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Laser speckle velocimetry for robot manufacturing

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ABSTRACT

A non-contact speckle correlation sensor for the measurement of robotic tool speed is presented for use in robotic manufacturing and is capable of measuring the in-plane relative velocities between a robot end-effector and the workpiece or other surface. The sensor performance was assessed in the laboratory with the sensor accuracies found to be better than ±0.01 mm/s over a ±70 mm/s velocity range. Finally an example of the sensors application to robotic manufacturing is presented where the sensor was applied to tool speed measurement for path planning in the wire and arc additive manufacturing process using a KUKA KR150 L110/2 industrial robot.

Keywords: Laser speckle, tool speed sensor, velocimetry, robotic sensor

1. INTRODUCTION

In many areas of manufacturing it is desirable to replace expensive Computer Numerical Control (CNC) systems with a robotic approach providing increased flexibility and lower costs. However, robots struggle to achieve high positioning accuracy and are more prone to disturbances from process forces due to the comparatively low mechanical stiffness of typical industrial robots.[1] Additionally, there can be significant deviations from the desired tool-path and tool-speed due to the kinematic model used to convert joint encoder positions to Cartesian end-effector position. Hence, characterisation of the robot motion is of great importance in many manufacturing operations, for example, in many continuous machining or processing operations the feed rate or tool speed is critical to process quality.[2] External measurements systems such as laser trackers, iGPS or vision system can be used to track the motion of the robot end-effector. However, these methods of monitoring the motion also suffer limitations; vision systems have limited update rates and laser scanners are expensive and inflexible due to the need to maintain a continuous line-of-sight. The use of speckle correlation has great potential as an alternative technique, allowing rapid robot characterisation and measurement of robot trajectory and end-effector speed with a relatively low cost sensor. In this approach the sensor is attached to the robot end-effector and measures the relative motion between the end-effector and work-piece by high speed processing of laser speckle patterns (∼500fps) to determine the robot end-effector translation and velocity in a horizontal plane. This paper reports the design, signal processing and application of a speckle velocimetry sensor for use in path characterisation for the Wire and Arc additive manufacturing process.[3]

The concept of the speckle velocimetry sensor is shown in Figure 1 a) where the sensor is attached to the robot end-effector and measures the relative in-plane translation between the robot/sensor and workpiece. The signal processing principle is shown in Figure 1 b) where the two-dimensional normalised cross-correlation[4] between a reference speckle pattern and a newly acquired speckle pattern is computed. The offset of the peak from the centre of the correlation image gives the shift of the speckle pattern, (A_x, A_y) which can then be related to the x and y translations between the sensor and workpiece occurring between the images. It should be noted that the laser speckle patterns used by the sensor can be formed from a wide variety of surfaces as long as the surface is rough at the scale of the optical wavelength ($\sim 0.7\mu$m), i.e. diffusely reflecting.

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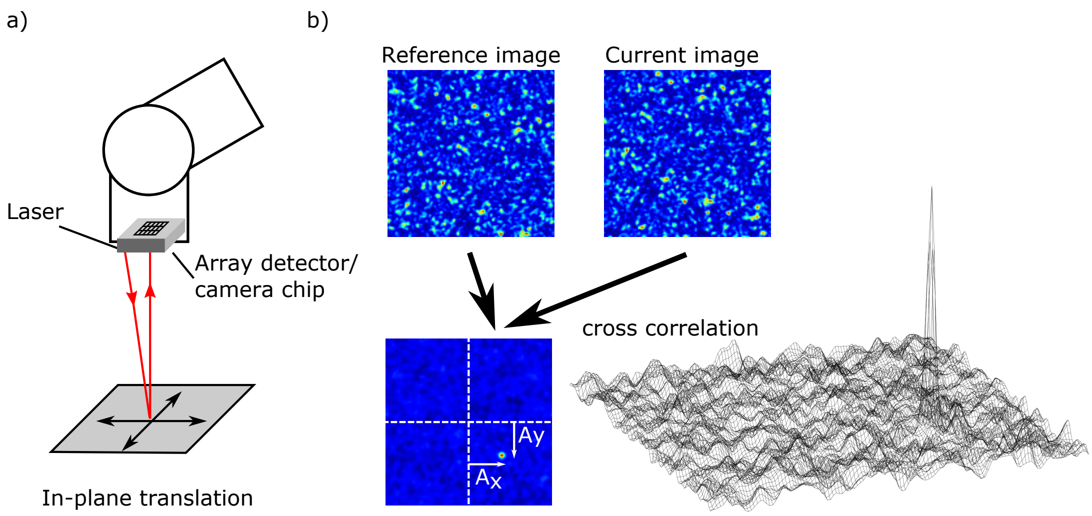

