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Path following performance analysis for Siemens 840 D sl controlled robotic machining platforms with secondary encoders

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Abstract

Robotic arms are widely known to fall short in achieving the tolerances required when it comes to the metal machining industry, especially for the aerospace sector. Broadly speaking, two of the main reasons for that are a lack of stiffness and a lack of accuracy. Robotic arm manufacturers have responded to the lack of stiffness challenge by producing bigger robots, capable of holding high payloads (e.g., Fanuc M-2000iA/2300) or symmetric robots (e.g., ABB IRB6660). Previous research proved that depending on the application and the material being machined, lack of stiffness will still be an issue, even for structurally bigger robotic arms, due to their serial nature. The accuracy issue has been addressed to a certain extent by using secondary encoders on the robotic arm joints. The encoder enhanced robotic arm solutions tend to be expensive and prior knowledge proves that there are still limitations when it comes to achieved accuracy. The current work aims to provide a performance analysis of the path following capabilities of two robotic machining platforms, namely the Accurate Robotic Milling System (ARMS) and the MABI MAX-100-2.25P. Both platforms are equipped with secondary encoders (optical and inductive, respectively) and Siemens 840 D sl controllers and have been designed to be used in machining applications. The performance analysis will be demonstrated with a novel path that takes into consideration the BS EN ISO 9283:1998 standards for manipulating industrial robots while utilizing machining specific feed rates and feasible working volumes for both platforms. Furthermore, an accuracy study is performed for the 840 D sl controller Sinumerik Trace tool capabilities and verified by using a Leica Absolute AT960 laser tracker to assess its reliability for usage in accuracy analysis. This would remove the need to use expensive external metrology equipment for tracking path accuracy.

Introduction

The number of installed industrial robots in the manufacturing industry (metal, machinery, welding, assembly, etc.) has seen a worldwide decline in 2022 according to the latest report by the International Federation of Robotics (1). This is perhaps unsurprising considering that the performance of industrial robots is represented by their ability to repeat a task and not by the accuracy with which that task is accomplished. The manufacturing industry is constrained by tolerances which can be tight in certain sectors (e.g., aerospace, defense, medical, etc.) (2). An off-the-shelf industrial robot will struggle to hit the tight tolerances required in the aerospace manufacturing industry, especially for such applications as machining and high accuracy assembly (3). Accuracy is not the only issue with using industrial robots in machining and high accuracy assembly applications. Reduced stiffness, complex dynamic behavior, gear friction, backlash and jerk are contributing factors as well (4). The lack of stiffness in industrial robots has been addresses by original equipment manufacturers (OEMs) through three main approaches: (a) producing bigger structures, capable of higher payloads (e.g., KUKA Titan KR1000), (b) producing symmetric structures for an improved distribution of forces along the body of the robot (e.g., FANUC LR Mate series) , and (c) improving stiffness characteristics in key joints (e.g., MABI robots with increased stiffness in the 5th joint (5)). For the lack of accuracy, the preferred industrial approach for improvement when it comes to robot structures is the implementation of secondary encoders. Secondary encoders can be optical, inductive, or magnetic, but they all serve the same purpose – measure the true value of each of the robot’s joints position and feed it back into the robot controller to generate an updated robot kinematic model that will bring the robot tool center point (TCP) closer to the nominal/programmed position. Secondary encoders enhanced industrial robots were initially produced by integrators (e.g., Electroimpact (6)) but are nowadays supplied by robot manufacturers as well (e.g., FANUC (7) and MABI Robotic (5)).

While secondary encoders improve an industrial robot’s accuracy, the improvement is not necessarily valid across the entire working volume of the robot. Furthermore, each robot manufacture or system integrator has different approaches when it comes to assessing an industrial robot’s accuracy, even if they all tend to follow the BS EN ISO 9283:1998 – ‘Manipulating industrial robots – Performance criteria and related test methods’ standards (8). While laser trackers are suggested to be used for measuring robot TCP position and orientation in the BS EN ISO 9283:1998 standards, a variety of metrology equipment exists that could potentially be utilized. Furthermore, the equipment used by the manufacturer to assess repeatability and accuracy of a robot are not necessarily reported on in the datasheet of a purchased industrial robot. Environmental temperature conditions during testing can widely vary and most often are not reported on in the datasheet of a purchased industrial robot. The BS EN ISO 9283:1998 standard sets out criteria for an industrial robot’s performance assessment when no external excitation is present, which means that the standards might not necessarily be fit for purpose when it comes to machining applications.

