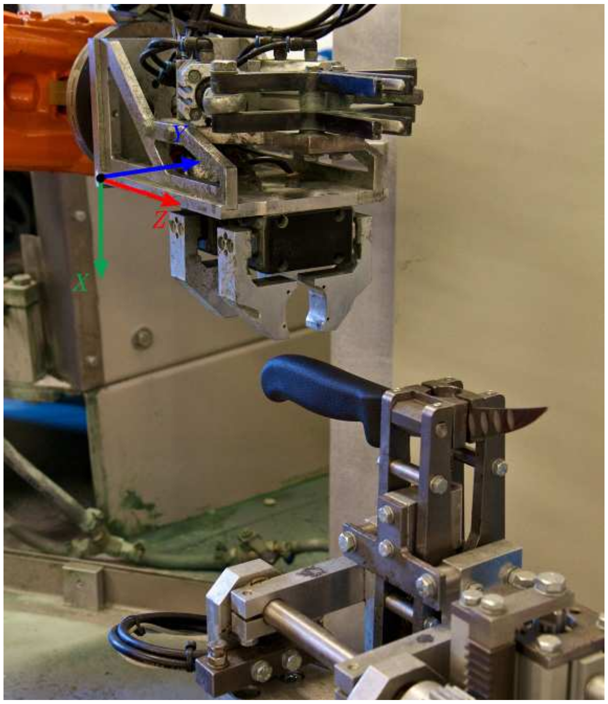

Fig. 2. The knife reorientation station and the knife gripper mounted on the robot. The orientation of the robot flange coordinate system is also shown.

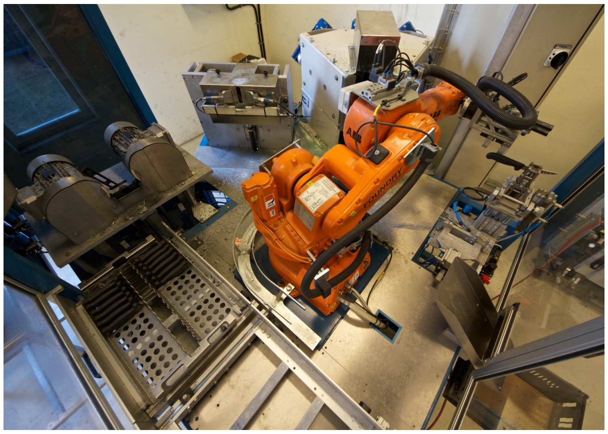

Fig. 3. The industrial knife grinding setup.

resharpened, the width of the blade increases as it is thinner towards the cutting edge, which leads to a different angle of the cutting edge. Thus, the blade needs to be thinned before the cutting edge can be grinded. This is done in a manner similar to the sharpening, but with a different set of grinding wheels that has a constant distance between them (in this study approximately 0.4 mm). In addition to the thinning process, once a knife has been sharpened, the resulting raw cutting edge needs to be polished in order to remove the burr. This is done for each side of the blade by applying pressure against a revolving felt disk at an angle greater than the cutting edge angle. A picture of the industrial setup is displayed in Fig. 3.

B. RAPID implementation

In order to implement the proposed strategy in RAPID, the functionality of certain commands needs to be investigated to ensure that the desired behavior is achieved.

The *MoveL* command in RAPID executes a linear movement of the robot TCP, and takes several arguments; Cartesian position, orientation represented in quaternions, speed data (mm/s), zone data (mm) and what tool and work object is used:

```
MoveL pos, v100, z10, tool1 \WObj:=wobj1;
```

Once the robot TCP has entered the zone defined as a radius around the desired position in the *MoveL* command, the motion will be interpolated with the position defined in the consecutive *MoveL*. During force control, the same method of motion is applied with the addition of modifying the position to compensate for the force error, displacing the defined path in the direction of the force reference. This ensures that the motion of the robot is executed with the desired speed along its path, since the robot does not stop and wait for a new position reference, which is crucial for the grindings. If it would stop while keeping a constant pressure against the revolving grinding wheels, the knife will either get gashed or become scorched due to the rapid heat generation. To initiate the force control, the command

```
FCPress1LStart pos, v100, \Fx:=fx, ...
95, z1, tool1 \WObj:=wobj1;
```

is used, which defines the force control coordinate system, initial force reference and a force threshold given in percent of the force reference, which will start the motion once fulfilled.

