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OPTICAL ENGINEERING

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Development of adaptive laser head for compensating error of beam waist position during processing materials using laser beam spot detection method

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Abstract
The purpose of this research is to develop a device capable of compensating for laser beam positioning error during processing of workpieces. This research is relevant, since several errors occur when processing workpieces with a laser beam, which lead to decrease in the level of accuracy. Two factors lead to these errors, such as the presence of vibrations and unstable beam waist position of the laser beam. It is known that one of the main reasons of unstable beam waist position of the laser beam is uneven surface of the workpiece. When processing a workpiece with a laser beam, the uneven surface of the workpiece causes the beam waist position to change. The position of the beam waist is important because it affects the accuracy of the workpiece. In order to reduce errors in the positioning of the beam waist, a system or mechanism is needed that can compensate for these errors. To achieve this, the system or mechanism must have ability to adapt to the surface of the workpiece. Thus, the development of the device in this study is a solution to the problem that arises during laser processing. In this research, an adaptive laser beam head device is designed which has adaptive capabilities to the surface of the workpiece so that it can compensate for position errors, stabilize the beam waist position, and reduce internal vibrations during workpiece processing. The laser beam head in this research can move in 3 degrees of freedom. With this ability, the laser beam head can move to follow the surface shape and adjust the beam waist position to the workpieces. During operation, to be able to track the position of the laser beam on the workpiece, the device is equipped with a camera. In this research, an experiment with mockup of this device was conducted to determine the level of its capabilities. From the experiment, it can be concluded that device is performing its objectives successfully. It can maintain the position of the laser beam waist on the surface of workpiece with a relatively high level of accuracy. This is evidence by the relatively low error rate. In general, this device can be used and implemented as a system for compensating the positioning error of the laser beam during workpiece processing and also can be implemented to improve the technology of workpiece processing with a high level of accuracy.

Keywords
modified Stewart platform, laser processing, adaptive laser beam head, laser spot detection system

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УДК 681.5.073

Разработка адаптивной лазерной головки для компенсации погрешности положения перетяжки пучка во время лазерной обработки с использованием метода обнаружения пятна лазерного излучения

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Аннотация

Введение. Представлены результаты разработки устройства, предназначенного для компенсации погрешности положения лазерного пучка при обработке заготовок. Погрешности, которые возникают при обработке заготовок лазерным пучком, приводят к снижению уровня точности. Погрешности вызваны двумя факторами: наличием вибраций и нестабильным положением перетяжки лазерного пучка. Одной из основных причин нестабильного положения точки фокусировки лазерного пучка является неровная поверхность заготовки, которая приводит к изменению положения перетяжки пучка относительно плоскости обработки. Погрешность положения перетяжки пучка по углу относительно плоскости обработки влияет на точность обработки заготовки. Для уменьшения погрешности в позиционировании перетяжки пучка относительно плоскости обработки, необходимо устройство (система или механизм), способное ее скомпенсировать. Устройство должно обладать способностью адаптироваться к поверхности заготовки. **Метод.** Таким образом, разработка устройства служит решением проблемы, возникающей при лазерной обработке. Разработанное устройство адаптивной головки лазерного пучка адаптируется к поверхности заготовки для компенсации погрешности положения, стабилизирует положение перетяжки пучка относительно плоскости обработки и уменьшает внутренние вибрации во время обработки заготовки. Головка с фокусирующей оптической системой может перемещаться в трех степенях свободы. Благодаря этому головка может отслеживать форму поверхности и корректировать положение точки фокусировки в соответствии с формой заготовок. Во время работы, чтобы иметь возможность отслеживать положение лазерного пучка на заготовке, устройство оснащено камерой. Выполнен эксперимент с макетом полученного устройства для определения уровня его возможностей. **Основные результаты.** В результате эксперимента определено, что устройство успешно выполняет свои задачи. Оно обеспечивает удержание лазерного пятна в требуемой точке и постоянное положение лазерного пятна на заготовке так, чтобы искажения его формы были минимальны. **Обсуждение.** Представленное устройство может быть использовано и применено в качестве системы компенсации погрешности позиционирования лазерного луча при обработке заготовки, а также для совершенствования технологии обработки заготовок с высоким уровнем точности.

Ключевые слова

модифицированная платформа Стюарта, лазерная обработка, адаптивная головка лазерного пучка, система обнаружения лазерного пятна

