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Development of a Non-Parametric Robot Calibration Method to Improve Drilling Accuracy

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Abstract

The drilling of large quantities of repetitive holes during the manufacture of large aerospace components is often considered a key limiting factor with regards to production efficiency. Whilst the desire within aerospace is to use relatively cheap six axis robot arms with drilling end effector units, their poor accuracy remains an obstacle. Robot calibration presents a way of improving robot accuracy such that aerospace drilling tolerances can be met, without permanently committing metrology equipment to an automation cell during production. Extensive research has been conducted into robot calibration by correcting the kinematic model, known as parametric calibration. This method is highly complex, and calibrates the robot across the entire working volume. This is often not required in industrial drilling applications, as drilling routines are often contained within a smaller volume of the robot reach. In this paper, a non-parametric method of robot calibration is proposed. This method involves calibrating within regions of the working volume where the robot pose is similar, and thus the effects of geometric errors in the kinematic model are roughly constant. By establishing the average positional error for each region, the accuracy can be locally improved by compensation through definition of the tool centre point. The proposed method can be completed without the use of kinematic models or complex mathematics, making it more suitable to industrial users. From experimental trials, a significant improvement in the positional accuracy of holes drilled using a standard six axis robot is reported, from 2 mm to 0.1 mm, well within the requirements of the majority of aerospace applications.

Introduction

The drilling of many repetitive holes is often required for large aerospace components. This type of drilling is considered to be one of the key limiting factors with regards to production efficiency. In order to increase production rates in the aerospace sector, there is a desire to bring six axis robot arms with drilling end effector units into production lines. These systems can provide a flexible automation solution, with smaller factory footprints compared to large automation systems previously used for drilling operations.

A challenge with these systems is that off the shelf robot accuracy is not sufficient for aerospace applications, where the majority of components can call for tolerances in the range of ±0.2 mm [1]. Positional accuracy is rarely quoted for six axis robots, however from previous research conducted at the University of Sheffield's Advanced Manufacturing Research Centre (AMRC), the accuracy of standard six axis robots is in the order of millimetres. Traditionally, robot inaccuracy is compensated for by manually 'touching-up' each programmed point. This is a prohibitively time consuming process for large components with many holes, and the accuracy of these touched up points is inherently limited as it relies on operator judgement. This touching-up method also requires repeatable fixturing, and is inherently inflexible due to the work required to modify a part location.

To compensate for this inaccuracy without requiring the manual touch-up of each point, industrial robot drilling systems can utilise a metrology system such as a laser tracker. After the robot has reached a programmed point, the position is measured with a tracker, and corrective data is provided to the robot to amend its position prior to drilling. This process can be completed iteratively, as shown by the authors in [2], and repeated for each hole in order to ensure accuracy across the part. Similarly, dynamic correction of a robot path can be implemented using a laser tracker [3]. The drawback to correction methods is that they require a metrology system to be in place whenever the cell is running, which commits expensive equipment that could be used for other tasks. Another option is to retrofit encoders to the joints of the robot to improve joint angle measurement, as demonstrated in [4]. Whilst this method is promising, it does require significant work in the installation and integration of the robot and encoder system, increasing the complexity and cost of the automation solution.

Robot calibration presents an alternative. Robot calibration can cover a broad range of methods, but it essentially consists of measuring and quantifying robot error. This information is then used to inform and correct future production programs. The key benefit of robot calibration, compared to position correction as discussed above, is that a metrology system is only required for the calibration process. Once calibration has been completed, the metrology system is no longer required and can be freed up for other tasks. Retrofitting of additional sensing equipment is not required for robot calibration, allowing off the shelf robots to be used.