In order to define the positions for gripping, shape identification, grinding etc., as well as to perform calibration, *FCAct* is used. This command activates a *lead-through* force controller, which is basically a force controller with zero as force- and torque reference, in all Cartesian directions. This makes the robot compliant and allows the operator to ”lead” the robot through its workspace by only applying pressure on the force sensor. This calibration only has to be done once for every knife type.

The program for running a complete cycle is composed by several sub-programs, executing different tasks in the knife sharpening procedure. For example, the routine *grip_knife()* brings a knife from the cartridge to the reorientation station, starts the reorientation of the knife while the robot simultaneously brings the succeeding knife in order to minimize waiting time. Once the knife is gripped, the program can move on to the subsequent task. A flowchart for a full cycle is shown in Fig. 4. The cycle is initiated by the operator, who specifies the knife type and quantity. The grinding and polishing tasks takes a number of parameters, such as speed and force during grinding, which are set offline and cannot be altered while the program is running.

V. RESULTS

Simulations and experiments. In the force control simulations, the controller parameters $K_p = 0.4$ and $K_i = 0.5$

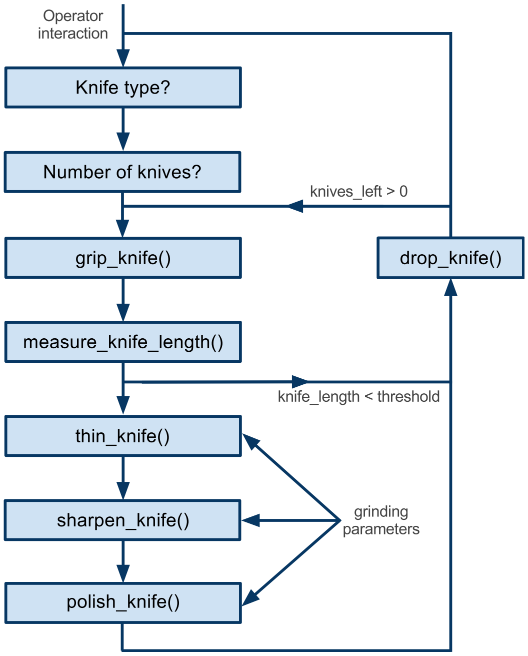

Fig. 4. Flowchart for the full knife sharpening cycle.

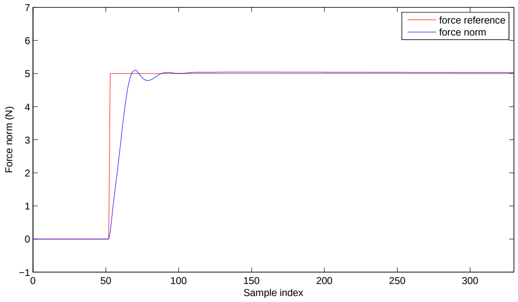

Fig. 5. Simulated step response with $K_p = 0.4$ and $K_i = 0.5$.

were used, obtained from the pole placement performed in Section III-B. This controller gives a fast and well-damped step response, see Fig. 5, and the knife shape is accurately identified. The same force controller is evaluated in experiments, and it is observed that the response is not fast enough. Increasing the controller gain to $K_p = 0.7$ improves the response, the result is shown in Fig. 6. This force controller is used in the knife calibration experiments. As expected, when the knife changes rotation point, a change in the torque measurements appears, see Fig. 1. However, when the knife is close to being correctly aligned prior to the experiment, the change in torque is not very pronounced. This is most likely a result of the knife flexibility, but it is solved by exaggerating the deviation by setting an offset to the rotation before starting the calibration.

