

Robotized Polishing and Deburring with Force Feedback Control

**Marthin Krantz
Rikard Andersson**

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Summary

Force control is introduced to robots to solve the problem in machining applications due to the fact that the robot compliance might cause deviation between actual and desired robot path. Also large tolerances in the casting process as well as positioning errors from the clamping create deviations for which the force control technology can adept. Force control has also shown successful in automatic learning of paths along non linear surfaces.

This study investigates the possibility of introducing robots equipped with force control at Volvo Aero Corporation in order to robotize polishing and deburring processes. These are today performed by manual labor. This study investigates more specifically the ABB Force Control machining application package. The polishing process has shown to be very complex and today's version of the ABB force control package cannot give sufficiently robust results to be recommended for implementation. The major issue is the non-existing compliance of tool orientation needed to adapt to casting and positioning deviations due to varying work piece dimensions. The deburring process has however shown to be easier to handle, and a robot cell and methodology is proposed in this report.

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Symbols and glossary

A/D	Analogue to Digital Converter
CMM	Coordinate measuring machine
DAQ	Data acquisition board in the measuring computer
FC	Force Control
HMI	Human Machine Interface
IRC5	Robot Control System for ABB industrial robots
PCI	Peripheral Component Interconnect, an industry-standard bus for attaching peripherals to computers.
Pendant	The operator on-line interface
PMC	PCI Mezzanine Card
Pose	Position including orientation
RAPID	Programming Language for ABB robots
RWMFC	RobotWare for Machining FC
TCP	Tool Center Point
TEC	Turbine Exhaust Case
VAC	Volvo Aero Corporation
VFD	Variable Frequency Converter

1 Introduction

A large proportion of the hours spent on the components produced at Volvo Aero are done by manual labor. In order to reduce these hours two processes are identified for which automated robot cell solutions will be proposed.

Today before welding of sub components to complete weld assemblies, a manual polishing is done. The purpose is to remove oxides which can exist in the surface of these components. By use of force control a constant polishing pressure can be applied to the work piece as well as adaptation for deviation between programmed and actual path along the work piece.

During the milling process of casted components burrs are generated. Since the casting process gives large tolerances, robotized deburring is impossible without a system to adapt to these position errors.

Machining is a demanding task for a robot. Lack of stiffness in the robot structure, tool wear, tolerances of parts and fixtures will introduce position errors that will give inconsistent process results. Introducing force feedback opens the possibility to reduce these position errors. Today the major European industrial robot providers like Stäubli, Kuka, and ABB offer some possibility of utilizing force control.

1.1 Task

The purpose of this study is to examine and demonstrate robotized solutions for polishing and deburring on aero engine structural components. The work is performed together and with help of a team consisting of members from Volvo Aero Corporation (VAC), Azon Robotix, RDS and University West. ABB is supplying a robot cell for evaluating the force control for polishing. The study is including:

- A literature study of relevant research of weld preparation, robots with force control, polishing, deburring and machining with robot.
- Simulations in RobotStudio [1] in order to evaluate ABB's machining power pack for off-line programming.
- Test runs for evaluation of a robot utilized with force control for deburring and polishing applications.

1.2 Goal

The goal of the study is to:

Present relevant research done in the field of robotic force control, polishing and deburring.

Evaluate RobotStudio with the machining power pack as an off-line programming tool. Generate paths for polishing of a work piece represented by a CAD model. Investigate reachability for a robot in a deburring cell for the total assembly of the TEC (Turbine Exhaust Case).

Perform test runs of polishing and deburring on test pieces with the robot cell, to evaluate advantages and limitations of the force control technology.

1.3 Limitations

This master thesis study includes tests performed in a pre-determined robot cell supplied by ABB (Västerås, Sweden). The test includes evaluation of tools and path following abilities. In this study results of the test runs and simulations in RobotStudio are presented. The work does not include selection of robot, design of electrical, control and safety system.

2 Related research

Research in this field has been active the last 30 years, but industrialized robotic systems with user friendly interfaces have only been a reality the last couple of years. The department of Automatic Control in Lund University has published a series of articles, which is the foundation of the force control system available for a range of ABB robots and also utilized in this project. Their work is well summarized and demonstrated in [2].

2.1 Oxide removal with force control robot

Removing oxides is done by polishing. The task of polishing with a force control robot can be divided into three sub problems:

The polishing process, choice of tool(s), feed rates, rotation speed of tool. Force against surface/environment.

Force Control Loop, bandwidth of control loop, feedback from sensor.

Path generation and following.

These three sub problems do affect each other and these affects need to be considered during design, programming and configuration of the system.

2.2 Force control

A large amount of robots are utilized in the industry, most of these applications are of the type not requiring a compliant system to solve. These applications are of the type moving a tool in path from A to B, see Figure 1 with an example of linear path.

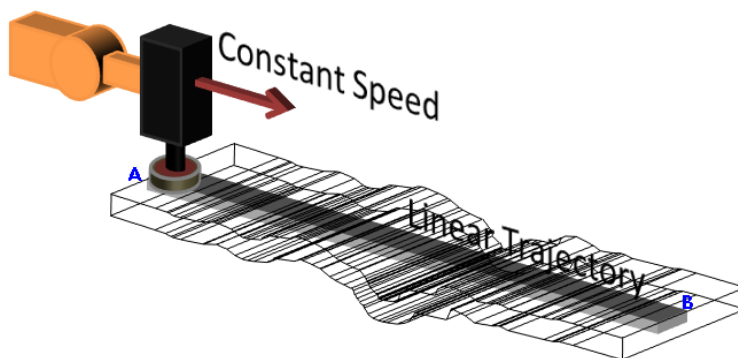


Figure 1 Linear Motion without Force Control.

In order to apply a constant force to a surface with variations while moving from A to B see Figure 2, a compliant system is needed.

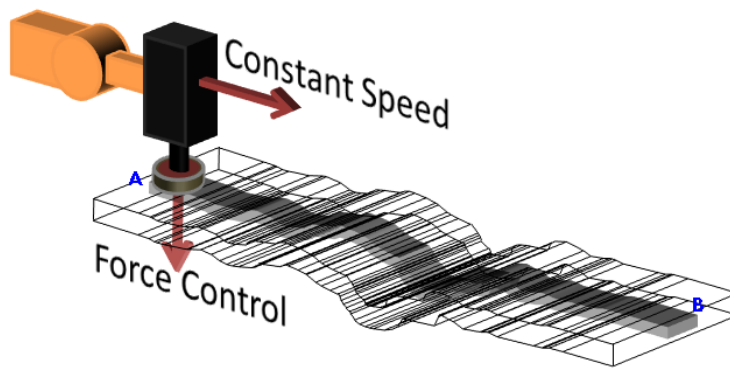


Figure 2 Linear Motion with applied Force Control.

Compliant systems can be categorized into mechanical compliance, robot controlled compliance or a combination of the both.

A force controlled robot offers the possibility of gaining a higher stiffness of the robot as without compromising the six degrees of freedom that an articulated robot offers [2]. Stiffness is an important property when discussing machining equipment. One of the main disadvantages of using a robot in machining is the lack of stiffness. Stiffness of a robot is usually less than $1 \text{ N}/\mu\text{m}$, which is much less than that of a CNC machine, which very often has stiffness more than $50 \text{ N}/\mu\text{m}$. For an example 500N cutting force during a milling process will cause a 0.5 mm position error for a robot instead of a less than 0.01 mm error for a CNC machine [3]. Different orientations/positions of the robot will affect the stiffness. So design of the working cell and the different working positions will have large impact on the stiffness of the robot. Elevators and rails can be utilized to keep robot in an optimized orientation. A pure force control system requires a higher bandwidth control loop, compared to a system combined with a compliant tool. A compliant tool filters high frequency irregularities and the force control loop can handle contour changes [2]. The other large advantage of a Force Control is the feature of adaptation to misaligned trajectories due to tolerances of the preceding casting process and fixation of the component. Casting parts are delivered with typical tolerances, especially form tolerances ($\pm 0.75\text{mm}$). The force control loop will help the robot find the contour of a misaligned work piece.

2.2.1 Control strategies

As early as in 1981 a hybrid position/force control of manipulators was presented [4]. The hybrid technique combines force and torque information with positional data to satisfy simultaneous position path and force restrains in a convenient task related coordinate system. This has been the foundation for almost all research in the field, since it does not limit any choice of control loop algorithm. The system masks out the wanted force and torque direction using a matrix. The available tuning parameter for the control loop indicates a type of impedance control algorithm [5] applied in the ABB force control robots.

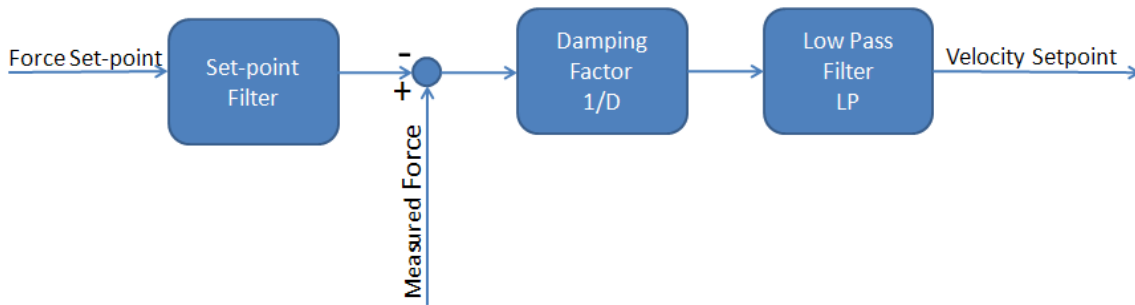


Figure 3 Model of simplified force control algorithm.

The Figure 3 shows a simplified picture of the force control loop. In a force controlled direction the measured forces are subtracted from the corresponding reference forces (set-point). This difference is divided by D ($=$ damping). Damping is a force to speed factor and it therefore gives a speed reference to the manipulator. This speed reference is low pass filtered with a cut off frequency that should be chosen depending on your robot model and process.

2.2.2 Bandwidth and stability

It is well known that the sampling frequency affects the stability of a computer controlled systems. ABB and Stäubli are using a bandwidth of 250 Hz for updating their position control loops. It has been shown that this bandwidth is sufficient for implementing a hybrid position/force control loop, however in applications with demands of extreme stiffness or high feed rates higher bandwidths may be considered [6].

2.2.3 Low frequency chatter

Ever since robots have been used for machining application, the problem of chatter has been noticed as a significant obstacle when optimizing machining processes. Chatter is induced by the low stiffness and the coupled structure of an industrial robot. The chatter frequency is the natural resonance frequency of the robot typically 10Hz. When chatter occurs, the entire robot structure starts to vibrate and the contact force during the machining process will no longer be constant. The chattering will affect the end result of the machining process like chattering marks on the work piece. A study of mode coupling chatter has shown that if the structure stiffness is not significantly higher than process stiffness, mode coupling chatter may happen [7]. The stiffness of robot structure is depending on the current position of the robot axes as well direction of movement. The work piece position and direction of feed during machining affects the tendency of chatter generation, also a compliant tool will give less process stiffness and therefore the tendency of generating of chatter is less.

2.3 Robotized polishing

Polishing is a labor intensive process and manual operation like this can result in inconsistent quality as well as higher costs in terms of products in work. The work is also a hostile environment with noise, dust from particles and heat. Polishing is a type of material removal process. According to Robotic Industries Association in 2003 only 4% of all robots in North America were used for material removal operations. The polishing process can be described by the following properties [8]:

- Type of surface finishing: determined by the polishing tool.
- Velocity (feed rate): The linear feed rate at the contact point.
- Pressure, force against surface at the contact point between detail and tool.
- Width: the width of the polishing tool.

To achieve a high quality result of the polishing a constant force between the tool and the detail and constant feed rate is of great importance. Linear speed to achieve a fixed feed rate is no problem of a modern speed robot, obtaining accurate force against the detail is a larger challenge. Control of force during machining will enhance productivity and quality. Wear of tool can be minimized and tool breakage can be avoided [9]. Polishing sequence can be divided into five phases:

- Approach.
- Force Build-up.
- Process.
- Decline.
- Withdraw.

Entry and Exit from the polishing process are two hard steps to manage. Therefore all of the above five phases should have the possibility of defining feed rate, force and machine tool speed on an individual basis [2].

2.3.1 Polishing tools

Tools considered during this study are the flap wheel with grit size of 80 and 120 and different rotating carbide tools, see Figure 4. There are other alternatives available e.g. diamonds polishing ball tools, but these tools are not approved at VAC.



Figure 4 Flap wheel and rotating carbide tool.

The flap wheel adds compliance to the system by the natural compliance of the flaps. Limited lifetime may be an issue, but it is inexpensive. The wear of the flap wheel is not an issue since the force control should be able to correct this deviation. The flap wheel is able to leave a smooth surface (grain size depending) but is not as good at removing material as most rotating carbide tools. During the tests the flap wheel is slightly tilted to achieve a more even wear of the tool. A rotating carbide tool is a good choice when there is not enough space available for the rotating flap wheels.

