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High-Speed 6DoF Tool Monitoring Using a Low-Cost Photogrammetric System

Ben Sargeant [1], Pablo Puerto [2], Charles Richards [1], Ibai Leizea [2], Asier Garcia [2] and Stuart Robson [1,*]

[1] University College London, Gower Street, London WC1E 6BT, UK; ben.sargeant.12@ucl.ac.uk (B.S.); charles.richards@ucl.ac.uk (C.R.)
[2] IDEKO, Basque Research and Technology Alliance (BRTA), 20870 Elgoibar, Spain; ppuerto@ideko.es (P.P.); ileizea@ideko.es (I.L.); agarciaberdote@ideko.es (A.G.)
* Correspondence: s.robson@ucl.ac.uk

Abstract: The capability of low-cost photogrammetric systems to provide live six degrees of freedom (6DoF) tracking of multiple objects offers great value in providing high-quality and consistent part production by automated manufacturing systems. However, monitoring of high-speed components, such as cutting heads, presents several unique challenges that existing systems struggle to meet. The solution given here uses a small number of short-exposure imaging sensors coupled with high-intensity lighting and retrorefective markers to allow for high-speed capture. The use of an initial characterization process carried out using IDEKO's VSET© system is followed by live object tracking in bespoke image processing software running on a consumer-grade computer. Once this system is in use, it can simultaneously capture images of multiple markers in less than 0.1 milliseconds and use these to determine the 6DoF of the objects that the markers define. 6DoF recalculation of all objects within each measurement instance makes the system resilient to large movements, object occlusion, and sensor relocation. Feasibility tests of a four-camera system as a machine characterization tool tracking a cutting tool spinning at up to 3000 rpm across a volume of 1 m^3 achieved a mean reference marker agreement between tool poses of 2.5 µm with markers moving at up to 17.5 ms^{-1}. Given good photogrammetric geometry, 6DoF parameters of the spinning tool were determined to standard deviations of 37.7 µm and 0.086°.

Keywords: photogrammetry; 6DoF tracking; high-speed measurement

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1. Introduction

The ability to provide metrological support in industrial manufacturing environments enables greater reliability and quality, reducing rework and creating new opportunities. For example, enabling more advanced component designs that make better use of materials. This provides advantages both economically and environmentally, especially in the automotive and aerospace industries. Advancing industrial manufacturing processes and increasing automation provides opportunities for metrology to enhance Industry 4.0–driven digitalization at larger scales and presents new research challenges in meeting changing requirements [1].

1.1. Motivation

Optical non-contact metrology solutions have been developed for six degrees of freedom (6DoF) robot end-effector tracking to enhance robot tool location accuracy on the basis that industrial robots tend to be highly repeatable but relatively inaccurate.

Solutions may be offline, via generation of inverse kinematic correction maps, or in-line, where kinematic corrections are augmented by a moving measure correct control loop operating at frequencies of 4 Hz and faster and delivering sub-millimetre corrections. Established applications range from single-robot end-effector guidance to multi-robot assembly processes. The EMPIR Dynamite Project [20IND02-DynaMITE] responded to an EU manufacturing challenge to develop a high dynamic rate in-line 6DoF solution with the capability to track multiple objects moving at high speed over large volumes, which could open new industry 4.0 opportunities.

The work reported in this paper is one of a series of Dynamite project demonstrators exploring the potential of low-cost photogrammetric systems comprising off-the-shelf cameras and lenses to track multiple objects in 6DoF. In this case, the novelty is the application to objects moving at greater than 10 ms^{-1}, an application requirement that can be met by 6DoF tracking of the cutting head of a high-rotational speed machine tool as it is moved through the volume of a high-precision milling machine. Providing a solution in this area would allow parts and machines to be tracked and monitored during high-speed manufacturing processes, aiding in-process control.

A low-cost method implies off-the-shelf cameras, lenses, and continuous LED lighting running on a generic computer without recourse to hardware customizations. The novelty is in understanding what is achievable with such equipment for tracking rapid motion. Our photogrammetric method is explained here, along with results from initial feasibility tests. These investigate if a set of machine head motions within a multi-axis milling machine can be usefully tracked over a range of different cutting tool poses, each of which has a variable line of sight occlusions whilst the cutting tool is spinning to deliver object motions in excess of 10 ms^{-1}. This paper reports on the capability of low-cost, off-the-shelf cameras to deliver precise, robust, and reliable results that are resistant to occlusion whilst avoiding the cost of bespoke commercial photogrammetric hardware.

1.2. Photogrammetry

Photogrammetry is a long-established full-field optical metrology technique that combines measurements made in two or more 2D camera images to simultaneously estimate the coordinates and uncertainties of multiple 3D points in space via triangulation [2]. The technique has several properties that make it a viable approach to achieving measurement of high-speed objects and events:

- Photogrammetry is a non-contact technique using multiple overlapping camera views that can simultaneously measure multiple objects across a large volume without the need to articulate in any way whilst capturing data. This lack of physical movement within the tracking system means that, whilst objects being tracked remain visible in the camera images, the challenges of high-speed measurement are constrained to synchronized data capture and online processing.
- Secondly, the use of retroreflective circular photogrammetric markers enables highly accurate results by providing known features for extraction during 2D image processing, even when using low-cost off-the-shelf components [3]. Retroreflective materials can reflect an amount of light back to the illuminating source in the order of magnitude of 1000 times that of diffuse reflection from a white surface and can be coded for 2D image identification [4,5]. High reflectance permits the very short exposure durations needed to obtain high-quality, blur-free marker images in the presence of rapid motion between objects and time-synchronized cameras.
- Thirdly, a greater number of cameras results in a stronger network of intersecting lines of sight, conferring more accurate and reliable results when processed by bundle adjustment [6–9]. Low-cost, off-the-shelf cameras enable multiple cameras to be

deployed cost efficiently, making the technique affordable and more robust to the many occlusions that can occur in dynamic environments.

