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Design and experimental evaluation of a prototype adaptive laser mechanism for inclined surface processing

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Abstract
Laser-based material processing on inclined or non-uniform surfaces is often affected by beam defocus and alignment errors which can reduce process accuracy and repeatability. Adaptive laser mechanisms provide a promising approach to mitigating these effects; however, their practical implementation requires validated system architectures that support reliable integration of sensing, actuation, and control functions. This paper presents the design and experimental evaluation of a prototype adaptive laser mechanism developed as a dedicated test platform for laser beam autofocusing and laser beam detection subsystems. The prototype is intentionally constrained to a single rotational degree of freedom to limit mechanical and computational complexity while retaining the essential characteristics of adaptive beam control. The experimental setup integrates a continuous-wave visible laser source operating at a wavelength of 532 nm, a camera-based sensing unit with polarization filtering, an actuator system, an MPU6050 inclination measurement subsystem, and a rotating platform to introduce controlled surface inclinations. Experimental evaluation conducted at surface inclination angles up to 0.262 rad demonstrated stable and repeatable laser beam projection under varying angular conditions. Quantitative assessment of the inclination measurement and positioning subsystems showed a maximum measurement error of 0.001 rad, settling times between 2.52 s and 5.18 s, and steady-state positioning errors below 0.001 rad. Qualitative observations further confirmed the capability of the prototype to support systematic investigation of laser beam behavior in response to surface inclination, although visual differences in beam spot size, shape, and intensity distribution remained subtle. The presented prototype contributes a practical and scalable foundation for the development of adaptive laser mechanisms by enabling controlled evaluation of beam projection performance in a simplified experimental environment. The results indicate that quantitative characterization of laser beam behavior cannot rely on visual inspection alone, thereby motivating the development of dedicated laser beam detection methods. Future work will focus on extending the mechanism to multiple degrees of freedom and on the quantitative analysis of laser beam spot characteristics using advanced image-based detection algorithms.

Keywords
adaptive laser mechanism, laser beam autofocusing, laser beam detection, prototype development, inclined surface processing

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УДК 681.5.073

Проектирование и экспериментальная оценка прототипа адаптивного лазерного механизма для обработки наклонных поверхностей

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Аннотация
Введение. Лазерная обработка материалов на наклонных или неоднородных поверхностях часто сопровождается расфокусировкой и ошибками позиционирования лазерного пучка, что приводит к снижению точности и повторяемости технологического процесса. Адаптивные лазерные механизмы представляют собой перспективный подход к снижению влияния указанных факторов; однако их практическая реализация требует верифицированных архитектур систем, обеспечивающих надежную интеграцию сенсорных, исполнительных и управляющих функций. **Метод.** Представлены разработка и экспериментальная оценка прототипа адаптивного лазерного механизма, предназначенного в качестве испытательной платформы для подсистем автоматической фокусировки и детектирования лазерного пучка. Для снижения механической и вычислительной сложности прототип намеренно ограничен одной вращательной степенью свободы при сохранении основных принципов адаптивного управления лазерным пучком. Экспериментальная установка включает источник непрерывного видимого лазерного излучения с длиной волны 532 нм, сенсорный модуль на основе камеры с поляризационным фильтром, исполнительную систему, подсистему измерения угла наклона на базе датчика MPU6050 и вращающуюся платформу для формирования контролируемых углов наклона поверхности. **Основные результаты.** Экспериментальная оценка при углах наклона поверхности до 0,262 рад показала стабильную и воспроизводимую проекцию лазерного пучка при различных угловых положениях платформы. Количественный анализ подсистем измерения и позиционирования продемонстрировал максимальную погрешность измерения угла наклона 0,001 рад, время установления от 2,52 до 5,18 с и установившуюся ошибку менее 0,001 рад. Качественный анализ также подтвердил возможность использования прототипа для систематического исследования поведения лазерного пучка при изменении ориентации поверхности, хотя различия в размере, форме и распределении интенсивности пятна лазерного пучка визуально выражены незначительно. **Обсуждение.** Разработанный прототип формирует практическую и масштабируемую основу для дальнейшего развития адаптивных лазерных механизмов, обеспечивает контролируемую оценку характеристик проекции лазерного пучка в упрощенной экспериментальной среде. Показано, что количественная оценка характеристик лазерного пучка не может основываться исключительно на визуальном анализе, что обусловливает необходимость разработки специализированных методов детектирования и мониторинга лазерного пучка. В дальнейших исследованиях планируется усложнение механизма до нескольких степеней свободы, а также проведение количественного анализа характеристик пятна лазерного пучка с использованием усовершенствованных алгоритмов обработки изображений.

Ключевые слова
адаптивный лазерный механизм, автоматическая фокусировка лазерного пучка, детектирование лазерного пучка, разработка прототипа, обработка наклонных поверхностей

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Introduction

Laser-based manufacturing technologies have become indispensable tools in modern materials engineering due to their high spatial coherence, monochromaticity, and ability to deliver highly concentrated energy with precise spatial control. These characteristics enable accurate modification of surface and near-surface material properties across a broad range of engineering materials, including metals, ceramics, and composites. Consequently, laser processing is widely applied in biomedical implant fabrication, structural component manufacturing, and advance surface engineering. In particular, laser-assisted surface modification plays a crucial role in tailoring microstructure and functional performance in bioceramic-coated scaffolds, engineering steels, and advanced alloys, where controlled energy delivery is required to establish well-define structure-property relationships [1, 2].

To fully exploit these capabilities, a detailed understanding of material response to laser irradiation is essential. The interaction between laser energy and matter involves complex physical phenomena, including optical absorption, heat transfer, phase transformations, and chemical reactions within the irradiated zone. These processes are strongly influenced by laser parameters, such as wavelength, beam quality, power density, pulse duration, and focal position. Precise control of these parameters is therefore necessary to achieve repeatable and predictable material modification [3].