Figure 1. Sensor concept. In a) the sensor is attached to the robot end-effector to measure relative in-plane translation between the robot and workpiece. In b) the signal processing principle is shown with the 2D cross-correlation between a reference and new speckle pattern computed with the peak giving the translation of the pattern (A_x, A_y).

2. SENSOR DESIGN

The prototype sensor used in this work (Figure 2) consisted of a fibre coupled diode laser source operating at 658nm (FibreTec II FTEC2658-P60PA0, operating output 0.6mW) delivered to the sensor head via an armoured fibre cable containing a single-mode optical fibre (Nufern PM-S630-HP). The output from the fibre is then shaped and focused to a waste at point S, via collimation and focusing lenses (f=15 mm and f=50 mm) contained in the lens assembly. The beam then expands to spot, R of approximately 8 mm diameter on the workpiece. The resulting speckle patterns formed by scattering from the surface are recorded by a detector array, D, a high speed camera (Ximea MQ013CG-ON) operating at 500fps with exposure times of 200 μs and acquiring a region-of-interest of 512x512 pixels. A laser-line band-pass filter (Semrock FF-1=655/40, 655nm centre wavelength, 40nm bandwidth, optical density > 5) is mounted in front of the camera detector array to reduce ambient background light and prevent sensor blinding.

A simple sensor geometry was implemented for this work, with the laser focus, S, and the centre of the detector array arranged symmetrically around the z-axis and centred on the laser spot R. This balanced-angle geometry, shown in figure 2 a), shows good in-sensitivity to out-of-plane motions[5] and allows a compact sensor design. In addition it offers strong signal levels due to operating the narrow scattering cone of the metallic surface of the WAAM build plate. Further the angle SRD is kept small ($\sim 7.6°$) to minimize sensitivity changes due to working height variations[6] and surface gradients.[7] This was then installed on a KUKA KR150 L110/2 industrial robot used in the WAAM process in place of the welding torch, with the laser spot position at the tool centre point used for WAAM, as shown in figure 2 c). In this way the measured velocity will correspond to that seen by the welding torch, and any modifications to the robot programming or wire-feed rate to compensate can be determined.

3. SIGNAL PROCESSING

The signal processing, shown in figure 1 b) and figure 3, consists of acquiring and processing frames at high frames ($\sim$500 fps). Initially the first speckle pattern is stored as the reference with relative position initialised to $(0, 0)$. The translation between each newly acquired frame and this reference image is then calculated via the computation of the 2D normalised cross-correlation[4] where the peak position gives the translation between the two images. This peak position is determined to sub-pixel accuracy using a three-point Gaussian fit.[8] Once the speckle shift with respect to the reference image has been found, this is converted to a real translation via