An image from a single camera provides angular measurements to each marker appearing in that image. Whilst directions can determine the relative 3D locations of each marker, further information is needed to determine scale. Types of information that can be added include known point locations coordinated, for example, using a laser tracker, lengths between points in the form of a physical calibrated scale bar, or calibrated mechanical separations between pairs or groups of cameras during data capture [6,8]. Processing these data as measurements with estimated uncertainties in a combined least-squares bundle adjustment enables the propagation of the uncertainties in the individual measurands into the 3D coordinate and 6DoF estimates along with their associated variance–covariance matrices. Whilst supporting statistical analysis of the output quantities, this approach also allows analysis of the contribution of each individual marker image measurement and its role within the overall solution.

The photogrammetric requirement for multiple images lends itself to two data capture approaches, which we refer to here as static and dynamic measurement. In static measurement, a single camera is used for all images captured, moving it around the static object being measured. This approach enables a great many images to be captured for a single measurement, with no need for additional equipment, allowing systematic errors in the camera optics to be corrected as part of the measurement process, thereby increasing accuracy [10]. However, the static approach requires that the points being measured remain static throughout, with no movements or deformations in the elements being measured. If the object or objects being measured move during image acquisition, then points will be measured at different locations across the images captured, leading to erroneously calculated results. In dynamic measurement, we consider how photogrammetry can be used to measure a moving object. In this approach, multiple cameras are used, with all images being captured simultaneously. Each camera contributes measurements from a single image into the network of observations. This has the advantage of allowing dynamic objects to be measured, independent of how they move, as features on the object will be in the same relative locations across all images in a synchronized set. The disadvantage is that the number of images that can reasonably be captured is limited to the number of cameras deployed. Combined with a need to make prior corrections for systematic optical errors, this constraint on the number and geometry of lines of sight per marker reduces accuracy [11]. The opportunity is to maximize the number of available cameras by keeping hardware costs low.

Dynamic measurement of objects moving at high speed relative to the cameras presents additional challenges in ensuring the accuracy of the data captured. Each camera must be able to provide a frozen image of the features to be measured on the object with minimal blurring, geometric distortion, or noise [12]. In situations where dynamic data are required to control or monitor the object, the period of time over which a set of images is captured must be minimized, and data must be rapidly transferred from the cameras and processed so that it can provide useful feedback to an operator or control system.

1.3. Alternative Technologies

Since the process requires full-field measurement of rapidly moving objects, there are few competing technologies that might deliver a suitable solution. Existing methods of machine and robotic calibration typically rely on static measurements of sequential tool poses, with some machine builders recommending using physical contact with spheres for this type of calibration. Metrology approaches include mechanical probing and gauging to ascertain tool center points [13], laser tracker systems capable of sequential single point coordination in offline mode [14], and live 6DoF tracking of single elements using specialized 6DoF devices which combine the tracker single line of sight with 6DoF determination using either an in-built camera into the laser tracker or adding return angle structure into the laser beam [15]. A new generation of sensors is emerging based on frequency scanning interferometry and multiple measurement heads, allowing trilateration of sequential spherical optical markers [16] and potentially multiple spheres by spatially splitting and directing the measuring laser to multiple markers and decoding their return signal [17]. Whilst of potentially higher accuracy, all of these optical techniques are at least one order, and in the latter cases tens of orders, of magnitude more costly than a low-cost photogrammetric system.

1.4. Low-Cost Photogrammetric Test Case

Testing of the photogrammetric system was carried out on a Soraluce large multi-axis milling machine. Milling machines such as these have a range of behaviors that can benefit from metrology in error detection, tracking, and correction [18,19]. This machine is of the moving-column type, as shown in Figure 1, featuring three linear axes and two rotational axes.

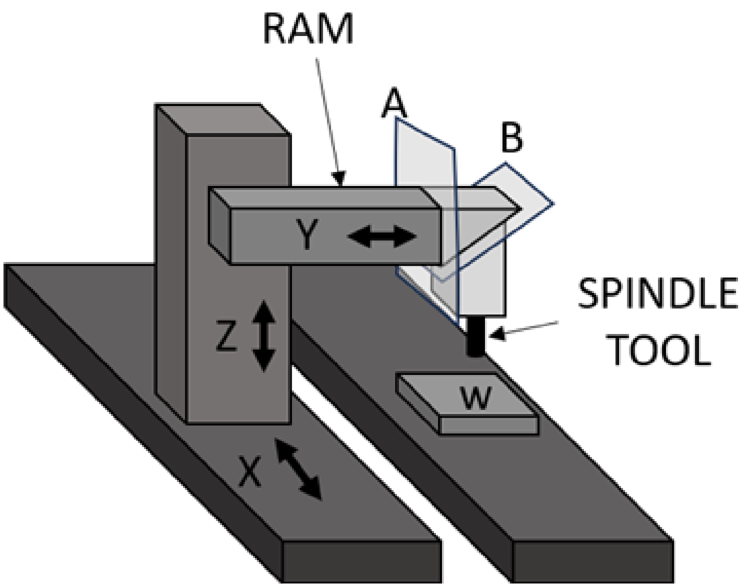

Figure 1. Diagram of the Soraluce multi-axis milling machine with linear axes X, Y, Z and rotational axes A and B. Optionally work space W may also include a rotation table.