Among these parameters, focal position and beam waist location are particularly critical, as they directly determine the spatial distribution of laser energy on the material surface. When processing uneven or curved surfaces, deviation from the optimal focal plane are often unavoidable and lead to defocusing effects. Numerical modeling and experimental studies demonstrate that even minor focal offsets can significantly alter energy density and thermal behavior, resulting in unstable laser-material interaction and reduced processing accuracy, especially in high-precision application [4].

These challenges are further intensified during the processing of complex geometries. Curved, freeform, and non-planar surface introduce continuously varying orientations and focal distances, making it difficult to maintain consistent laser interaction conditions. Investigations involving thin films, freeform surfaces, and non-planar substrates indicate that, in the absence of active compensation, laser structuring, ablation, and texturing frequently yield non-uniform features and inconsistent surface quality [5–7].

Numerical modeling provides deeper insight into the underlying mechanisms of these limitations. Simulations of ultrafast interaction with freeform surfaces reveal pronounced sensitivity to both beam incidence angle and focal offset. These findings indicate that static optical configurations are insufficient for stable, high-quality laser processing and highlight the necessity for dynamic beam alignment and focus control strategies [8, 9].

To mitigate these issues, adaptive optical techniques have been increasingly explored. Systems incorporating deformable mirrors, spatial light modulators, or adaptive lenses enable active control of beam shape and wavefront distortion, thereby improving processing flexibility and uniformity, particularly in ultrafast laser application [10, 11]. However, most existing adaptive optical approaches primarily target beam profile correction and do not offer comprehensive control over beam position and orientation relative to the workpiece surface.

Despite ongoing progress in optical adaptation, significant limitations persist. Current solutions predominantly focus on wavefront correction or thermal distortion compensation, while integrated systems capable of simultaneously correcting focal distance, beam position, and beam orientation in real-time remain scarce, particularly in industrial laser processing environments [12, 13].

Collectively, these observations reveal a critical research gap. Existing approaches often address individual error sources in isolation, rely on single-degree-of-freedom mechanisms, or depend on predefined surface models and offline calibration procedures. Vision-based methods are commonly employed for monitoring purposes rather than active close-loop control, and only a limited number of systems provide coordinated compensation of focal, translational, and angular misalignment under actual processing conditions. These constraints significantly limit processing reliability, accuracy, and scalability for uneven and freeform surfaces in industrial applications.

To address these limitations, this study presents the conceptual design of an adaptive laser processing system and the development of a prototype adaptive laser mechanism intended as an experimental platform for future beam monitoring and autofocusing research.

Conceptual design of laser beam autofocusing system based on an adaptive mechanism

To accurately compensate for or eliminate laser beam spot positioning errors on material surfaces, particularly those that are uneven or irregular, an adaptive laser mechanism is essential. In numerous industrial applications the precision and accuracy of laser beam positioning directly affect the quality consistency and reliability of the resulting processes. Consequently the integration of a mechanism capable of dynamically adjusting to surface variations is critical for achieving stable and optimal laser material interactions.

An adaptive mechanism enables the laser system to detect variations in surface geometry in real-time and autonomously adjust the focal point to maintain the desired beam spot shape and size [14]. This capability ensures that even under nonuniform surface conditions the laser beam spot remains consistent, thereby improving process stability positioning accuracy and overall material processing quality.

Previous studies have investigated various adaptive mechanisms for laser positioning. For instance the study in [15] introduced a modified Stewart platform as a potential solution. The Stewart platform consists of a lower base and an upper platform connected by four actuators with variable lengths allowing motion with three Degrees of Freedom (DOF), one translational and two rotational. This parallel kinematic structure offers several advantages including high positioning precision structural rigidity and mechanical flexibility making it well suited for fine motion control in environments with complex surface geometries.

Building upon this concept, the present study proposes a novel adaptive mechanism that extends beyond the conventional Stewart platform by introducing additional DOF specifically three translational motions along the X, Y and Z axes. This enhancement significantly improves the system capability to adapt to varying surface topographies with higher precision. The incorporation of these additional DOF not only increases the platform flexibility but also enables more accurate and responsive compensation for variations in surface inclination and contour.

The mechanical design developed in this work adopts a hybrid system architecture that integrates the fundamental principles of the modified Stewart platform with newly designed linear motion units. These units are strategically incorporated to enhance adaptability while maintaining structural integrity and operational robustness. As a result, the proposed mechanism offers a comprehensive solution to laser beam spot distortion by enabling precise spatial adjustments across multiple axes, thereby ensuring consistent laser material interaction regardless of surface irregularities.

A detailed schematic of the adaptive mechanism is presented in Fig. 1 illustrating the mechanical configuration actuation system and motion capabilities. This design forms the foundation for implementing an intelligent real-time adaptive control system further enhancing the effectiveness and reliability of laser processing on complex or nonuniform surfaces.

As illustrated in Fig. 1, the proposed mechanical design integrates several key components, each serving a