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Introduction

Laser process technology has been in development for more than 40 years. At this time, laser processing has been widely applied in various fields, especially in the manufacturing process. The use of the laser processing includes ablation, surface texturing, laser welding, hybrid welding, laser cutting, etc. [1]. Accuracy and high speed in materials processing are the main reasons for the widespread use of laser processing technology in manufacturing processes [2, 3]. This is related to the manufacturing process which demands high-quality results. The higher the accuracy of the machine in the manufacturing process, the higher the quality of the product obtained. However, several variables, including energy distribution, laser power, focus diameter, focus position, and others, have a significant impact on how accurate the process laser is. The focus position has the greatest impact of all these variables. The beam diameter incident on the surface of the material or workpieces changes when the focus position is changed. Setting the beam waist position during the laser process is important to obtain the optimal level of accuracy and maximum product quality [4–7]. During laser processing it is always necessary to ensure that the beam waist position is stable on surface of the workpieces, since changes in focus point position (negative focus and positive focus) will change the size of the laser spot diameter by a larger amount, thereby reducing the energy density per unit area. This greatly affects the quality of the product obtained, especially when processing high precision workpieces such as single crystal silicon and thin films or other semiconductor materials where the magnitude of the error is measured in fractions of a micron [8]. During laser processing, the stability of the beam waist position is greatly affected by two factors, namely the uneven surface of the workpiece and vibration. Workpieces with uneven surface cause the position of the beam waist to change (defocus). To compensate for defocusing and to ensure that the beam waist is always on the surface of workpieces, a method or device is needed that can move or adapt on the surface of the workpiece so that the laser beam is always perpendicular to the workpiece surface and the size of the laser spot diameter does not change.

Research on stabilization systems in laser processing has been developed before. The research is about the focus stabilization method using optical system [9, 10]. The optical systems used include Hollow Retroreflector Mirrors (HRM) and Fast Steering Mirrors (FSM). The control system is added with the aim of being able to control the HRM and FSM pasts using a Piezoelectric actuator. This research gave good results by showing that the method can compensate for the effect of vibration generated so as to provide stability at the beam waist position. However, the method given in this research still cannot compensate for problems with processing workpieces or materials with freeform surfaces.

Research is to be able to solve problems when laser processing on uneven surfaces of workpieces has also been developed before. Stabilization of the focus position on complex component was proposed by research [11–13]. The method used in this research is to apply a scanner and camera to be able to detect the surface of the material and a five-axis laser machine tool to be able to process the material. The results of the research indicate that the proposed method can provide stability to the beam waist position on workpieces or material with freeform surfaces. However, in this study, laser processing of materials with uneven surfaces was carried out by scanning the first. After performing a scan, the machine stores data and provides movement coordinates. So that the focus position of the material has determined beforehand. Also with this method, the accuracy of the movement is greatly influenced by the result of the scan and calibration of the laser machine on the workpieces. By not detecting the laser process with this method is not adaptive to the workpiece surface, because if the calibration results are bad, the focus position becomes inaccurate.

Based on previous and how important it is to maintain the stability of the focus position during the laser process, this research proposes a method that can compensate for the vibration present in the system and workpieces with freeform surfaces. In this study, laser beam head is proposed that has adaptive capability to the surface of the workpieces or materials and is resistant to vibration and has self-calibration capability. In addition, this laser beam head can be applied to existing laser machines. The proposed laser beam head consists of three important parts, namely focusing and stabilization system, laser spot detection system and control system. Focusing and stabilization system is a moving part that aims to project the laser beam and move and adapt to the surface of the workpiece. This part is developed using the working principle of the modified Stewart platform. The Stewart platform has the capabilities of being flexible, payload capability, repeatability and positioning accuracy [14–18]. With the capabilities possessed by the Stewart platform, the laser beam head can move adaptively to follow the shape of the surface of workpieces, so that the beam waist position can be maintained. Laser spot detection system is designed to detect or recognize the laser spots. This part is developed using a camera and image processing program. The working principle of this system is the camera captures the laser spot and then the image coming from the camera is being processed by the program image processing [19, 20]. Therefore, if there is a deviation from the focus position of the laser beam during the laser process, the beam waist position can be corrected immediately. So by using the proposed adaptive laser beam head, the two main factors that affect the stability of the beam waist position during the laser process can be compensated and increase the accuracy of the laser process. The proposed solution is relevant in relation to workpiece surface processing using the laser. For instance, laser marking, laser engraving and laser annealing.

Influence of the Focus Position on Laser Spot Size on the Workpieces

Focus position is the distance between the beam focus and the surface of the workpiece. There are 3 types of focus that need to be considered during the laser process, namely zero, positive and negative focus [21, 22]. Zero focus is a focus position where the laser beam focus position is located directly on the workpiece surface or in the other words where the beam waist position is right on the surface of the workpieces. Positive focus is a focus position where the laser beam focus far above the surface of the workpiece or the beam waist is located above the surface of the workpieces. Negative focus where the focus is located below the workpiece surface or the beam waist is located below the surface of the workpiece. For more details it can be seen in Fig. 1 below.

Focus position greatly affects the quality of the workpiece being processed. This is because changing the focus position will change the size of the laser beam spot. The accuracy of the laser processing is influenced by the size of the laser beam spot. So, to be able to process workpieces that have results with high accuracy, a type of zero focus is needed.

As explained earlier, the focus position is highly dependent on the surface of the workpiece. So, the surface of the workpiece is one of the factors that affect the stability of the beam waist position. However, if the workpiece being processed has an uneven surface, the beam waist that has been set becomes unstable. Thus, to obtain good quality results during workpiece processing, a system is needed that can compensate for error caused by uneven workpiece surfaces. Another factor that causes the beam waist position to become unstable is the vibration generated during workpiece processing. To provide a more detailed illustration of the beam waist position on uneven workpiece, it can be seen in Fig. 2 below.