The dynamic components, including the slide (X 4000 mm), column (Z 1500 mm), and boom (Y 1200 mm), as well as the machine head, are all mounted on a stationary bedplate, fixed to the ground. Workpieces are positioned on another bedplate, also affixed to the ground. These two bedplates have no direct contact or connection between them. The machine head can be rotated around two axes (A and B) covering a −180-to-180-degree rotation and in steps of 2.5 degrees. The machine tool spindle can spin a milling head at up to 3000 rpm.

2. Materials and Methods

To achieve project requirements, two separate photogrammetry systems, one dynamic and one static, were used. These both worked with compatible marker solutions and were brought together in the full metrology process.

2.1. Dynamic Photogrammetry System

The dynamic photogrammetry system is based around UCL's VMS Capture software(Version 4200) [3,11]. This software is designed to interface with a wide range of off-the-shelf cameras and provide a consistent, traceable photogrammetric process for rapidly generating and displaying 3D data and their metric qualities. VMS Capture allows multiple rigid-body objects to be defined and for independent 6DoF tracking to be carried out with each of these objects. When performing tracking operations, one of the tracked elements can be designated as a static set of reference markers, with the location of all other tracked elements being reported relative to the reference marker coordinated system. For each set of synchronized images, the system recalculates the location and orientation of each camera relative to the reference markers, enabling the cameras to move in the measurement space whilst 6DoF object tracking is running.

Whilst there must be a minimum of at least two lines of sight to each marker for 3D coordination, there is no requirement for a consistent set of observations or lines of sight as the objects move within the measurement volume. These properties mean that measurements made are resilient to camera movement, temporary occlusion, and changing angles of view between tracked objects and cameras. VMSCapture can provide a rapid measurement through a simple resection of the camera location and orientation with respect to the reference marker locations, followed by an intersection measurement of the tracked marker locations. More commonly, this measurement is improved by performing a bundle adjustment. With a bundle adjustment, all variables in the photogrammetric measurement are simultaneously adjusted to find the best measurement solution through least-squares analysis. As well as having its own text-based and graphical display and export options, VMSCapture is designed to network with other software such as Hexagon/NRK Spatial Analyzer for compatibility with established industrial metrology processes.

For this application, four cameras and a trigger box were used. Each camera was an IDS UI-3290SE-M-GL (IDS Imaging Development Systems GmbH, Obersulm, Germany)equipped with a 10-megapixel Sony Pregius S sensor(Manufacturer, City, US State if applicable, Country) These were selected because they meet several criteria required for high-speed photogrammetric imaging. The sensors have a global shutter, rather than a rolling shutter, which avoids geometric image distortions caused by a line-by-line scanning capture rather than a simultaneous capture across the complete camera sensor. The physical layout of the Sony Pregius S sensor is designed to maximize light sensitivity, allowing for a shorter exposure time with less noise whilst maintaining a small pixel size. The selected cameras can capture and transmit images at tens of frames per second over industry standard USB3.2 connections, allowing for easy compatibility with a host computer. The cameras are connected with a 60 m fiber optic cable into a multi-port multi-bridge host adapter card with zero data loss at 5Gbs per camera enabling flexible deployment of the system over large measurement volumes. These cables also provide power to the cameras, whilst the data connection supports both data transfer and camera control, such as setting startup parameters in the camera firmware. Continuous access to camera functions allows sensor settings to be tuned for optimal image capture.

The cameras are fitted with Kowa (Kowa Optronics Co, Ltd, Tokyo, Japan) 9 mm fixed focal length "C" mount lenses selected to match the sensor dimensions, pixel size, and lens optical properties whilst providing physical stability over time. The location of the cameras and the focal length of the lenses were selected to cover the working volume of the milling machine. The cameras were mounted inside the machine on the secondary bedplate below the milling tool and pointed upward in such a way as to ensure the greatest number of convergent lines of sight with no occlusion of the milling tool and minimal occlusion of the machine head.

The cameras were additionally fitted with consumer-level green "angel eye" light rings. Broadband green illumination was selected to match the peak sensitivity of the camera sensors, with the lenses also featuring high transmission and image sharpness over this wavelength band. An example camera, with lighting ring, can been seen in Figure 2.

Figure 2. One of the four tracking system cameras deployed in the milling machine workspace.

To ensure that images were captured simultaneously across all cameras, a Gardasoft CC320 lighting controller (CCS Inc., Cambridge, UK) was used to provide a cabled trigger pulse to each camera. The pulse frequency can be set to run at an adjustable continuous rate, typically between 1 and 100 Hz. The synchronicity of the cameras was confirmed using similarly pulsed, adjustable phase LED lights, and the interval between each light was adjusted as a function of the input trigger frequency. An integrated PSU was used to power both the trigger unit and the light rings. For the work described in this paper, the trigger frequency was set to 4 frames per second on the basis that the motion of the milling head would build up by sampling over time. The result was a set of four synchronized images captured with a 0.02 ms global shutter duration with continuous LED illumination sufficient to eliminate marker image motion blur from a milling head operating at 3000 rpm. The overall cost of the hardware used in the system was €10K.