2.3.2 Path planning

An automatic polishing system requires support for the generation of collision-free robot trajectories [8]. Surfaces on components to be polished can be of complex shapes in three dimensions as well as large tolerances in the cast industry makes it hard or impossible using other than manual labor until now when introducing robots with force control. To define an accurate polishing robot path hundreds of coordinates and orientations may be needed. Without proper software aids this work of defining these points would be tedious. Path planning tools can be divided into off-line and on-line. Off-line planning can be done in software tools such as RobotStudio [1] and Tecnomatix Process Simulate [10]. CAD models of the detail are analyzed and used to design paths along the detail. The paths are then used to generate robot code, e.g., RAPID Code. RobotStudio has an option, Machining PowerPac [11]. The PowerPac aids the user with wizards to develop machining applications. ABB's force control package RobotWare for Machining FC (force control) offers the user to define coarse points on-line (within a couple of mm). The points can be defined by the operator "dragging" the robot arm around to the correct spots while the robot is in a soft mode. The rough points are then used as input when the robot learns the path by an auto-learn sequence. The sequence utilizes the force sensor to detect the edges/surfaces of the work piece. The result of the off-line path generation can be calibrated and updated through the on-line auto-learning sequence. The different procedures to generate RAPID program for polishing is shown in Figure 5.

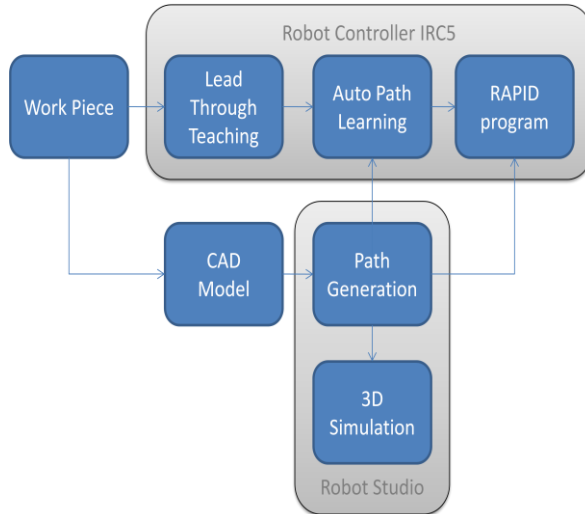


Figure 5 Workflow for generation of RAPID robot program.

Without tools for generating paths, planning the polishing paths is tedious and could lead to that it is not possible to defend automation in the economical sense. With intuitive easy programming interfaces of new products also polishing of small series could be robotized.

2.4 Casting oxides

Oxide is a result from the casting process and evaluations has shown that the affected surface layer has a depth of oxide up to 0.06 mm, see Figure 6. Therefore the recommendation is that a minimum of 0.06 mm is removed before welding. A recommendation of maximum material removal of 0.15 mm has been decided by VAC.

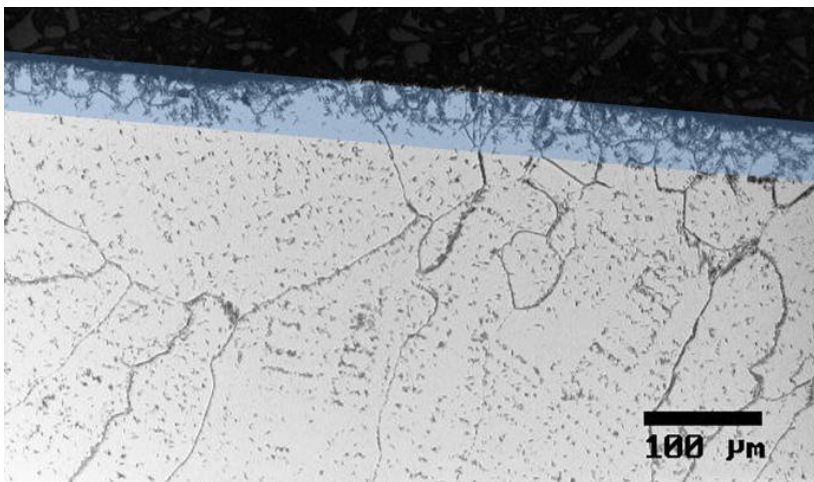


Figure 6 Casted component before polishing. Showing grit blasting in surface shaded in blue.
Source: VAC Test Request Reg. No 10089914.

Removal of the oxide layer on metals is essential to achieve the best possible weld results. Aluminum is the metal that has to have an oxide removal procedure, but many other metals also need a procedure. A. Haboudou et al. has made a study were they compare

polishing, sand blasting and YAG laser as surface preparation on aluminium [12]. There are two common procedures in the industry today, chemical and mechanical removal. There are many different methods for each. The mechanical procedure can be divided into sand-blasting (different sands), scraping, wire brushing, grinding, filing and polishing (different tools). A disadvantage of chemical processes is that the chemical waste has to be taken care of. The mechanical procedure has the disadvantages of dust and noise. There is methods under research that does not have these disadvantages, like low pressure arc [13]. Dust and noise is not taken into consideration in this study were the process is robotized. Previous trials at VAC with manual polishing using a flap wheel grain size P150 and speed of 4500 rpm has given a result of 0.04-0.05 mm of removed material, see Figure 7. Therefore tools with larger grain size (P80 and P120) will be utilized in trials with the robot cell.

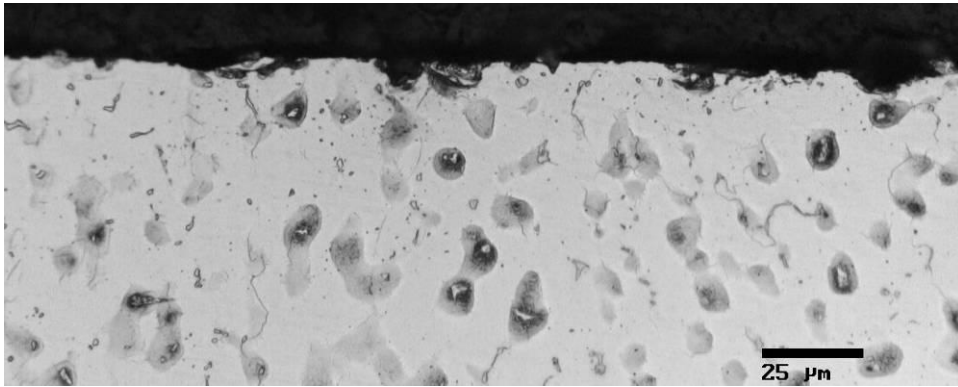


Figure 7 Casted Component after manual polishing, material removed is 0.04-0.05 mm.

2.5 Components

The component in this study that will be object to an oxide removal procedure is called a reg hub, see Figure 8.

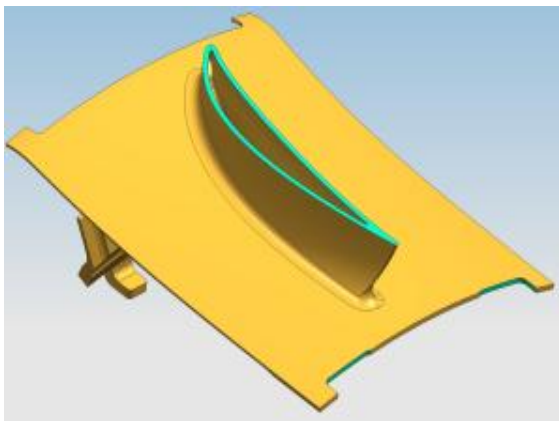


Figure 8 Model of reg hub, component to be polished at side of the green top surface.

It consists of Inconel 718[®] a nickel-based alloy with good weld-ability compared to the nickel-based alloys with aluminum and titanium. The reg hub is to be plasma welded to a vane and an elliptic metal sheet to form a curved H-beam (segment). These segments are

welded together to form the final component a TEC, see Figure 9. Polishing will have to be performed on all seams of the reg hub were a weld seam will be applied (light green in Figure 9). Both the inside and outside have to be polished approximately 6-10mm from the edge and down.

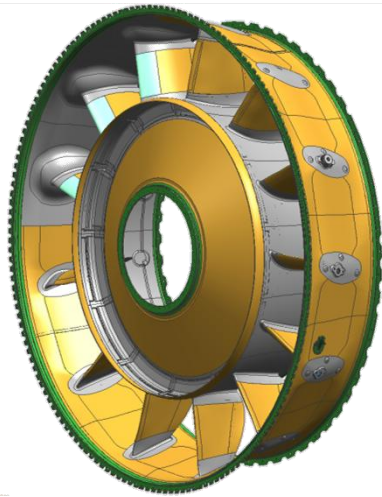


Figure 9 Model of complete assembly of TEC after welding.

During this study several dummy work pieces with a simplified geometry are used, see Figure 10. The sides are parallel and mounted on a square pipe for easy fixation.

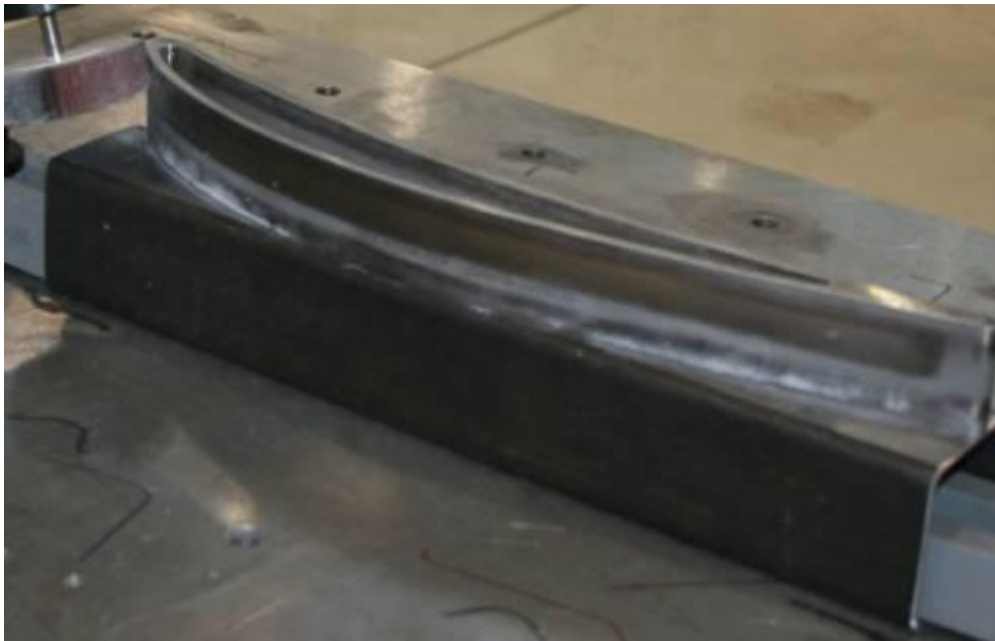


Figure 10 Example of dummy work piece used in this study.

2.6 Robotized Deburring

Burrs are plastic deformed material caused by a material removal process such as turning, milling and grinding, see Figure 11. Deburring is the process of removing this deformed

material. Manual deburring is a costly and time consuming process. It is also a health aspect with many hours of monotone work for large part with many locations which is difficult to reach. Today manual deburring is used at VAC, but also deburring robot cells with radial compliant tools (Engraflexx [14]) are used. Compliant tools require a lower rpm than is normally used, the tool also has a tendency to get stuck and then snap back.

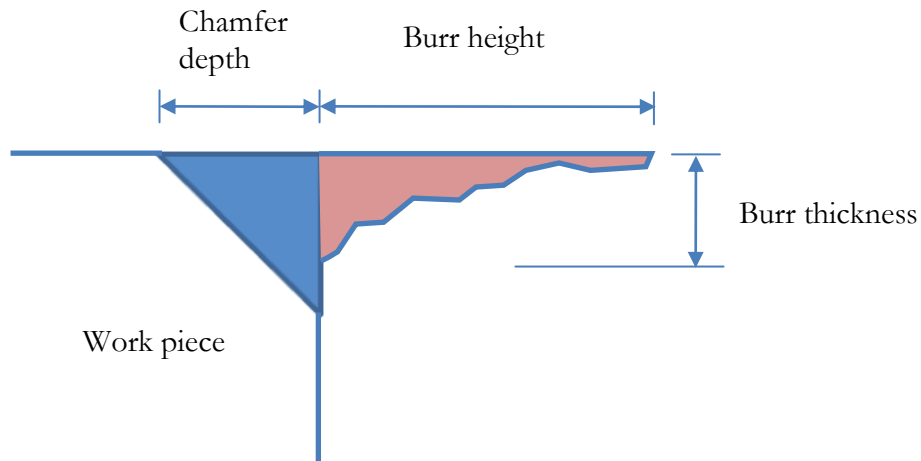


Figure 11 Typical burr on work piece edge after milling 1:10.