Considering all the above, the present work is focused on assessing the performance of two secondary encoders industrial robot platforms, the Accurate Robotic Milling System (ARMS) and the MABI MAX-100-2.25P, by utilizing the BS EN ISO 9283:1998 standard but adapting the speed, payload, path form and working volume considered within the standard for a robot machining application driven approach. In addition, taking advantage of the fact that both platforms are controlled by Siemens 840 D sl controllers, an assessment of the Sinumerik Trace tool capabilities in assessing accuracy performance will be conducted.

The next section will provide a brief overview of previous research conducted in the space of accurate robotics that was deemed relevant to the present work.

Background

Since industrial robots started being used for applications beyond pick-and-place, which was their original intended use, the research on improving their performance, mainly the accuracy with which they perform tasks (such as machining or assembly), has intensified and the methodologies developed have been vast (9) (10) (2). The required accuracy of industrial robots is very much application driven. Broadly classified, there are two main approaches to improving a robot's accuracy: parametric and non-parametric. Most academic research concentrates on parametric calibration, which looks at improving the kinematic and dynamic modelling of a robot, which in turn will make the robot more accurate (11). For a less academic approach, the preferred method is non-parametric, where an iterative method is adopted in which a robot's TCP is corrected by a move-measure-correct routine (12). The iterative method is based on the fact that if enough iteration of the move-measure-correct routine are conducted, the error between the actual position or path of the robot's TCP and the nominal/programmed position or path of the robot's TCP will eventually reach zero. To achieve the calibration procedures discussed (kinematic, dynamic, iterative, etc.), sensors and highly accurate metrology equipment is needed for measuring the robot's TCP (13). Even if the calibration method is based on model identification and parameter estimation using kinematic and dynamic modelling, at some point, the accuracy of the methodology will need to be verified and validated and here is where measurements are needed. A variety of measuring equipment exists on the market with varying capabilities in terms of measuring a target – some can only do static measurements (in which case they can only be used to measure positional accuracy of a robot's TCP), some can do dynamic measurements but only unidirectional (in which case only x, y or z deviations in robot TCP can be measured but not all of them at the same time), some can do 3-axis dynamic measurements (in which case x, y and z deviation in robot TCP can be measured but rotational deviations around the 3-axis cannot be measured) and finally, some of them can do 6 degrees of freedom (DoF) deviations but will most likely come at a considerable mark up. With each type of measurement discussed, one key aspect to bear in mind is measurement uncertainty. Uncertainty is a measure of how much you can trust a measurement. One can reduce uncertainty in measurements but not eliminate it.

The preferred metrology equipment to measure robot TCP generally fall under two categories: laser trackers or vision systems (cameras, photogrammetry). Ballbars have been used in the past as well (10) and with the release of Renishaw's RCS L-90 ballbar aimed specifically at robot calibration, it is expected that more research is to come in this space.

For the current work, a Leica Absolute Tracker AT960 with a Leica T-Mac Inspect TMC30-I have been used to track the robot TCP of both the ARMS and MABI MAX-100-2.25 platforms.

The next section of the paper, Methodology, is split between a description of the equipment utilized and the experimental methods implemented.

Methodology

For the work presented in this paper, two different platforms have been tested for path following capabilities. Both platforms were controlled via Siemens 840 D sl controllers at the time the experiments took place. Since then, the MABI MAX-100-2.25P platform has been upgraded to Sinumerik One. As previously mentioned, the measurements have been taken using a Leica Absolute Tracker AT960. The methodology implemented for the experimental stage of the work, including robot TCP speeds, robot paths development and robot payload description, is presented in this section.