Robot calibration can broadly be split into two methods, parametric and non-parametric calibration. Parametric calibration involves modifying parameters in the robot model, and can further be sub-divided into kinematic, and non-kinematic parametric calibration. An overview of the theory of robot calibration is given in [5], where the authors discuss the theory surrounding parametric calibration. Kinematic calibration involves modifying the kinematic model of the robot based on geometrical error measurement, and is also referred to as level 2 calibration. In [5] the authors state that kinematic calibration can be split into four steps: producing a kinematic model of the robot, taking measurements of the robot about its working volume, identifying parameters from the measurements, and then correcting the kinematic model using the identified parameters. Furthermore, kinematic calibration assumes that the joints of the robot are rigid, and that no undesired motion occurs in the robot axes. Where this assumption is not valid, non-kinematic calibration can be used. Non-kinematic calibration involves the measurement of non-geometric sources, such as joint flexibility, gear backlash, and temperature. When kinematic and non-kinematic calibration are combined, this is also known as level 3 calibration.

Robot calibration is often achieved using portable 3D metrology equipment, such as a laser tracker [6], a portable measuring arm [7], an optical Co-ordinate Measuring Machine (CMM) [8], or a portable photogrammetry system [9]. In [10] the authors demonstrate a calibration using a fixed CMM, however this is not appropriate for an industrial setting as a CMM typically requires laboratory conditions, rather than those found in an industrial cell.

In [6] the authors used a Faro Xi laser tracker to perform a parametric kinematic calibration of an ABB IRB 2400/L robot, using a single spherically mounted retroreflector (SMR) on the robot flange to measure Tool Centre Point (TCP) co-ordinates. The authors then used an iterative technique to solve the robot model, which used modified Denavit-Hartenberg (D-H) parameters. This resulted in a Root Mean Square (RMS) and maximum positioning error after calibration of 0.507 mm and 0.641 mm respectively. In [7], an ITG ROMER measurement arm was used to perform a parametric kinematic calibration of an ABB IRB2000 robot. The authors measured the TCP point co-ordinates using the arm, and also used an iterative method to solve the robot kinematic parameters, and resulted in an average accuracy improvement from 1.4 mm to 0.3 mm.

Non-kinematic errors, specifically joint compliance errors and thermal errors are investigated by the authors in [11], in addition to kinematic errors. In [11] the authors develop an empirical thermal model by measuring the position of the robot, along with the temperature at varying locations on the robot with thermistor sensors.

In [12] the authors develop a level 3 calibration (a combination of kinematic and non-kinematic calibration) using a laser tracker. A model of the robot is created using a combination of modified D-H parameters, parameters to locate the robot root frame, compliance parameters for joints two to five, and additional parameters to describe the non-linear behaviour of joint six. Optimal robot calibration configurations were determined using an iterative algorithm, and the accuracy measured in 1000 robot configurations. This resulted in mean and maximum error values of 0.364 mm and 0.696 mm respectively, down from an initial 0.968 mm and 2.158 mm. In [9], both a Creaform MaxSHOT 3D photogrammetry system and a FARO ION laser tracker are used to calibrate a FANUC LR Mate 200iC. This paper focussed on the performance of the photogrammetry system calibration, with the laser tracker calibration used as a standard to compare against. The nominal mean / max errors of the un-calibrated robot are given as 1.744 mm and 3.841 mm respectively. After photogrammetry calibration this was reduced to 0.197 mm and 0.619 mm, compared to 0.147 mm and 0.589 mm achieved with laser tracker calibration. This shows comparable results for both systems, with the photogrammetry system being a more cost effective solution compared to a laser tracker.

Portable 3D metrology equipment of the required accuracy for robot calibration can be costly, although the cost can vary depending on the technology chosen. A benefit of using portable 3D metrology equipment however, is that many industrial users of robot calibration may already have access to this type of equipment as part of a product inspection process. Owing to its portable nature, the metrology equipment given above can easily be re-purposed to conduct a robot calibration.

A ball bar system has also been used for robot calibration in [13]; the benefit of this method is the low cost of a ball bar when compared to a portable metrology system. It is limited to small robots operating in a small working area however, although the authors propose further work to extend the working volume of the calibration.