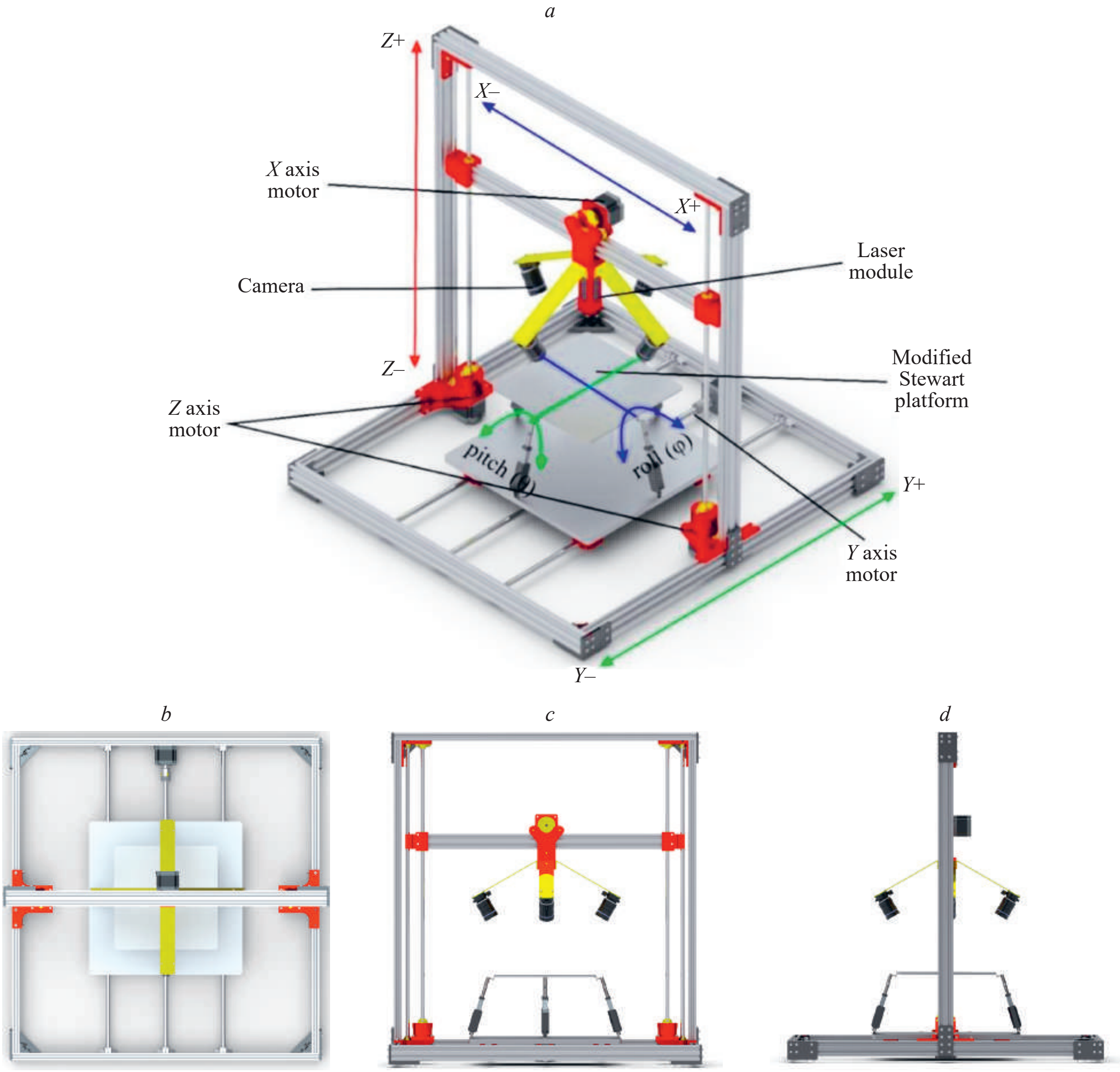


Fig. 1. Design of an adaptive laser mechanism: isometric view (*a*); top view (*b*); front view (*c*); side view (*d*)

specific function to enable precise adaptive control of the laser beam spot on uneven material surfaces. The primary components are described as follows:

— Modified Stewart platform. The modified Stewart platform is equipped with four linear actuators that enable one translational motion along the *Z* axis and two rotational motions about the *X* axis (roll) and *Y* axis (pitch). The *Z* axis translation provided by the platform has a limited range and is primarily used for vertical positioning of the platform.

— *Z* axis motor. Two stepper motors are employed to provide high-precision translational motion of the laser module along the *Z* axis, enabling accurate vertical positioning and focal distance adjustment.

— *Y* axis motor. A stepper motor is used to generate translational motion along the *Y* axis, allowing horizontal adjustment of the platform in the front–back direction.

— *X* axis motor. A stepper motor enables translational motion along the *X* axis, facilitating horizontal adjustment in the left–right direction.

— Camera system. The camera system plays a critical role in monitoring and capturing the laser beam spot position on the material surface during processing.

— Laser module. The laser module serves as the primary processing element, projecting the laser beam onto the material surface.

Through the integration of these components, the developed adaptive mechanism achieves five DOF, comprising three translational motions (*X*, *Y*, and *Z* axes) and two rotational motions (roll and pitch). This configuration significantly enhances system flexibility and adaptability, making it well suited for laser processing on uneven or inclined surfaces.

The rotational motions (roll and pitch) are essential for compensating angular misalignment of the laser beam caused by surface inclinations or geometric irregularities.

When the material surface is tilted, the laser beam intersects the surface at an oblique angle, resulting in defocusing and beam spot distortion, typically transforming a circular spot into an elliptical or elongated shape. By applying precise roll and pitch adjustments, the adaptive mechanism dynamically aligns the laser emitter to maintain near-normal incidence relative to the local surface orientation. This ensures a circular, well-focused beam spot and preserves the intended energy distribution during processing.

The translational motions provide complementary functionality. Movements along the *X* and *Y* axes enable lateral positioning of the laser beam, allowing controlled scanning or tracing across the surface in the left-right and front-back directions, respectively. This capability is essential for applications, such as laser engraving, surface structuring, and material removal, where precise beam traversal along planar or contoured paths is required.

The *Z* axes translational motion plays a critical role in maintaining the correct focal distance between the laser emitter and the material surface. Variations in surface height can lead to fluctuations in focal distance, directly affecting beam spot size and energy density due to defocusing. The *Z* axes motion compensates for these variations by adjusting the vertical position of the laser module in real-time, ensuring that the beam remains focused at the predefined working distance throughout the process.