2.2. Static Photogrammetry System

Before carrying out the dynamic 6DoF measurement, it is crucial to measure both the reference element and the elements that will be in motion. For this purpose, IDEKO's VSET system is used [20,21]. This system was composed of various elements, and image acquisition was performed using a Nikon D500 digital single-lens reflex camera (Nikon Corporation, Tokyo, Japan) with a 24 mm lens, accompanied by a circular electronic flash. Traceability was ensured using 1 m long carbon fiber scale bars. It is important to note that in each measurement, intrinsic parameters were calculated with the aim of reducing measurement uncertainty. The calculation of these intrinsic parameters and the complete bundle used to obtain the measurement are detailed in [20].

The VSET system was developed to measure the overstock of large-scale workpieces, and its precision has been assessed for lengths up to 12 m (Maximum Absolute Length Measurement Error (LME) 0.435 mm); however, it has also been used in smaller-scale scenarios (LME 0.157 mm) following VDI/VDE 2634 part 1 [21]. For instance, it has been used for setting up dynamic photogrammetric systems, as described in [22]

2.3. Markers and Marker Placement

Both VMSCapture and VSET's use of purpose-engineered circular markers rather than pre-existing features allows for greater accuracy in photogrammetric measurement. These markers provide easily identifiable points in the desired locations for detection. Accurate image measurement is achieved by fitting a circle, or an ellipse in the case of large marker images, to the detected marker, enabling its center to be determined with sub-pixel precision. In common with many industrial photogrammetry systems, both VMSCapture and VSET use coded markers to allow software to automatically identify markers in each 2D image prior to combining 2D measurements across multiple images in a 3D least-squares solution. This capability allows for rapid automatic processing without prior knowledge of how the objects to be tracked are moving within the measurement volume of the system.

The VMSCapture system uses 'domino' markers constructed from a square arrangement of eight individual circular markers. These comprise four corner markers to give consistent 3D coverage and four markers in a unique arrangement that provides a unique marker identification. As each domino consists of eight markers, this allows the 6DoF estimation of each single domino, with the limitation of planarity. A larger number of domino markers attached to a rigid body will allow for a greater physical measurement spread, increasing precision and enhancing accuracy where multiple dominos occupy a 3D rather than a 2D planar volume. VMSCapture markers use retroreflective material beneath a black vinyl mask. This ensures that a high amount of light is returned to each light-ring-equipped camera, decreasing the effect of noise, especially when using sub-millisecond exposure times. Marker examples, as laid out for the test, can be seen in Figure 3.

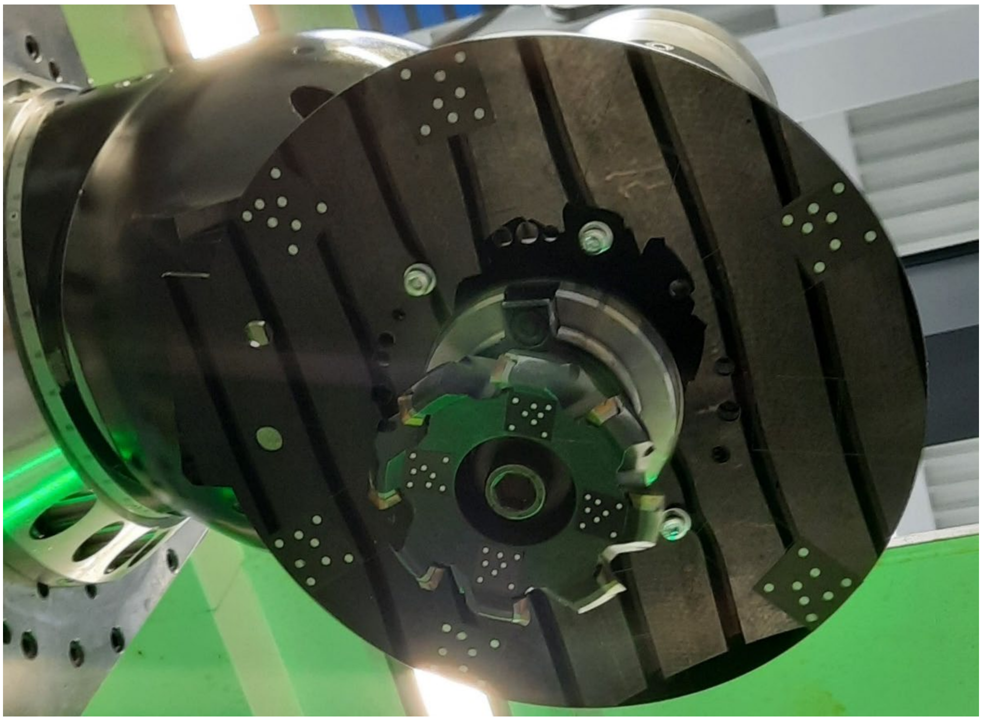

Figure 3. VMS 'Domino' markers on the Soraluce machine head and machine tool.

As the milling tool was the main element to be tracked, four small domino markers were affixed to its surface. To provide a strong local reference, a ring with six domino markers was fitted to the machine head, ensuring these markers were near the milling tool and visible to the cameras. As an additional option for measuring the rotation of the machine head, four domino markers were affixed to the underside of the machine boom. These domino constellations provide three rigid elements that can be independently tracked in a common reference frame.

The VSET-coded markers consist of single circular markers, each with uniquely identifiable circular barcodes around them. Whilst this means that each coded marker can only provide location information, multiple markers were combined on 'Igloos' to allow for 6DoF estimation. Each VSET Igloo comprises a pre-characterized magnetic hemisphere with 14 coded marker facets and could be flexibly located on the desired element. Scale was defined using pre-characterized scale bars consisting of two VSET-coded markers with a known separation, which were included in the measurement network. The arrangement of VSET markers, on both Igloos and scale bars, as used for static measurement of the system, is shown in Figure 4.