3 Experimental robot system setup

The robot in the cell is an ABB IRB 4400/45, see Figure 12. The robot has a handling capacity of 45 kg and a reach of 1.96 m, see Appendix A. The robot can be ordered with an option of Foundry Plus, which gives the robot an IP67 (IEC 60529) protection. With this option the robot is suitable for harsh environment and can be washed with high pressure steam.



Figure 12 ABB Robot with Colombo spindle and ATI force sensor.

3.1 Spindle

The spindle used in this study is a PDS Colombo single shaft with following specs, 5,5kW; 18000/24000RPM; ER25; 18kg, see Figure 13 and Appendix D. The ABB robot is integrated with a spindle Human-Machine Interface (HMI) that controls the on/off, rpm, cooling etc. A small RAPID code was written to communicate with the system to turn on and off the spindle as well as setting the rpm see Appendix F.



Figure 13 Spindle PDS Colombo, utilized in Robot Cell.

3.2 Force/Torque Sensor

A description of the force/torque sensor from ATI can be found in section 5.1.

4 Robot programming, force control

The Force Control for Machining application [15] includes two different options; Pressure Control or Speed Control. Using FC SpeedChange, machining speed is reduced when process force exceeds a limit value. Our application will however utilize the FC Pressure. FC Pressure is maintaining a constant pressure against a work piece while moving along the surface.

4.1 On-line programming

The on-line programming of the robot is done through the following steps:

Force Control Payload is automatically identified by robot controller while moving axes five and six to their maximum positions in free air. This has only to be done once as long as the tool is the same.

Teaching, target points are taught by jogging or dragging the robot to the desired targets, see HMI presentation in Figure 14.

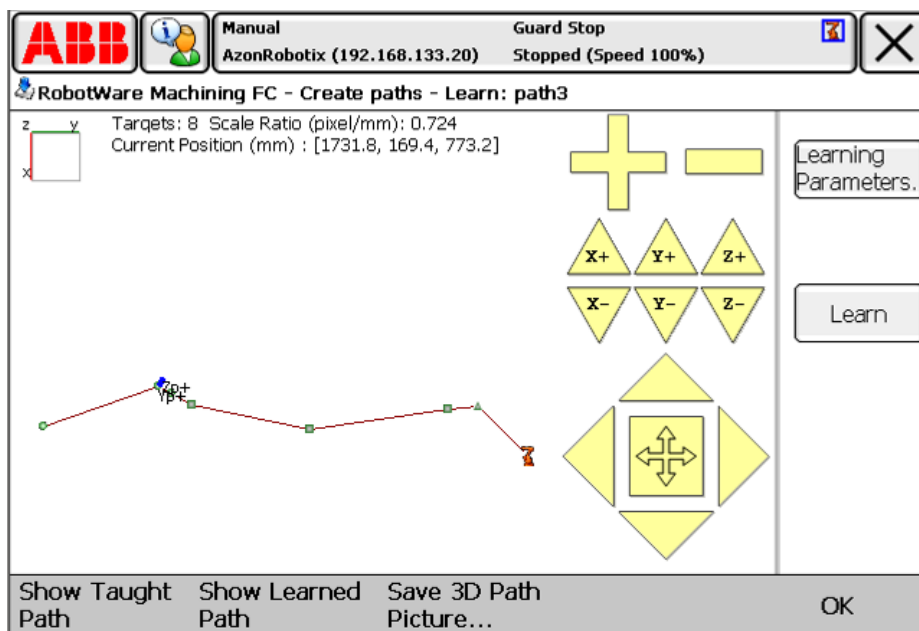


Figure 14 Taught path, poses taught by operator dragging robot to right position.

Learning, robot follows previously taught path and moves along the work piece with specified speed and force accessible from the HMI. During the learning phase targets are recorded and an accurate path is fitted to the targets, see Figure 15.

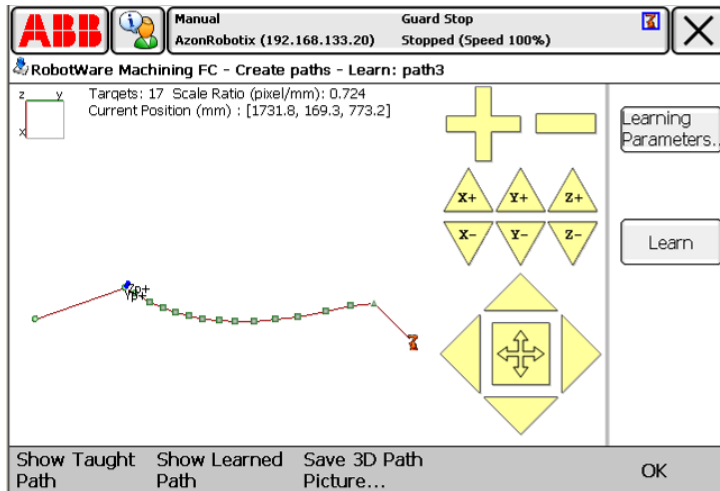


Figure 15 Path is updated with extra targets after running learning by moving along the taught path with force control.

Exporting, the path is exported to RAPID code. A module is generated with the learned path as a basis. The RAPID code needs some manual adjustment of speeds and force values to get a satisfactory result.

Testing, after some final adjustment the module of code is ready to be implemented into a robot program to be tested.

4.2 Off-line programming

A model of the component was imported as a RobotStudio library into RobotStudio. ABBs machining power pack needs to be installed to use the force control off-line programming capabilities of RobotStudio. A seven step solution wizard is used to create the machined path with force control. The surface of the component was easily detected by software and poses for the path were automatically generated by the software. Poses for approach to and withdrawal from the work piece were also automatically added, templates exist for different approach and withdrawal sequence, a default template was used in this study. After the path creation phase the paths can be simulated and recorded, see Figure 16.

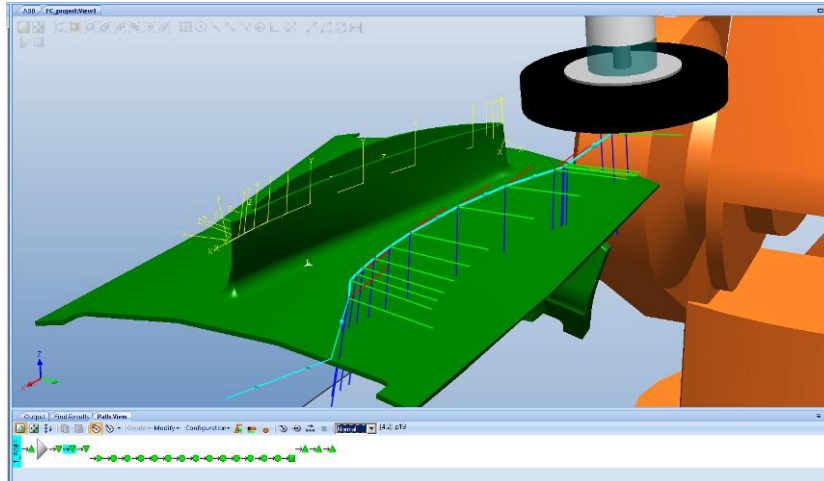


Figure 16 Work piece with generated polishing path in RobotStudio.

RobotStudio generates RAPID code modules that can be imported directly into the robot controller for execution, see Figure 17. An easy five point calibration is recommended to use the offline programmed code in a real simulation.

```
CONST Robtarget p22:=[[7792.60842107322,531.206017171827,-17.1879330063672],[0.0274805743536392,0.023707348633583,-0.639
CONST Robtarget p23:=[[7814.25344560514,525.447028526713,-59.9157888777966],[0.0274805743536432,0.023707348633583,-0.639
PROC Path_1()
MoveJ p18,v500,z1,tool23\WObj:=WObj_S_1;
MoveJ p19,v500,z1,tool23\WObj:=WObj_S_1;
MoveJ p20,v500,z1,tool23\WObj:=WObj_S_1;
FCPressILStart p1,v100\Fx:=0\Fy:=0\Fz:=10,50\ForceFrameRef:=FC_REFFRAME_PATH\ForceChange:=50\DampingTune:=100\TimeOut:=5
FCPressL p2,v10,10,z1,tool23\WObj:=WObj_S_1;
FCPressL p3,v10,10,z1,tool23\WObj:=WObj_S_1;
FCPressL p4,v10,10,z1,tool23\WObj:=WObj_S_1;
FCPressL p5,v10,10,z1,tool23\WObj:=WObj_S_1;
FCPressL p6,v10,10,z1,tool23\WObj:=WObj_S_1;
FCPressL p7,v10,10,z1,tool23\WObj:=WObj_S_1;
FCPressL p8,v10,10,z1,tool23\WObj:=WObj_S_1;
FCPressL p9,v10,10,z1,tool23\WObj:=WObj_S_1;
FCPressL p10,v10,10,z1,tool23\WObj:=WObj_S_1;
FCPressL p11,v10,10,z1,tool23\WObj:=WObj_S_1;
FCPressL p12,v10,10,z1,tool23\WObj:=WObj_S_1;
FCPressL p13,v10,10,z1,tool23\WObj:=WObj_S_1;
FCPressL p14,v10,10,z1,tool23\WObj:=WObj_S_1;
FCPressEnd p17,v100\ForceChange:=50\ZeroContactValue:=5,tool23\WObj:=WObj_S_1;
MoveL p21,v500,z1,tool23\WObj:=WObj_S_1;
MoveL p22,v500,z1,tool23\WObj:=WObj_S_1;
MoveL p23,v500,z1,tool23\WObj:=WObj_S_1;
ENDPROC
PROC Solution_1()
```

Figure 17 Part of generated RAPID Code for polishing the work piece.

Generation of paths off-line in RobotStudio has shown large difficulties of the sections A and B in Figure 18. These sections at the turning points of the path have small radii and the poses generated by software do not seem to be sufficient for generating proper force controlled paths along the work piece sections.

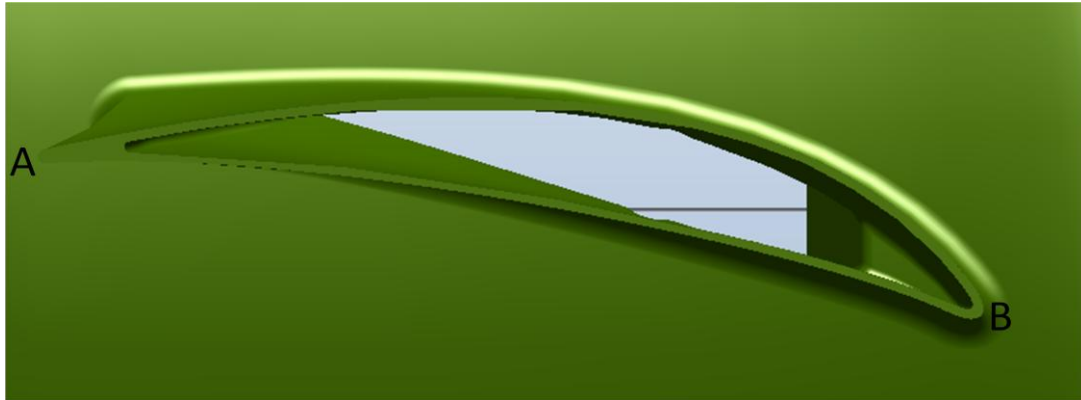


Figure 18 Top view of work piece, A and B is most challenging parts of the polishing path.

In this study no CAD model has been available for the work pieces used in the test-runs. Therefore it would be interesting in future studies to compare results of simulations in RobotStudio to proper test runs in cell to find out if the robot has similar limitations.

5 Data collection/measurements

To be able to measure and analyze the result of the polishing process, a number of measurements are performed before, during and after the test runs.

5.1 Force sensor system

The sensor supplied by ATI senses applied forces/torques in six degrees of freedom (F_x , F_y , F_z , T_x , T_y and T_z), see Appendix B. The transducer has the interface board for computer/controller communication integrated in the same housing, see Figure 19 and D in Figure 20.

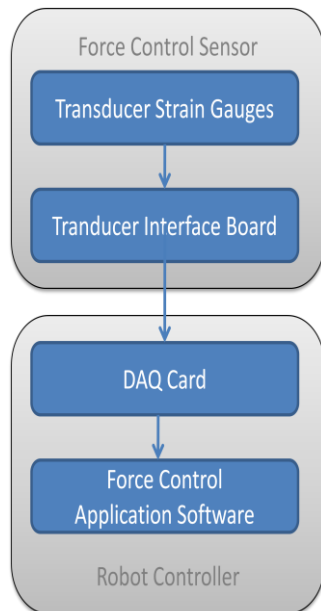


Figure 19 ATI Force/Torque sensor signal path.

