Assessment of the positioning accuracy of a small articulated robot during machining operations

Hamza Alzarok, Simon Fletcher, Andrew Longstaff, Alan Myers

Centre for Precision Technologies, School of Computing and Engineering, University of Huddersfield,

University of Huddersfield, Queensgate, Huddersfield HD1 3DH, UK

Abstract

The application of industrial robots for machining of complex parts is a very promising field that refers to the ability of the robot to produce parts with complex geometries that typically requires multi-axes machine tools. However, there are many restrictions that limit the use of robot in advanced manufacturing industry such as positioning errors and low stiffness. This work investigates the positioning accuracy and the path repeatability of a Mitsubishi RV-1A robot with six degree of freedom during machining movements by using a Faro laser tracker. The results obtained show a significant motion error caused by the robot, even with the absence of cutting force. A comparison has been made between the positions of the commanded path measurements taken by the robot controller and the actual position of the end effector of the robot measured by the tracker.

Keywords: Robot, Laser tracker, Positioning errors, Accuracy, Repeatability

Introduction

Robots are often used in simple manufacturing operations such as assembly, painting, welding, and handling processes which do not need any intensive contacts between robots and their workpieces. The advantage of using industrial robots is in the programmability, adaptability, flexibility, and low cost compared to multi-axis CNC machines.

Nevertheless, there are some issues that limit the ability of using robots in complex machining operations such as drilling and milling where the low positioning accuracy of robots especially obtained under the force of the process. Moreover, the high mechanical compliance leads to deflection of the tool centre point (TCP). Test results taken by E. Abele *et al* [1] indicated that the deviations in milling process reached up to 0.6mm. The deviation was reduced to 0.1mm by their method “path adaption for machining based on measurement data”, even though this deviation still quite high. The stiffness of today’s industrial robots is another problem which is much lower than that of standard CNC machines. In heavy machining operations such as milling, the researchers found that a perfect robot program without any considerations of contact and deformation fail to obtain the desired path once the robot starts executing the machining task. As a result of the lower stiffness, a 500 N cutting force during a milling operation will result in a 1mm positioning error for a typical industrial robot compared with less than 0.01mm positioning error for standard CNC machines.

Wang *et al* [2] indicate that a robot typically has a motion error of 0.1mm without contact, and the majority of positioning errors come from the force of the contact causing deformation during heavy machining operations adversely affecting the robot structure. They state that the problem of using robots in machining process is different and include the aforementioned deformation caused by the contact force and limitations such as maximum velocity, accelerations or torques.

In the case of the deformation, Wang *et al* use a force sensor (ATI Omega) situated on the wrist of the robot in order to measure the external force on the robot. The magnitude of the external force is adjusted by using air pressure. The problem with the proposed method is related to delaying in the compensation (around 50ms). The justification for the delaying is because of the poor synchronization between the measurement of the force sensor and the digitizer method.

There are many ways to improve the positioning accuracy of robots starting from geometric calibration methods and ending to using high accuracy measuring equipment. Recent researches concentrate on developing on-line measurement systems (tracking systems) that can provide accurate information with less time and cost and operate in unprepared environment, such as using CCD cameras for tracking one object [3], or by adding a laser stripe sensors to CCD camera [4]. However, the disadvantage of CCD cameras is in consuming a lot of processing power, and the delay in the processing time because of its nature as a digital system which require time for extracting the motion and position from the image. Han *et al* [5] use ultrasonics because of the simplicity to be implemented and the ability to track the movement of the object with a quicker detection and good accuracy, Wang *et al* [6] introduce a comparison between two high accurate metrology systems indoor GPs and laser trackers, the repeatability for both systems are similar. However, the accuracy of laser tracker is still better than iGPs. Additionally to the issue of accuracy for iGPs, it is still one of new metrology systems under developing, and new researches work on improving the software which may decrease a bias error. In our experimental work, a laser tracker (Faro ION) is selected for tracking the movement of the robot during machining operation because of the high ability to track one object, in addition to its high accuracy compared with other metrology systems.

This paper aims to highlight on the limits of using robots in machining operations in the absence of any contact force by investigating the repeatability and positioning accuracy (motion error) of a Mitsubishi MELFA RV-1A robot. The motion error of the robot and deviations for the actual positioning path are measured by the tracker and compared to those taken from the robot controller.