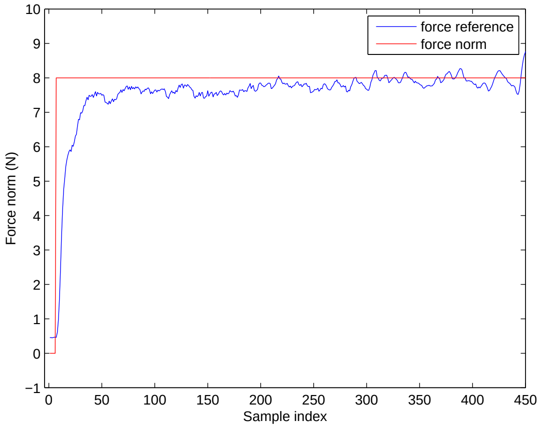

Fig. 6. Force plot during shape identification with $K_p = 0.7$ and $K_i = 0.5$.

With the knife orientation calibrated, the shape identification is performed successfully. Using the knife shape as the path reference, the grinding is done first with the grinding wheels stopped, and then with the wheels turning at 3000 rpm. In the latter case, process forces that appear during the grinding act as a disturbance in the force control. Also, the accuracy of the identified shape and the grind speed affects the achieved control performance. Fig. 7 shows the force control performance during a grinding experiment, which results in a satisfactorily sharpened knife.

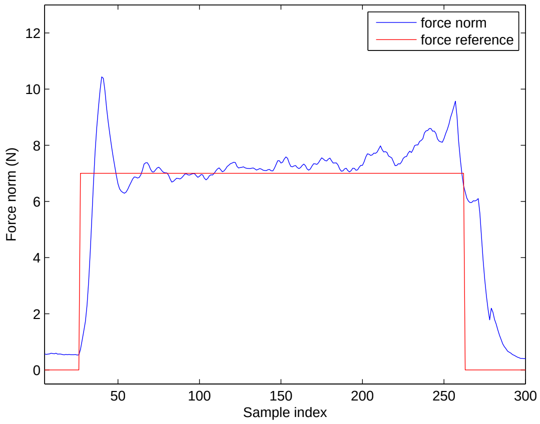

Fig. 7. Force plot during grinding with $K_p = 0.7$ and $K_i = 0.5$.

Industrial application. In the industrial application, the cycle time for sharpening a knife averages at around 60 seconds, depending on, *e.g.*, the length, thickness, and stiffness of the knife. This gives a throughput of approximately 60 knives per hour. The knife sharpness can be tested by performing a destructive test where the knife cuts through a homogeneous material at a constant speed, while the reaction force is measured and averaged. If the knife is sharp it should result in a low average reaction force, see Table I for a comparison of some randomly sampled knives.

TABLE I

KNIFE SHARPNESS MEASUREMENTS

Knife	*Avg. reaction force (N)*
New knife	9
Manually sharpened knife 1	5.5
Manually sharpened knife 2	20.5
Manually sharpened knife 3	15
Robot sharpened knife 1	6
Robot sharpened knife 2	5.5
Robot sharpened knife 3	7
Robot sharpened knife 4	5.5

VI. DISCUSSION

The accuracy of the recorded knife shape is of great importance to the control performance during the grinding procedure. Ideally, if the recorded knife shape is perfectly accurate, the grinding only has to be initiated with the desired force, and the motion of the robot will keep the force constant. Since it is time consuming to record a highly accurate shape, the use of a force controller, which can correct for possible errors in the recorded shape, is highly advantageous.

Another important aspect is that the robot can follow the path optimally; if not, high accuracy of the recorded shape is irrelevant. In the experiments performed in this paper, rather moderate speeds were used. However, if faster speeds were to be used, the risk of joint speed saturation, i.e., when the maximum joint speed is reached, would increase. This would result in a deviation from the path and a poor grinding result. Even without joint speed saturation, the path-following controller is of great importance to the force control performance, following the earlier discussion. This study shows that further work is needed on improving the path controller, *e.g.*, by adding a *path velocity controller* as described in [12].

The industrial application is able to sharpen approximately 450 knives per day. When sharpening knives manually, a single worker may reach at maximum 300–400 knives a day, and the result may vary as it is dependent on the state and skill of the worker. On the other hand, if the gripper cannot guarantee 100 % identical gripping from knife to knife (assuming the same knife type), the results from the robot may vary as well. From Table I, it is noted that all of the robot sharpened knife samples result in a low reaction force, even lower than a new knife. Further, the variation in force of the samples is small, which indicates that the gripping is satisfyingly accurate. It is also noted that the three samples of manually sharpened knives differ considerably in reaction force, confirming the claim that the result is dependent on the worker.