The integration of a multi-camera vision system further enhances the adaptability of the proposed mechanism. The four strategically positioned cameras provide real-time visual feedback from multiple perspectives, enabling accurate localization and tracking of the laser beam spot. This multi-view observation expands the effective field of view around the interaction zone and supports reliable surface geometry estimation. The acquired image data serve as feedback for closed-loop control system, which continuously calculates positional corrections and commands the actuators accordingly.

At the core of the system is the laser module, whose performance is directly dependent on the effectiveness of the adaptive mechanism. Deviations in beam shape, size, or position can significantly affect processing outcomes. By integrating the laser module with the adaptive mechanical platform and vision-based feedback system, the proposed setup functions as an intelligent and autonomous laser processing unit capable of compensating for surface irregularities in real-time.

In summary, the five DOF adaptive mechanisms presented in this study provides a comprehensive solution for maintaining consistent laser beam spot shape, size, and position during dynamic surface processing. By actively compensating for both angular and distance-related errors, the system ensures stable and optimal laser-material interaction throughout operation. This capability is particularly advantageous for processing complex, non-flat, or textured surfaces, where conventional fixed-beam systems often suffer from reduced accuracy and efficiency. The proposed design therefore represents a significant advancement toward intelligent and adaptive laser processing platforms for high-precision industrial applications.

Design and development of a prototype adaptive laser mechanism

The mechanism presented in this study serves as a prototype for the adaptive laser mechanism under development, aimed at addressing laser beam defocus on material surfaces, particularly those that are uneven or inclined. This prototype plays a critical role in the early stages of system development and experimental validation. Its primary purpose is to facilitate and accelerate the development of the two essential subsystems introduced in the previous section, namely the laser beam autofocusing system and the laser beam detection system, which together form the core of the adaptive laser mechanism.

A key distinction between the prototype mechanism and the fully developed adaptive mechanism lies in the number of DOF it provides. While the complete adaptive mechanism is designed to operate with multiple DOF, incorporating both translational and rotational motions to achieve comprehensive compensation for surface irregularities, the prototype mechanism is intentionally limited to single DOF. Specifically, it provides one rotational motion about the X axis, commonly referred to as roll. Despite this reduced motion capability, the prototype is sufficiently representative for investigating fundamental system behavior in a simplified and well controlled experimental environment.

The reduced complexity of the prototype mechanism offers several advantages during the development phase. By simplifying both the mechanical structure and the associated control architecture, the platform enables efficient testing, refinement, and validation of the proposed control strategies. This includes the adaptive control algorithms responsible for commanding the actuators in response to laser beam focus deviations as well as the image processing algorithms designed to detect and quantify variations in the laser beam spot shape and size under different surface conditions.

In the context of laser beam autofocusing, the prototype mechanism functions as an effective experimental testbed for the formulation and tuning of adaptive control algorithms. These algorithms regulate the actuator response to angular induced focus errors, ensuring that the laser beam remains optimally focused on the target surface. The implementation of a single roll motion allows the isolation of angular misalignment effects, enabling the development of real-time compensation strategies that can later be extended to the multi-DOF adaptive mechanism.

Similarly, the development of the laser beam detection system benefits significantly from the use of the prototype platform. Controlled experiments conducted using the prototype enable systematic analysis of image data acquired by the camera system. This data supports the development and validation of algorithms for detecting changes in the laser beam spot shape, size, and intensity distribution. Such characteristics are influenced by multiple factors, including surface tilt, lateral offset, and surface texture or unevenness. By examining the relationship between these parameters and the resulting beam spot deformation, robust and reliable detection algorithms can be established.

Beyond subsystem development, the prototype mechanism also serves as a valuable tool for evaluating the overall system performance in terms of stability, precision, and responsiveness. The simplified platform enables rapid iteration, calibration, and debugging of both hardware and software components, thereby reducing the time and cost associated with testing the complete adaptive mechanism. Early stage experimental validation using the prototype further provides insight into potential implementation challenges, allowing design improvements to be introduced prior to system scale integration.

The modular and simplified design of the prototype mechanism makes it particularly suitable for conducting repeatable and quantifiable experiments. As such, this prototyping stage represents a critical step in ensuring reliable subsystem performance before transitioning to a more complex and resource intensive adaptive laser platform.

The structural layout and component configuration of the prototype mechanism are illustrated in Fig. 2 which provides a clear overview of its mechanical design and demonstrates how the prototype functions as a scaled and simplified representation of the full adaptive laser system.

Fig. 2 presents a comprehensive overview of the prototype adaptive laser mechanism, providing insight into its overall configuration and functional arrangement. This prototype represents a critical milestone in the development and prospective deployment of adaptive laser mechanisms for material surface processing applications. The system is designed to address a fundamental challenge in laser-based manufacturing, namely the reduction of laser beam placement and focus errors on non-uniform surfaces through adaptive control of laser focus and beam alignment. In this context, the prototype establishes the foundation for the subsequent development and integration of the laser beam autofocusing and laser beam detection