Equipment

Accurate Robotic Milling System (ARMS)

The Accurate Robotic Milling System (ARMS) shown in Figure 1, is a six-axis industrial robot (KUKA Titan KR1000 L750) upgraded with the 'Accurate Robot' solution provided by Electroimpact (6), which includes:

- Replacement of the original KUKA KRC 4 controller with a Siemens 840 D sl controller.
- Renishaw optical secondary encoders on each of the six joints of the robot.

The ARMS platform is fitted with a GMN HCS 280-18000/60 high frequency spindle which features an HSK-A-100 spindle interface and has a maximum spindle speed of 18,000 RPM (approximate weight 525 kg). ARMS has dual motors on joints 1, 2 and 3; this motor configuration is referred to as 'master-slave' motor grouping. A constant torque offset between the master and slave motors can be applied using the controller to minimize backlash and reduce any lost motion in the drive when changing direction.

Figure 1. Accurate Robotic Milling System (ARMS).

MABI MAX-100-2.25P

The MABI MAX-100-2.25P system, seen in Figure 2, is a six-axis industrial robot that had at the time of experiments inductive encoders on each of the six joints of the robot body. At the time of writing, the system was controlled via Siemens 840 D sl controller. The robot also has enhanced mechanical stiffness in its fifth joint and single motor drives on all its six axes (5). The robot was unloaded during trials.


Figure 2. MABI MAX-100-2.25 P.

Leica Absolute Tracker AT960 with T-Mac Inspect TMC30-I and T-Probe

The Leica Absolute Tracker AT960, seen in Figure 3, is a metrology solution offered by Hexagon. It is capable of measurements of a frequency of 1000Hz in 6DoF and can be used with a variety of accessories such as spherically mounted retroreflectors (SMR), T-Mac Inspect TMC30-I or T-Probe (Figure 4). The accuracy of the Absolute Tracker AT960 is specified as: ±15 µm + 6µm/m (14). The Leica T-Mac Inspect TMC30-I is a 'machine control probe' that works in 6DoF and is used mainly in applications requiring automation (15). The Leica T-Mac can be mounted onto robots and large machines which made it suitable for the present work. The Leica T-Probe is a 'portable coordinate measurement machine (CMM)' solution used for probing in 6DoF (16).

Figure 3. Leica Absolute Tracker AT960 (14).

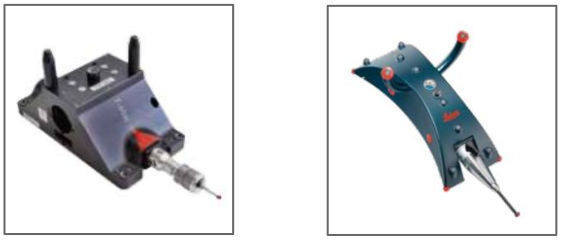
Figure 4. Left – Leica T-Mac Inspect TMC30-I; Right – Leica T-Probe (15) (16).

Method

As seen in Figure 1 and in Figure 2, the ARMS platform has a machining spindle attached to it and a feasible working area defined by the machining bed (part of which can be seen in Figure 1, right corner), while the MABI MAX-100-2.25P robot has no end-effector attached to it. As such, it is worth mentioning that the experimental method had the following limitations:

1. The likely negative impact on the path following accuracy of the ARMS platform, due to being loaded with an end-effector weighing approximately 525 kg, should be taken into consideration.
2. The experimental trials were conducted with the two platforms not experiencing any external excitations (such as machining forces). Therefore, in the context of robot machining, the path accuracy results should be considered indicative only.

The nominal path to be followed by the robot TCP of ARMS platform robot and MABI MAX-100-2.25P robot was designed based on the optional positioning path accuracy test path outlined in BS EN ISO 9283:1998 standard (8), however, it has been specifically adapted to include features representative of a machining operation:

- Linear motions parallel to base coordinate system (X+, X-, Y+, Y-).
- Linear motions 45 degrees to base coordinate system.
- Clockwise semi-circular motion (80 mm radius).
- Anti-clockwise semi-circular motion (40 mm radius).
- Matching clockwise and anti-clockwise circular motions. (5 mm; 10 mm; and 25 mm radius).
- Rapid changes in direction.

