Galvanometric Optical Laser Beam Steering System for Microfactory Application

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***Abstract*—This article presents a kinematic model and control of a galvanometric laser beam steering system for high precision marking, welding or soldering applications as a microfactory module. Galvo systems are capable of scanning laser beam with relatively high frequencies that makes them suitable for fast processing applications. For the sake of flexibility and ease of use 2D reference shapes to be processed are provided as CAD drawings. Drawings are parsed and interpolated to $x-y$ reference data points on MATLAB then stored as arrays in C code. C header file is further included as reference data points to be used by the system. Theoretical kinematic model of the system is derived and model parameters are tuned for practical implementation and validated with respect to measured positions on rotation space with optical position sensor and image field with position sensitive device. Machining with material removal requires high power laser to be employed that makes position measurement on image field unfeasible. Therefore for closed loop applications optical position sensor embedded in galvo motors is used for position feedback. Since the model approved to be approximately linear in the range of interest by simulations, a PI controller is used for precise positioning of the galvo motors. Experimental results for tracking circular and rectangular shape references are proved to be precise with errors of less than 2%.**

I. INTRODUCTION

Today technology is continuously transforming from greater size to more compact and denser forms. It enables ease of integration of the miniature products in various fields such as medicine, aerospace or automotive industry where small size, high performance and precision are of great interest. However with the miniaturization of products a demand for relevant fine precision manufacturing machines arises. Currently, relatively large manufacturing systems are employed to produce technology in micro scales such as semiconductor chips, MEMS, micro actuators and sensors. Main disadvantages of such production machines are their bulky size, high power consumption and excessive material usage that create integration, transportation, maintenance and economic issues. Active research has been conducted for last two decades in order to overcome these problems and a concept of microfactory is proposed [1-4]. Simple idea behind microfactory is to use small and precise machines for manufacturing of very small parts or systems.

Micro-manufacturing systems generally consist of assembly stages [5,6], machining modules [7], inspection system and conveyor mechanisms. Micro-machining is crucial for micro-manufacturing applications where micro-mechanical cutting, electrochemical (ECM), electrical discharge (EDM) or laser machining techniques are widely used [8]. Main advantage of laser micro-machining over other mentioned techniques is it has minimized focus resolution, low heat input and high flexibility of power and beam control. With the development of short and ultrashort pulse lasers such as femtosecond lasers it become possible to machine parts with ultra precision [9]. It is due to laser light that consists of photons. They are much smaller than electrons and suitable for very high precision machining applications down to few microns. Laser technology can be used for welding, cladding, ablation, stripping, trimming, cleaning of micro parts, texturing of micro-channels, 3D printing and marking [10]. Two laser machining techniques are widely employed such as synchronised overlay scanning (SOS) with masking and sync scan (SS) by direct write method where laser beam is scanned by mirrors or sample is moved by motion stage [11]. First method is widely used for MEMS fabrication with use of masks that determine the pattern to be machined and aperture describes the depth of the substrate. In direct writing method the laser beam is focused and used for machining purposes where high speed is of main concern. It is flexible since it doesn't require mask and the texture data to be machined can be provided in software program preserving low cost and flexible implementation compared to masking method. Galvanometric laser beam steering systems are widely used for writing 1D images thus single mirror is used for reflection of laser light, or 2D and 3D dimensional patterns can be machined with employment of two or more mirrors [12]. They are also employed for laser material microprocessing [13], medical imaging [14] or marking [15]. By controlling angular position of the motors with attached mirrors in a proper way a desired image can be achieved on the image field. Image is measured and assessed by means of position photodetectors [16]. Minimum rotation angle and size of mirrors determines the resolution of an image and scanning speed [17]. One advantage of galvo scanners over motion stages is their faster scanning speed. Therefore it is important to consider any structural vibrations that may exist at high speeds of positioning of the galvo motors and compensate them if necessary by means of a controller [18]. Higher resolution means higher amount of data to be processed hence smaller mirrors permit fast processing. Higher data processing for galvos can be achieved by employment of fast computational units such as DSPs and FPGAs [19]. However large image processing may require addition of motion stage. This work presents application of commercial galvo system [20] for machining or marking images in micron scale for microfactory.