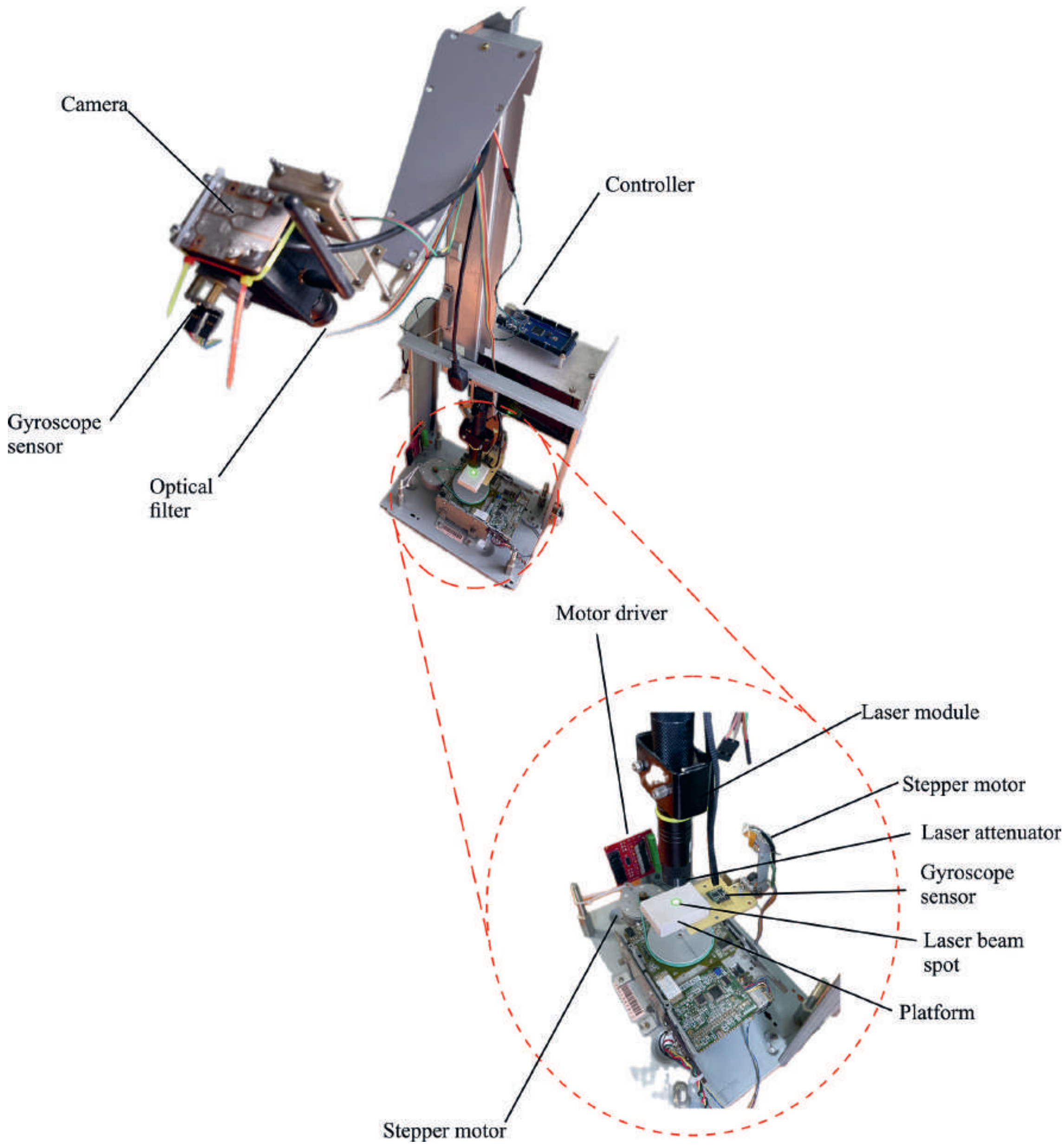


Fig. 2. Prototype of adaptive laser mechanism

subsystems, both of which are essential for achieving high precision and process reliability.

The prototype is carefully assembled, with each component strategically integrated to ensure reliable and repeatable operation. The system consists of four primary components: a laser module, a camera-based sensing unit, gyroscope sensor, and a rotating platform. Together, these components enable controlled investigation of laser beam behavior under varying surface orientation and alignment conditions.

The laser module employed in the prototype is a 1000 mW continuous-wave green laser operating at a wavelength of 532 nm. This laser source was selected primarily for its high visibility and safe operating characteristics, making it well suited for experimental evaluation and image-based laser beam monitoring. In contrast to high-power industrial lasers, the selected module minimizes risks such as surface damage and thermal hazards, thereby enabling repeated experimentation under controlled laboratory conditions. Although the present study utilizes a 532 nm visible laser source, the proposed monitoring method is based on image analysis of laser beam spot characteristics, including spot shape, size, and position, and is therefore not fundamentally limited to a specific wavelength. Consequently, the method can be extended to laser systems operating at other wavelengths, including 1064 nm, provided that suitable imaging sensors and optical filtering components capable of detecting near-infrared radiation are employed.

The laser beam detection subsystem is centred on a camera that functions as both a visual sensing device and a feedback sensor. The camera captures real-time images of the laser beam spot projected onto the target surface, supplying the image data required by the image processing algorithms. This feedback enables accurate detection of beam spot deformation, positional deviation, and focus related errors. In this study, an IP camera with model number BLK18E 0012 and a resolution of 3 megapixels is utilized. The high spatial resolution enables detailed observation of laser beam spot characteristics, including shape, size, and intensity distribution, thereby supporting reliable performance evaluation under varying surface conditions.

However, accurate interpretation of the captured images also requires knowledge of the relative angular orientation between the camera, the laser beam, and the platform. Particularly when the camera is not perfectly perpendicular to the beam spot. To address this limitation, inertial sensing is integrated into the system. A gyroscope sensor is employed to provide angular inclination information for the adaptive laser mechanism. The sensor is installed at two locations: on the platform and on the camera. The gyroscope mounted on the platform is used to detect and measure the platform inclination, while the gyroscope attached to the camera provides information about the camera angular orientation. The measured camera inclination is incorporated into the image processing algorithms to compensate for perspective distortion arising from the non-perpendicular alignment between the camera and the laser beam spot. In this study, an MPU6050 gyroscope sensor is used.

To emulate the interaction between the laser beam and an uneven or inclined material surface, the prototype incorporates a rotating platform that serves as the target surface for laser projection. The platform introduces controlled angular variation by rotating about the X axis, corresponding to roll motion. Although the conceptual design of the full adaptive laser mechanism employs a modified Stewart platform with up to three DOF for comprehensive surface adaptation, the prototype intentionally limits the motion to a single DOF in order to reduce mechanical and computational complexity during the early development stage.