The test path (toolpath in machining terms) was generated using Mastercam CAD/CAM software and is illustrated in Figure 5. The arrows represent direction of travel of the robot TCP and are colour coded dependent on the type of motion (e.g., the yellow arrow is the start of the path, and it is in the negative X-Y plane, while the red arrow is in the positive X-Y plane). Robotmaster add-on in Mastercam was then used to generate the NC programs for the two robot platforms.

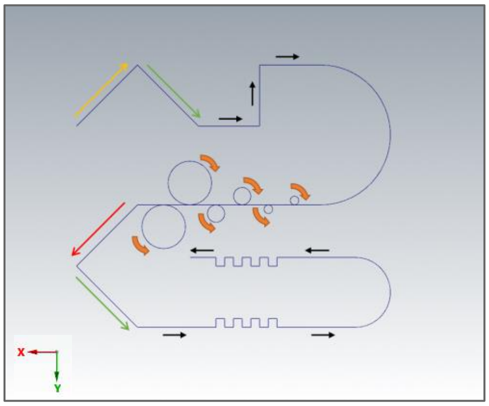

Figure 5. Test path.

On both platforms, the test path was designed to fit within a 400 x 400 mm square test plane, to keep to the BS EN ISO 9283:1998 standards procedure. 'Plane 3' (Figure 6) defined in BS EN ISO 9283:1998, was used as it was considered most representative to robotic machining (i.e., parallel to the X-Y plane).

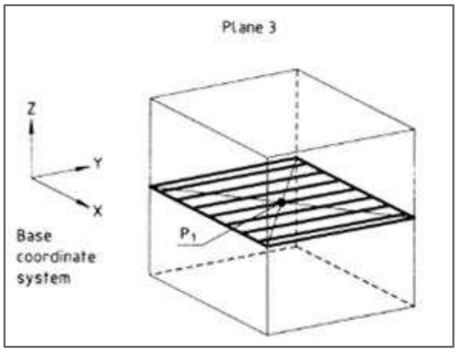

Figure 6. 'Plane 3' test path location in BS EN ISO 9283:1998 standard (8).

On the ARMS platform, the test planes were located parallel to the machine bed in the area where machining operations are most typically performed (see Figure 7).

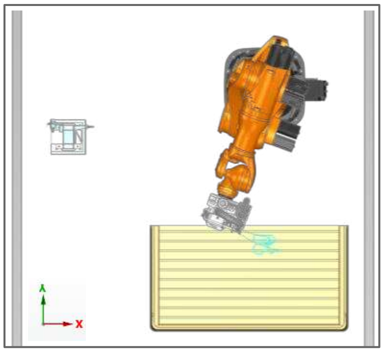

Figure 7. Robotmaster generated visualization of test path location on the ARMS platform.

These machining positions were replicated on the MABI MAX-100-2.25P platform using a ratio-based approach, dependent on the maximum reach of the MABI MAX-100-2.25P robot compared to the KUKA Titan robot in X, Y and Z directions. It is also worth mentioning that the test path was generated so that the edges of the test cube were parallel to the base coordinate system of each robotic platform to comply with the BS EN ISO 9283:1998. Each test path was run 10 times as per the same standard.

The datum locations (or G54 in machining terms) for both platforms are presented in Table 1. The coordinate system for both platforms was defined as seen in Figure 7 and Figure 8, with +Y towards the back of the robot and +Z in the upward direction.

Table 1. ARMS and MABI MAX-100-2.25P datum location.

	X (mm)	Y (mm)	Z (mm)	A (°)	B (°)	C (°)
ARMS	0	-2500	1200	0	0	0
MABI	0	1558	748	0	0	0

The datum locations were calculated with respect to the robot base. The robot base was measured with the Leica Absolute Tracker AT960 and the Leica T-Probe.

The method for performing the path accuracy trials on ARMS and the MABI MAX-100-2.25P were equivalent. Therefore, for brevity, only the method for performing the path accuracy trials on ARMS will be described.