Based on Fig. 2, it is known that the workpiece is uneven causing the focus position to change to positive or negative focus even though the position of beam waist has been previously set. The changed focus position causes the laser spot to change in shape and size. The laser spot on the uneven workpiece is shown in Fig. 3.

In order to compensate for the changing shape and size of the laser beam spot and provide stability to the beam

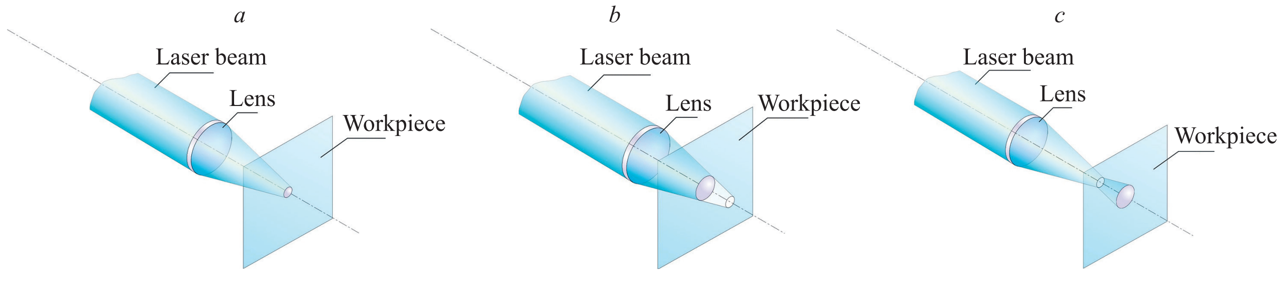

Fig. 1. Scheme of focus point position on the workpiece during laser processing: zero focus (*a*); negative focus (*b*); positive focus (*c*)

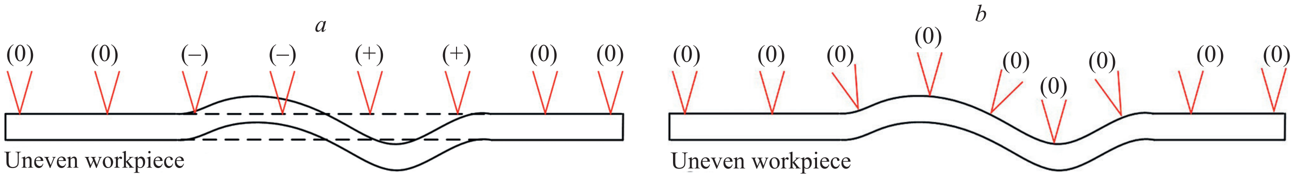

Fig. 2. Position of the beam waist on uneven workpieces: if the laser head is not adaptive to the surface of the workpiece (*a*); if the laser head is adaptive to the surface of the workpiece (*b*)

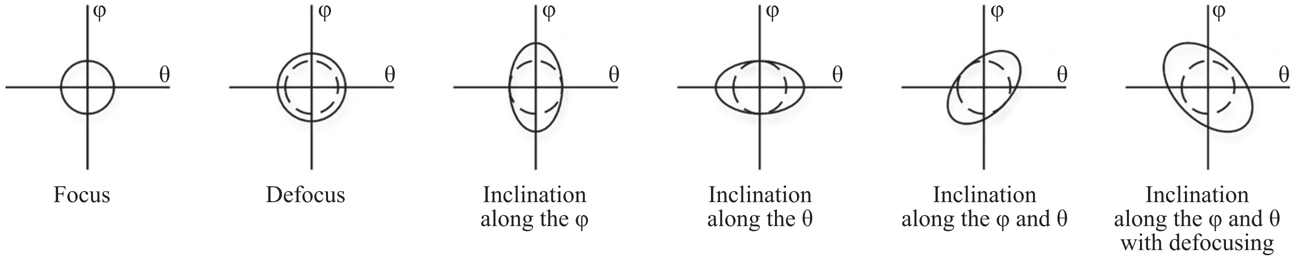

Fig. 3. Laser beam spot on the uneven workpiece, where φ is roll axis; θ is pitch axis

waist position on uneven workpieces, a method is needed to solve these problems. In this research, a laser head is developed that has adaptive capabilities so that it can adapt to the surface of the workpiece and allow the laser head to be always perpendicular to the workpiece and maintain the beam waist during the laser process.

Laser Beam Positioning Error Compensation Device

In this research, a laser head is developed which has adaptive capabilities to the surface of the workpiece so that it can compensate for position errors, stabilize the beam waist position, and reduce internal vibrations during workpiece processing. The laser beam head in this research can move in 3 Degrees Of Freedom (DOF), which is rotating in the X axis or commonly referred to as roll (φ) and rotating in the Y axis or commonly referred to as pitch (θ) and also translating in the Z axis. With this ability, the laser beam head can move to follow the surface shape and adjust the beam waist position to the workpieces. Fig. 4 shows the design of the adaptive laser beam head.