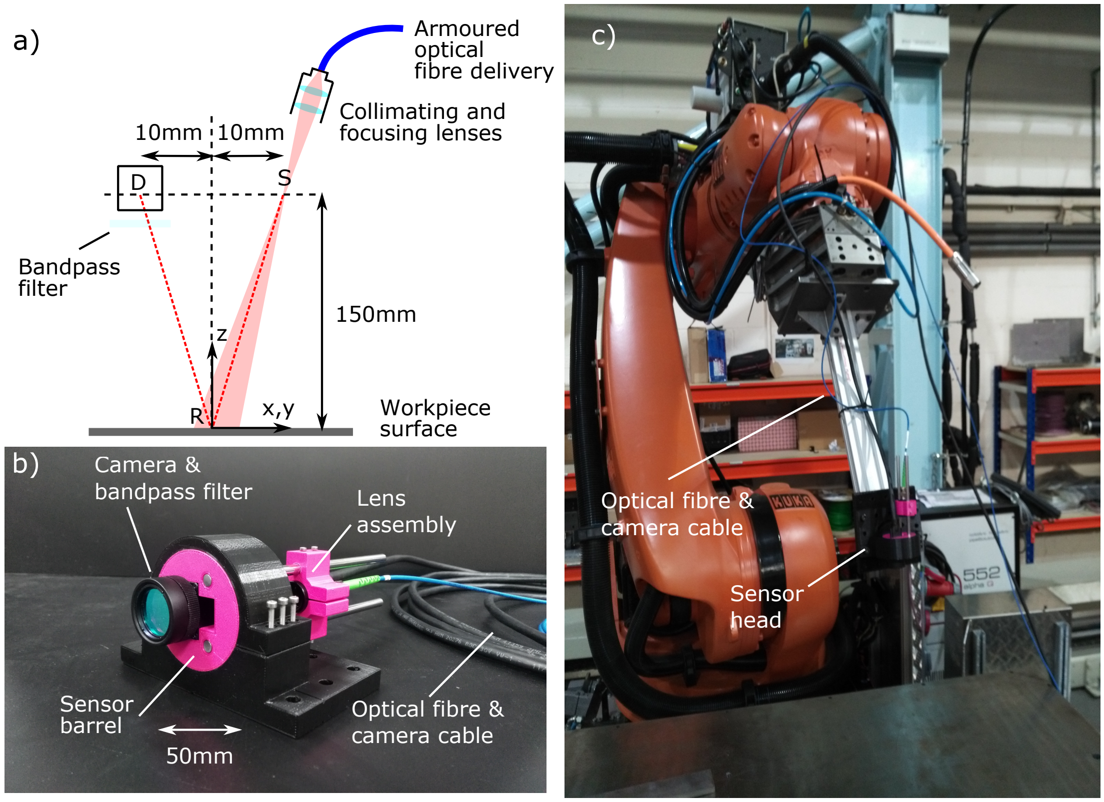

Figure 2. a) A schematic showing the balanced angle geometry used for the sensor with the beam focus and detector located in the same x-y plane 150mm from the workpiece surface and b) a photograph of the 3D printed sensor prototype. In c) the speckle velocimetry sensor is shown mounted on a Kuka KR150 robot.

the pre-calibrated scaling factors, discussed below, and the velocity can be found by differentiation with the previous position. This process of correlating new images with a fixed reference, instead of sequential image pairs as has been done previously for robot vehicle odometry,[6,9] has the advantage of allowing easier, more accurate calibration of the sensor as the total shift of the speckle pattern from the initial reference position can be integrated over a larger distance. This gives a better estimate of the robot position than is possible by integrating noisy velocity measurements derived from sequential image pairs. However the total shift will be limited by the size of the reference image used, after which point a new reference image and position must be stored.

To allow larger translations before re-referencing is necessary, and reduce the accumulation of error in the integrated position, it is desirable to use a larger reference speckle pattern, however a larger pattern will also lead to a decrease in the achievable processing speed. To overcome this limitation a moving correlation window scheme is applied as shown in Figure 3. This allows a smaller correlation image size, enabling higher processing rates, whilst reducing the number of re-referencing operations and the accumulation of error in the integrated position used for calibration. In figure 3 a) initially the reference and current image frame overlap the same region of the scattered speckle field and the correlation window (shown as the hatched rectangle) is centred in both frames. In figure 3 b) after a sensor translation, the reference image and current image are now offset with respect to each other in the scattered speckle field, hence to ensure maximum overlap between them the correlation windows are offset in opposite directions in the two frames. This additional offset is then added to the peak shift found from the correlation to give the total shift between the two frames. In figure 3 c) the sensor has reached the maximum translation where the correlation windows fully overlap, and the correlation windows now lie on opposite sides of the two images. For the next frame a re-referencing is performed as shown in figure 3 d).The previous frame is stored as the new reference with the position updated to reflect the new reference