The papers discussed above have all considered parametric calibration, covering both kinematic and non-kinematic calibration. The issue with parametric calibration is that it is highly complex, and requires a detailed knowledge of robot modelling to complete. This can make parametric calibration undesirable for industrial automation users. In [14], the authors demonstrate a non-parametric method of robot calibration through iterative teaching of points. A KUKA KR240 R2900 ultra robot was calibrated by measuring the robot TCP positions using a Leica AT960 tracker with a T-Mac 6 Degrees of Freedom (DoF) probe over 30 runs and calculating a mean attained pose. The error between the mean attained pose and the command pose was then used to correct the command pose. This calibration process was repeated three times, resulting in a maximum error 0.058 mm. For this work the robot end effector was kept in a constant orientation, i.e. a 3 DoF process. The calibration performance was re-measured after a week, with a maximum error of 0.1 mm found, suggesting that the calibration could remain valid for a number of weeks. In the same paper, the accuracy of the robot over small scales was measured using a Renishaw XL-80 laser interferometer after the calibration process. It was found that the errors of the robot were similar across small areas, with only minor errors being measured within 10 mm of the taught pose. This is attributed to the robot pose being similar to that of the taught pose within small deviations; as expected the accuracy of the robot deteriorated as the robot travelled further away from the taught pose.

The benefit of non-parametric calibration is that it is a simpler process, not requiring complex mathematics or modelling to solve. This lack of complexity means that it can be more readily adopted by industry, and can be easily repeated as required to ensure calibration validity. A limitation compared to parametric calibration is that it does not calibrate for the entire robot working area, however in practise this is not such a major concern. Industrial robot cells are rarely required to be accurate over their entire volume; instead, they are focussed over a smaller range for accurate applications such as drilling.

The aim of this work was to develop a non-parametric calibration method to improve robot accuracy for 6DoF drilling applications, by calibrating over an area by averaging the errors measured in that area. There are two main benefits to calibrating over an area, rather than individual points. Firstly, for complex parts with large numbers of holes; less measurement points are required, speeding up the process. Secondly, calibrating over an area allows for an amount of flexibility in the robot program; meaning that one calibration could be valid for either a family of similar shaped parts, or could accommodate small changes due to misalignment in the workpiece or fixture. The effectiveness of the calibration was tested by conducting 6DoF drilling trials with the robot.

The following sections of this paper show the equipment and methodology used during this work, followed by the results of the drilling trials. The paper concludes with a discussion on the results.

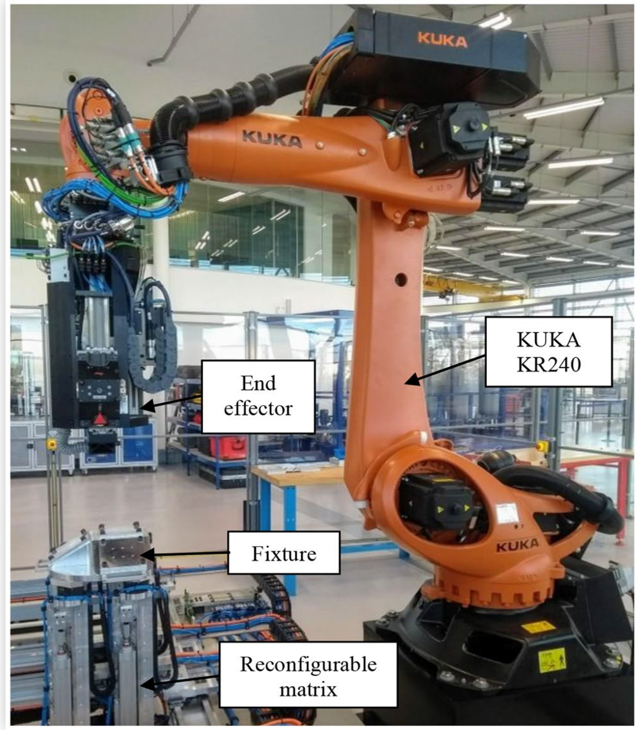
Methodology

Cell Setup

The VIEWS cell within the AMRC's Factory 2050, Sheffield, UK was used for this work. This cell contains a KUKA KR 240 R2900 ultra robot, which has a rated payload of 240 kg and a specified pose repeatability to ISO 9283 of ±0.06 mm [15]. The drilling end effector is of a bespoke design developed by the AMRC for a previous project, and includes a pressure foot to pre-load the robot prior to drilling. A reconfigurable matrix is contained within this cell to allow for reconfigurable fixturing, however for this project the fixture was kept nominally in the same location directly in front of the robot. This setup is shown in Figure 1 below.