The transducer cable is a long-life flexible cable specially designed for noise immunity.

This durable cable protects the transducer signals from electrical fields and mechanical stress, see C in Figure 20 .

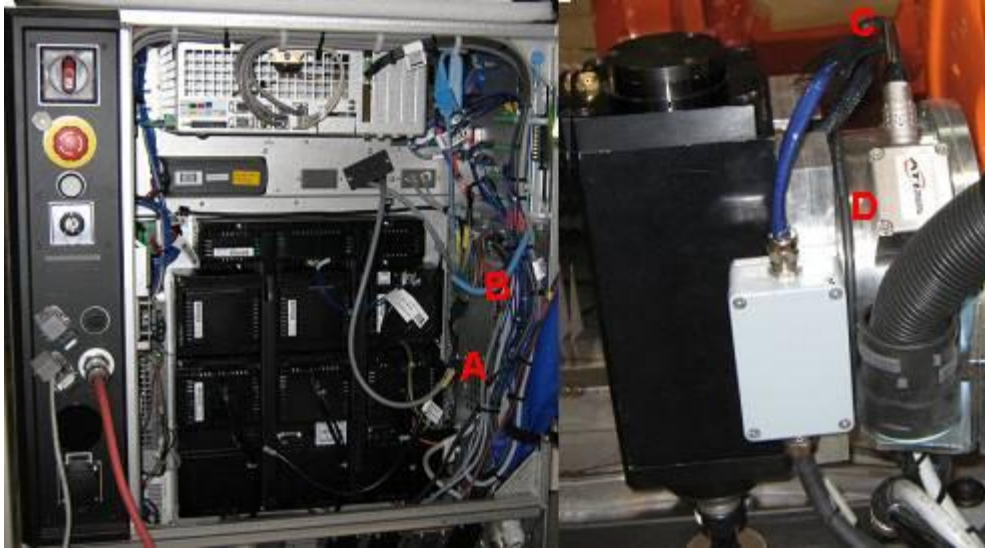


Figure 20 ABB controller IRC5 and force/torque sensor.

The PMC330 DAQ is a PCI card which resides in a PMC card, see Appendix C. The DAQ card has a 16-bit A/D converter, with a recommended sampling rate at 11 kHz.

5.2 Logging of Forces

Forces were logged using ABB Test Signal Viewer [16]. The software is logging signals through an Ethernet cable connected to the robot controller. The software can log up to 12 channels with 6 signals simultaneously with a sampling time down to 4 ms for the three forces and torques.

5.3 Logging of Spindle motor current

The spindle's rotational speed is controlled by a variable frequency drive (VFD). The VFD has two analogue outputs connected to a distributed I/O node connected to the robot. The outputs are speed of the spindle and spindle motor current. The motor current was logged during the test-runs.

5.4 Coordinate-measuring machine

A coordinate measuring machine (CMM) Leitz PMM-C at Hexagon Metrology was utilized to do measurement of the amount of removed material, see Figure 21.



Figure 21 Coordinate-measuring machine Leitz PMM-C, used to measure removed material.

The CMM has an accuracy of 0.6 micrometer. For a selection of test runs the work piece was measured before and after polishing, in order to determine removal of material.

6 Results

In this section the result of the test runs in the robot cell is presented. The results are divided into results for FC Pressure and FC SpeedChange. The FC Pressure is used for polishing and FC SpeedChange is used for deburring. For example of the structure of RAPID code see Appendix E and F.

6.1 FC Pressure

FC Pressure is used by introducing a number of application specific instructions in the RAPID code: FCPress1LStart, FCPress and FCPressEnd.

FCPress1LStart is starting the approach and force build-up sequence. The tool is approaching the work piece to build up an introductive pressure.

FCPressL is similar RAPID MoveL instruction, with a process parameter for pressure.

FCPressEnd is starting the decline and withdrawal sequence. The tool is declining force and withdrawing from the work piece.

6.1.1 Positioning errors

Tests were performed to investigate the robot capabilities to adapt to tolerance and position errors. A path was programmed with a work piece clamped in a fixed position, then the path was run and the force against the work piece was recorded. Then the position of the work piece was moved 2 mm in x and y directions see Figure 22 and a new test run were performed with the previously programmed path. The test run was performed all around the work piece with a rotating carbide tool with the spindle stopped.

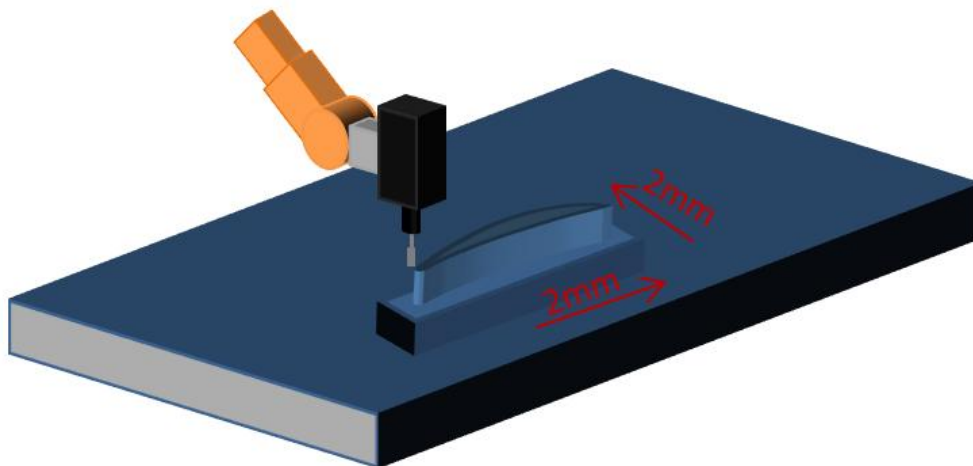


Figure 22 Test setup for positioning errors.

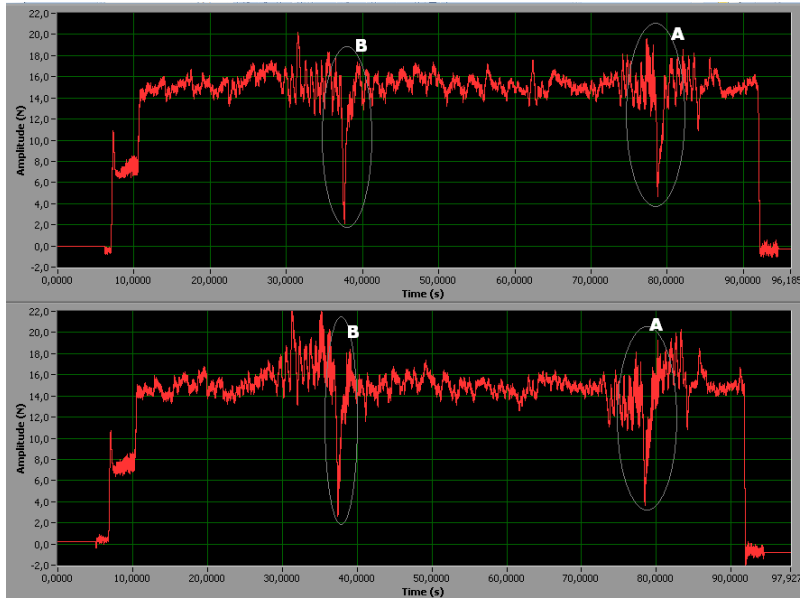


Figure 23 Upper graph shows force with no positioning error. Lower graph shows force with a positioning error of 2 mm in x direction and y direction.

When comparing the two runs shown in Figure 23 there are no major differences between the correctly positioned work piece and the work piece positioned 2 mm off in x and y direction. For this polishing application the force control adds the capability of adapt to positioning errors and casting tolerances. These tests were performed with path coordinate system as reference system for the force. This enables the robot to move around corners without re-orientation of the tool. At sharp corners it could be beneficial to use tool coordinate system as reference due to that the path coordinate system's updating rate is limited. For using the tool coordinate system in this application it would be necessary to do off-line programming of the path with a CAD model of the work piece in order to get the right tool re-orientation around corners. The drops of force marked A and B in Figure 23 are most likely due to limited updating rate of the reference frame when using the path coordinate system.

6.1.2 Analysis of low frequency chatter during force control

During the performed various tests, different degrees of chatter has been noticed on the measured force signal. Tests were performed in order to determine how the position of the work piece relative to the robot effects the generation of chatter. It should be noted that the table was placed far away from the robot in the robot cell used in this study. Three different positions were used during the test. One far away, one as close as possible and one rotated 90 degrees as seen in Figure 24 marked 1, 2 and 3 respectively. The tests were performed from the end of one corner of the work piece to the beginning of the same corner. The path only contains corner B as seen in Figure 18.

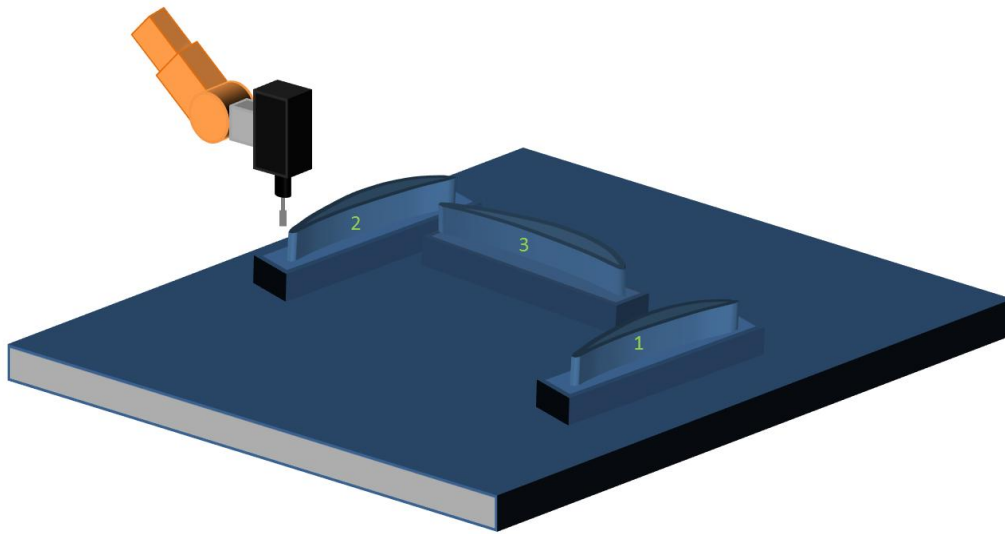


Figure 24 Setup for position tests.

With position 1 the chatter increased up to the point of the corner (the dip in the curve is the corner of the work piece) and after the corner the chatter decreased, see Figure 25. The set-point force was 15 N. The chatter measured by force sensor is between ± 5 -10 N. The second test the work piece was placed as close as possible to the robot. An improvement could be seen in the beginning but around the corner the chatter increases to the same levels as before.

The last work piece placement test was rotated 90 degrees. This was done to investigate the stiffness of robot in different directions. This position resulted in larger chatter levels than the previous tests. It is also noted that visible vibrations of the robot cell and robot structure were observed. During test 3 robot axes 2 and 3 move while axis 1 is barely moving.

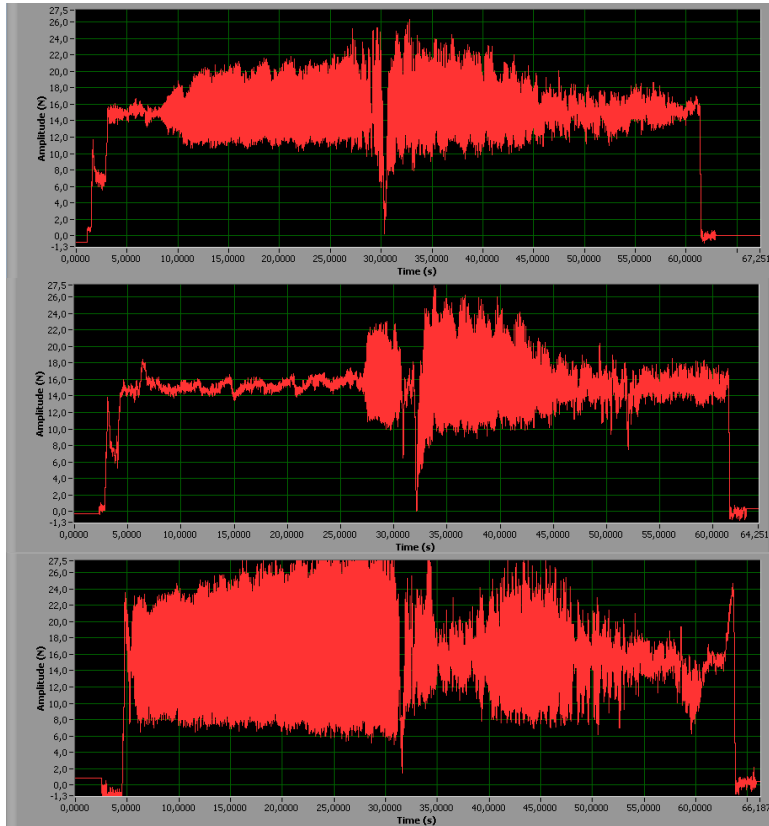


Figure 25 Pilot file runs in position 1, 2, 3.

