Iterative Learning Control for Milling with Industrial Robots in Advanced Manufacturing

This document is a short summary of [Daun, 2013]

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There is a demand in industry for manufacturing of advanced parts with high precision due to the increasing complexity of modern technology. These parts are typically made by CNC (Computer Numerical Control) machines, which are both expensive and comparably big. These machines can produce complex metal parts with high accuracy by milling in materials such as aluminum or titanium.

By using industrial robots that are significantly cheaper, costs can be reduced. This cost reduction is particularly beneficial for small and medium-sized enterprises (SMEs). However, robots are not as stiff or accurate as CNC machines. The idea of this thesis was that by using feedback control, this could be compensated so that the robot could perform machining with high precision.

Background

This thesis was part of an EU co-funded research project called COMET, which is a collaboration between the Robotics Lab at Lund University and other academic and industrial partners [COMET, 2013].

The research evaluates the use of industrial robots for advanced machining. It requires that robots can be made accurate enough to produce parts within specified tolerances. Compared to CNC machines, robots are significantly cheaper [Berselli et al, 2013], have a smaller work cell, and if mounted on rails they can machine larger parts.

Figure 1 Robot cell at AML, Sheffield, UK.

Problem Definition

Industrial robots have lower absolute accuracy than CNC machines because of their lower stiffness. This needs to be compensated for in order to produce parts within the specified tolerances. In this project it was decided that an acceptable tolerance was a maximum position error of ± 0.1 mm for milling with a robot [Berselli et al, 2013].

The aim in this thesis was to evaluate if it was possible to reach acceptable tolerances by designing a controller that could compensate for position deviations. It required an algorithm that could calculate the error from measured positions and then update the milling path of the robot according to these errors.

Method

A robot cell was set up at AML Ltd in Sheffield, UK, one of the COMET partners. The cell was used for testing and evaluation in this thesis. An image of the experimental setup can be seen in Figure 1. Experiments based on the methods described in this thesis were also done on a similar robot cell by SIR in Modena, Italy, which is another COMET partner.

Robot Cell The robot cell at AML was set up with an industrial robot from ABB with a work object mounted at its end-effector. A milling tool was placed in a fixed spindle. The robot had six degrees of freedom and to measure the position and orientation of the work object, relative to the spindle, a high precision optical tracking system from

Nikon Metrology was used. With infrared LEDs mounted on the spindle and the work object, the camera could measure their positions. An overview of the robot cell is seen in Figure 2.
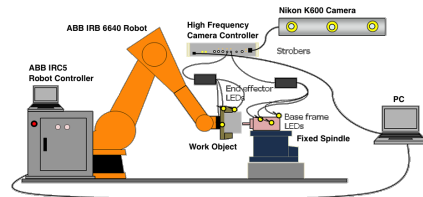

Figure 2 Overview of the robot cell at AML [Berselli et al, 2013].

An ABB control cabinet was used for trajectory generation based on predefined tool paths, which include coordinates and robot speed.

The Robot Task The task in this project was to mill a surface finish in pockets that had been pre-milled in the aluminum block, see Figure 3. These pre-milled pockets had 1 mm of material left to be milled on the walls inside the pocket. To analyze the results from using compensated tool paths, the surface finish was first milled and measured with the nominal path. The compensated tool paths were then used for milling the finishing of the pockets. The measurements from the different executions were then compared to each other to investigate if there had been an improvement.

ILC Method

The Iterative Learning Control (ILC) algorithm was chosen as a suitable control strategy, since the position errors
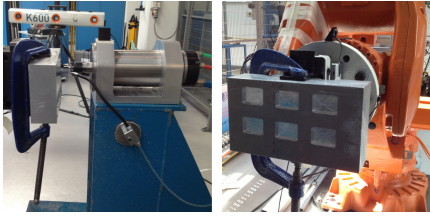
Figure 3 Placement of aluminum block and robot arm relative to tool and spindle.

rithms.

that occurred when milling were considered to be repetitive. ILC uses the error from previous iterations and adds it to the control signal, which is called the ILC update law. With a correct mathematical model of the system, the optimal solution is to invert the system dynamics and add the inverted position error to the controller input. Eventually the output will converge towards successful results. If the position errors from milling were completely repetitive, ILC should significantly reduce them.