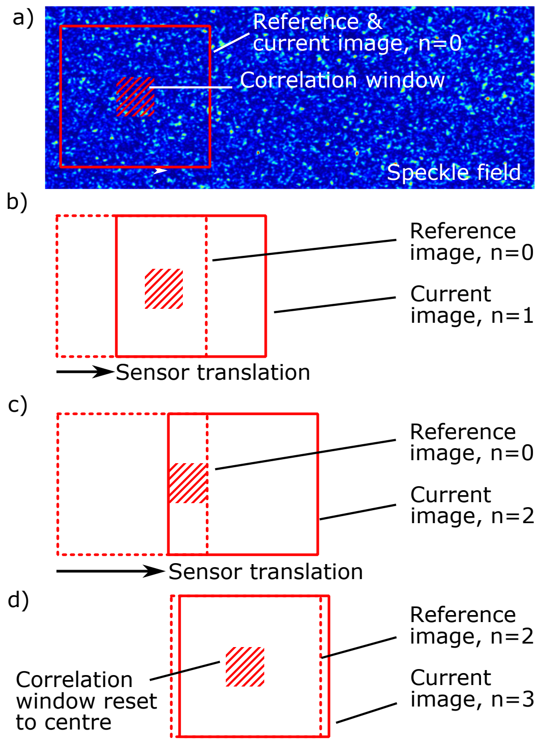

Figure 3. Overview of windowing scheme used in signal processing. In a) the initial reference image and current image overlap in the speckle field and the correlation is performed over the hatched window shown in both images. In b) and c) the windows are shifted in opposite directions in the reference and the current frame as the sensor translates. In d) a re-reference is performed where the previous frame is stored as the reference and the correlation windows reset to the centre. The total translation is stored internally and the process repeats.

image offset. This process is then repeated as the total translation increases and this moving window scheme is applied in both the x and y directions simultaneously to account for shifts not aligned along image rows or columns. In this work a 512x512 pixel image size, which allows re-referencing approximately every 1.2 mm, and a 128x128 pixel correlation window size allowed the processing to proceed at 500 fps using a circular normalised cross-correlation.[8]

The sensor can then be calibrated to find the translational scaling factors[7] T_{xx}, T_{xy}, T_{yx} and T_{yy} that relate the speckle shift to object translation. These are found using the integrated speckle shift, (A_x, A_y), obtained from the moving window scheme as described above and translating the sensor by a known distance first in the x and then y directions. This calibration can be performed in-situ on the robot with a typical calibration distance of 200-300 mm. Once calibrated, the scaling factors can be applied to scale the translation, (a_x, a_y) measurements made by the sensor and the velocity can be found by differentiation with the previous position, via:

$$a_x = \frac{(A_x T_{yy} - A_y T_{xy})}{(T_{xx} T_{yy} - T_{xy} T_{yx})}$$

$$a_y = \frac{(A_y T_{xx} - A_x T_{yx})}{(T_{xx} T_{yy} - T_{xy} T_{yx})} \tag{1}$$

4. LABORATORY CHARACTERISATION

The accuracy of the sensor was tested in the laboratory using a high-accuracy translation stage (ALIO Hybrid-Hexapod AI-HYBRID-HEX-60XY-15Z-56R) with an accuracy of $< 4\mu m$ and repeatability of $< 3\mu m$. The stage was used to translate an aluminium plate over distances of up to 200 mm at velocities of up to 70mm/s with the sensor mounted above the plate as shown in 4.

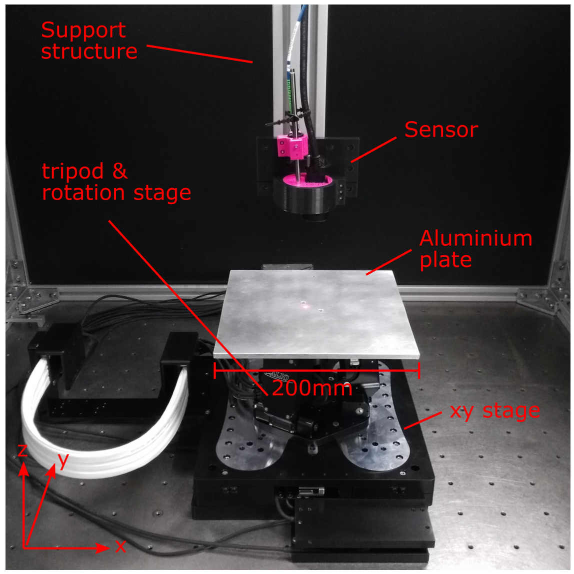

Figure 4. Experimental setup for laboratory measurements.