The rotating platform provides an inclination range of up to 15 deg, equivalent to 0.262 rad, which is sufficient for investigating the influence of surface tilt on laser beam spot deformation. This controlled angular variation allows systematic analysis of how changes in surface orientation affect laser beam focus quality and spot shape consistency. Such observations are essential for refining both the adaptive control strategy and the image processing algorithms to be implemented in the full scale adaptive mechanism. During operation, the camera continuously acquires images as the platform rotates, enabling real-time monitoring of beam spot behavior under different angular conditions. Additional details of the rotational mechanism and its influence on laser beam projection are presented in Fig. 3.

A critical component of the laser beam detection system is the camera which functions as both a visual sensing device and a feedback sensor. The camera captures real-time images of the laser beam spot projected onto the target surface and provides the image data required by the image processing algorithm. To improve image quality, a polarization film is applied directly to the camera lens. The primary purpose of the filter is to reduce glare and unwanted reflections originating from the platform surface, thereby improving image contrast and enhancing the visibility of the laser beam spot.

Fig. 4 illustrates the difference in the captured images obtained with and without the polarization film. In the image acquired without the filter, strong reflections and glare from the platform surface reduce image contrast and partially obscure the laser beam spot. When the polarization film is applied, the reflected light is attenuated, resulting in improved contrast and clearer visualization of the beam spot boundaries. However, it should be noted that the polarization film primarily reduces reflected light intensity and does not eliminate the possibility of image sensor saturation in the high-intensity central region of the laser spot. Therefore, the images presented in this study are intended for qualitative observation and development of the image-based monitoring methodology rather than for precise determination of the physical laser beam diameter in accordance with standardized beam characterization procedures.

In summary, the prototype adaptive laser mechanism developed in this study provides a controlled and effective experimental platform for investigating laser beam defocus and misalignment on inclined surfaces. By intentionally limiting the system to a single rotational DOF, the prototype enables focused analysis of angular-induced focus errors while maintaining sufficient representativeness of the full adaptive mechanism. The experimental observations obtained from this platform support the *a* *b*

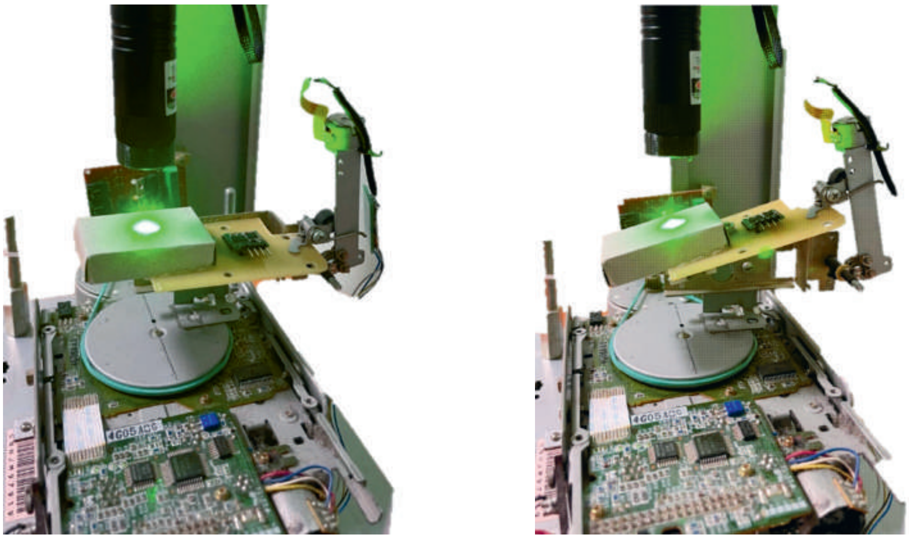


Fig. 3. The rotation of the platform on the prototype adaptive laser mechanism: flat platform (*a*); inclined platform (*b*)

a *b*

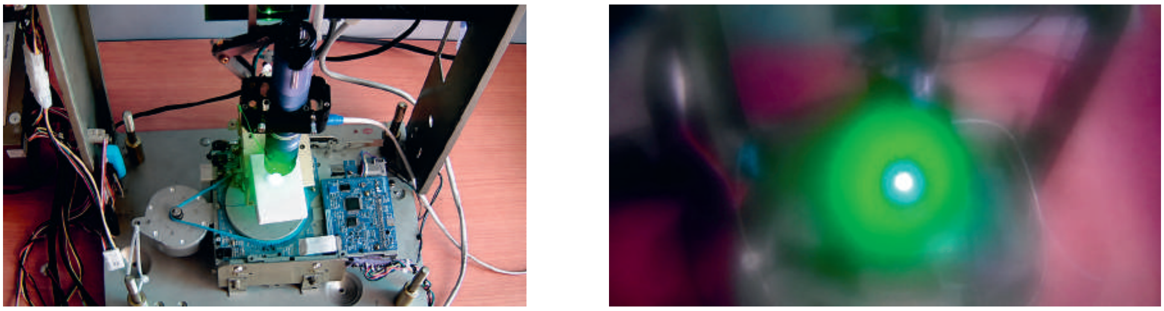


Fig. 4. Captured laser beam spot images: without optical filter (*a*); with optical filter (*b*)

systematic development and validation of both the laser beam autofocusing and beam monitoring subsystems. Although the captured images are intended primarily for qualitative observation rather than standardized laser beam characterization, they provide valuable information for the development and evaluation of image-based monitoring algorithms. Consequently, the prototype establishes a solid technical foundation for the future extension of the system toward multi-DOF adaptive laser processing applications.

Experimental

The experimental setup is based on the prototype adaptive laser mechanism describe in previous section. The system consists of a laser module, a camera-based sensing unit equipped with a polarization filter, and a rotating platform providing a single rotation DOF about the *X* axis. During the experiments, the laser beam was projected onto the inclined platform surface while the camera captured images of the resulting laser beam spot.