Figure 4. VSET markers across the Soraluce machine for static measurement.

VSET markers are white, rather than retroreflective, against a black background; however, both systems can detect the markers produced for use with the other system. While the two systems are not integrated to automatically identify the other marker code systems, they can be measured as uncoded markers and have their designations applied either manually or by automatic back driving from the known 3D coordinates of one system into the 2D images of the other. This allows location data to easily be shared between the two systems in a common coordinate framework, avoiding the need for more complex alignment, such as described in [17].

2.4. Measurement Process

The initial stage of the measurement process was to set up the cameras and markers. The cameras were mounted to the bedplate, and the VMSCapture markers were mounted to the milling machine as described above. After this, the cameras were focused to ensure sharp images of the milling tool markers. After this, the milling tool was spun up to 3000 rpm, and the camera exposure, aperture, and gain settings were tuned to find the optimal balance of image brightness, image sharpness, and image noise. In this work, the main adjustments were to exposure time, which increases sharpness by minimizing motion blur but decreases marker image brightness; aperture, which increases marker image brightness but decreases sharpness away from the plane of sharp focus; and gain and other image amplification firmware settings, which increase marker image brightness but also increase image noise. In addition to analyzing the images directly, the VMSCapture online 2D marker identification and measurement software is used to confirm marker detection consistency. Camera and marker locations may also be adjusted during this process if necessary, based on the coordinate uncertainties output by the system during measurement.

Having proven that the capture of suitable synchronized image sets was possible, the next stage was to characterize the VMS markers and tracked objects. The characterization process was carried out with VSET. Firstly, Igloo markers were arranged around the VMSCapture markers on the milling machine in order to strengthen the measurement network by maximizing optical lines of sight and to provide markers that can be automatically identified by VSET. One-meter scale bars were also used, arranged in a variety of orientations, to ensure that the scale was well defined across the measurement volume. A static VSET photogrammetric imaging network also coordinated the VMSCapture markers to a high degree of precision and accuracy. Coordinates of the VMSCapture markers were extracted from the VSET data and grouped according to the three objects to be tracked (the milling tool, machine head, and boom).

The next stage was to calibrate the cameras' intrinsic parameters. This was conducted by using the characterized ring around the machine head as a rigid-body calibration object. The milling machine was used to move the ring across the field of view of all four cameras, and a photogrammetric self-calibrating bundle adjustment was carried out on the images captured. In this test case, the lens model parameters were based on the established "Brown model", estimated within the bundle adjustment as a distortion model, and then applied an iterative correction to image measurements made with the system [8]. Once this calibration was complete, reliable data could be captured and processed by the VMSCapture system and shared via NRK Spatial Analyzer for display and further processing.

To produce meaningful information based on the coordinate frame of each machine component, a transformation needed to be applied to the marker groups related to each of the three elements. These transformations align the origins of the three objects with their respective axis of rotation. Transformation parameters for each object were estimated by making repetitive measurements as the neighboring joint was rotated. This creates a ring of locations with an arbitrary origin. By fitting a circle through the ring of locations and finding the line normal to the center of the circle, the axis of rotation is found, and the origin is then moved to align with it. This process can be repeated across each moving component object pair to determine relative alignment. Alignment was carried out in Spatial Analyzer, with Figure 5 showing a set of 6DoF frames aligned to the machine tool spindle.

To test the system, the milling tool was rotated at 3000 rpm in the center of its operating volume. Successive image sets were captured and processed until at least 150 data points were recorded for each object, using the ring markers as the reference. The location of the milling tool was then offset in each axis in turn to the edge of the trackable volume, and the data capture process was repeated. Similarly, the angle of the machine head was adjusted to the extreme detectable by the measurement system, and the data capture was repeated. This full data capture process was then repeated using the markers on the boom as the reference.

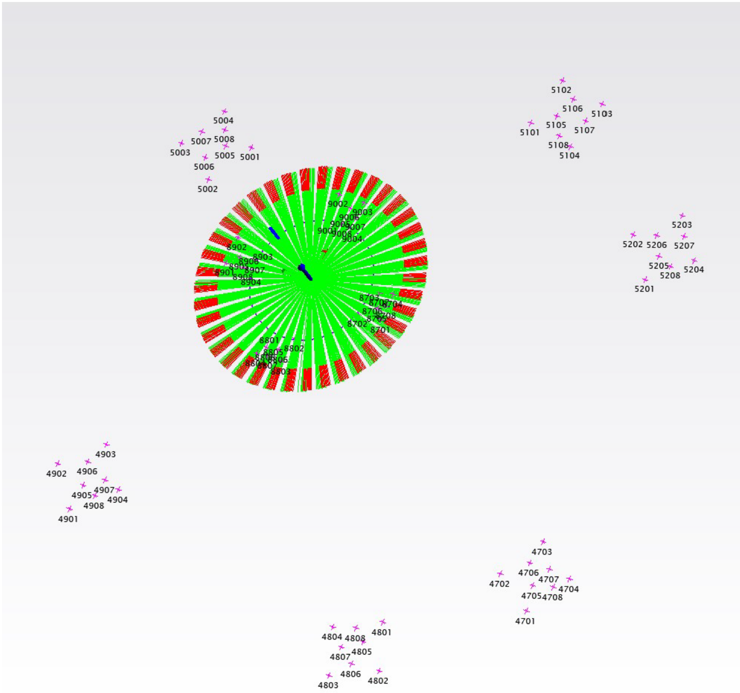

Figure 5. Aligned machine tool spindle frames as shown in Spatial Analyzer. Successive 6DoF frames are colored in green and red showing the local Y and X axes spinning about the Z axis in blue. Transmitted at 2 Hz into Spatial Analyzer, the graphic shows progressive sampling of the spinning tool.