In this way the sensor accuracy (bias error) and linearity could be assessed for v_x and v_y velocity components with the results shown in figures 5 and 6 respectively. From these results it can be seen that the sensor accuracy is high with good linearity and a maximum error of ± 0.01 mm/s in the mean recorded velocity over the range ± 70 mm/s. Over the lower velocity range of ± 10 mm/s the error is reduced further to < 0.004 mm/s. The cross-talk into the orthogonal velocity component is also low at < 0.005 mm/s.

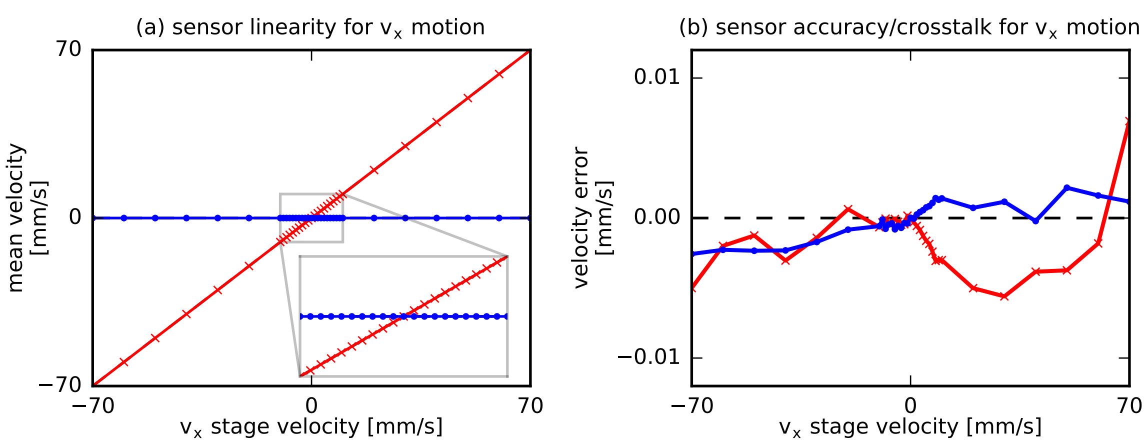

Figure 5. Sensor velocity and accuracy measurements for a translation in the x direction for speeds of ± 70mm/s. In (a) the measured v_x and v_y velocities are shown plotted against the applied stage velocity in (red) and (blue) respectively and the inset shows the range ± 10 mm/s. (b) Shows the sensor accuracy/crosstalk for the v_x and v_y components in (red) and (blue) respectively.

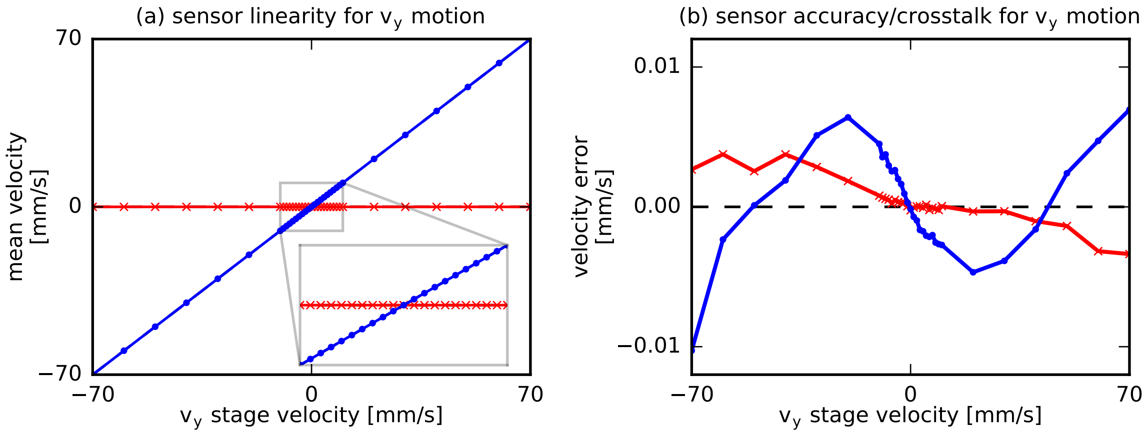

Figure 6. Sensor velocity and accuracy measurements for a translation in the y direction for speeds of ±70mm/s. In (a) the measured v_x and v_y velocities are shown plotted against the applied stage velocity in (red) and (blue) respectively and the inset shows the range ±10 mm/s. (b) Shows the sensor accuracy/crosstalk for the v_x and v_y components in (red) and (blue) respectively.

