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A non-contact laser speckle sensor for the measurement of robotic tool speed

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ABSTRACT

A non-contact speckle correlation sensor for the measurement of robotic tool speed is described that is capable of measuring the in-plane relative velocities between a robot end-effector and the workplace or other surface. The sensor performance has been assessed in the laboratory with sensor accuracies of ± 0.01 mm/s over a ± 70 mm/s velocity range. The effect of misalignment of the sensor on the robot was assessed for variation in both working distance and angular alignment with sensor accuracy maintained to within 0.025 mm/s (<0.04%) over a working distance variation of ± 5 mm from the sensor design distance and ± 0.4 mm/s (0.6%) for a misalignment of 5°. The sensor precision was found to be limited by the peak fitting accuracy used in the signal processing with peak errors of ± 0.34 mm/s. Finally an example of the sensor's 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.

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, typical industrial robots have comparatively low mechanical stiffness [1] and are more prone to disturbances from process forces. In addition there can be significant deviations from the desired tool-path and tool-speed due to thermal and systematic errors in the kinematic model used to convert joint encoder positions to Cartesian end-effector position [2]. 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 [3]. External measurements systems such as laser trackers [4], iGPS [5], position sensitive detectors [6] or vision systems [7,8] 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, methods using position-sensitive detectors [6] are limited to operating within a fixed plane, and laser scanners or laser interferometric guidance systems [4] are expensive and inflexible as the scanning system needs to be mounted externally to the robot and maintain a continuous line-of-sight and which may become obstructed.

This paper describes an alternative approach using laser speckle correlation sensing to make live measurements of the robotic tool speed and is intended to introduce the technique to researcher, demonstrate the achievable performance, and discuss potential challenges and limitations of the technique. 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. Laser speckle patterns, named for their characteristic granular appearance, are formed when coherent light, such as the output from a laser, illuminates a surface with a roughness larger than the optical wavelength[9]. The translation and de-correlation of a speckle pattern are related to the illuminated object's translation, rotation, strain and surface roughness in a family of techniques termed laser speckle correlation that were first described in the late 1970s and early 1980s [10]. Although well understood, the techniques have only recently become viable for practical applications in manufacturing and robotics due to advances in camera and signal processing technology. This has led to renewed interest in the technique with researchers investigating new applications in robotics vehicle odometry [11,12] and robotic positioning and stabilisation applications [13,14].

Speckle correlation sensors have the potential to provide low-cost on-line measurement of tool speed and position and in this paper the design and signal processing of a speckle correlation sensor for tool speed measurement is described. The sensor performance is then assessed in Section 3, including the achievable accuracy and precision,

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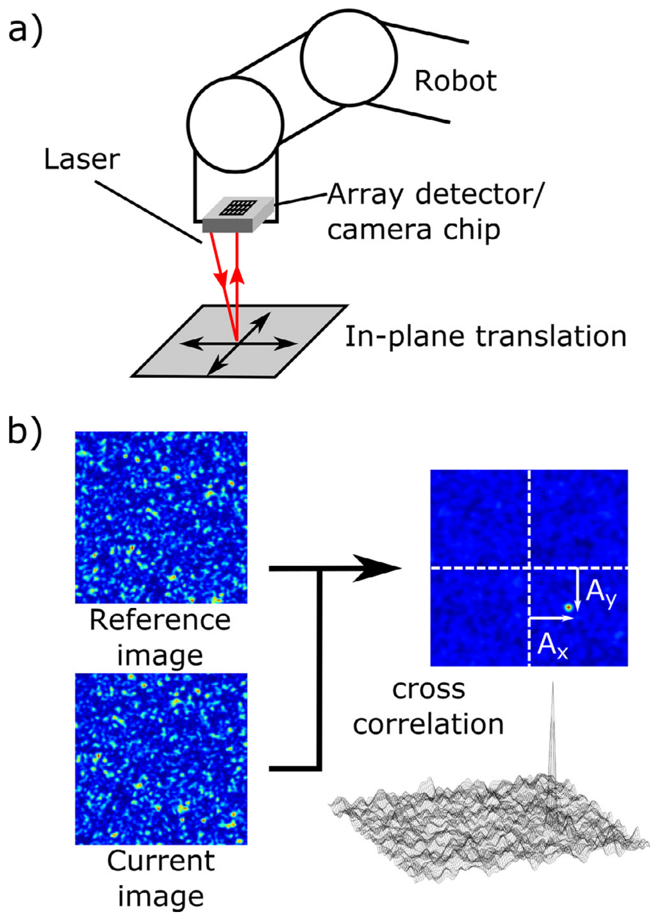

Fig. 1. Sensor concept. In (a) the sensor is attached to the robot end-effector to measure relative in-plane translation between the robot and workpiece. In (b) the signal processing principle is shown with the 2D cross-correlation between a reference and new speckle pattern computed with the peak giving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

along with the sensitivity to misalignments and robot error motions. Finally, in Section 4, an example application of speckle correlation sensing for a robotic manufacturing process is reported where the sensor was applied to tool speed measurement for path planning in the wire and arc additive manufacturing (WAAM) process [15,16]. This application shows the potential of the speckle correlation approach for real-time measurement of end-effector speed that could be applied in a wide range of other robotic manufacturing processes.