3. Results

3.1. Center Point Consistency

With the tool rotating at 3000 rpm, images were captured and processed by the system at 2 Hz for at least 75 s, ensuring that over 150 6DoF measurements were made. As an initial test, the tool was spun in the centre of the measurement volume. The 6DoF frames generated for each of the 153 measurements made are shown in Figure 6. The spatial deviation of the origin of the measured frames is 22.7 µm, while the angular deviation in X and Y, ignoring the rotation about the Z axis in which the tool spins, is 0.061°. However, as can be seen in Figure 6, there are several large outliers.

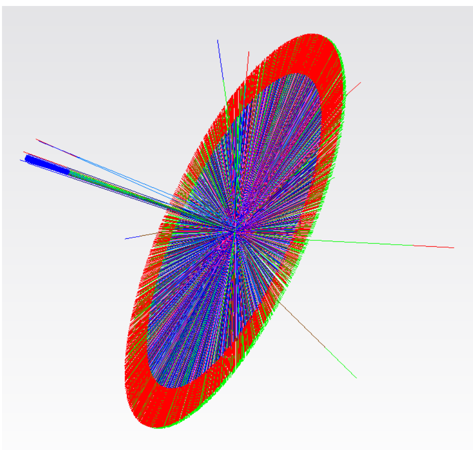

Figure 6. Example of 6DoF frames from the rotating spindle captured at a single machine pose and showing a number of gross outliers. Contrast to Figure 7 where after outlier removal the colour red, green, blue axis coding of the spin about the local Z axis is clear.

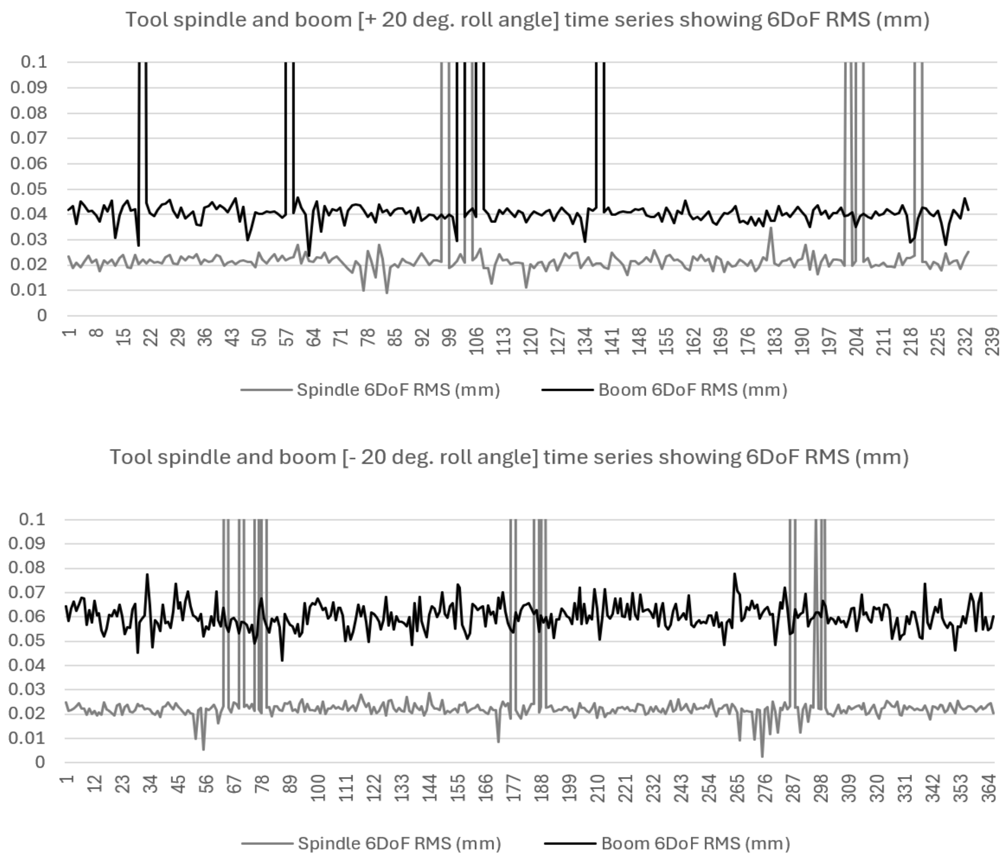

Figure 7. Sample plots from combined boom and tool spindle 6DoF tracking at tool poses of +/−20 degrees prior to filtering. Jumps in the traces extend from 0.1 mm to 5 mm and represent worst-case non-convergence failures in the 6DoF processing.

3.2. Outlier Removal

Analysis of the least-squares 6DoF solutions highlighted that these outliers were attributable to 6DoF non-convergence and were identifiable by high RMS discrepancies between the measured and the reference coordinates on each part of the tool.

Two time series example plots are presented in Figure 7, where the system was simultaneously tracking both the tool spindle and boom arm at poses of + and −20 degrees. Here, it can be seen that in both machine poses typical tool spindle 6DoF RMS data lie in the 0.02 mm +/− 0.01 mm range [light gray traces], whilst the boom arm 6DoF fit is slightly worse for the −20 degree case in the 0.06 mm +/− 0.01 mm range and 0.04 mm +/− 0.01 mm range in the +20 degree case. Amidst these data are clear RMS jumps in the range of 0.1 to 5 mm in each of the traces. These are most notable for the rotating tool spindle.