To summarize the results, the advice would be to position the work piece close to the robot and also have the pressure force pointing in the direction of the robot base in order to optimise the robot stiffness.

The pilot file and rotating carbide tool used in this study are hard non-compliant tools. Even a small amount of compliance in the tool can reduce chatter generation. Using setup 1 a test run was conducted with a rotating tool without cuts (flat circular rod) compared with the same tool but this time a few layers of insulation tape around. A significant improvement could be seen with the tape, as seen in Figure 26.

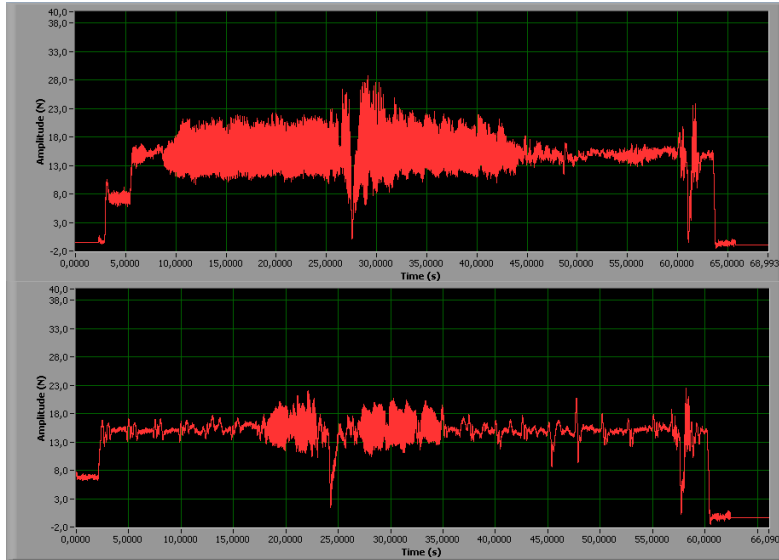


Figure 26 Initial tests without and with tape around rod.

The results from these tests were combined to a test run with taped tool and positioned close to the robot (as test 2 previously). The resulting force signal shows a significant decrease in chatter throughout the path, see Figure 27. Even the dip in the sharp corner has decreased from around 6 N to 2 N.

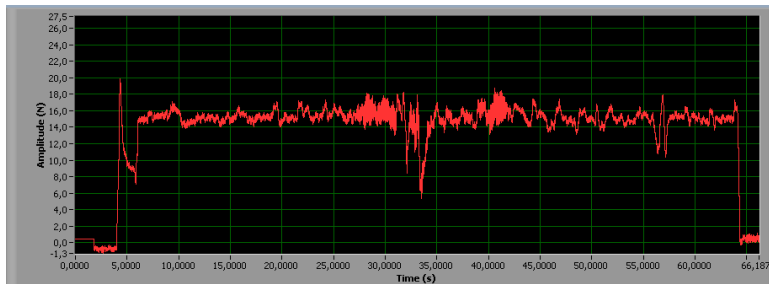


Figure 27 Run with rod with insulation tape.

6.1.3 Control Loop Parameters

In order to tune the control loop behaviour there are three tuneable parameters, damping, low pass filter and set-point filter as discussed in 2.2.1. A test was setup to evaluate the effect of changes of these parameters. The test consists of a step of the force set-point from 10N to 20N and also a step in the change of profile of 50 mm, see Figure 28.

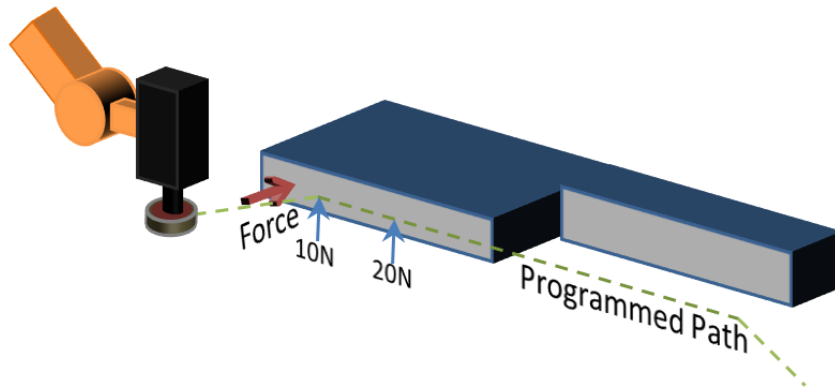


Figure 28 Test setup for evaluation of control loop parameters.

The damping is tuned by a percentage controlled from RAPID code of the defined value in the system parameters. The system parameter *damping in force z direction* can be found in folder *FC Kinematics*. The default value is 3000 Ns/m. The difference between actual measured force and the set-point is divided by the damping. With a set-point of 20N and a measured force of 0 N will give a speed in z direction of $(20-0)\text{N} / (3000 \cdot 100\%) \text{ Ns/m} \approx 6.7 \text{ mm/s}$. The test runs with a damping of 80, 100, 150%, a lower damping result in a shorter time until the tool hits the work piece again after the ledge see Figure 29.

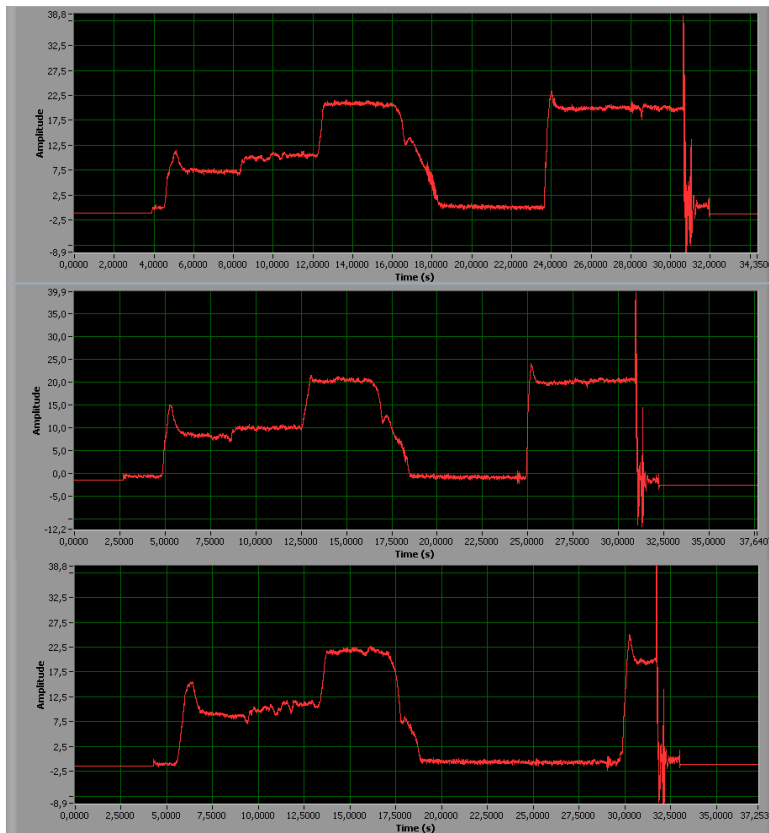


Figure 29 Result from test runs with different Damping settings 80,100,150 %.

The speed reference generated from the damping algorithm is passed through a low pass filter with a tuneable cut off frequency. In Figure 30 tests with 1, 5, 25 Hz cut-off frequency low pass filters are shown. Using 1 Hz cut-off frequency filter leads to a more sluggish behaviour with larger overshoots. There are no major differences between the runs with 5 and 25Hz low pass filter.

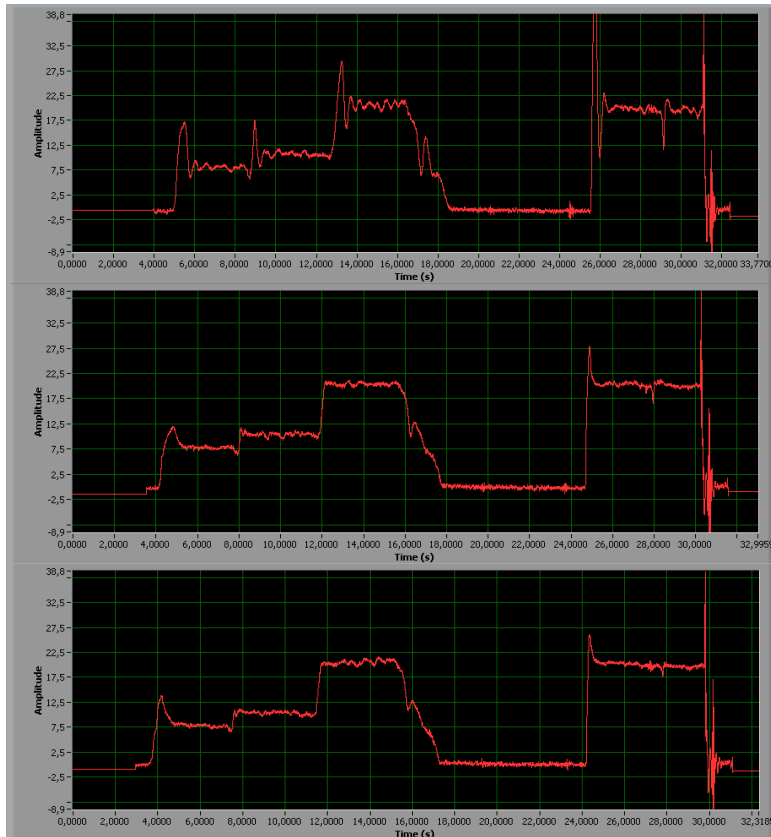


Figure 30 Result from test runs with different LP-Filter settings 1,5,25 Hz.

When starting the pressure process with the Press1LStart instruction a set-point filter can be applied. In Figure 31 a filter is set to 5N/S. When changing set-point from 10N to 20N the force set-point gradually increased up 20N.

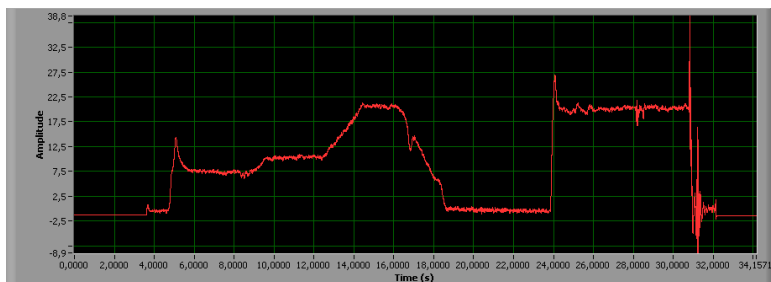


Figure 31 Force Change 5N/s, damping 80% LP 5Hz.

In all tests performed there is always an overshoot of force during the approach sequence. The only method shown to give a smaller overshoot during the tests is to decrease the approach speed. Figure 32 shows the result when using a TCP speed of 2 mm/s. The peak of overshoot is reduced to about 3 N.

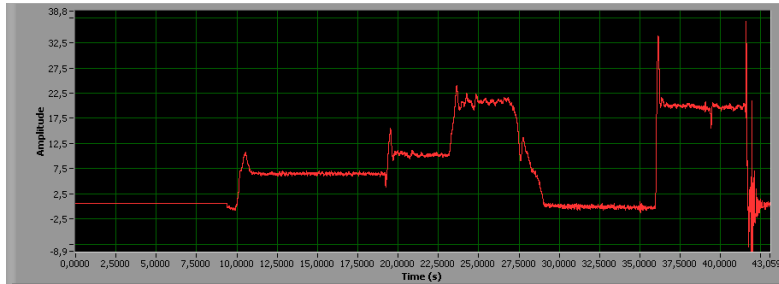


Figure 32 Test run with feed rate of 2 mm/s gives lower overshoot during approach of work piece.

6.1.4 Polishing with flap wheel

An initial polishing test was performed with a flap wheel. The test run was done with a path over a relatively straight surface. The robot was programmed by teaching eight targets including the approach and withdraws targets. Then the robot learned a more precise path by the automatic learning sequence as discussed in section 4.1. 10 additional targets were added to the path, as a result of learning. By using a recommended spindle speed of 6300 rpm with a flap wheel, a feed rate of 10 mm/s and force against the work piece of 25N a polishing test was performed. This first initial try of polishing has given an indication of being robust. The material removed was measured in 5 points with a dial gauge see Figure 33.