Based on Fig. 4, there are two parts of the adaptive laser beam head. The first important part is the focus position stabilization system. The focus position stabilization system is the part which functions to move the laser head so that can move following the shape of the workpiece surface. This part also functions to adjust the beam waist position on the surface of the workpiece. In this research, the focus position stabilization system is built on a platform called the modified Stewart platform. The modified Stewart platform has the ability to move in 3 DOF, namely rotating in the φ and θ axes, and translating in the Z axis. With the capabilities possessed by the modified Stewart platform,

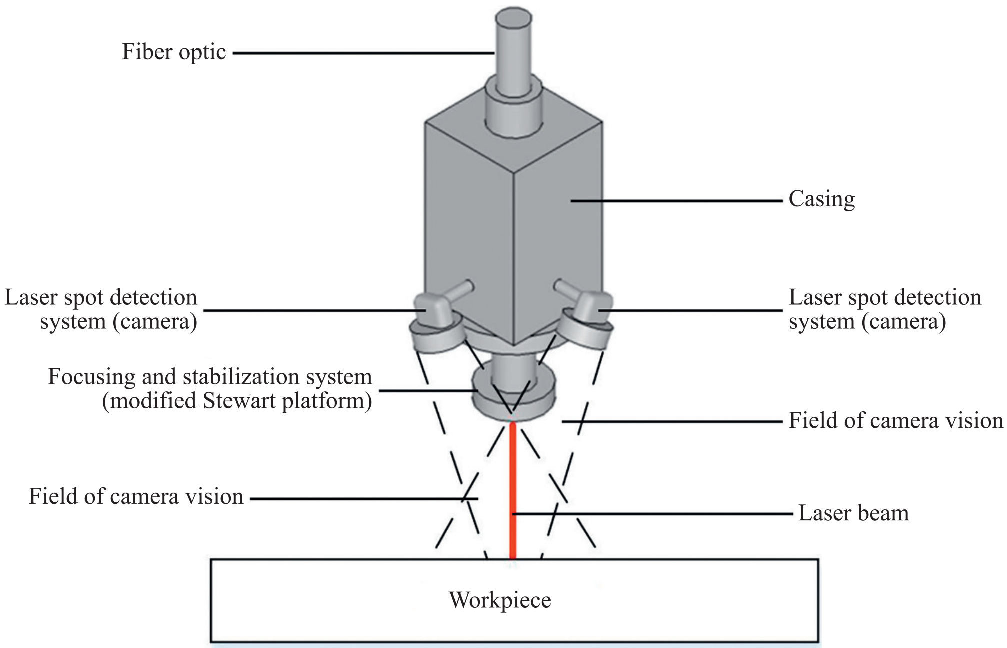

Fig. 4. Design of the adaptive laser beam head

the system can provide stability to the beam waist position during laser processing of the workpiece.

The second important part is laser spot detection system. This system is applied using camera. The camera functions to detect the laser beam spot and trajectory during the laser process on the workpiece. As previously stated, the laser beam spot is strongly influenced by the surface of the workpiece so that its size and shape can change. Therefore, a camera is needed to solve this problem. The camera will real-time capture the image of the laser beam spot on the surface of the workpiece.

The working principle of this adaptive laser beam head is as follows. The initial position of this device is above the reference workpiece which aims to perform calibrations. When the calibration takes place, the laser beam will be activated so that the image of the laser beam spot can be captured by the camera. Furthermore, the size and shape of the laser beam spot will be compared with the predetermined laser beam spot reference. If there is a difference, the control will instruct the modified Stewart platform to move and adjust the beam waist position as close as possible to the reference. This provides the device with self-calibration capabilities. After the calibration is complete, the device moves towards the work area to process the workpiece. During workpieces processing, the camera will always capture images of the laser beam spot and process and compare them with the reference in order to achieve stability in the beam waist position. However, if during the laser processing there is unevenness on the surface of the workpiece that causes the beam waist position to be disturbed or position error occurs, such as the size or shape of the laser beam spot changing, the device automatically adapts to the surface and adjusts the size and shape of the laser beam spot again according to the reference. This also applies if the beam waist position becomes unstable due to internal vibration. Therefore, with the capabilities of this device, positioning error during laser processing can be compensated.

It should be noted that applying the proposed solution is mainly intended for systems in which laser radiation is brought to the surface via optical fiber. When using a system of mirrors and galvanometric deflecting systems, the correction of the laser spot shape will be difficult due to the lack of the necessary optical elements.

Focusing and Stabilization System of Laser Beam Positioning Error Compensation Device

The focusing and stabilization system is one of the important parts of the position error compensation device. This system was developed using the working principle of the modified Stewart platform. Based on research [14], the Stewart platform is a manipulator device used to control position and movement. This platform has the ability to move in 3 DOF. With its flexibility and accuracy, this manipulator can be used and applied as the laser head part of the laser beam position error compensation device, namely as a laser beam focusing and stabilization system. This ability can provide the device to be able to move adaptively and position of the laser head always perpendicular to the surface of the workpiece so that the laser spot position is always at zero focus. To be able to experiment with this focusing and stabilization system, this research has developed a modified Stewart platform mockup. In the experiment, the mockup is used to compare its characteristics and operating mechanism. The modified Stewart platform mockup used in this experiment is shown in Fig. 5.