Assessing the path accuracy of robots

Precision in machining involves two different concepts: repeatability and accuracy, repeatability is the ability of the robot to obtain consistent results by performing the same task when the command is repeated n times and under the same conditions (such as using the same laboratory). However, the accuracy is the difference between the obtained readings and the desired value of that measurement [7]. According to ISO 9283:1998 [8], "definitions of path accuracy and repeatability are independent of the shape of the command path. Path accuracy characterizes the ability of a robot to move its mechanical interface along the command path in the same direction n times. Path accuracy is calculated by the following two factors:

- The difference between the positions of the command path and the barycentre line of the cluster of positions of the attained path (i.e. positioning path accuracy, AT_P, in figure 1 below) ;
- The difference between command orientations and the average of the attained orientations (i.e. orientation path accuracy).

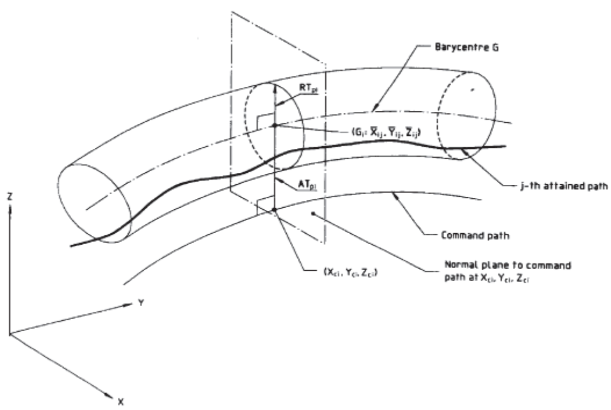

Figure 1: Path accuracy and path repeatability for a command path [8]

The positioning path accuracy is determined as follow:

$$AT_p = max\sqrt{(\overline{x_i} - x_{ci})^2 + (\overline{y_i} - y_{ci})^2 + (\overline{z_i} - z_{ci})^2} \qquad (1) \quad i = 1 \ldots\ldots m$$

Where: $\overline{x_i} = \frac{1}{n}\sum_{j=1}^{n} x_{ij}$ $\overline{y_i} = \frac{1}{n}\sum_{j=1}^{n} y_{ij}$ $\overline{z_i} = \frac{1}{n}\sum_{j=1}^{n} z_{ij}$

x_{ci}, y_{ci} and z_{ci} represent the coordinates of the i-th point on the command path.

x_{ij}, y_{ij} and z_{ij} represent the coordinates of the intersection of j-th attained path and the i-th normal plane.

Table below provides a summary for testing the conditions of path accuracy of robots".

Table 1: summary of test conditions for path accuracy within ISO standards [8]

Load	Velocity	Shape of path	Number of cycles
100% of rated load	**100% of rated velocity 50% of rated velocity 10% of rated velocity**	**Linear path $E_1 - E_3$ Circular paths Large and small circles See 6.8.6.2 and figure 6**	**10**
The mass of rated load reduced to 10% (optional)	**100% of rated velocity 50% of rated velocity 10% of rated velocity**		

Path repeatability can be measured via the same procedure as that used for measuring the accuracy of the path as shown above in Table 1.

Experimental setup

The setup of the experiment can be shown in Figure 2. A Faro ION laser tracker (with the option of laser interferometer) was used for tracking and measuring the position of the Mitsubishi robot RV-1A end effector. The robot was programmed and tested via RT-toolbox software in order to perform linear movement paths in front of the tracker to maintain line of sight between the tracker and one retro reflector (SMR 0.5) mounted on the top of the end-effector of the robot (shown in Figure 3).

Figure 2: Experimental setup with the RV1-A robot and the faro laser tracker

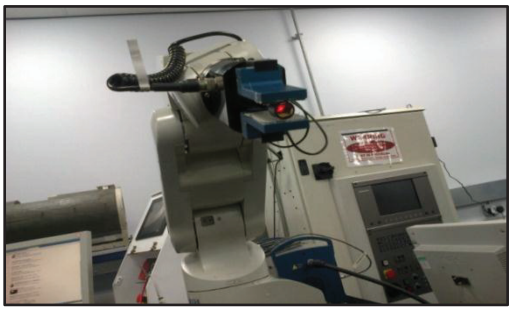

Figure 3: SMR 0.5 reflector mounted between the hands of the end-effector

The robot will perform a linear movement in the X direction by using the controller of the robot, and data for the path was recorded by FARO ION software (CAM10), and stored in a form of three coordinates (X, Y, Z) which represents the positions of the end-effector of the robot with respect to the robot base. Converting the reference frame from the laser tracker frame to the robot base frame was obtained by using one SMR reflector for creating the alignments of the new frame in Faro software.