In order to provide a permanent reference between calibration and drilling trials, seven Brunson 1.5THNDN 1.5" SMR nests were fixed to either the cell floor or the fixed robot base casting. The relative location of these nests was mapped using SpatialAnalyzer 2018.01.12 (SA) and an AT960-LR laser tracker to generate a Unified Spatial Metrology Network (USMN). These seven points were located with a RMS error of 0.007 mm.

FIGURE 1 Robot and end effector in the VIEWS cell at the AMRC's Factory 2050.



Fixture and Coupons

A bespoke fixture was designed and manufactured to hold four test coupons during drilling trials, this is shown in Figure 2. These coupons were labelled top, front, left, right; with front facing away from the robot. The assembled fixture with coupons is shown in Figure 3. The fixture was machined from 2014 series aluminium, and was designed to hold 4 coupons at a nominal angle of 30° from each other. This was in order to force the robot to adopt a wide range of 6DoF poses

FIGURE 2 The fixture used for drilling trials. Three of the SMR nests are shown, with the remaining three on the back face of the fixture.

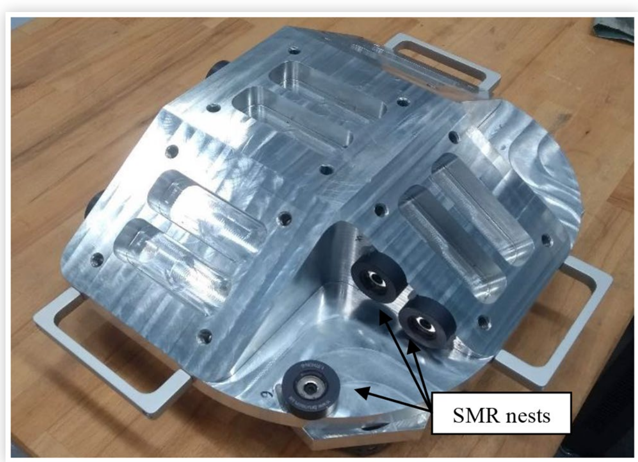
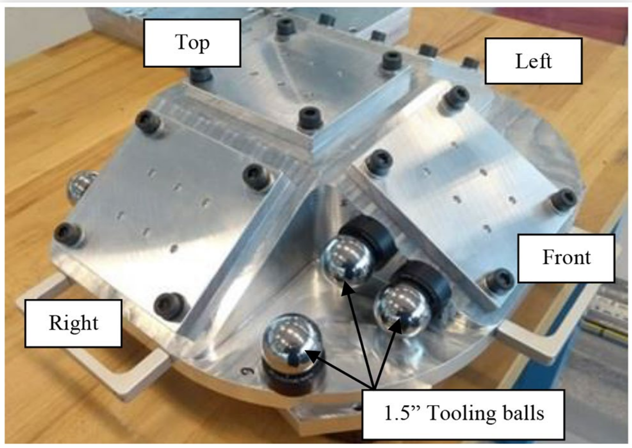


FIGURE 3 Assembled fixture with coupons and tooling balls after drilling.



to bring the end effector normal to a coupon for drilling. Six Brunson 1.5THDN-B bolt on 1.5” SMR nests were bolted to the fixture, as shown in Figure 2. These were used with 1.5” SMRs to locate the fixture prior to trials with an AT402 laser tracker, and subsequently with 1.5” tooling balls to locate the fixture in a CMM prior to inspection as shown in Figure 3. Using these nests for locating the fixture had the advantage that both the on-site tracker measurements and CMM inspection measurements referenced the same co-ordinate system.

After manufacture, the fixture was characterised with a Mitutoyo 122010 model CMM. This inspection reported the as-manufactured angles of coupon contact planes relative to the fixture co-ordinate system. Plane angle data was used to construct a characterised ‘as-manufactured’ model of the fixture, which was used in robot programming and analysis. Flatness was also measured on the coupon contact planes, and a maximum flatness error of 0.013 mm was reported.