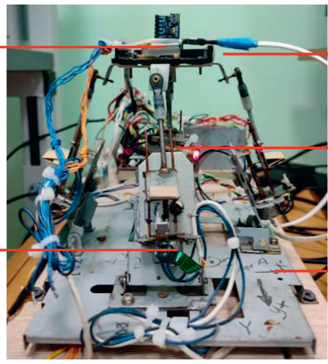

Fig. 5. Mockup of modified Stewart platform as focusing and stabilization system of laser beam positioning error compensation

Mechanical and electronic systems are required to design and implement the modified Stewart platform mockup. Several electronic parts, including a stepper motor and a gyroscope sensor, are employed in the mockup modified Stewart platform to support its movement and mechanism. The modified Stewart platform legs are propelled by a linear motor, and the platform tilt is sensed by a gyroscope sensor. On this modified Stewart platform there are 4 stepper motors on each leg which are referred to as motor X, motor Y, motor Z and motor A. The modified Stewart platform will lengthen by 2,815 μm every step as a result of input steps used to control the linear motor movement. The simulation model parameters will also be taken from the modified Stewart's parameters. The platform can rotate maximum of 7°18′ on the φ and θ axes. The platform can translate maximum 11.3 mm in the Z axis. The accuracy of the inclination angle generated from this platform has been tested in previous research. The test results showed that there was no significant difference between the simulation model data and the experimental platform. With these results, it is found that the modified Stewart platform can be used to build an adaptive laser head as focusing and stabilization system.

Laser Spot Detection System of Laser Beam Positioning Error Compensation Device

Laser spot detection is important in the development of laser beam positioning error compensation device. Laser spot detection allows knowing the coordinates of the location of the laser spot. This spot detection system is performed by image processing program. In developing the laser spot method in this research, several devices and programs are required to support the development of the image processing method. Fig. 6 shows laser spot detection device used in the development of detection method in this research.

When developing imaging systems, the camera is one of the main devices. The purpose of the camera is to be able to *a* *b*

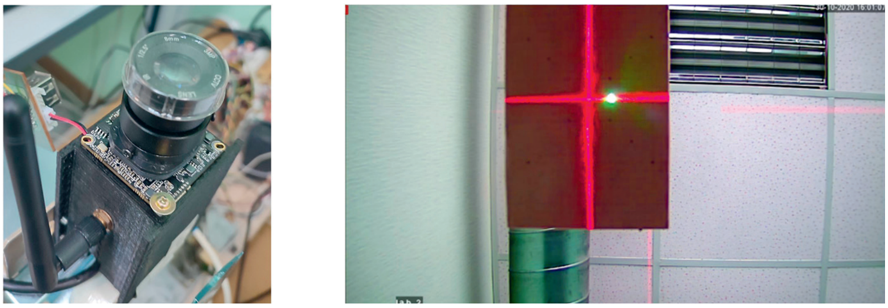

Fig. 6. Laser spot detection system: camera (*a*); image captured by the camera (*b*)

take images of the laser spot while the workpiece is being processed. The images taken from the camera will be sent for processing. In this research a digital camera is used. The resolution of the digital camera used is 5 megapixels. In the development of the laser spot detection system, two lasers are used called the reference laser and the platform laser. The reference laser is a green and spot-shaped laser. This reference laser is the part that will be processed and detected by this system. The platform laser is a red and cross-shaped laser. This laser is located above the modified Stewart platform, so this laser shows the moving point of the laser head of the laser beam position error compensation described earlier.

Laser spot detection program is developed using several image processing functions with the objective of knowing the position or coordinates of the reference laser (green laser) on the target. The program was designed using MATLAB software. After images are acquired from the camera, the images will be processed in the detection program. The first function of image processing is to convert a color image into black and white using rgb2gray and bw functions. The purpose of converting an image to black and white is to make it easier to identify objects or laser spot contained in the image. To locate the center point of the laser spot, a function called centroid is needed. Using this function, the position or coordinate of the laser beam spot can be found. The location or coordinate obtained with this function is the pixel coordinates of the central point of the object. In MATLAB, this function can be used with a block program called Blob Analysis. In addition, using the coordinate points from the Blob Analysis function, the laser beam spot identification process can be carried out with Draw markers block program. With this block program, the laser beam spot can be marked with different shapes such as crosshairs, circles, squares and so on. Once the laser beam spot detection has been developed, the next thing to be developed is a conversion program from pixels to millimeters. Millimeters units are needed for the control program of laser beam positioning error compensation device as input data. For more details, Fig. 7 shows the laser spot detection program that has been developed.

The results of the image processing obtained from the functions used in the laser spot detection program can be seen in Fig. 8 below.