In order to analyse the positioning and repeatability of the robot, the experiment was repeated in accordance with ISO standards [8], and by using Matlab software for the mathematical analysis. The standard deviations and RMS errors for the actual path of robot have been calculated each time and compared to those determined from the command path.

Results and discussion

Table 2 shows the commanded linear path of the robot and linear model identified by curve fitting approach, it can be clearly seen that a negligible control error occurred in Y-axis, while in the Z-axis, there is a small motion error of $0.00418mm$, root mean square error (RMSE) and the standard deviation (s_D) have been mathematically determined by using the following equations (respectively):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}[f(x_i) - y_i)^2} \quad (2), \quad s_D = \frac{1}{n}\sum_{i=1}^{n}\sqrt{(x_i - \overline{x})^2} \quad (3) \quad \text{Where } \overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

Table 2: RMSE error for the positions of command path

position path	x	y	z	RMSE in Y-axis (mm)	RMSE in Z-axis (mm)
10	22.98	427.43	469.83		
9	17.08	427.43	469.84		
8	13.89	427.43	469.83		
7	10.48	427.43	469.83		
6	6.39	427.43	469.84	0	0.004
5	1.15	427.43	469.84		
4	-2.03	427.43	469.84		
3	-6.58	427.43	469.84		
2	-13.86	427.43	469.84		
1	-18.64	427.43	469.84		

The previous results show that robot has a negligible error of only 4μm in the closed loop control system of the robot. The next step is to use a reliable device which can provide precise information about the status of the robot mechanical positioning accuracy. The Faro Laser tracker has been used as a reference and positions of the robot path have been measured eight times (as shown in table below).

Table 3: repeatability for the positions of the actual path

Points	Repeatability in x-axis	Repeatability in y-axis	Repeatability in z-axis
Point 2	0.018	0.045	0.008
Point 3	0.017	0.045	0.009
Point 4	0.017	0.045	0.008
Point 5	0.016	0.047	0.008
Point 6	0.017	0.047	0.009
Point 7	0.016	0.048	0.008
Point 8	0.029	0.041	0.006
Point 9	0.035	0.054	0.010

According to ISO 9283:1998 [8], in the test conditions for the path accuracy and repeatability, the start and end points shall lie outside the selected test path (i.e. points 1 and 10 are removed).

From the Table 3, it can be seen that during the movement of the robot through the programmed path, there is no significant change in the values of the repeatability, except for point 9 which deviates considerably

(Figure 5). The reason for this is the change in the direction of the robot from +x to –x which requires a significant rotation of joint 4 (θ_4) from 38.81° to 13.60°. Moreover, during the repeatability experiment, it was noted a rise in the temperature of the joint 4 which may be caused by the motors and bearings. This suggests that the repeatability of the robot is sensitive to moves requiring large rotary movements typically occurring near singularities in the kinematic loop.

Table 4: number of iterations of the experiment and RMSE

Iteration	RMSE in Y-axis (mm)	RMSE in Z-axis (mm)
1	0.220	0.233
2	0.218	0.236
3	0.219	0.236
4	0.206	0.243
5	0.199	0.212
6	0.245	0.233
7	0.215	0.229
8	0.219	0.236
Average	0.218	0.232