Prior to performing the trials, ARMS was calibrated to ensure optimal path following accuracy. The Leica Absolute Tracker AT960 was then setup so that the laser tracker's line of sight was aligned with the Y-axis of ARMS (Figure 8). For maximum measurement accuracy, the laser tracker was then warmed up for two hours. Following this, the standard setup and pre-usage procedures for the laser tracker were followed.

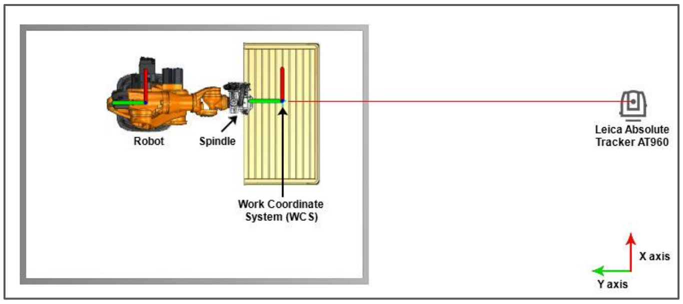

Figure 8. Experimental setup on ARMS platform.

Prior to conducting the path following accuracy trials, a robot warmup routine was executed for 40 minutes. Following this, the NC programs were loaded into the Siemens HMI, and measurement plans were executed in SpatialAnalyzer (SA) software, which was the software used for the Leica Absolute Tracker AT960. At the start of each test cycle the NC program first moved the robot TCP to the datum location/ Work Coordinate System (WCS) (as defined in Table 1). At the datum location, a measurement frame of the robot TCP was recorded using the Leica Absolute Tracker AT960. This measurement frame would later be used to align the test path measurements recorded by the laser tracker (and Sinumerik Trace tool) with the nominal test path in SA to allow for the path accuracy of the robot to be evaluated. The Sinumerik Trace tool was setup to dynamically measure the robot TCP. The NC variable 'VA_IW[n]' was loaded into the trace function to dynamically measure the robot TCP location of individual axes in relation to the datum location; entering the numbers 1-6 in the '[n]' field indexes axes X, Y, Z, A, B and C, respectively. The trace function sampling rate was set to an effective rate of 0.0640 s/samples or 15.625 Hz. With the Sinumerik trace function activated and the Absolute Tracker AT960 measuring, the NC program executed the test path in air at a feed rate (robot TCP speed) of 5000 mm/min for 10 test cycles. The chosen feed rate was based on a realistic feed rate for machining aluminium. As mentioned before, the feed rate and payload were the variables in which the present experimental methodology deviated from the BS EN ISO 9283:1998 – 'Manipulating industrial robots – Performance criteria and related test methods' standard.

The next section of the paper will cover the results.

Results

The data analysis was conducted mainly in SpatialAnalyzer (SA) software and Microsoft Office Excel.

To evaluate the path following capabilities of the two robotic platforms (ARMS and MABI MAX-100-2.25P), the test path measurements recorded by the Leica Absolute Tracker AT960 were compared with the nominal test path in SA using measurement plans. A CAD file of the nominal test path at the pre-measured datum location was imported into SA. This allowed for the deviation of the measured test path from nominal to be calculated. The deviation of each measured test path from the nominal test path was calculated using the Query Points to Objects function in SA; the measured test path was selected as 'Points'; and the nominal test path was selected as the 'Object' (Figure 9). Furthermore, the X, Y, Z, A, B, C recordings from the Siemens Trace tool were imported into SA to allow performance analysis between the Absolute Tracker AT960 measurements and the Trace tool.

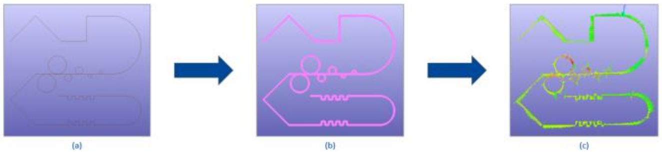

Figure 9. (a) Nominal test path; (b) Measured test path; (c) Vector visualisation of deviation between measured and nominal test path in SpatialAnalyzer.