When manually sharpening, a knife can be resharpened approximately 30–40 times before its life cycle reaches its end. Another advantage of grinding knives using industrial robots is that since the robot exercises more precise control over how much material is removed from the knife, its life cycle may be increased by up to 3–4 times.

In order to obtain the results presented in Table I in the current application, manual calibrations of the grinding machines and knives are required. As an error of even $1/10$ of a mm has an impact on the grinding result, the accuracy of these calibrations is of great importance. The manual calibrations have, as presented in this paper, produced satisfying results, but the calibrations can be time consuming. If, for example, one of the grinding machines was to be replaced and thus change position, its calibration would have be done all over again. It would therefore be desirable to, in the future, implement an algorithm for automatic calibration in the industrial application.

VII. CONCLUSIONS

This paper has described a method for sharpening knives with unknown contour profile and orientation, using a force controlled industrial robot. A flexible solution was achieved, which is able to grind knives to the desired sharpness and is robust to unknown properties of the knife. As the experimental results were successful, further development of the method was performed by designing and implementing an industrial application. The application prototype is now in operation at a knife sharpening plant in Hörby, Sweden. The prototype will hopefully contribute to an increased use of force controlled grinding applications in the industry.

REFERENCES

[1] A. R. Tate, “Closed loop force control for a robotic grinding system,” Ph.D. dissertation, MIT, 1986.

[2] Y. Wang and Y. Jan, “Path planning for robot-assisted grinding processes,” in *Proc. IEEE Int. Conf. on Robotics and Automation*, Seoul, Korea, May 2001.

[3] A. Robertsson, T. Olsson, R. Johansson, A. Blomdell, K. Nilsson, M. Haage, B. Lauwers, H. de Baerdemaeker, T. Brogårdh, and H. Brantmark, “Implementation of industrial robot force control - case study: High power stub grinding and deburring,” in *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS2006)*, Beijing, China, Oct. 2006.

[4] K. Kashiwagi, K. Ono, E. Izumi, T. Kurenuma, and K. Yamada, “Force controlled robot for grinding,” in *Proc. IEEE Int. Workshop on Intelligent Robots and Systems (IROS1990)*, Ibaraki, Japan, 1990.

[5] L. Liu, B. J. Ulrich, and M. A. Elbestawi, “Robotic grinding force regulation: Design, implementation and benefits,” in *Proc. 1990 IEEE International Conference on Robotics and Automation (ICRA1990)*, Cincinnati, OH, USA, May 1990.

[6] I. Dressler, “Force control interface for ABB S4/IRC5,” Department of Automatic Control, Lund University, Tech. Rep., July 2009.

[7] A. Blomdell, I. Dressler, K. Nilsson, and A. Robertsson, “Flexible application development and high-performance motion control based on external sensing and reconfiguration of ABB industrial robot controllers,” in *Proc. of the Workshop of "Innovative Robot Control Architectures for Demanding (Research) Applications—How to Modify and Enhance Commercial Controllers", the IEEE Int. Conf. on Robotics and Automation (ICRA2010)*, Anchorage, Alaska, USA, June 2010, pp. 62–66.

[8] *Real-Time Workshop 7: User's Guide*. Natick, Massachusetts: The MathWorks, Inc., 1994–2010.

[9] B. Siciliano and L. Villani, *Robot Force Control*. Kluwer Academic Publishers, 1999.

[10] T. Olsson, “High-speed vision and force feedback for motion-controlled industrial manipulators,” Ph.D. dissertation, Department of Automatic Control, Lund University, Sweden, May 2007.

[11] K. J. Åström and B. Wittenmark, *Adaptive Control*. New York: Dover Publ., 2008.

[12] B. Olofsson, H. Nilsson, A. Robertsson, and J. Åkesson, “Optimal tracking and identification of paths for industrial robots,” in *Proc. 18th World Congress of the International Federation of Automatic Control (IFAC)*, Milano, Italy, Aug. 2011.