The primary objective of the experimental procedure is to verify the operational performance and functional behaviour of the proposed adaptive laser mechanism under controlled surface inclination conditions. The experiments were designed to confirm that the prototype operates as intended, enabling stable laser beam projection, reliable image acquisition, and consistent system response across the defined range of platform inclinations.

During the experiments, the rotating platform was incrementally adjusted to predefined inclination angles, while the laser beam was continuously projected onto the target surface. At each inclination, the camera position, laser output parameters, and environmental conditions were maintained constant throughout the experimental sequence to ensure repeatability and consistency of observations.

The experimental procedure was designed to evaluate both the qualitative functionality and selected quantitative performance characteristics of the prototype adaptive laser mechanism. During the experiments, the rotating platform was incrementally adjusted to predefined inclination angles while the laser beam was continuously projected onto the target surface. In addition to assessing the stability of laser beam projection and image acquisition, the performance of the inclination measurement and positioning subsystems was evaluated. The platform inclination was monitored using the MPU6050 gyroscope sensor integrated within the closed-loop control architecture. Experimental verification demonstrated a maximum inclination measurement error of 0.001 rad over the investigated operating range of 0–0.262 rad. Furthermore, the selected PID controller configuration (Kp = 40, Ki = 0.1, Kd = 5), where Kp denotes the proportional gain, Ki denotes the integral gain,

Table 1. Quantitative performance characteristics of the prototype adaptive laser mechanism

Parameter	Value
Inclination range	0–0.262 rad
Maximum inclination measurement error	0.001 rad
Camera resolution	3 MP
Laser wavelength	532 nm
Laser operating mode	Continuous-wave
Selected PID controller	$Kp = 40$, $Ki = 0.1$, $Kd = 5$
Settling time	2.52–5.18 s
Steady-state error	Less than 0.001 rad

and *Kd* denotes the derivative gain of the PID controller, achieved settling times between 2.52 s and 5.18 s and steady-state positioning errors below 0.001 rad. A summary of the principal quantitative performance characteristics of the developed prototype is presented in Table 1. These parameters provide an indication of the accuracy and dynamic response of the prototype and serve as a basis for assessing its suitability as an experimental platform for adaptive laser beam investigations.

The quantitative results summarized in Table 1 indicate that the developed prototype provides accurate and repeatable generation of controlled inclination conditions. The maximum inclination measurement error was limited to approximately 0.001 rad throughout the investigated operating range, demonstrating good agreement between the reference and measured inclination values. The settling time represents the time required for the platform inclination to reach and remain within an acceptable range of the target angle following a commanded position change. In contrast, the steady-state error represents the residual difference between the desired inclination angle and the final stabilized platform position after transient effects have decayed. The relatively low settling times and small steady-state errors obtained during the experiments confirm the capability of the prototype to rapidly establish stable and accurate inclination conditions. To further illustrate the accuracy of the inclination measurement subsystem, the relationship between the reference inclination angle and the corresponding measured inclination angle is presented in Fig. 5.

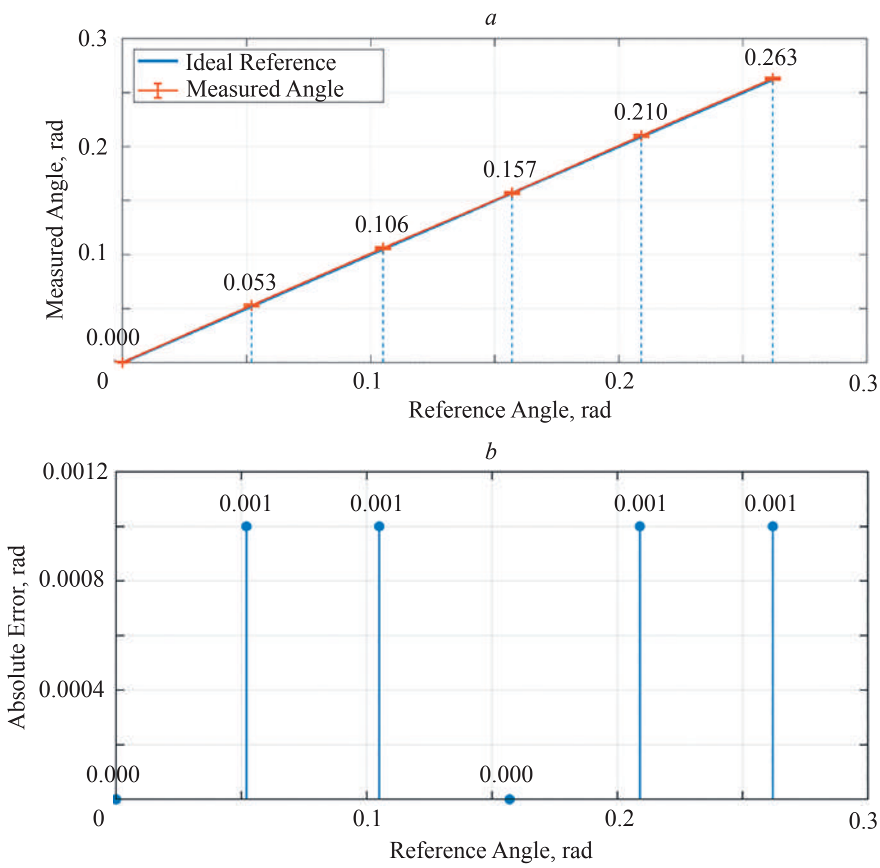
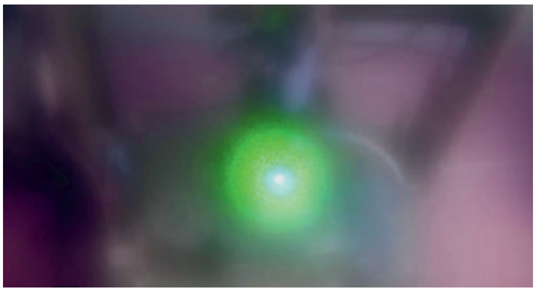
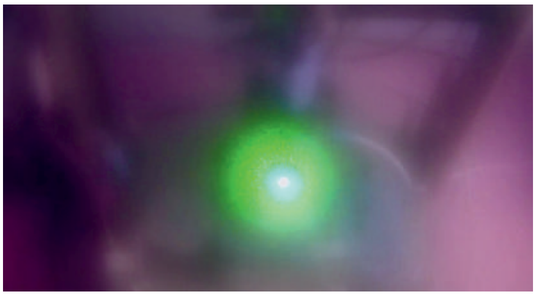
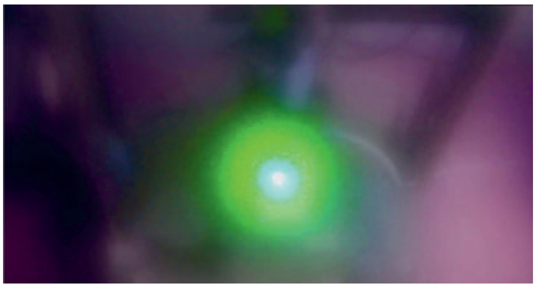


