Investigation of laser spot size on relative position displacement sensing using laser speckle imaging

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In this paper the influence of laser spot size on surface on the displacement estimation result in laser speckle imaging is investigated. Mean intensity gradient as quality criteria for laser speckle images is also introduced and evaluated as a potential quality control parameter for laser speckle displacement measurement.

1 Introduction

To enable low-cost robots for laser material processing (LMP) positional path accuracy during motion needs to be improved [1]. Precise estimations of the robot tool state are the basis for position control approaches. Laser speckle imaging-based velocimetry can be a solution to measure a part of the tool state, velocity in the image plane. Here, velocity is estimated based on the relative in-plane displacement and the time between two consecutive frames. [2] Laser speckle size σ significantly influences the accuracy of displacement estimation. It is considered optimal at 3 – 5 pixel. This size can be adjusted by altering the diameter of the illuminated area and hence control of estimation quality. [3] However, a suitable quality control parameter must be defined. This paper aims to explore the influence of the laser spot and consequently speckle size on displacement estimation accuracy. Further, it is investigated if mean intensity gradient (MIG) can be used as a quality control parameter for such a set-up in the future.

2 Experiments

The proposed set-up is designed to take images of laser speckle patterns during planar motion and is depicted in figure 1.

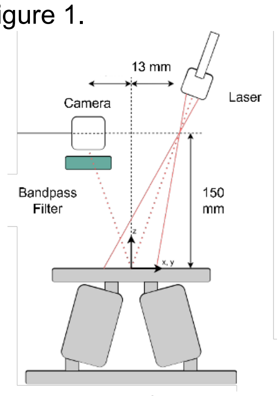

Fig. 1 *Schematic drawing of experimental set-up.*

It consists of a Mako G-040B camera by Allied Vision with a frame rate of 286 fps at full resolution of 0.4 megapixel using Sony IMX287 image with a pixel size of 6.9 µm x 6.9 µm. The camera lens body consists of an Edmund optics camera lens with a fixed focal length of 25 mm and an aperture size in range of f /1.85 to f /16. Further a bandpass filter FLH635-10 from ThorLabs allows 85 % transmission of laser with wavelength of 635 nm. The passband for this filter is 10 nm full width half-maxima The used laser module CPS635F from ThorLabs has typical wavelength of 635 nm. It has adjustable focal length and produces a laser beam of elliptical shape. Motion is executed by means of a M-824.3DG hexapod from PI which offers a motion range along each axis of ±22,5 mm with a resolution of 0.3 µm a maximum final position error of ± 0.5 µm. Speckle size is given by:

$$\sigma = \frac{\lambda L}{A} \quad (1)$$

With wavelength of the laser λ, observation distance L and diameter of the illuminated surface A. The first two parameters are mostly fixed due to the used laser beam source and the mounting of the optics (see Fig. 1). Here, A is changed by moving the focus position along the optical axis of the laser beam.

Image data is collected at maximum framerate of the camera. A linear diagonal motion in the hexapod coordinate system starting from P_0 = [0,0] to the target position P_T is executed for different laser spot diameter. The parameters are given in table 1.

Exposure time [µs]	Gain	Speed of Hexapod [mm/s]	Laser Spot Diameter A [mm]	Target Position P_T [mm]
150	0	1	1; 2; 3; 5; 7; 9	[0.3, 0.3]

Tab. 1 *Experimental parameters of camera and hexapod.*

3 Methodology

In each motion experiment, the initial template position in the current laser speckle frame is determined using normalized-cross correlation (NCC), as outlined by Charrett et al. 2018. A calibration matrix

translates pixel positions from NCC into actual coordinates and compensates for rotational discrepancies between the camera and hexapod systems. Position errors are calculated by comparing these coordinates with the hexapod's reference position.

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Additionally, the position root mean square error (RMSE) between the hexapod position and the estimated position is computed across all tests for each spot size to evaluate estimation accuracy. MIG, a measure of speckle image quality that uses the second derivative of intensity, is further detailed in Hu's work (2021) [3].

4 Results

In figure 2, the positions from NCC over the course of the motion for all laser spot diameters is depicted.

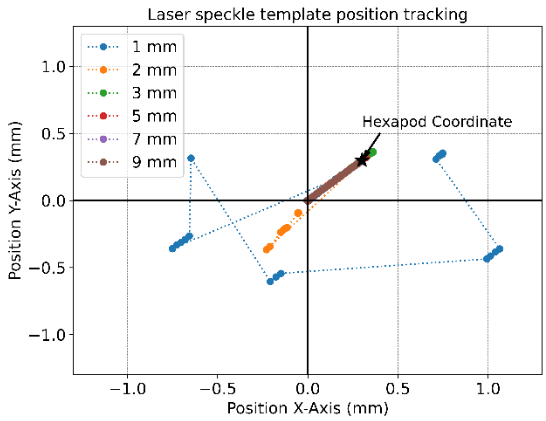

Fig. 2 *Position of laser speckle template position tracking.*

In figure 3 the position error of the estimated position is plotted over the course of the motion.

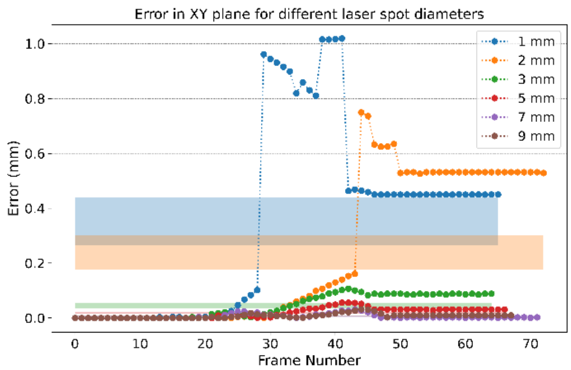

Fig. 3 *Position error of laser speckle template.*

In table 2 the RMSE for each motion and the according MIG value is given.

Laser Diameter A [mm]	RMSE [mm]	MIG
1	0.352	147.2
2	0.24	251.1
3	0.045	350.7
5	0.019	393
7	0.006	370.8
9	0.008	354.8

Tab. 2 *RMSE and MIG values for different laser diameter.*

5 Discussion

Errors are dependent on spot diameter, and tracking motion effectively begins with a 3 mm spot diameter, achieving a MIG value of 350. This indicates that enough features are present in the image for accurate tracking. The minimum RMSE of 0.006 mm is achieved with a 7 mm spot diameter, corresponding to a MIG of 370. Beyond this size, decreasing intensity may lead to less distinctive speckle patterns, reducing accuracy. The results show greater robustness against changes in the illuminated surface for spot sizes from 7 mm and above. For smaller spot sizes, robustness decreases, as evidenced by higher RMSE and lower MIG values when the spot size is reduced by 2 mm. Thus, MIG can be used as a control value for speckle size and estimation quality with a 2 % error. In this setup, a MIG value of 370 is considered optimal.

6 Outlook

It was shown that with a low-cost set up a minimal RMSE of 0.006 mm positional accuracy can be achieved and that MIG value is a suitable parameter to analyze estimation quality and set focus position based on that. However, MIG only accounts for image quality induced errors. Influence of orientation changes on the MIG value and corresponding estimation results should be further investigated. If constant orientation can be guaranteed (e. g. perpendicular camera chip to surface), MIG can be used to enable automated optimization of the setups focus position.

Literature

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