The following statistical metrics were reported on: Deviations Root Mean Square (RMS), Minimum Deviation Magnitude (Min Mag), Maximum Deviation Magnitude (Max Mag). The measurement deviations from the nominal path and the Trace tool deviations from the measurement deviations were analyzed over the 10 runs and an average for each metric was then calculated. The results for the ARMS platform are summarized in Table 2 and the results for the MABI MAX-100-2.25P are summarized in Table 3.

Table 2. ARMS results.

Leica Absolute Tracker AT960 measurements VS nominal path			
Average RMS over 10 runs (mm)	**Average Min Mag over 10 runs (mm)**	**Average Max Mag over 10 runs (mm)**	**Average StdDev from Average over 10 runs (mm)**
0.14657	-0.30837	0.45356	0.10483
Siemens Trace tool recordings VS Leica Absolute Tracker AT960 measurements			
0.12841	0.00804	0.33736	0.05633

Table 3. MABI MAX-100-2.25P results.

Leica Absolute Tracker AT960 measurements VS nominal path			
Average RMS over 10 runs (mm)	**Average Min Mag over 10 runs (mm)**	**Average Max Mag over 10 runs (mm)**	**Average StdDev from Average over 10 runs (mm)**
0.1187	-0.27854	0.45209	0.10673
Siemens Trace tool recordings VS Leica Absolute Tracker AT960 measurements			
0.11905	0.00413	0.39775	0.06504

Figure 10 represents a visual representation of the deviations from the nominal path for the ARMS platform, while Figure 11 represents the deviations of the Siemens Trace tool recordings from the Absolute Tracker AT960 measured data.

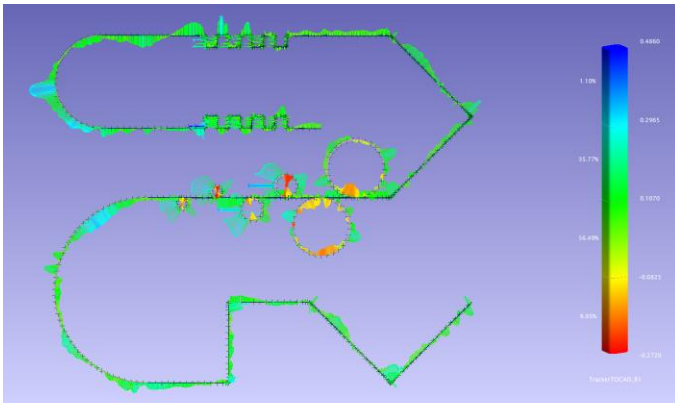

Figure 10. ARMS platform – deviations from nominal path.

In both Figure 10 and Figure 11, the sizes of the vector objects have been magnified for visualization purposes.

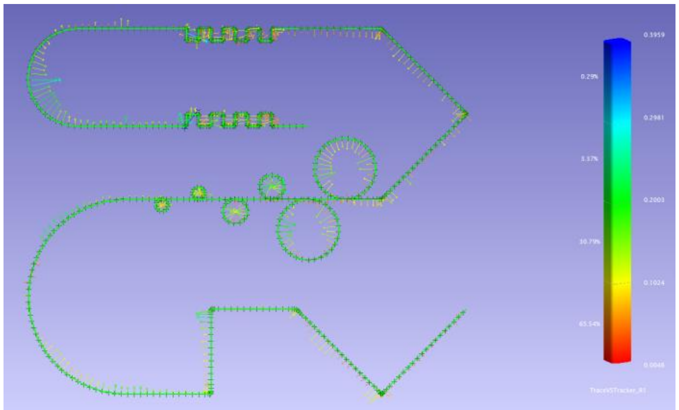

Figure 11. ARMS platform – deviations of Siemens Trace tool data from measured points.

In Figure 11 the density of the vector objects is reduced compared to Figure 10. This is due to the low sampling frequency of the Siemens Trace tool data.

In the same way, in Figure 12 and Figure 13 the results for the MABI MAX-100-2.25P platform are presented.