Fig. 5. Evaluation of the inclination measurement subsystem: reference versus measured inclination angles with error bars of ±0.001 rad (*a*); absolute measurement error (*b*)

Table 2. Representative images of laser beam projection captured at selected surface inclination angles

Inclination angle, rad	Captured laser beam spot	Description
0		Baseline / reference condition
0.157		Intermediate inclination
0.262		Maximum platform inclination

As shown in Fig. 5, *a*, the measured inclination angles closely follow the corresponding reference values throughout the investigated operating range of 0–0.262 rad. The close agreement between the reference and measured angles confirms the effectiveness of the MPU6050-based sensing subsystem and the positioning mechanism used in the prototype. Error bars representing the maximum observed deviation of ±0.001 rad are included in Fig. 5, *a*. However, due to the relatively small magnitude of the measurement error compared with the overall scale of the graph, the error bars are only weakly visible.

To provide a clearer representation of the measurement accuracy, the absolute measurement error was additionally calculated and is presented in Fig. 5, *b*. The absolute error was determined as the absolute difference between the reference inclination angle and the corresponding measured inclination angle for each experimental condition. The results show that the maximum observed deviation did not exceed 0.001 rad across the entire investigated range, while zero error was observed at a reference inclination angle of 0.157 rad. The consistently low error values demonstrate the reliability and repeatability of the inclination measurement subsystem and confirm that the prototype is capable of generating stable and reproducible inclination conditions for laser beam projection experiments.

Representative images of the projected laser beam acquired at selected platform inclination angles are presented in Table 2. These images provide a qualitative assessment of beam projection behavior and demonstrate the capability of the prototype to maintain stable laser beam projection under varying surface orientations.

Visual inspection of the images presented in Table 2 confirms that the prototype adaptive laser mechanism is capable of projecting the laser beam onto inclined surfaces in a stable and repeatable manner across the tested range of platform inclinations. The images are intended primarily for qualitative demonstration of system operation and image acquisition under varying surface orientations. Due to the presence of a saturated central region in the recorded beam spot images, they are not intended for precise determination of the physical beam spot size or standardized laser beam characterization. Nevertheless, the observations demonstrate the suitability of the prototype as an experimental platform for the development and validation of image-based laser beam monitoring methods. Consequently, a dedicated laser beam detection approach is required for quantitative evaluation of beam characteristics and will be addressed in future work.

Conclusion

This study presented the design and experimental evaluation of a prototype adaptive laser mechanism intended to investigate laser beam focus and alignment challenges on inclined and non-uniform material surfaces. The prototype was deliberately designed with reduced mechanical and computational complexity while maintaining the essential functional characteristics required for the development of adaptive laser processing systems. The modular configuration enabled effective integration and testing of the laser source, camera-based sensing unit, inclination measurement subsystem, and rotating platform within a controlled experimental environment.

Experimental evaluation demonstrated that the prototype is capable of generating stable and repeatable inclination conditions for laser beam projection experiments. Quantitative assessment of the inclination measurement and positioning subsystems showed a maximum inclination measurement error of 0.001 rad within the investigated operating range of 0–0.262 rad. The absolute measurement error remained at or below 0.001 rad throughout the tested range, confirming the reliability and repeatability of the proposed sensing and positioning architecture. In addition, the selected PID controller configuration achieved settling times between 2.52 s and 5.18 s and steady-state positioning errors below 0.001 rad, confirming the ability of the prototype to provide accurate and reliable platform positioning.

Qualitative observations of the captured laser beam spot images demonstrated stable laser beam projection under varying surface inclination conditions. However, visual inspection alone revealed that changes in beam spot size, shape, and intensity distribution are difficult to evaluate quantitatively without dedicated image-processing techniques. Furthermore, due to the presence of saturation in the central region of the recorded beam spot images, the acquired images are intended primarily for qualitative observation and development of image-based monitoring approaches rather than standardized laser beam characterization.

The developed prototype provides a practical experimental platform for the future development and validation of adaptive laser beam monitoring and autofocusing methods. Potential application areas include laser marking, laser engraving, laser micromachining, and other laser material processing operations involving inclined or non-uniform surfaces. Future work will focus on the development of quantitative laser beam detection algorithms, image-based error estimation methods, and extension of the mechanism toward a multi-DOF adaptive laser processing system capable of compensating beam positioning and focusing errors under complex surface conditions.

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