In general, the laser spot detection program using image processing has been successfully developed in this

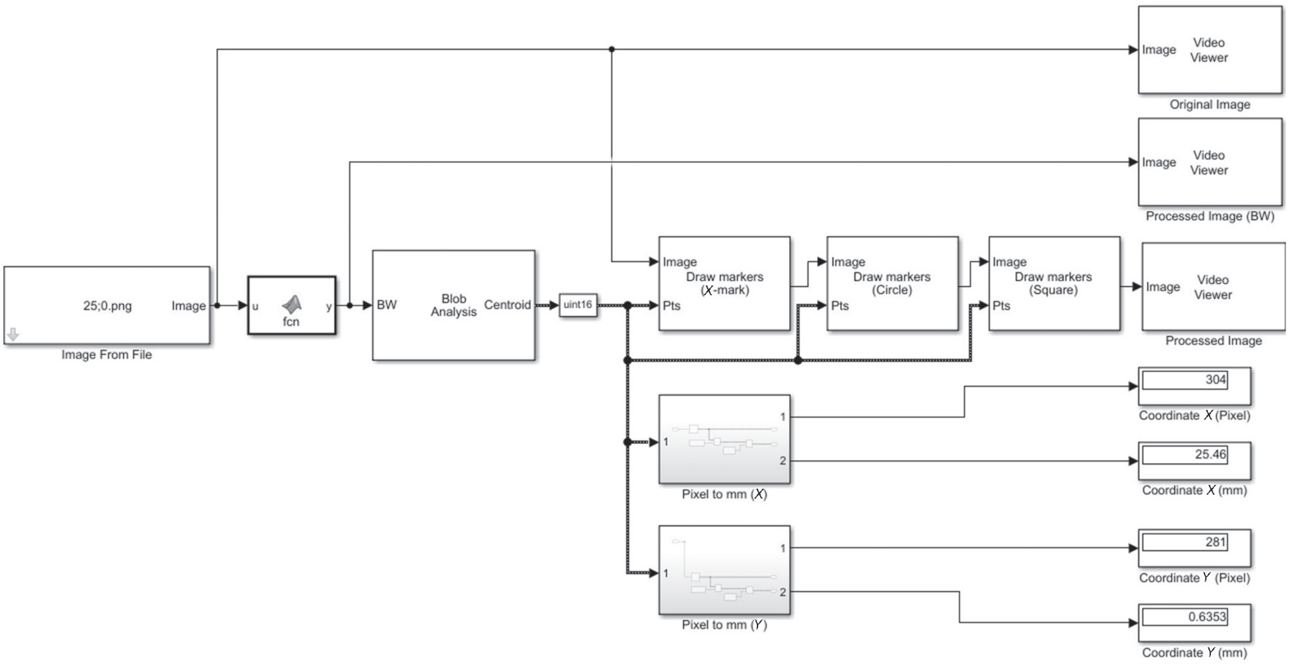

Fig. 7. Laser spot detection program

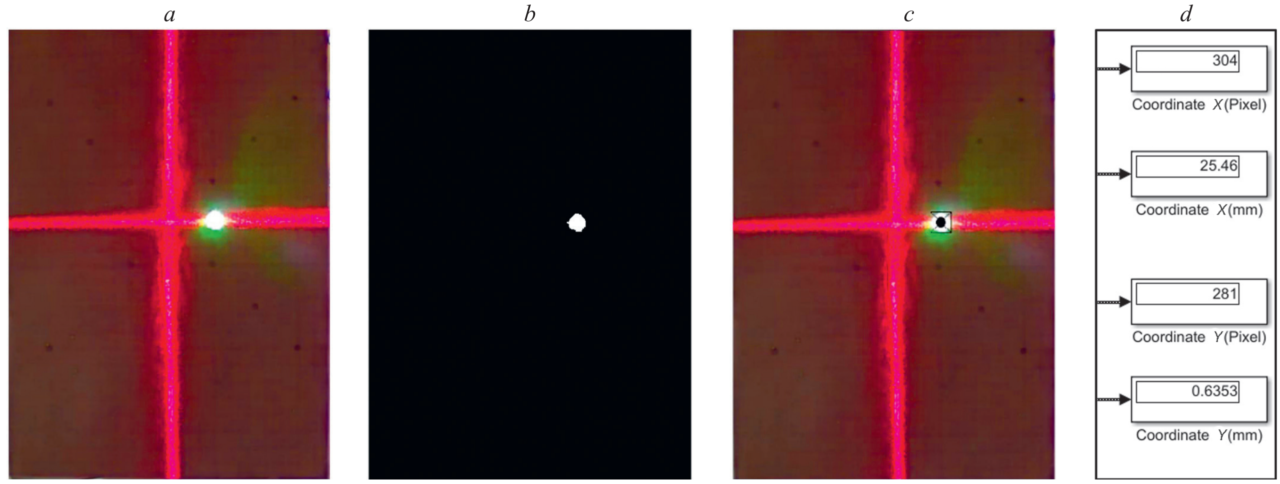

Fig. 8. Process for detecting laser spot position: original image (*a*); processed image (black and white) (*b*); processed image (marked) (*c*); coordinate and position of the laser spot's location (*d*)

research. The detection program can solve its task which is to detect the laser beam spot and provide the coordinates of its location. Using this detection program, it can be used as a laser spot detection system of laser beam positioning error compensation.