5. APPLICATION TO WIRE AND ARC ADDITIVE MANUFACTURING

The speckle velocimetry sensor has been applied to robot path characterisation in the wire and arc additive manufacturing (WAAM) process developed at Cranfield.[3] WAAM is an additive manufacturing process using a combination of an electric arc as the heat source and wire as feedstock[3] together with motion provided either by robotic systems or computer numerical controlled gantries. The use of robotic systems is desirable due to their increased flexibility, ease of integration with other processes and ability to produce larger parts however the increased deviations in tool path and tool speed can potentially limit the quality of the manufactured parts.

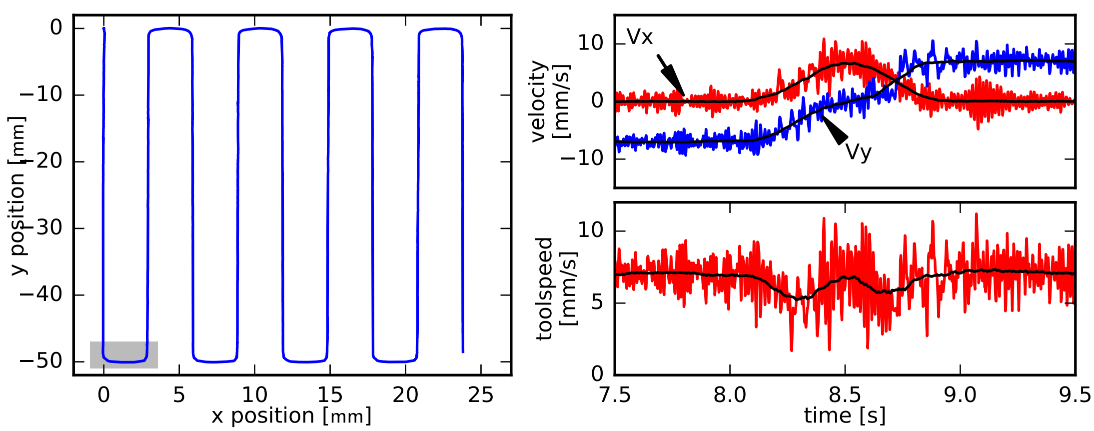

Figure 7. a) Oscillatory wall building path; arrows show direction of travel and highlighted rectangle showing the path traversed in a).

The speckle velocimetry sensor described above was used to characterise tool speed deviations for a number of different wall building strategies using a KUKA KR150 L110/2 industrial robot. Figure 7 a) shows the speckle sensor mounted on the robot in place of the welding torch to ensure that the measured velocities correspond to that of the torch, with no additional components from yawing motions. In figure 7 b) an example of an oscillatory wall building path is shown, throughout which the robot was instructed to maintain a constant tool speed of 7 mm/s. In figure 7 c) the x and y velocity components and overall tool speed are shown for the portion of the path highlighted by the rectangle in figure 7 b), with a 0.2 second mean filtered signal overlaid to remove the influence of robot vibrations. The results, showed tool speed variations of ∼25% when traversing corner radii, which resulted in increased material deposition at these points. This leads to uneven top surface profiles, with non-uniformities of ∼3mm after five layers of the build process, and increased wall width.[10] Such non-uniformities lead to an increase in both material usage and in the finishing machining required, however with knowledge of the robotic tool speed this could be corrected by controlling the wire-feed rate used in the WAAM process.[10]

6. CONCLUSIONS

A speckle velocimetry sensor has been developed and applied to a robotic manufacturing process for path characterisation in the Wire and Arc additive manufacturing (WAAM) process.[3,10] The sensor accuracy was assessed in the laboratory using a high-precision motion stage system, with a maximum error of ±0.01 mm/s in mean recorded velocity over ±70mm/s. Over a lower velocity range of ±10 mm/s, that is more typically used in the WAAM process, this error is reduced to <0.004 mm/s.

Finally an example of the sensors application in the WAAM process has been presented using a KUKA KR150 L110/2 industrial robot, where results showed ∼25% reduction in tool speed when traversing corner radii.

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