2. Sensor design and signal processing

The concept of the sensor is shown in Fig. 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 Fig. 1(b) where the two-dimensional normalised cross-correlation [17] between a reference speckle pattern and a newly acquired speckle pattern is computed. The offset of the peak from the centre of 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 (~ 0.7 µm), i.e. diffusely reflecting. For the work here the workpiece surface is assumed to be metallic for example the build plate used in the WAAM process [15].

The prototype sensor used in this work (Fig. 2) consisted of a fibre coupled diode laser source operating at 658 nm (FibreTec II FTEC2658-P60PA0, max output 60 mW, operating output 0.6 mW) 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 500 fps with exposure times of 200 µs and acquiring a region-of-interest of 512 × 512 pixels. A laser-line bandpass filter (Semrock FF01-655/40-25, 655 nm centre wavelength, 40 nm bandwidth, optical density > 5) is mounted in front of the camera detector array to reduce ambient background light and prevent sensor blinding.

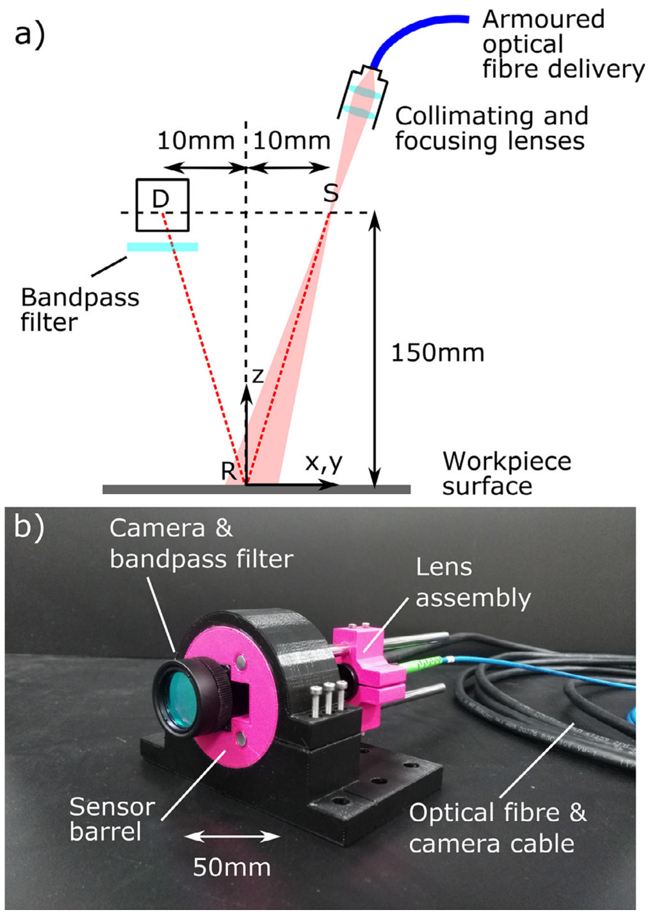

Fig. 2. (a) A schematic showing the 'balanced angle' geometry used for the sensor with the beam focus and detector located in the same x–y plane 150 mm from the workpiece surface and (b) a photograph of the 3D printed sensor prototype in mount.

The detector array centre point, D, and beam waist, S are aligned to lie within a common xy plane at z=150 mm from the workpiece, and are arranged symmetrically around the z-axis centred on the laser spot, R. This balanced-angle geometry offers several advantages: strong signal levels due to operating in the narrow scattering cone of the metallic surface around the specular reflection angle; and theoretically zero sensitivity to out-of-plane motion when D and S are located in the same xy plane [18]. The distance DS was kept small to create a compact sensor (diameter 50 mm) and to reduce the angle between SRD and minimise sensitivity changes due to working height variations [11] and surface gradients [19]. Whilst a co-linear system with the vectors SR and RD coincident would be optimum, the small angle geometry was chosen due to the reduced number of optical components required, and the simpler, more compact implementation. The components where