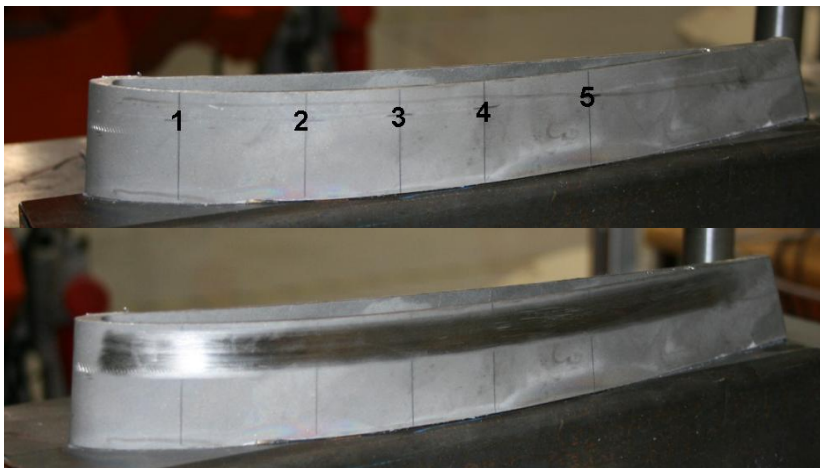


Figure 33 Before and after polishing with flap wheel, Force of 25N and 10 mm/s feed rate.

The result shown in

Table 1 shows an even material removal of 0.02-0.03 during the test run.

Table 1 Material removed (thickness) during test run, Force 25N and 10 mm/s feed rate.

Point	Material Removed
1	0.03 mm
2	0.03 mm
3	0.03 mm
4	0.02 mm
5	0.02 mm

The demand of a material removal between 0.06-0.15 mm was not reached, but the logging of the force against the surface showed a stabile behaviour of the force control loop, see Figure 34.

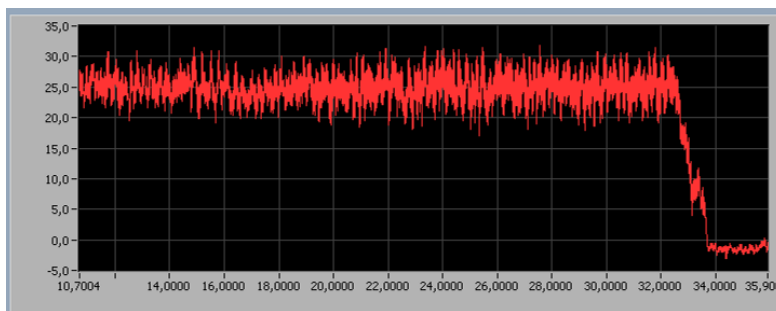


Figure 34 Force in N in Z-direction during test, first test run.

6.1.5 Polishing with rotating carbide tool

Tests have shown that the requirement of a minimum material removal of 0.06 mm can be achieved with a rotating carbide tool. The test also shows the importance of high accuracy of the orientation of the tool alignment against the surface. As can be seen in Figure 35 back side of the work piece has nearly the same material removal along the surface compared to front side where the orientation of the tool has not been properly aligned. To optimize the force and feed rate the polishing path was divided into subsections with different force and speed. The spindle speed was 5000 rpm on the front side and 10 000 rpm for the back side of the work piece. The red area shown in the figure indicates the material removed from the work piece. The results are determined by measurements in a CMM before and after polishing test run.

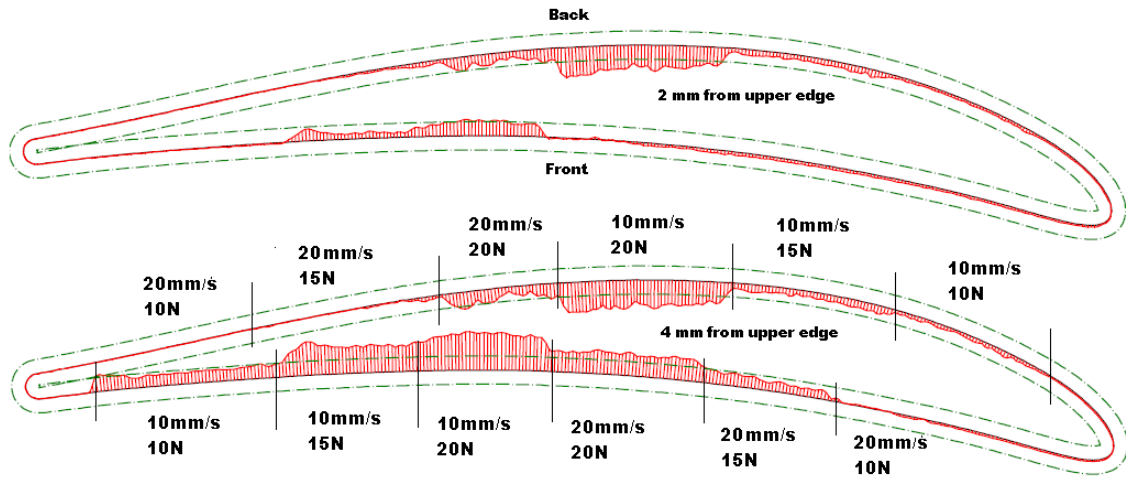


Figure 35 Result of polishing with rotating carbide tool. The green dashed line represents a tolerance of ± 0.10 mm. Height of removed material is 10 mm. Machining speed of spindle is 5000 rpm for the front and 10 000 rpm for the back of the work piece.

Removal of material around corners has shown great difficulties, when moving around the corner the contact surface between the work piece and the tool is minimal and the force per area is increasing. Figure 36 shows a test run where the feed rate around the corners was reduced from 10 mm/s to 5 mm/s in order to keep a constant contact and force against the work piece. The figure shows that a smaller radius gives a larger removal of material. The actual tool speed at the contact with surface is decreased when moving around a corner. If the speed is increased in order to keep the tool feed rate constant when moving around a corner the robot will struggle to keep in contact with the surface. In order to keep the material removal within the specified limits, the force can be decreased. Due to the noise of the force/torque measurements it could be difficult to reduce the force set-point see section 2.2.3.

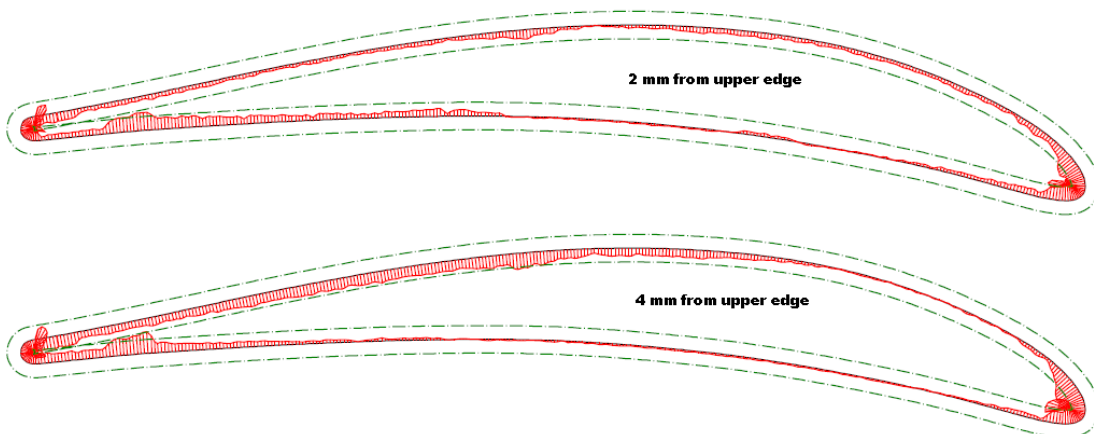


Figure 36 Test run with rotating carbide tool using 15000rpm, 15N, 10 mm/s and 5 mm/s around corner.

6.2 FC SpeedChange for deburring

FC SpeedChange measures the tangential force (same as movement direction) and lowers the speed (feed-rate) if a set force threshold is exceeded. Compared to polishing, the tool orientation is not as critical to deburring process. FC SpeedChange is used by introducing two application specific instructions in the RAPID code: FCSpdChgAct and FCSpdDeact. FCSpdChgAct is activating FC speed change functionality. FCSpdChgDeact is deactivating FC speed change functionality. In-between these instructions there are a regular robot path with MoveL instructions, which moves the robot in a programmed path. When robot moves through the programmed path the sensor measures the force in the movement direction. If the force exceeds a set upper threshold the speed is reduced with a percentage of the programmed speed. This lower speed is applied until a lower threshold is reached and the speed is increased to the original programmed speed, see Figure 37.

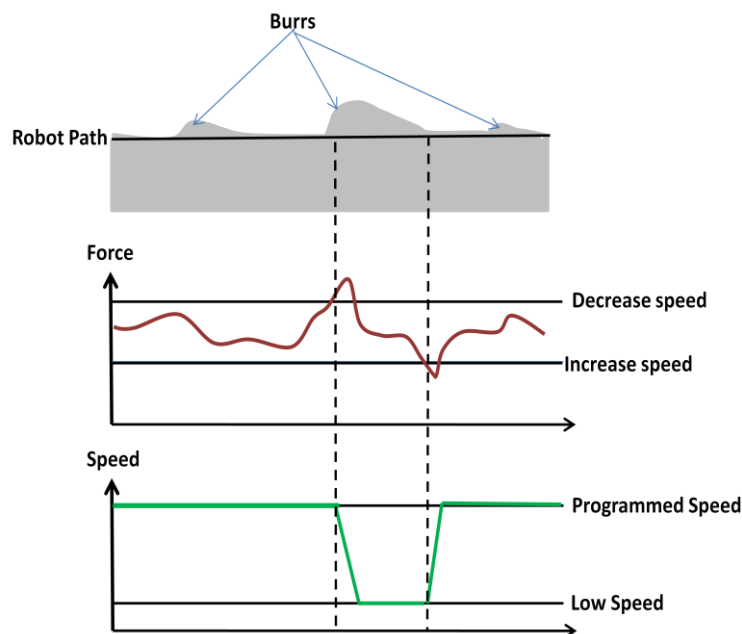


Figure 37 Functionality of FC SpeedChange

6.2.1 Deburring with modified tool

VAC Classified information

6.2.2 Automatic learning

Automatic learning can be performed by defining a number of taught points and then letting the robot run a learning cycle. After the learning cycle the robot has a number of points to perform a deburring cycle of the learned path with FC SpeedChange activated. With this method it is possible to automatically achieve a desired path around the object which is needed for a FC SpeedChange application.

7 Cell for deburring of total assembly of TEC

Deburring of an assembled TEC requires a robot with good reach and/or a positioner (external axis) since the assembly has a large diameter (almost 1700 mm). All edges of the upper outer and upper inner circles that need to be processed are marked with dashed lines in Figure 38. A fixed path (taught points) is required to be used as a guide for the robot learning a deburring path around the edges using an automatic learning sequence. The automatic learning sequence will be run for each individual TEC and will result in a customized path for the each individual TEC. This step is needed because the total work piece weld/assembly carries large tolerances. A deburring process is then feasible with the learned path (FC SpeedChange).

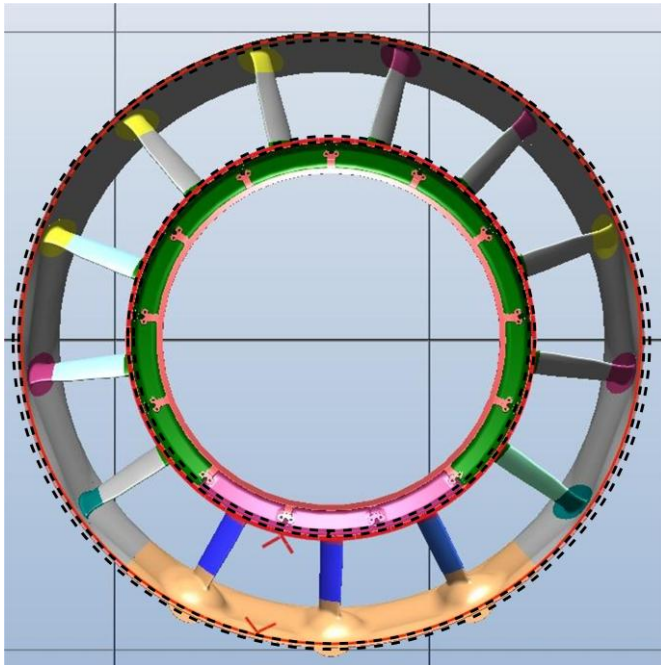


Figure 38 TEC-edges for deburring are marked with dashed lines.

A possible setup for deburring process is proposed as follows:

- ABB IRB 6640 with a reach of 2.55 m equipped with force control application package.
- Work piece positioner ABB IRB5000L for mounting and positioning of work piece.
- PDS Colombo spindle equipped with tool changer ability.
- The modified tool used for learning the path before deburring.