Control System of Laser beam Positioning Error Compensation Device

The purpose of this control system is to control the movement of the laser beam positioning error compensation device. In addition, the control system is intended for the laser head to move automatically based on the laser position. The control program developed in this research is obtained by combining the laser spot detection program with the inclination angle tracking program of the modified Stewart platform that has been developed previously. This control program was designed using MATLAB software. Fig. 9 shows the control program of the laser position error compensation device.

In this control program, the input is an image. The image is taken from a preliminary installed camera. The image is processed to get the coordinates of the laser beam spot location; also, after obtaining the laser spot

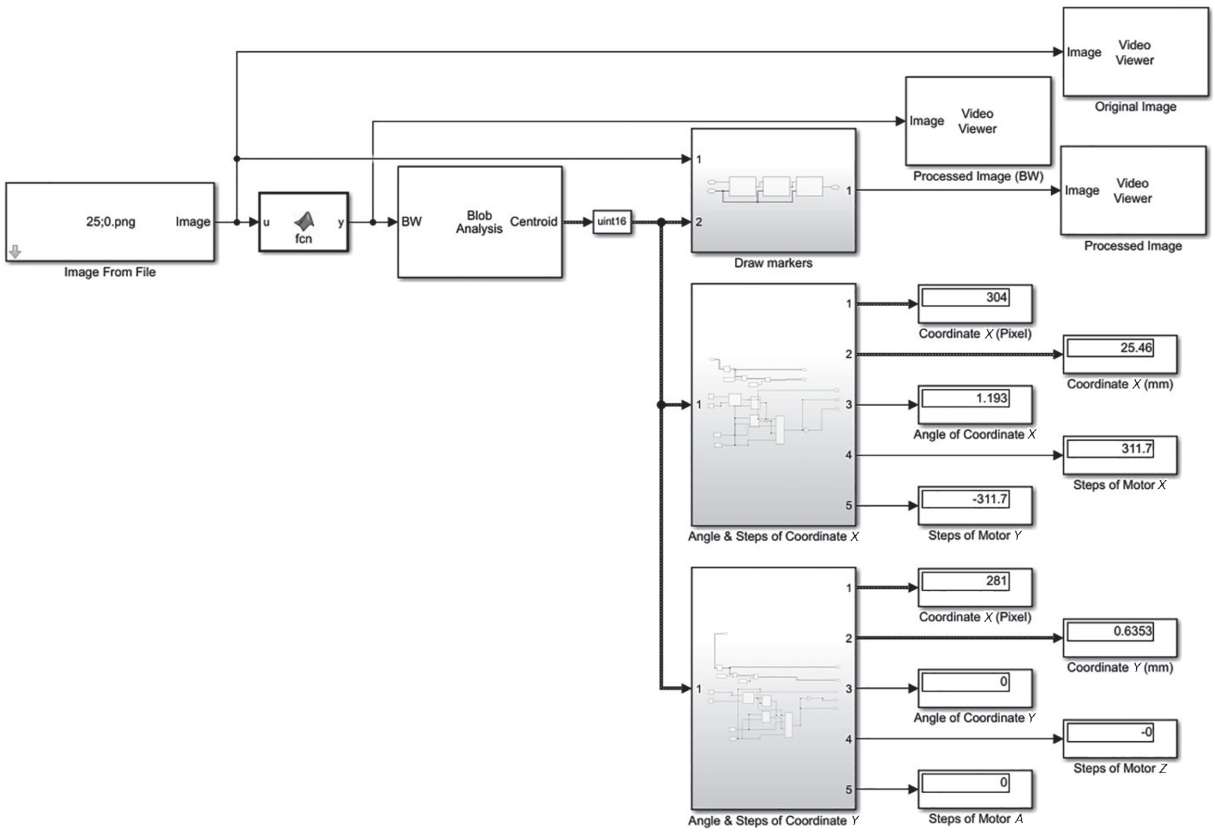

Fig. 9. Control program of the laser position error compensation device

location and after obtaining the laser beam spot location coordinates, the data will be processed to obtain the inclination angle values. As shown in Fig. 9, the output of this control program includes: *X* coordinates (pixel), *X* coordinates (mm), platform angle in *X* coordinates (°), *Y* coordinates (pixel), *Y* coordinates (mm), platform angle in *Y* coordinates (°), motor step *X*, motor step *Y*, motor step *Z*, motor step *A*. These steps data will be the input of mockup to generate the inclination angle. The inclination angle is read by the gyroscope sensor. All obtained data will be processed and analyzed for further development of the laser beam position error compensation device.

Experiment of Laser Beam Positioning Error Compensation Device

In this research, experiments were conducted to determine the accuracy of the position error compensation device in movement at a certain distance and angle. In addition, the purpose of this experiment is to determine the effectiveness of laser spot detection program and control program that have been developed previously. To determine the success of the experiment, the experiment results are compared with the simulation results that have been developed previously. Fig. 10 shows the installation of the laser position error compensation device in the experiment.