Test coupons for drilling trials were manufactured from 5083 series aluminium, and were 140 x 130 x 12.7 mm in size. This grade and thickness was chosen as it could be supplied with a thickness and flatness tolerance of ±0.1 mm. The coupons were held in place with four M8 bolts, as shown in Figure 3. Six 6.35 mm diameter holes were drilled in each coupon as part of these trials, with a minimum spacing of 30 mm between hole centres.

Drilling Trial Procedure

For each drilling trial, the fixture was assembled and located using an AT402 laser tracker. Prior to each drilling trial the fixture coupon contact faces, SMR nests, and coupons were cleaned using lint free cloth and cleaning solvent. This was to remove any contamination, in order to ensure repeatability of the location of coupons and SMRs between trials. The thickness of the coupons was checked prior to being bolted to the fixture, to ensure that they were within specification. The fixture was then placed on the reconfigurable matrix and locked into place, as shown in Figure 1.

Once the fixture was in place, the location of the fixture relative to the robot root was measured. The robot program was then updated to match this measured fixture location. This was achieved by updating a single robot base co-ordinate, which corresponded to the measured fixture co-ordinate system. No individual points were touched-up. After fixture location, the drilling program was then executed.

Once the drilling program had been completed the 1.5” tooling balls were placed in the fixture SMR nests, and the fixture was transported to the CMM lab. The fixture was then left overnight to thermally adjust to the lab environment prior to inspection. The CMM inspected hole centre position by measuring a cylinder and local plane for each hole. The axis of the cylinder was then projected onto the local plane to give a centre point.

Six drilling trials were completed during this work, three with the robot in a baseline state, and three after calibration.

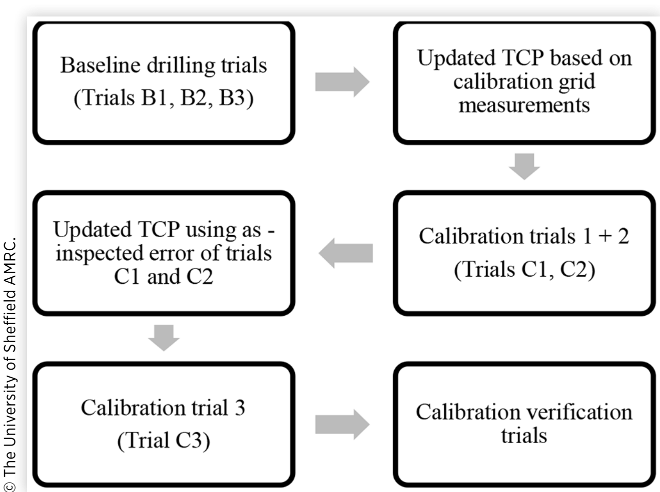
Process Overview

Figure 4 shows an overview of the process used in this work. These steps are described in further detail in the following sections.

Baseline Trials

In order to benchmark the performance of the calibration method used in this project, drilling trials were completed with the robot in an ‘off the shelf’ baseline state. In order to locate the fixture relative to the robot, the robot was measured with an AT960-LR laser tracker and SA to calculate the robot root position. This was reported relative to the USMN nests for ease of location in subsequent trials. The TCP of the end effector was taken from nominal CAD data, as is common in industry. Both TCP and robot root location were kept constant throughout the baseline trials.