The proposed setup can be seen in Figure 39. The setup also requires a fixture for the work piece which is not present in the figure, but is already developed and existing at VAC. A simulation of this setup was performed in RobotStudio with the add-on machining powerpac which is needed for off-line programming of force control applications. The path is programmed to use the positioner as much as possible for movement and let the robot do the orientation of the tool. Force frame reference is set to tool during the automatic learning, while for the deburring a reference is not needed since the force is measured in the path direction.

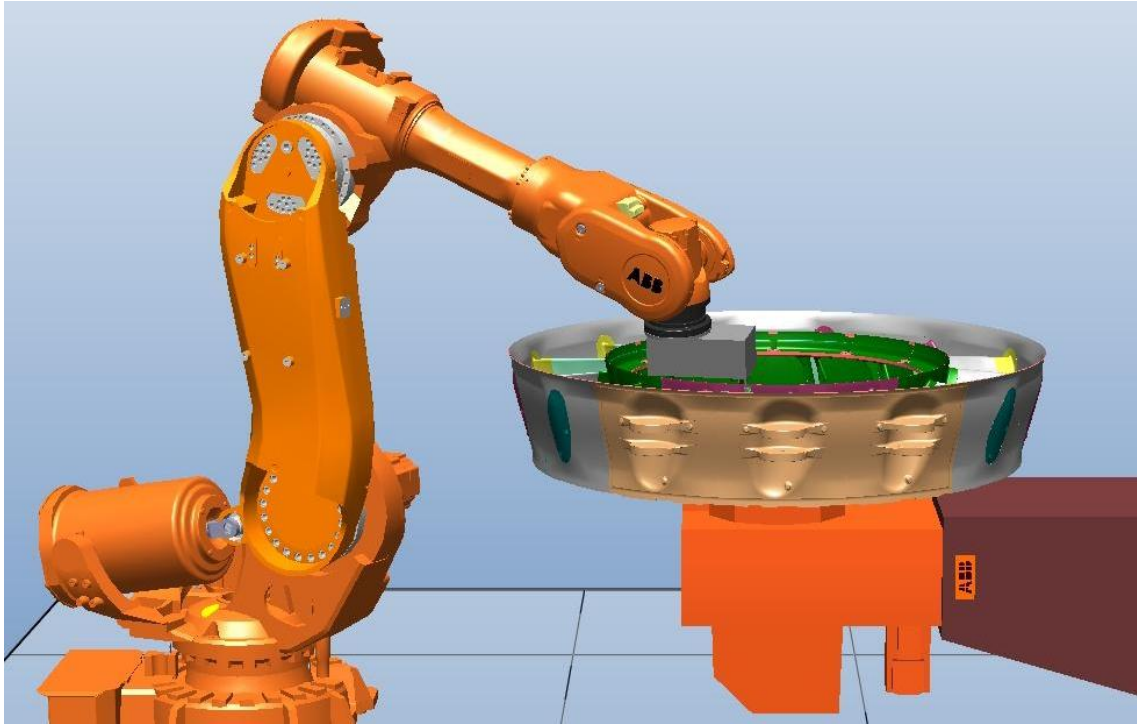


Figure 39 Proposed robot cell setup for deburring of total assembly of TEC.

8 Conclusions and future work

This study has shown that the force control technology is not mature for a polishing process for casted aero engine structural components. Main reason is the lack of adaptation properties available from the robot system in term of orientation. When using a rotating carbide tool the alignment of the tool is crucial for a polished surface. Since the casting process will give deviation of the surface perfect alignment of tool against work piece is not possible. In discussions with ABB R&D department, there is a possibility to investigate and develop such feature in cooperation with University West. During the study a flap wheel was evaluated, its compliant capabilities were desirable unfortunately the rate of material removal was too low to fulfil the requirements. The possibility of using a compliant tool axis to align the tool against surface is an option well worth researching. This study has been limited to the use of path frame reference during an activated pressure control due to lack of CAD models for the work pieces. The ability to keep a constant pressure against surface around sharp corners has shown poor results in this study. There is a possibility that the use of tool frame references could improve the surface tracing around sharp bends. Test of off-line programming to generate RAPID code in order to polish a work-piece of a CAD-model work is of great interest to evaluate the path following abilities around sharp corners.

Tests have shown the great importance of the position of the work piece and the direction of the polishing motion in order to minimize chatter. If a non-compliant tool is planned for a polishing process it is a strong recommendation that the utilizing of a 2-axes turn table and position of such is investigated, in order to optimize the robot stiffness during the polishing process. This is done to map the optimal work position/orientation of the robot.

Tests performed of deburring have shown good results. The FC speed change application is a straight forward and simple application. The application controls the feed-rate during the deburring operation and reduces speed if necessary in order to remove all burrs. Due to the large tolerances of the total assembly of a TEC, the deburring needs to be preceeded of a learning sequencing to determine the path. During this study the learning sequence has been initiated manually from the pedant; in an automated robot cell the learning sequence needs to be fully automated. Discussion with ABB has resulted in a promise of a release of RAPID code for such functionality to VAC. A reachability study has been performed in RobotStudio, which has resulted in a proposal of possible setup for a robot cell used for deburring of the total assembly of the TEC. A possible solution in order to eliminate the preceeding learning sequence would be to utilize a sensor fusion control scheme of the force sensor and a vision system or a laser distance sensor. The force sensor would control the feed rate during the deburring operation and the vision system/laser sensor would adjust the path.

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A. ABB IRB 4400/45

TECHNICAL DATA, IRB 4400 INDUSTRIAL ROBOT

SPECIFICATION

Versions	Reach	Payload	Standard	Foundry Plus	Wash	Clean Room
IRB 4400/45	1.96 m	45 kg	X	X	X	X
IRB 4400/60	1.96 m	60 kg	X	X	X	X
IRB 4400/L10	2.55 m	10 kg	X	X	X	X
IRB 4400/L30	2.43 m	30 kg	X	X	X	X
IRB 4450S	2.40 m	30 kg	X	X	X	X

Supplementary load

on axis 2	35 kg
on axis 3	15 kg
on axis 4	0-5 kg

Number of axes

Robot manipulator	6
External devices	6

Integrated signal supply

23 signals and
10 power on upper arm

Integrated air supply

Max. 8 bar on upper arm

PERFORMANCE

Positional repeatability 0.07-0.1 mm

Path repeatability at 1 m/s 0.25-0.4 mm

Axis movements

Axis	Working range
1, C Rotation	330°
2, B Arm	165°
3, A Arm	125°
4, D Wrist	400°
4, Option	Unlimited
5, E Bend	240°
6, P Turn	800°
6, Option	Unlimited

Movement on ISO test plane, all axis in motion

Max. TCP velocity	2.2 m/s
Max. TCP acceleration	12-14 m/s ²

ELECTRICAL CONNECTIONS

Supply voltage 200-600 V, 50/60 Hz

Rated power,

Transformer rating 7.8 kVA

PHYSICAL

Robot mounting

IRB 4400	Floor
IRB 4400/L	Floor
IRB 4450S	Shelf

Dimensions

Robot base 920 x 640 mm

Weight

Robot 980-1 060 kg

ENVIRONMENT

Ambient temperature

Manipulator 5 - 45°C

Relative humidity

Max. 95%

Degree of protection

Standard version IP 54

Foundry Plus and

Wash versions IP 67 and high pressure steam washable

Noise level

Max. 70 dB (A)

Safety

Double circuits with supervision,
emergency stops and safety functions,
3-position enable device

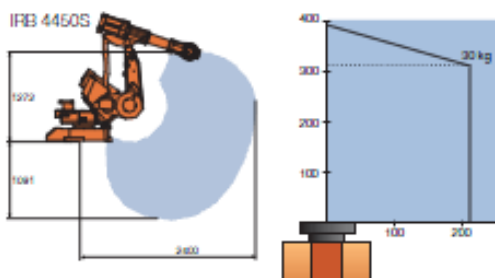
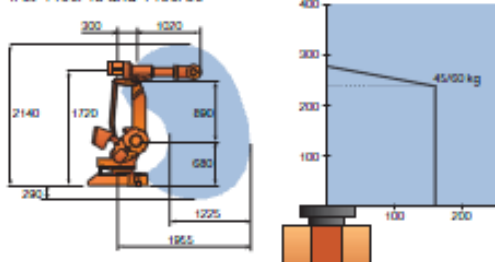
Emission

EMC/EMI-shielded

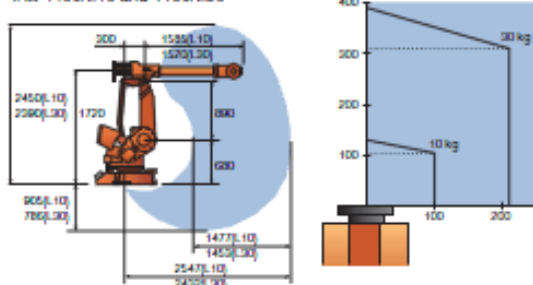
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WORKING RANGE AND LOAD DIAGRAM

IRB 4400/45 and 4400/60



IRB 4400/L10 and 4400/L30



B. Force/Torque Sensor

OMEGA160

Product Advantages

Extremely High Strength:


- EDM wire-cut from high yield-strength stainless steel.
- Maximum allowable single-axis overload values are 4.2 to 7.7 times rated capacities.
- Through-hole available in some cases.

High Signal-to-Noise Ratio: Silicon strain gages provide a signal 75 times stronger than conventional foil gages. This signal is amplified, resulting in near-zero noise distortion.

IP60, IP65 and IP68 (10m) Versions Available: An IP60 version is for use in dusty environments. The IP65 version of the transducer provides protection against water spray. The IP68 version is for underwater environments to a maximum depth of 10 meters in fresh water. Contact ATI Industrial Automation for drawings and more information.

Typical Applications

- Rehabilitation research
- Product testing
- Orthopedic research
- Robotic assembly
- Telerobotics
- Part placement and removal in precision fixtures



The Omega160 F/T transducer
The transducer is made of hardened stainless steel, and the tool and mounting adapters are made of high-strength aircraft aluminum.

SENSING RANGES		Calibrations					
Axes		US-200-1000		US-300-1800		US-600-3600	
ENGLISH CALIBRATIONS	Fx, Fy (±lbf)	200		300		600	
	Fz (±lbf)	500		875		1500	
	Tx, Ty (±lbf-in)	1000		1800		3600	
	Tz (±lbf-in)	1000		1800		3600	
	RESOLUTION	System Type*					
Axes		CTL		Net/DAQ		CTL	
Fx, Fy (lbf)		1/16		1/32		5/34	
Fz (lbf)		1/8		1/16		5/17	
Tx, Ty (lbf-in)		1/4		1/8		5/8	
Tz (lbf-in)		1/4		1/8		5/16	

SENSING RANGES		Calibrations					
Axes		SI-1000-120		SI-1500-240		SI-2500-400	
METRIC CALIBRATIONS	Fx, Fy (±N)	1000		1500		2500	
	Fz (±N)	2500		3750		6250	
	Tx, Ty (±Nm)	120		240		400	
	Tz (±Nm)	120		240		400	
	RESOLUTION	System Type*					
Axes		CTL		Net/DAQ		CTL	
Fx, Fy (N)		1/2		1/4		1	
Fz (N)		1/2		1/4		1 1/2	
Tx, Ty (Nm)		1/20		1/40		1/10	
Tz (Nm)		1/40		1/80		1/10	

*CTL: Controller F/T System; Net: Net F/T System; DAQ: 16-bit DAQ F/T System. The resolution is typical for most applications and can be improved with filtering. Resolutions quoted are the effective resolution after dropping four counts of noise (Net/DAQ) or eight counts of noise (CTL). All sensors calibrated by ATI. **Applied loads must be within range in each of the six axes for the F/T sensor to measure correctly** (refer to the transducer manual for complex loading information).