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A simple kinematic model of two motors with attached mirrors is derived. Model is tuned and verified for both forward and inverse kinematics by two sensors; position sensitive device (PSD) placed on image field and the optical position sensor (OPS) embedded in the galvo motors. Reference shapes to be tracked are provided as CAD drawings. Drawings are parsed to $x-y$ coordinate points, interpolated in MATLAB environment and further fed to the system as reference points on image field. By implementation of PI controller the angular position of the motors are regulated to minimize laser beam position error on image field. Paper is organized as follows: in section II operational characteristics and theoretical kinematics model of galvanometric mirror steering system under consideration in this paper is presented. Reference generation, model tuning, measurement and control methodologies are given in section III. Experimental setup and results are presented in IV. In V conclusion and future work is discussed.

II. Problem formulation

A. System overview

Galvo scanner system [20] under consideration in this work is depicted in Fig. 1. Two silver-coated octagon shaped mirrors are attached to galvanometer motors with limited angular travel of $\mp 20^\circ$ mechanical degrees. Its acceleration is directly proportional to the current applied to the stator coils. Optical position sensor embedded into the motor provides motor position information. As the galvos move different amounts of light are detected by photodiodes and the produced current is proportional to motor position. Commercial servo driver boards that include both controller and amplifier circuits is used to drive the actuators. The servo circuit interprets current position of the motors from the position detector then by means of PID controller regulates drive currents, vibrations and synchronizes positioning of both motors. The driver is voltage controlled meaning that applied voltages are proportional to certain degrees of angular rotation. This rotation of the mirrors result in certain motion of the reflected laser ray on image plane. Hence by controlling voltages, control of an image coordinates can be achieved on $x-y$ plane.

B. Kinematics of the system

For precise marking laser beam should be guided accordingly to draw desired image on the surface of a specimen. In order to find the relation between the angular positions of the mirrors that correspond to applied voltages and the position of reflected laser spot on image field, a kinematic model should be derived. Theoretical model based on the geometry of the reflected laser beam is presented in [21, 22]. These models are based on ideal assumptions where in practical implementation for micro-positioning the position of the beam on $x-y$ plane greatly sensitive to the size of the mirrors, orientation of the laser light source, distance between two mirrors, distance from the sample of interest and imperfection in drive electronics. The relation between applied voltage and the optical angle of reflected light should be determined with minimum error for accurate positioning on image field. For this purpose parameters of transformation from angle space to image space should be tuned in order to achieve the best performance. Fig. 2 demonstrates the geometry of laser light reflection and effect of galvos rotation on the beam reflected to the $x-y$ image plane. The laser ray first hits the mirror X, reflected light further hits the mirror Y and finally appears on image field as a spot. When mirror X or mirror Y are rotated the beam moves in x or y direction on $x-y$ coordinate plane, respectively. Then the relation between optical angles and $x-y$ coordinate points can be expressed as follows

$$x = (r + \sqrt{d^2 + y^2}) \tan\theta_x \tag{1}$$

$$y = d \tan\theta_y \tag{2}$$

Here, x and y are coordinates of beam position on image field, θ_x and θ_y are optical rotation angles of mirrors, r and d are the distance between mirrors and the distance from mirror Y to image field respectively. According to vendors specifications applied voltage to the galvos is half of mechanical rotational angle where mechanical angle is proportional to optical angle. Then this relation can be expressed as follows

$$V_x = \frac{1}{2}\alpha_x = K_x\theta_x \tag{3}$$

$$V_y = \frac{1}{2}\alpha_y = K_y\theta_y \tag{4}$$

Here, K_x and K_y are scaling constants due to commercial driver input voltage to output mirror angle relations. Then substituting Eq. 3 and Eq. 4 into Eq. 1 and Eq. 2 a following voltage to scalar coordinate points relation can be obtained

$$x = (r + \sqrt{d^2 + y^2}) \tan(\frac{V_x}{K_x}) \tag{5}$$

$$y = d \tan(\frac{V_y}{K_y}) \tag{6}$$

given $x-y$ reference coordinates of the desired image the required voltages can be calculated by inverse transformation of the relation given in Eq. 5 and Eq. 6