FIGURE 4 Process overview



Calibration Procedure

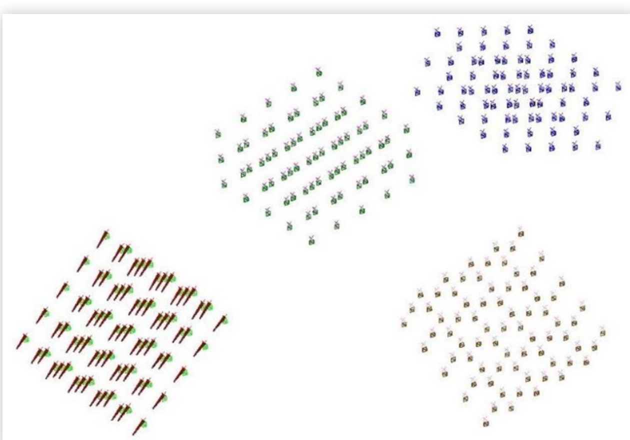
The key principle behind the developed calibration method is to calibrate the robot for a localised area, where the robot pose is similar throughout. The rationale for this approach is that often multiple points in a robot program have a similar robot pose, and the errors will frequently be similar across these points. This calibration is applied by establishing the average positional error for each area, and offsetting the TCP for that area accordingly. The size of these calibration areas is down to user discretion and will be dictated by accuracy requirements, program complexity, and part complexity.

For this work the program was split into four calibration areas, one for each coupon. A robot program was generated that drove the TCP to a 5x5x3 grid of points at 20 mm spacing centred on the centre point of each coupon. This spacing was selected to capture the accuracy of the robot around the drilled hole positions. The robot was driven to these points, and the TCP position was measured using an AT960-LR laser tracker and Leica T-Mac in SA. This measurement is shown in Figure 5. For the initial calibration program, the baseline robot root location and TCP were used.

Following this calibration measurement, each nominal grid point had a measured point and an associated error. The positional error for each point was averaged over the corresponding calibration grid to give an average grid error. Each grid corresponded to a coupon, and the TCP for that coupon was offset by the corresponding average grid error. The TCP was offset in the XY plane only, with Z representing the drilling axis. This was as minor deviations in Z were accounted for by the end effector through the pressure foot. These offset TCPs were kept constant for calibration trials C1 and C2.

Following calibration trials C1 and C2, the as-inspected error of drilled holes was used to further offset the coupon TCPs. This followed a similar approach as above; the drilled hole error was averaged per coupon over both calibration trials C1 and C2. The TCP for each coupon was then offset using the corresponding average coupon error. This further offset TCP was used for calibration trial C3. Throughout all of the calibration trials, the robot root frame was kept constant, only the TCP was modified.

FIGURE 5 Calibration grid with measured points. Error vectors are shown on the right coupon.



Calibration Verification

After drilling trials were completed, the calibration grid measurement used for calibration trials C1 and C2 was repeated 30 times. A full calibration grid program repeated 30 times would take in excess of 12 hours, so the program was split by coupon - i.e. the top coupon was ran 30 times in one program, the left coupon was ran 30 times in a following program, etc. The results of these 30 verification runs were used to assess the repeatability of the calibration grid process, and to verify the calibration grid used in drilling trials.

Results

Results are described graphically below for each calibration method. Both RMS and maximum error are reported, as is standard deviation from the average (StDev). Errors are reported for each trial, rather than each individual coupon.

Baseline Trials

Figure 6 shows the measured errors from the baseline trials. From previous AMRC experience the accuracy of six axis robots is typically 2-4 mm, and the baseline errors shown were of a similar magnitude. All three baseline trials produced similar results. This was as expected as the robot program was mostly identical between these trials, the only variable was fixture location which was kept to a minimum. This variation in data was attributed primarily to robot repeatability, but also effects due to the change in fixture location. It is thought that these effects would arise as different areas in the robot working volume would cause different characteristics in the robot kinematic model, such as gear backlash and hysteresis.