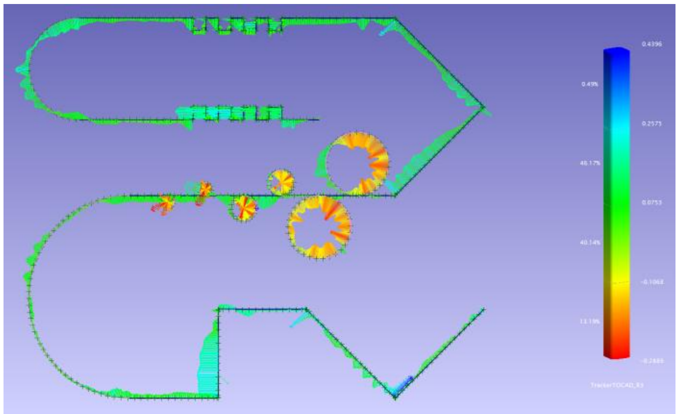

Figure 12. MABI MAX-100-2.25P platform – deviations from nominal path.

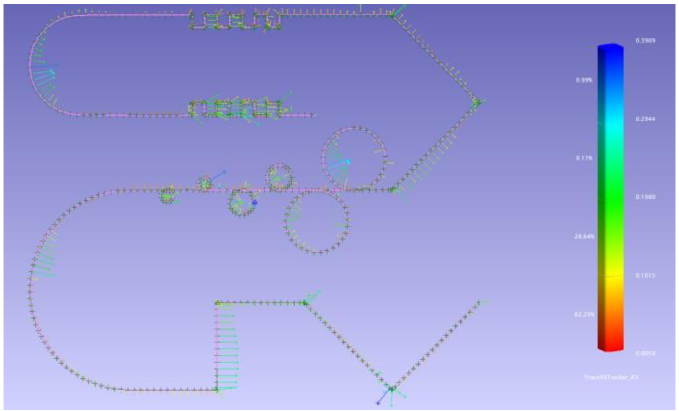

Figure 13. MABI MAX-100-2.25P platform – deviations of Siemens Trace tool data from measured points.

Summary/Conclusions

In this paper two secondary encoders, Siemens 840D sl controlled robotic platforms have been assessed for their capability in accurately following a novel test path. One platform, ARMS, has a maximum payload capacity of 750kg, while the MABI MAX-100-2.25P platform has a maximum payload capacity of 100kg. However, the ARMS platform was loaded with a spindle of an approximate 525kg weight, while the MABI MAX-100-2.25P was unloaded during the experimental trials. It is believed that the payload on the ARMS platform has influenced its performance. The robot TCP speed, 5000 mm/min, was kept the same for both platforms during the experimental trials and it is considered representative of machining of aluminum parts.

The average deviations RMS for the ARMS platform was found to be approximately 0.15 mm and the MABI MAX-100-2.25P average deviations RMS value was approximately 0.12 mm (over 10 identical runs). In terms of the maximum deviations' magnitude, for the ARMS platform and the MABI MAX-100-2.25P platforms it was approximately 0.45 mm. Depending on the application, a maximum deviation of 0.45 mm from a commanded path could be considered too high. Looking at Figure 10 and Figure 12, the MABI MAX-100-2.25P platform seemed to perform better in circular moves than the ARMS platform (with orange-red vectors indicating higher accuracy and green-blue vectors indication lower accuracy) but a direct comparison would be unfair as the ARMS platform is equipped with a heavy payload.

In terms of the Siemens Trace tool, one of the downsides was the low sampling frequency. Important data can be missed in a dynamic process if the sampling frequency is too low. When compared to the Leica Absolute Tracker AT960 results, an average deviations RMS of 0.12 mm for both platforms was calculated. This is indicative of the fact that the tracking tool could be utilized as a means of assessing the accuracy with which a nominal path is followed to a certain extent. However, with maximum deviations RMS of over 0.39 mm for both studied platforms, its utilization is dependent on the tolerance requirements of the considered application.

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Definitions/Abbreviations

SA	SpatialAnalyzer
RMS	Root mean square
SMR	Spherically mounted retroreflector
StdDev	Standard deviation
TCP	Tool centre point
WCS	Work coordinate system