Model and Control System   The software Matlab with Simulink was used for creating a mathematical model of the system. It was designed to handle the signals sent to and from the ABB control cabinet as well as the signals received from the camera. By processing the signals, measurements could be translated into x, y, and z coordinates. These signals could then be monitored and modified.

Matlab was also used to create a script that could calculate and generate ILC compensated tool paths in three dimensions (x, y, and z). The script can read and analyze chosen data files with measurements and then calculate compensated tool paths by using ILC algo-

Creating Tool Paths   An original reference path was created in Matlab for the robot to follow when milling the pocket's surfaces. This was called the uncompensated tool path. The robot's positions were then measured during the milling procedure. These positions were compared to the original reference, which revealed the position deviation of the robot. The position error was calculated along x, y, and z at each position in the program and was then filtered with a low-pass filter before it was added to the reference. By inverting the calculated position error and adding it to the original reference, a new tool path was created. This new modified reference was called the compensated tool path. The compensated tool path in the z direction, which is the attack direction of the tool, can be seen in Figure 4.
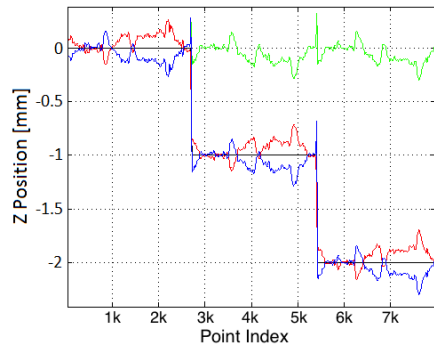

Figure 4   Original z reference (black), measured data (red), position error (green) and ILC compensation (blue) over time (*Point Index*) [250 Hz].

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Results

To evaluate the result of using ILC, experiments were done with the robot moving in free space and when milling. The results achieved when the robot was moving in free space showed a significantly increased accuracy. It exhibited a reduced error of 56-67%. Because of these successful results, tests were also done when milling.

Milling Results   The results were evaluated by comparing the measured data from milling with the uncompensated tool path to milling with an ILC compensated reference. Experiments were made with a milling speed of 10 mm/s. To get an accurate estimate of the errors in each direction, the variance, standard deviation, and improvement in standard deviation were calculated. The result showed an improvement from ILC compensation also when milling. With the values of standard deviations from the compensated path and the nominal path, the improved standard deviation could be calculated as

$$Improvement = 1 - \frac{Compensated\ path}{Nominal\ path}.$$

The result was a reduced error of 11.4% in x direction, 19.6% in y direction, and a significantly reduced error of 56.4% in z direction. A diagram that shows the milling result can be seen in Figure 5.

With these improvements, the z direction was well within the specified accuracy of ± 0.1 mm. For x and y the average error was reduced from about 0.4 mm to about 0.15 mm. These results were generated with only one iteration of ILC, which indicates that further iterations might improve the results even
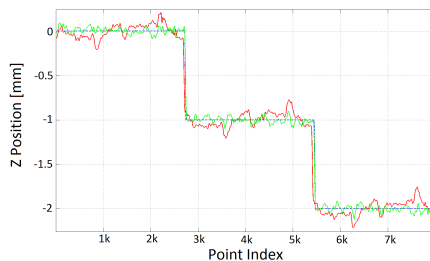

Figure 5   Overview of milling result in z position with the original z reference (blue), nominal path (red) and ILC compensation (green) over time (*Point Index*) [250 Hz].

further. When performing the same experiments on the robot at SIR in Italy, similar results were achieved.

These successful results show that robots can be used for advanced manufacturing when using ILC compensated tool paths.

References

[Daun, 2013] T. Daun, *Iterative Learning Control for Milling with Industrial Robots in Advanced Manufacturing*, Master's Thesis, Department of Automatic Control, Lund University, Sweden, 2013.

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