FIGURE 6 Baseline trial results

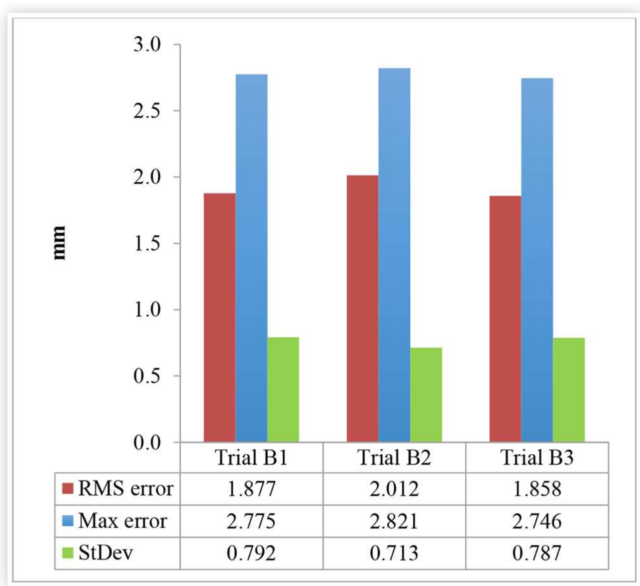
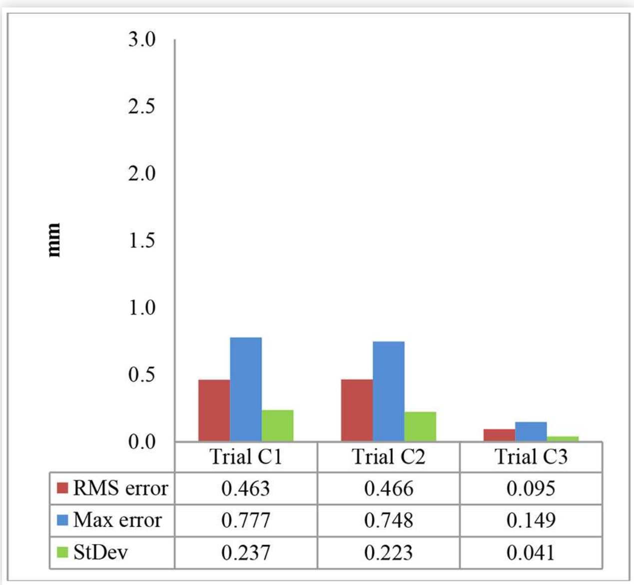


TABLE 1 Calibration trials TCP offset magnitude from baseline TCP

Coupon	Trial C1 and C2 TCP offset magnitude (mm)	Trial C3 TCP offset magnitude (mm)
Top	0.301	0.561
Left	2.088	2.750
Right	1.740	1.660
Front	2.210	1.881

FIGURE 7 Calibration trial results



Calibration Trials

For each coupon, the TCP was offset using the figures shown below in Table 1. The measured errors for the developed calibration method are shown below in Figure 7.

The results from trials C1 and C2 showed RMS and maximum errors considerably lower than the baseline trials. This method was then further refined for trial C3, as discussed above. The refinement resulted in a significant improvement; with an RMS error of 0.095 mm and a maximum error of 0.149 mm

Calibration Verification

For each calibration verification trial, the average X and Y errors per coupon grid were recorded, these figures were then combined into a resultant magnitude per coupon. Figure 8 shows resultant magnitude data for each coupon. The lower line of each box represents the 25% quantile, the middle line represents the median of the data points (50% quantile), and the upper line of the box represents the 75% quantile. The top and bottom whiskers are the maximum and minimum values of the data points. The red points represent the TCP offset magnitude used for calibration trials C1 and C2.

FIGURE 8 Calibration verification TCP offsets versus initial TCP offset for calibration trials C1 and C2

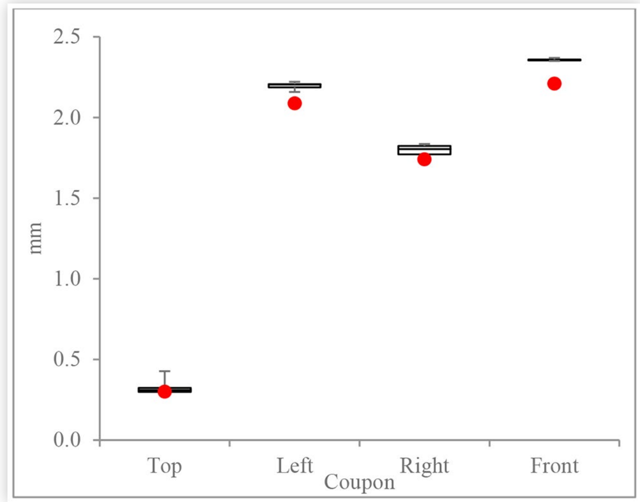


TABLE 2 TCP offset magnitudes from the calibration verification trials

Coupon	Maximum (mm)	Median (mm)	Minimum (mm)
Top	0.427	0.310	0.291
Left	2.221	2.204	2.158
Right	1.836	1.804	1.725
Front	2.369	2.355	2.350

The maximum, median, and minimum TCP offset magnitudes from the calibration verification trials are also shown in Table 2.