Our current 6DoF solution computes new starting values for every step in the time series without drawing on information from prior results. The rationale for this is that tracked objects can move and even appear and disappear and still be uniquely identified at any time instant. To preserve this assumption, a post-capture filtering process was adopted, which removed outliers where the 6DoF RMS fit was greater than 10 times the RMS fit standard deviation for each machine pose. Whilst a finer tuning of the 6DoF solution system could be developed, the method removed all of the gross outliers, producing sets of tool spindle rotation frames such as the set seen in Figure 8. Future running of the online system will remove non-convergent 6DoF solutions prior to data output.

Table 1. Tool spindle 6DoF measurement spatial and angular standard deviations after outlier removal for different spindle locations and poses within the machine volume.

Spindle Location and Pose	Measurements Used (Outliers Removed)	Spatial Deviation (µm)	Angular Deviation (°)
Central	153 (0)	22.7	0.061
+250 mm in X	169 (1)	35.3	0.079
−250 mm in X	167 (1)	26.0	0.061
+250 mm in Y	153 (0)	54.0	0.105
−250 mm in Y	153 (0)	44.7	0.112
+250 mm in Z	160 (1)	17.2	0.053
−250 mm in Z	153 (2)	53.2	0.092
+20 degrees	227 (4)	34.5	0.101
−20 degrees	358 (6)	51.8	0.113

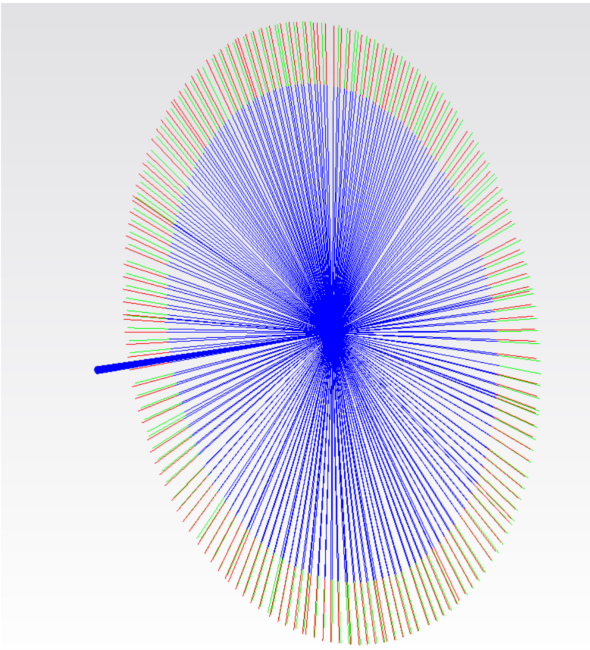

Figure 8. Example of rotating tool spindle frames captured at a single tool pose after gross outlier removal. Sampled rotations show the local X and Y axes of the tool in red and green respectively spinning about the local Z axis in blue. The small spread visible in the local Z axis is atributable to the deviation of the 6DoF as the tool rotates (Table 1).

3.3. Variation Across Volume

Tests were carried out using the VMSCapture system with the tool spindle in an optimal central location within the machine volume and repeated with physical offsets of 250 mm in both directions along each cardinal axis and of 20° in each direction about the milling machine rotation axis A. Results are shown in Table 1 and Figure 9, with Table 1 noting the number of outlying measurements excluded from each test.

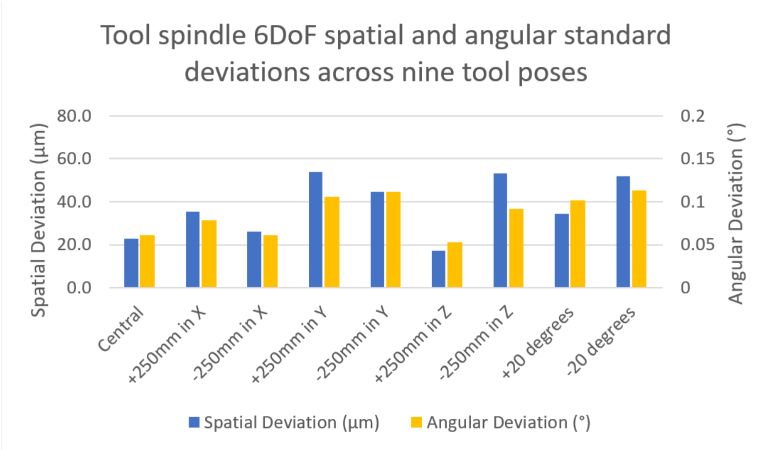

Figure 9. Tool spindle 6DoF spatial and angular standard deviations across nine machine poses after gross outlier removal.

3.4. Variation with Boom vs. Ring Reference Systems

A reduced version of the same test was repeated without adjusting the angle of the milling machine A rotation axis, using the markers on the boom as reference markers. This shows what can be achieved with a sub-optimal positioning of the reference markers, which here would also allow for the angle of the machine A axis to be measured during the machine usage. The results are shown in Table 2

Table 2. Tool spindle 6DoF measurement spatial and angular standard deviations, using boom markers for reference, after outlier removal for different spindle locations and poses within the machine volume.