$$V_x = K_x \arctan(\frac{x}{r + \sqrt{d^2 + y^2}}) \tag{7}$$

$$V_y = K_y \arctan(\frac{y}{d}) \tag{8}$$

When reference points x^{ref} and y^{ref} of the desired shapes are provided by the user the reference voltages V_x and V_y are generated and fed to the system to achieve the desired position on image plane. Fig. 3 and Fig. 4 present simulation results for the model given above. Here, voltage is applied between $V_{min} = -10V$ and $V_{max} = 10V$ due to driver limitations and corresponding x and y coordinates are plotted. For simplicity parameters are chosen as $K_x = K_y = 0.25$. Since applications in microfactory consider image sizes in microns and few millimeters the range of interest is taken between $V_{min} = -2V$ and $V_{max} = 2V$ as labeled with rectangular regions with dashed lines. In this regions the system has approximately linear behavior. The actual model can be determined by measuring positions on image plane and by tuning K_x and K_y parameters actual positions can be matched with the reference positions. Once the model is tuned offline, further fine positioning with employment of control additional compensation of errors online can be achieved.

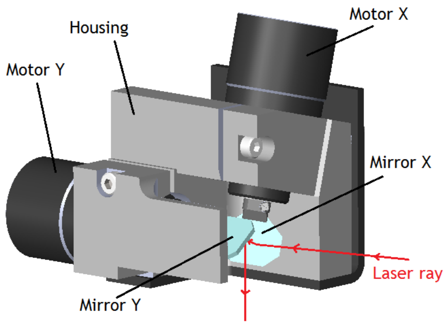

Fig. 1: Galvo scanning system

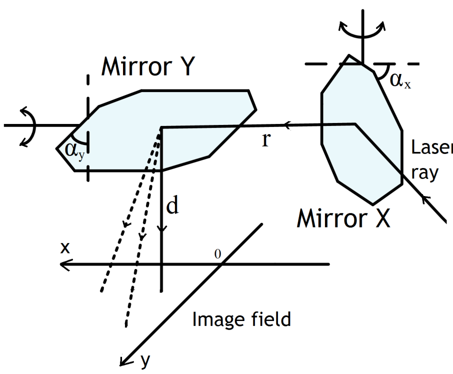

Fig. 2: Laser beam reflection by means of galvo mirrors

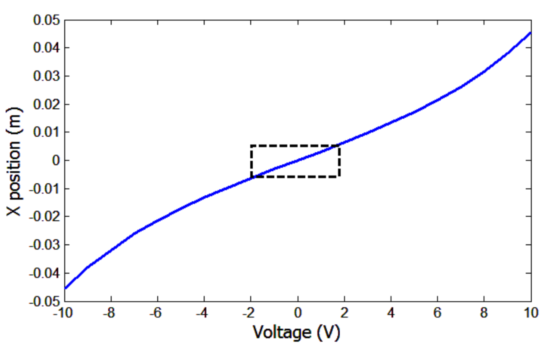

Fig. 3: System behavior in x coordinate

III. Methodology

A. Reference image generation

The overall system block diagram is depicted in Fig. 5. One advantage of the current approach is the ease and flexibility of reference image generation. Flexibility of desired image generation to be marked or machined is crucial especially in industrial applications where user doesn't have to constrain him/herself with fixed images to be machined. Instead operator

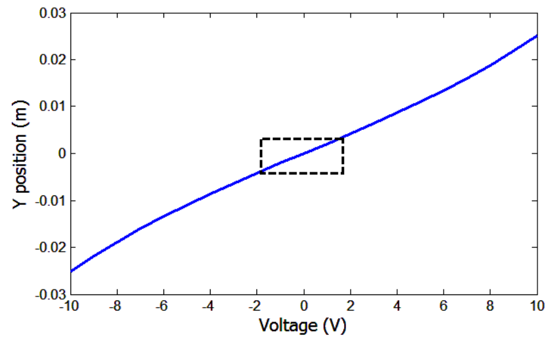

Fig. 4: System behavior in y coordinate

can simply draw any demanded pattern as CAD drawing. For this purpose coordinates of the desired output image for a galvo scanning system are generated from CAD drawing with implementation of coordinate points parsing algorithm on MATLAB. Before parsing, the desired image to be marked or machined should be saved as any 2D CAD file in dxf format. The parsing algorithm reads dxf file line-by-line and determines the geometry of the input shape as circle, line or etc. When appropriate shapes are detected that match any shape in program library equally spaced data points are fitted through the entire path of the pattern and stored as vectors. By means of interpolation algorithm more points are fitted in between the parsed data points in order to obtain more accurate shape. Generated x and y coordinate points are further extracted as arrays in C code by implementation of MATLAB $fopen$ and $fprintf$ functions. C file is then included as reference input data file to the system.