Conclusions and Discussion

The results shown in Figure 7 demonstrate that the developed calibration method can achieve the accuracies required of high accuracy robot drilling applications in the aerospace industry. From this, the developed calibration method can also be used for general accuracy improvements of robots for static processes (i.e. processes where the robot comes to a stop at key points, such as drilling or pick and place).

Figure 8 shows that the as-drilled TCP for trials C1 and C2 broadly aligns with the results from the calibration verification trials. There is a slight variation however, with a maximum variation of 0.146 mm between the as-drilled TCP offset magnitude, and the median results of the verification trials. The exact reason for this variation is unknown, however it is thought to be one of the following: firstly, the robot was not warmed up for the initial calibration grid measurements or drilling trials; both the grid and drilling program cycle times were short, meaning that mid-cycle temperature changes were not a concern. However, for the calibration verification trials the program for each coupon took approximately 3 hours, therefore a warm up cycle was required to prevent transient effects due to robot temperature change. This difference in robot warm up routine is thought to be one of the major factors in the variation of TCP offsets between as-drilled trials C1 and C2, and verification trials. Secondly, due to other project requirements, there was a period of over 18 months between initial calibration grid measurement and the calibration verification measurements. The robot was used for other work in this period, so physical changes to the robot such as wear may also have factored into the variation. Any variation in the initial calibration measurements were corrected, by using the as-inspected error of drilled holes to set the TCP for calibration trial C3.

The developed calibration method has several benefits when compared with other methods of improving robot accuracy. Metrology equipment is only required for the initial calibration procedure, not for production runs. This frees up expensive metrology resource that would otherwise be permanently committed to a production cell. In addition, the calibration can be further refined using drilled hole errors from an offline inspection (such as a CMM); this inspection step can also be used to correct any errors in initial calibration grid measurement. Calibration measurements can also be completed quickly; the calibration measurements for this work were completed in a day. This means that equipment hire can be a feasible option for companies that wish to improve robot accuracy, but cannot afford to purchase a laser tracker or other suitable metrology system.

In addition, the developed calibration method can be completed without specialist calibration software, saving significant cost. The calibration in this work was completed with SA and Microsoft Excel. As the calibration deals solely with TCP offsets, robot kinematic models and complex mathematics are not required. This results in a significantly simpler calibration process.

The main limitation of the developed calibration method is that it outputs calibrations that are fairly specific to a particular robot program. As the calibration is completed over areas, it is thought that the method could accommodate minor changes. These minor changes could include changing points within a calibrated area, or slight movements of parts between production runs due to a lack of repeatable fixturing. However the developed method could not accommodate a significant change to the program (new poses in an uncalibrated area) without requiring recalibrating. Whilst this is a limitation, it is thought that this would not be significant in an industrial setting. Robot cells in industry are commissioned with a particular program, which is intended to run for the entire production life of the cell. Minor changes are frequently incorporated, but a full reprogramming in production is rare as this would often require recommissioning of the robot cell.

Future work will focus on trialling the developed method on larger and more complex components. This will also investigate the relationship between calibration grid size, and resultant robot accuracy.

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Definitions/Abbreviations

AMRC - The University of Sheffield's Advanced Manufacturing Research Centre

CMM - Co-ordinate Measuring Machine

D-H - Denavit-Hartenberg

DoF - Degrees of Freedom

RMS - Root Mean Square

SA - SpatialAnalyzer 2018.01.12

SMR - Spherically Mounted Retroreflector

StDev - Standard deviation from the average

TCP - Tool Centre Point

USMN - Unified Spatial Metrology Network

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