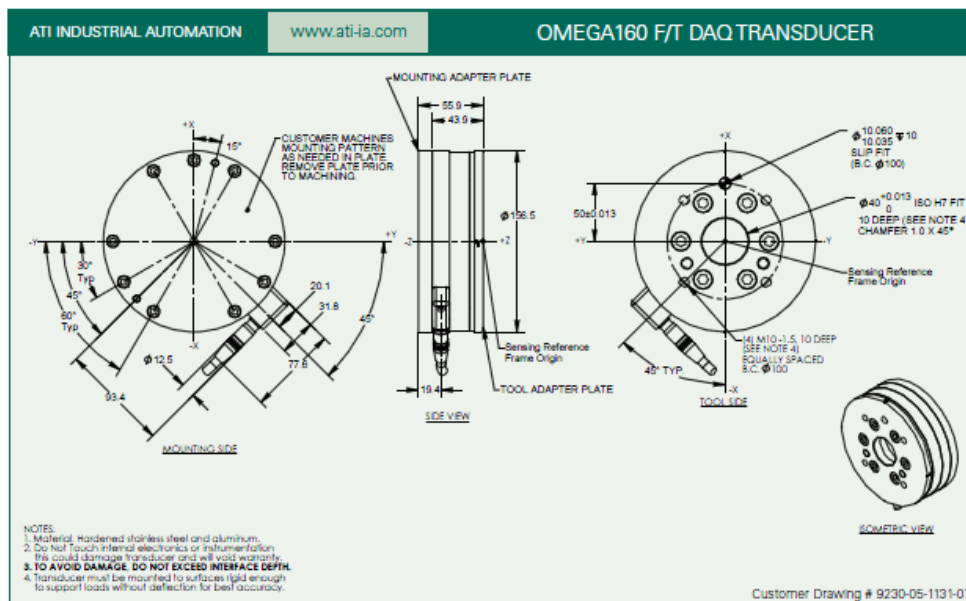


Single-Axis Overload	English	Metric
Fxy	±3900 lbf	±18000 N
Fz	±11000 lbf	±48000 N
Txy	±15000 lbf-in	±1700 Nm
Tz	±17000 lbf-in	±1900 Nm
Stiffness (Calculated)	English	Metric
X-axis & Y-axis force (Kx, Ky)	4.0x10 ⁶ lb/in	7.0x10 ⁶ N/m
Z-axis force (Kz)	6.8x10 ⁶ lb/in	1.2x10 ⁶ N/m
X-axis & Y-axis torque (Ktx, Kty)	2.9x10 ⁶ lbf-in/rad	3.3x10 ⁶ Nm/rad
Z-axis torque (Ktz)	4.6x10 ⁶ lbf-in/rad	5.2x10 ⁶ Nm/rad
Resonant Frequency (Non-IP rated, Measured)		
Fx, Fy, Tz	1300 Hz	
Fz, Tx, Ty	1000 Hz	
Physical Specifications	English	Metric
Weight*	6.0 lb	2.7 kg
Diameter*	6.10 in	160 mm
Height*	2.20 in	55.9 mm

*Specifications include standard interface plates and are for non-IP rated models.
Diameter excludes any connector block.

"ATI force/torque sensors use simple ActiveX controls that make it compatible with Open Robot Control Architecture. Ease of integration, rugged design and excellent performance are reasons that many customers use these force sensors with our robots, and it is now even easier with our PC-based SeikoRCS robot controller."

Everette Phillips
General Manager
Seiko Robotics



C. PMC330 DAQ card

PMC Modules



PMC330 16-Bit A/D Analog Input

PMC330 mezzanine modules provide fast, high resolution A/D conversion.

The PMC330 has many features to improve your overall system throughput rate. You can scan all channels or define a subset for more frequent sampling. Burst mode scans selected channels at the maximum conversion rate. Uniform mode performs conversions at user-defined intervals. Both modes can scan continuously, or execute a single cycle upon receiving a trigger.

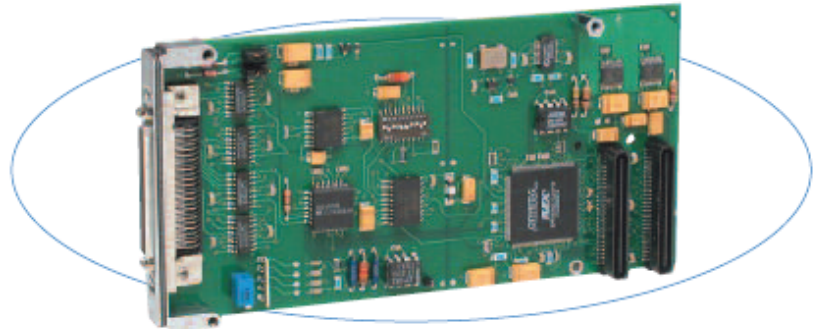
"Mail box" memory allows the CPU to read the latest data in 32 storage buffer registers without interrupting the A/D converter.

Features

- 16-bit A/D converter (ADC)
- 8 μ S conversion time (125KHz)
- 16 differential or 32 single-ended inputs ($\pm 5V$, $\pm 10V$, 0-5V, and 0-10V input ranges)
- Individual channel mailbox with one or two storage buffer registers per channel
- Programmable scan control
- Four scanning modes
- User-programmable interval timer
- External trigger input and output
- Programmable gain for individual channels
- Post-conversion interrupts

Benefits

- "Mailbox" memory eliminates scanning interruptions for optimum throughput.
- Data register indicates new and missed (overwritten) data values in the mail box.
- Programmable interrupts simplify data acquisition by providing greater control.



Advanced memory management techniques allow the PMC330 to operate with minimal interruption of the A/D converter.

Specifications

Analog Inputs

Input configuration: 16 differential or 32 single-ended.

A/D resolution: 16 bits.

Input ranges: $\pm 5V$, $\pm 10V$ *, 0-5V, and 0-10V*.

* Requires $\pm 15V$ external supplies.

Data sample memory: Individual channel mailbox with one or two storage buffer registers per channel.

Maximum throughput rate:

Only one channel can be updated at a time.

One channel: 125KHz (8 μ S/conversion)

(66KHz (15 μ S/conversion) recommended)

16 channels (differential): 4.2KHz (240 μ S/16 ch)

32 channels (single-ended): 2.1KHz (480 μ S/32 ch).

Programmable gains: 1x, 2x, 4x, 8x.

A/D triggers: External and software.

System accuracy: ± 3 LSB (0.0059%) typical (5V calib., gain=1, 25°C).

Data format: Straight binary or two's complement.

Input overvoltage protection: $V_{SS} - 20V$ to $V_{DD} + 40V$ with power on, -35V to 55V power off.

Common mode rejection ratio (60Hz): 96dB typical.

Channel-to-channel rejection ratio (60Hz): 96dB typical.

PMC Compliance

Conforms to PCI Local Bus Specification, Revision 2.2 and CMC/PMC Specification, P1386.1.

Electrical/Mechanical Interface: Single-Width Module.

32-bit PCI Target: Implemented by Altera FPGA.

4K Memory Space Required: One Base Address Register.

Signaling: 5V Compliant, 3.3V Tolerant.

Interrupts (INTA#): Interrupt A is used to request an interrupt.

Access Times: 8 PCI Clock Cycles for all registers.

To avoid Mail Box RAM read and write contention, a Mail Box read may be issued a retry termination.

Environmental

Operating temperature: 0 to 70°C (PMC330) or -40 to 85°C (PMC330E model)

Storage temperature: -55 to 100°C (all models).

Relative humidity: 5 to 95% non-condensing.

Power: 71mA at +5V, 14mA at +12V, 10mA at -12V.

MTBF: 1,745,521 hrs. at 25°C, MIL-HDBK-217F, notice 2

Ordering Information

PMC Modules

PMC330

32 single-ended or 16 differential inputs.

PMC330E

Same as PMC330 plus extended temperature range

Software (see [software documentation](#) for details)

PMCSW-API-VXW

VxWorks® software support package

PCISW-API-QNX

QNX® software support package

PCISW-API-WIN

Windows® DLL Driver software package

PCISW-LINUX

Linux® support (website download only)

Accessories (see [accessories documentation](#) for details)

5028-378

Termination panel, SCSI-2 connector, 50 screw terminals

5028-438

Cable, shielded, SCSI-2 connector at both ends

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D. Spindle Specification

RC 90/22 30 FP1 CPE 25 DX



ABB Art.Nr.:

PDS Art.Nr.: S90C144-7.5,3

S90C144-7.5,3

5.5 kW, RC 90/22 30 FP1 CPE 25 DX, Elektrospindel, 380 V, 18000/24000 UpM, 300/400 Hz, 2 polig, Zeichnung #90C144

Technische Daten:

Kühlung mittels Druckluft 80 l/min bei 4 Bar

Sperrluftdichtung für vordere Lagerung

Geräuschreduziert < 73 dBA

Einschaltdauer 90%

Spannzangenaufnahme ER 25 - max. Schaftdurchmesser 16 mm

inklusive Überwurfmutter UMER 25 DX

Doppelreihige Hochpräzisions-Spindellagerung - vorne und hinten

Keramiklagerung vorne

Ausgerüstet mit Kupfer-Rotor

Doppelreihige Hochpräzisions-Spindelkugellager - vorne und hinten

E. FC SpeedChange RAPID code example

```
PROC RunPathpath1 (bool bRecover, bool bSpindleOn)
    FCDeact;

    IF bRecover = true THEN
        FCCalib tvolvo_LD \Recovery;
    ELSE
        FCCalib tvolvo_LD;
    ENDIF

    IF bSpindleOn = true THEN
        Spindle_On\nRPM:=2000;
    ENDIF

    MoveL T1Approach1, v50, z1,tvolvo\wobj :=wobj0;
    MoveL T1Approach2, v50, z1,tvolvo\wobj :=wobj0;
    MoveL T1Approach3, v5, fine,tvolvo\wobj :=wobj0;
    FCSpdChgAct 50 \NonStopAllTime;

    MoveL T1Process1, v10, z1,tvolvo\wobj :=wobj0;
    MoveL T1Process2, v10, z1,tvolvo\wobj :=wobj0;
    MoveL T1Process3, v10, z1,tvolvo\wobj :=wobj0;
    MoveL T1Process4, v10, z1,tvolvo\wobj :=wobj0;
    MoveL T1Process5, v10, z1,tvolvo\wobj :=wobj0;
    MoveL T1Process6, v10, z1,tvolvo\wobj :=wobj0;
    MoveL T1Process7, v10, z1,tvolvo\wobj :=wobj0;
    MoveL T1Process8, v10, z1,tvolvo\wobj :=wobj0;

    FCSpdChgDeact;

    MoveL T1Withdraw1, v5, z1,tvolvo\wobj :=wobj0;
    MoveL T1Withdraw2, v50, z1,tvolvo\wobj :=wobj0;

    Spindle_Off;

ENDPROC

ENDMODULE
```

F. FC Pressure RAPID code example

```
PROC RunPathpath1 (bool bRecover, bool bSpindleOn)
    FCDeact;

    IF bRecover = true THEN
        FCCalib tflapwheel_LD \Recovery;
    ELSE
        FCCalib tflapwheel_LD;
    ENDIF

    IF bSpindleOn = true THEN
        Spindle1On\nRPM:=5;
    ENDIF

    MoveL T1Approach1, v50, z1,tflapwheel\wobj :=wvane;
    MoveL T1Approach2, v50, z1,tflapwheel\wobj :=wvane;
    MoveL T1Approach3, v10, fine, tflapwheel\WObj:=wvane;

    FCPressLStart T1Process1, v10\Fx:= n1ForceX\Fy:= n1ForceY
    \Fz:=n1ForceZ,50\ForceFrameRef:=FC_REFFRAME_PATH\ForceChange:=50
    \DampingTune:=100\TimeOut:=5\UseSpdFFW\PosSupvDist:=9e9, z1,
    tflapwheel\WObj:=wvane;

    FCPressL T1Process2, v20, 15, z1, tflapwheel, \wobj:=wvane;
    FCPressL T1Process3, v20, 15, z1, tflapwheel, \wobj:=wvane;
    FCPressL T1Process4, v20, 15, z1, tflapwheel, \wobj:=wvane;
    FCPressL T1Process5, v20, 15, z1, tflapwheel, \wobj:=wvane;
    FCPressL T1Process6, v20, 15, z1, tflapwheel, \wobj:=wvane;
    FCPressL T1Process7, v20, 15, z1, tflapwheel, \wobj:=wvane;
    FCPressL T1Process8, v20, 15, z1, tflapwheel, \wobj:=wvane;
    FCPressL T1Process9, v20, 15, z1, tflapwheel, \wobj:=wvane;
    FCPressL T1Process10, v20, 15, z1, tflapwheel, \wobj:=wvane;

    FCPressLEnd T1Withdraw1,v20,\ForceChange :=50,\ZeroContactValue := 7.5;

    MoveL T1Withdraw2, v50, z1,tflapwheel\wobj :=wvane;

    IF bSpindleOn = true THEN
        Spindle1Off;
    ENDIF
ENDPROC

PROC Spindle1On(\num nRPM)
    VAR num nVarv;

    Set doSIF_SPI_Cooling;
    Set doSIF_FRC_Spd_Forward;
    Set doSIF_FRC_SpindleOn;
    ! Spindel varv 0-10
    nVarv:=5;
    IF Present(nRPM) nVarv:=nRPM;
    SetAO aoSIF_SPI_SpdSetpnt, nVarv;
ENDPROC

PROC Spindle1Off()
SetAO aoSIF_SPI_SpdSetpnt, 0;
    WaitAi aiSIF_SPI_ActSpeed\LT, 0.03;
    Reset doSIF_FRC_SpindleOn;
Reset doSIF_SPI_Cooling;
    Reset doSIF_FRC_Spd_Forward;
ENDPROC
ENDMODULE
```