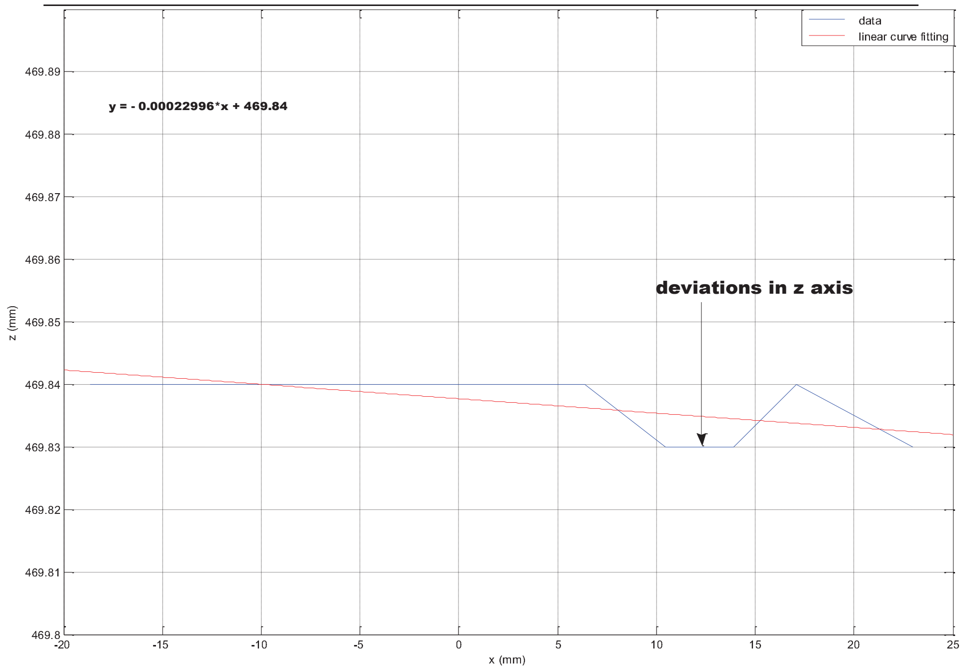

Figure 4: the change in the Z-axis while robot moves in X-axis

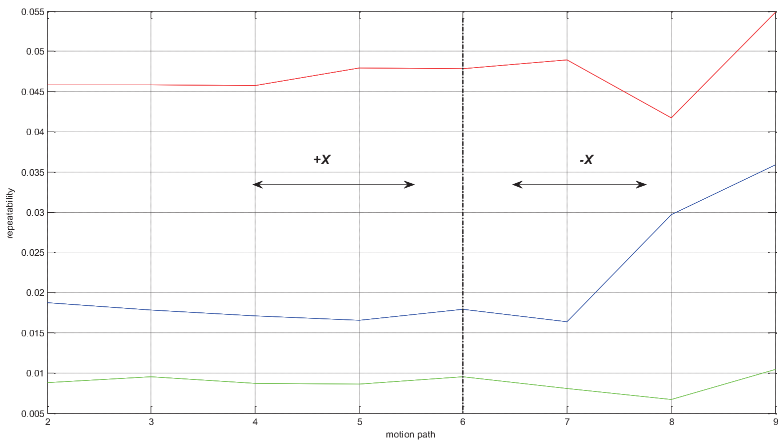

Figure 5: repeatability vs. motion path of the robot

Conclusions

In this paper, the positioning accuracy of a Mitsubishi MELFA RV-1A robot was investigated by using a Faro ION laser tracker during machining movements. This experiment has proved a significant effect of the joint angle rotation on the repeatability and should be reconsidered for any manufacturing operation. The experiment shows a rise in the temperature of the joint 4 which may be caused by the motors and bearings. A compensation of errors due to thermal effects and for a correction of the spatial position of the tool centre point (TCP) can be suggested as a future work.

Acknowledgement

The authors gratefully acknowledge the UK’s Engineering and Physical Sciences Research Council (EPSRC) funding of the EPSRC Centre for Innovative Manufacturing in Advanced Metrology (Grant Ref: EP/I033424/1).

References

1. Abele, E., et al., *Tool path adaption based on optical measurement data for milling with industrial robots.* Production Engineering, 2012. **6**(4-5): p. 459-465.
2. Wang, J., H. Zhang, and T. Fuhlbrigge. *Improving machining accuracy with robot deformation compensation*. in *Intelligent Robots and Systems, 2009. IROS 2009. IEEE/RSJ International Conference on*. 2009: IEEE.
3. Kim, K.K., et al. *Detecting and tracking moving object using an active camera*. in *Advanced Communication Technology, 2005, ICACT 2005. The 7th International Conference on*. 2005: IEEE.
4. Cheng, S.S. *Neural-PID visual tracking of moving object*. in *Electronics and Optoelectronics (ICEOE), 2011 International Conference on*. 2011: IEEE.
5. Han, Y., et al., *Tracking of a moving object using ultrasonic sensors based on a virtual ultrasonic image.* Robotics and Autonomous Systems, 2001. **36**(1): p. 11-19.
6. Wang, Z., et al., *Experimental comparison of dynamic tracking performance of iGPS and laser tracker.* The international journal of advanced manufacturing technology, 2011. **56**(1-4): p. 205-213.
7. de Lacalle, L.L. and A. Lamikiz, *Machine tools for high performance machining*. 2009: Springer.
8. International Standard, *Manipulating Industrial Robots - Peformance Criteria and Related Test Methods.* ISO9283.