B. Model tuning and measurement

In order to satisfy accuracy in positioning both in configuration space and image space one should guaranty that the model is valid for both forward and inverse transformations. To achieve accurate response of the system the derived model is tuned by alteration of K_x and K_y parameters of the kinematic equations that are in turn proportional to voltages applied to the system. The model is tuned offline by manually matching x_{PSD}^{meas} and y_{PSD}^{meas} positions measured by position sensitive device (PSD) placed on image field with those of reference data points x^{ref} and y^{ref} supplied to the system. Optical position sensor (OPS) embedded in galvo motors is used to measure angular positions of the galvo motors as voltage values V_x^{meas} and V_y^{meas}. Measured voltages can be used to obtain x_{OPS}^{meas} and y_{OPS}^{meas} points by forward transformation equations given by Eq. 5 and Eq. 6 and then compared with x_{PSD}^{meas} and y_{PSD}^{meas} (see Fig. 6). Therefore by minimizing the errors $e_x^{'}$, $e_y^{'}$, e_x^{meas} and e_y^{meas} the system model approaches to more accurate form. Since PSD device placed on image plane has to be removed for operations where high power laser is considered for machining and marking, online minimization of the errors in x and y become infeasible without PSD data. For further online control applications OPS is suitable for position feedback to compensate errors.

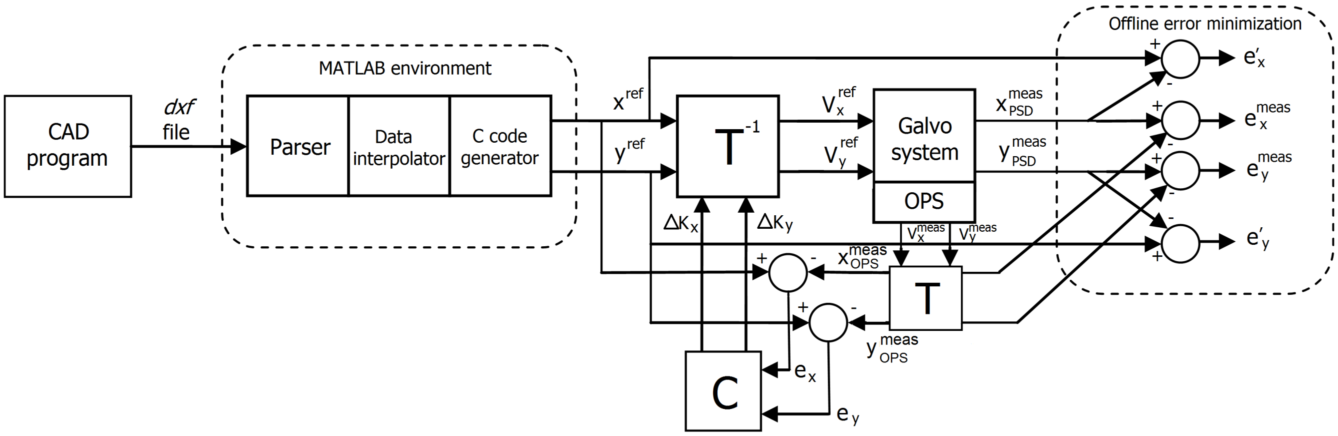

Fig. 5: Overall system block diagram

C. Controller scheme

For online applications the main goal is to compensate positioning errors e_x and e_y by appropriately regulating input voltages. For this purpose the inverse transformation equation is modified as

$$V_x = (K_x + \Delta K_x) \arctan\left(\frac{x^{ref}}{r + \sqrt{d^2 + (y^{ref})^2}}\right) \quad (9)$$

$$V_y = (K_y + \Delta K_y) \arctan\left(\frac{y^{ref}}{d}\right) \quad (10)$$

here, ΔK_x and ΔK_y are the regulatory variables. These variables are result of the controller. Since the galvo system has a linear behavior between inputs and outputs, a simple PI control method is employed to compensate positioning errors and can be expressed mathematically as follows

$$e_x = x^{ref} - x_{OPS}^{meas} \quad (11)$$

$$e_y = y^{ref} - y_{OPS}^{meas} \quad (12)$$

then

$$\Delta K_x = K_{px} e_x + K_{ix} \int e_x dt \quad (13)$$

$$\Delta K_y = K_{py} e_y + K_{iy} \int e_y dt \quad (14)$$

Here, e_x and e_y are the errors in x and y position on image plane, x, y^{ref} are the reference coordinates and x, y_{OPS}^{meas} are the measured points by optical position sensor. $K_{px,y}$ and $K_{ix,y}$ are the proportional and integral controller gains.