Spindle Location and Pose	Measurements Used (Outliers Removed)	Spatial Deviation (µm)	Angular Deviation (°)
Central	159 (2)	58.7	0.637
+250 mm in X	42 (5)	82.9	0.559
−250 mm in X	164 (2)	52.3	0.598
+250 mm in Y	155 (1)	67.3	0.606
−250 mm in Y	154 (2)	52.0	0.598
+250 mm in Z	186 (4)	39.6	0.601
−250 mm in Z	109 (6)	120.0	0.608

3.5. Comparison Between Bundle Adjustment and Resect/Intersect

While running the system, it was occasionally observed that camera measurements would fail to transfer from the photogrammetric system to the Spatial Analyzer. To reduce CPU processing requirements, a series of measurements were therefore carried out using only resection and intersection (Res/Int) rather than a full bundle adjustment. While this was not observed at the time to influence the number of images transferred, it is of interest to compare the results captured in these test runs to those captured through bundle adjustment. Results are shown in Tables 3 and 4

Table 3. Tool spindle 6DoF measurement spatial and angular standard deviations, using ring markers for reference and using only resection and intersection for different spindle locations and poses within the machine volume.

Spindle Location and Pose	Measurements Used (Outliers Removed)	Spatial Deviation (µm)	Angular Deviation (°)
Central	162 (2)	58.1	0.639
+250 mm in X	163 (0)	43.4	0.721
−250 mm in X	155 (0)	113.1	0.655
+250 mm in Y	155 (1)	76.5	0.677
−250 mm in Y	170 (0)	98.5	0.643
+250 mm in Z	160 (0)	22.4	0.635
−250 mm in Z	239 (0)	144.1	0.629

Table 4. Tool spindle 6DoF measurement standard deviations, using boom markers for reference and using only resection and intersection for different spindle locations and poses within the machine volume.

Spindle Location and Pose	Measurements Used (Outliers Removed)	Spatial Deviation (µm)	Angular Deviation (°)
Central	152 (2)	93.6	0.631
+250 mm in X	149 (2)	92.6	0.601
−250 mm in X	154 (2)	80.2	0.644
+250 mm in Y	153 (3)	135.9	0.604
−250 mm in Y	160 (5)	75.0	0.585
+250 mm in Z	156 (2)	94.1	0.596
−250 mm in Z	87 (18)	411.9	0.677

Figure 10 shows the average results across all tool spindle locations and poses for both sets of reference markers with both processing approaches. These data exclude rotations about machine axis A for the measurements using the ring reference markers with bundle adjustment, as these measurements were not repeated in the other tests.

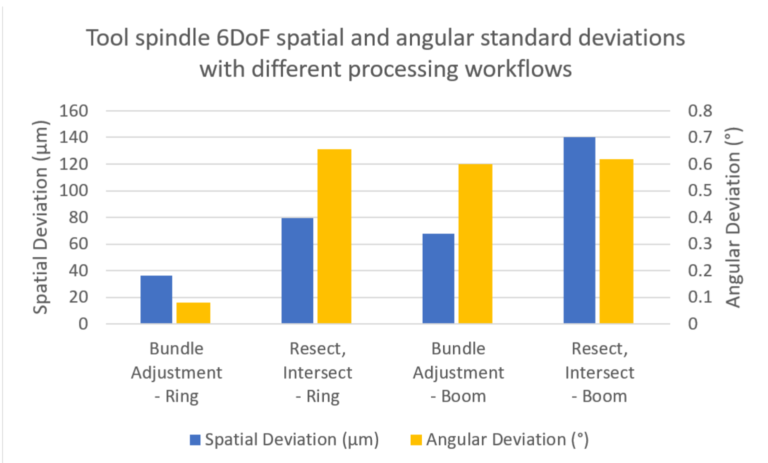

Figure 10. Tool spindle 6DoF measurement average standard deviations with different processing workflows and reference marker constellations.

4. Discussion

With optimal processing criteria, this €10K system was able to measure the 6DoF of the rotating tool across the working volume of the machine tool with an average standard deviation of 37.7 μm and 0.086°. Measurements were made consistently, with only 15 of 1712 producing gross outliers. This suggests a failure rate of less than 1%, with the highest incidence of failed measurements seen where the tool is tilted away from the initial measurement plane, resulting in a diminished light return to the cameras due to the properties of the retroreflective marker material. Markers on the tool surface are placed at an average of 50 mm away from the axis of rotation. At 3000 rpm, this accounts for a speed of 17.5 ms^{-1}, at which the system was shown as capable of achieving consistent results. With a suboptimal selection of reference markers, the average standard deviations increased to 67.5 μm and 0.601° after a greater number of gross outliers were removed, demonstrating the importance of a well designed photogrammetric network.

Comparing the use of a bundle adjustment to simple resection and intersection showed improved results from the bundle adjustment method, typically giving a two times improvement in terms of the tool pose standard deviations. This agrees with the underlying principle of the bundle adjustment process in simultaneously estimating all parameters. Overall, these experiments demonstrate the practical capabilities of the measurement system but also highlight where errors can occur. Further work will look into the physical causes of outliers, which appear to be camera/object geometry-specific. Investigation is underway to better understand the causes of 6DoF least-squares estimation non-convergence so that every measurement set delivers precise results. This work was carried out as a demonstration of what can be achieved with off-the-shelf, low-cost photogrammetry. It remains to be ascertained whether the quality of the achievable measurements can be useful in improving large machine tool alignment. Whilst markers on the main parts of the tool could be made robust to machining conditions, it is unlikely that marker-based measurements of an active cutting head, rather than a simple spinning head in this test, would be practical as a routine process.

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