IV. Experimental results

The experimental setup is depicted in Fig. 8 to assess the system for positioning (left) and the high power laser for marking (right). Two mirrors reflect the low power laser pointer ray coming from side to the image field where the PSD is placed. PSD has $4mm \times 4mm$ sensitive area with detection resolution of 1μm. The sensor is separated into

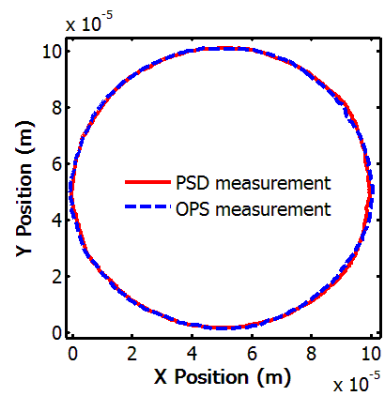

Fig. 6: PSD to OPS measurement plot

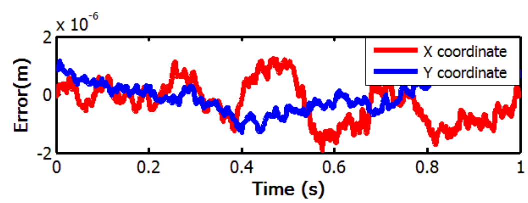

Fig. 7: PSD to OPS measurement error

four quadrants thus enabling both positive and negative $x - y$ coordinates. dSPACE 1103 is used as a RT controller unit and the commercial galvo driver electronics are employed to drive the motors. 2D images are drawn on Microsoft Office Visio 2007 software program and saved in dxf file format. The file is further parsed, interpolated and saved as C code. Voltage references are calculated and fed to the system. Position measurements are taken by calibrated optical position sensor and experimental results are presented below. System response with PI controller for 50 μm radius circle reference is provided in Fig. 9. Error plot for this reference is in the range of less than 2%. For assessing the system behavior for sharp edges rectangular reference shape is drawn as letter "G" as depicted

in Fig. 11 and Fig. 13. For these references system has also errors within 2%.
For assessment of the system in real marking applications, a 100 W laser with 25 KHz pulsed light configuration is used. Beam is focused by means of focusing lens and directed to anodized coated black aluminum substrate. The marked results for circular and rectangular references are provided in Fig. 15 and Fig. 16, respectively.

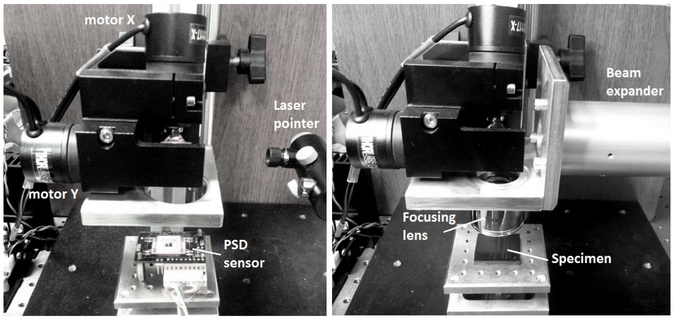

Fig. 8: Galvo experimental setup

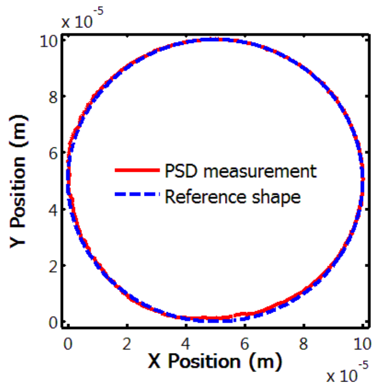

Fig. 9: 50 μm radius circle reference tracking response

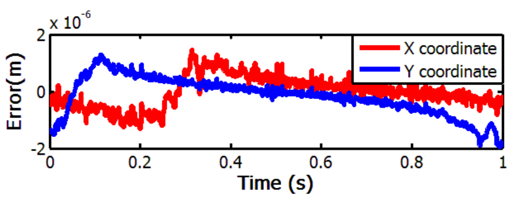

Fig. 10: 50 μm radius circle reference tracking error

V. Conclusion

In this paper a galvanometric laser beam scanning system is modeled and controlled for high precision marking, welding and soldering applications in microfactory. In order to understand the system behavior, a kinematic model is derived relating rotation angles of the galvo motors to $x-y$ coordinate points on image plane based on geometrical structure and optics. Simulations revealed that the system has approximately linear relation between angles and $x-y$ positions in the range

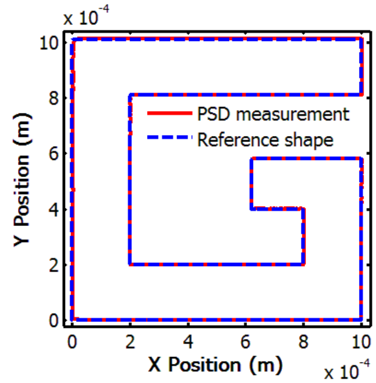

Fig. 11: 1 mm size rectangular "G" letter reference tracking response

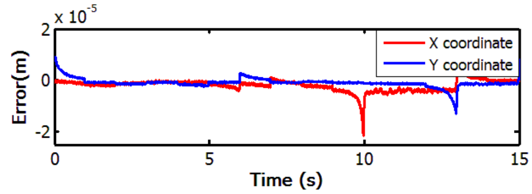

Fig. 12: 1 mm size rectangular "G" letter reference tracking error

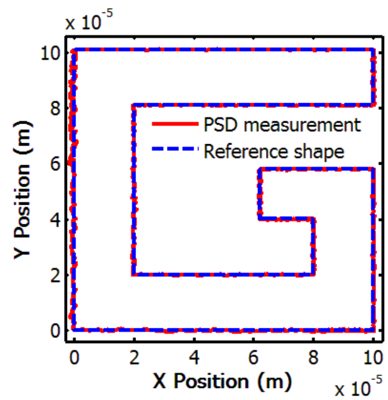

Fig. 13: 100 μm size rectangular "G" letter reference tracking response

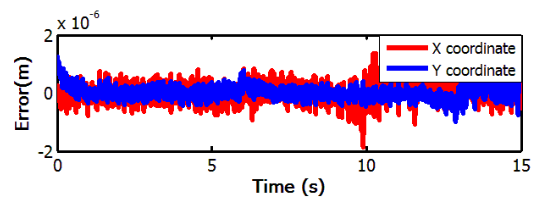

Fig. 14: 100 μm size rectangular "G" letter reference tracking error

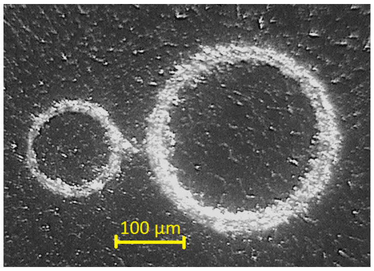

Fig. 15: 50 μm and 150 μm radius marked circles

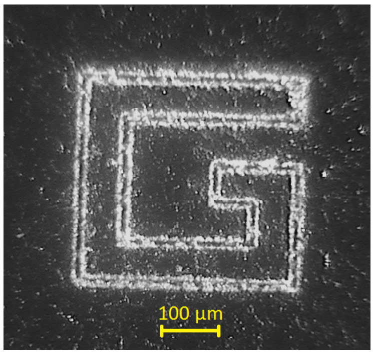

Fig. 16: 400 μm marked rectangular letter ”G”

of interest for microfactory application. Theoretical model is further tuned manually to satisfy for both forward and inverse kinematics. Once the model is tuned a PI controller with optical position sensor feedback is employed for fine positioning of the galvo motors to minimize the position errors on image field. Experimental results for circle reference of 50 μm radius and a rectangular references of 1 mm and 100 μm size are provided to assess the accuracy of the model and the controller. Real marking experiments on an aluminum specimen surface are also performed to verify the possibility of real marking applications. These results demonstrate high precision positioning capabilities of the motors with the proposed PI controller with repetitive errors of less than 2% of the reference figure.
As a future work authors consider to develop repetitive control methods to compensate periodic errors observed and synchronization of the system with additional motion stage to increase the machining area.

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