The first process performed in this experiment is for the camera to take an image, as shown in Fig. 11. Once the image is captured, it will be processed in the program that was developed earlier. The program will process the image to get the coordinates of the laser spot location, inclination angle and steps data for *X*, *Y*, *Z*, *A* motors. The data is processed and the mockup of modified Stewart platform changes position by inclining by a certain angle. As the mockup moves, the platform laser (red laser) moves to the reference laser (green laser) from its starting point. In addition, the angle data obtained will be compared with the angle obtained in the simulation. In addition, the *X*–*Y* coordinates contained in the laser target will be compared with the result of *X*–*Y* coordinates generated from the experiments. The coordinates located on the laser target in this experiment can be seen in Fig. 11 below.

To facilitate the experiment and data collection, coordinate points are set on the target. The coordinate points will be the reference points for the platform laser (red laser) and the reference laser (green laser). In addition, the coordinate points will make it easier to calculate the distance between the two lasers. In this experiment, the mockup of the modified Stewart platform works on both *X* and *Y* coordinates. On the target, the distance between coordinate points is given in millimeters. There are 25 points on the target with coordinates (*X*, *Y*): (0, 0); (0, 25); (0, 50); (0, 75); (0, –25); (0, –50); (0, –75); (25, 0); (25, 25); (25, –25); (–25, 0); (–25, 25); (–25, –25); (50, 0); (50, 50); (50, –50); (–50, 0); (–50, 50); (–50, –50); (75, 0); (75, 75); (75, –75); (–75, 0); (–75, 75); (–75; –75). The coordinate point (0, 0) is the initial positioning point of the laser platform (red laser) and the other coordinate points are the positioning point of the reference laser (green laser). These coordinate points will be illuminated by the reference laser beam which will be detected by the laser spot detection program. The distance (height) between the platform and the laser target is 120 cm.

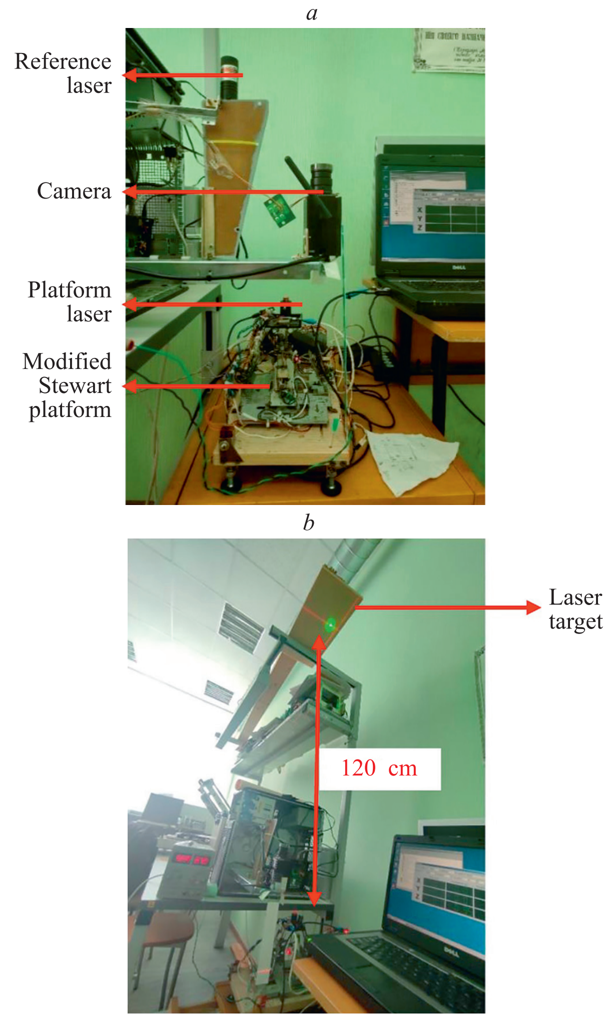

Fig. 10. Installation of laser position error compensation device in the experiment: modified Stewart platform with platform laser (red laser), camera, and reference laser (green laser) (*a*); laser target (*b*)

Experiment Results of Laser Beam Positioning Error Compensation Device

At this stage, the results of the experiment on laser beam positioning error compensation are presented. In this experiment, the accuracy of the movement of this device

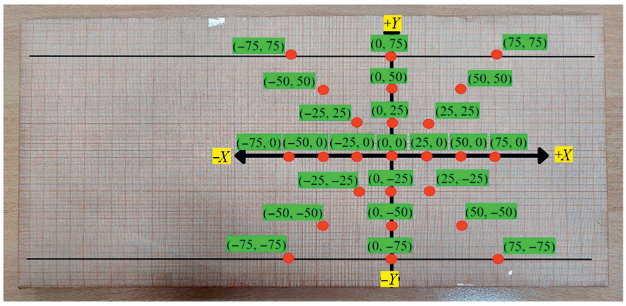

Fig. 11. Coordinates located on the laser target in this experiment

is evaluated from the movement of the platform laser (red laser) against the position of the reference laser (green laser) on the laser target. As previously explained, there are 25 coordinate points that have been conducted. The movement of the laser beam in the experiment can be seen in Fig. 12.

To simplify the data analysis process, please refer to Fig. 12. In Fig. 13, the blue dot is the reference point on

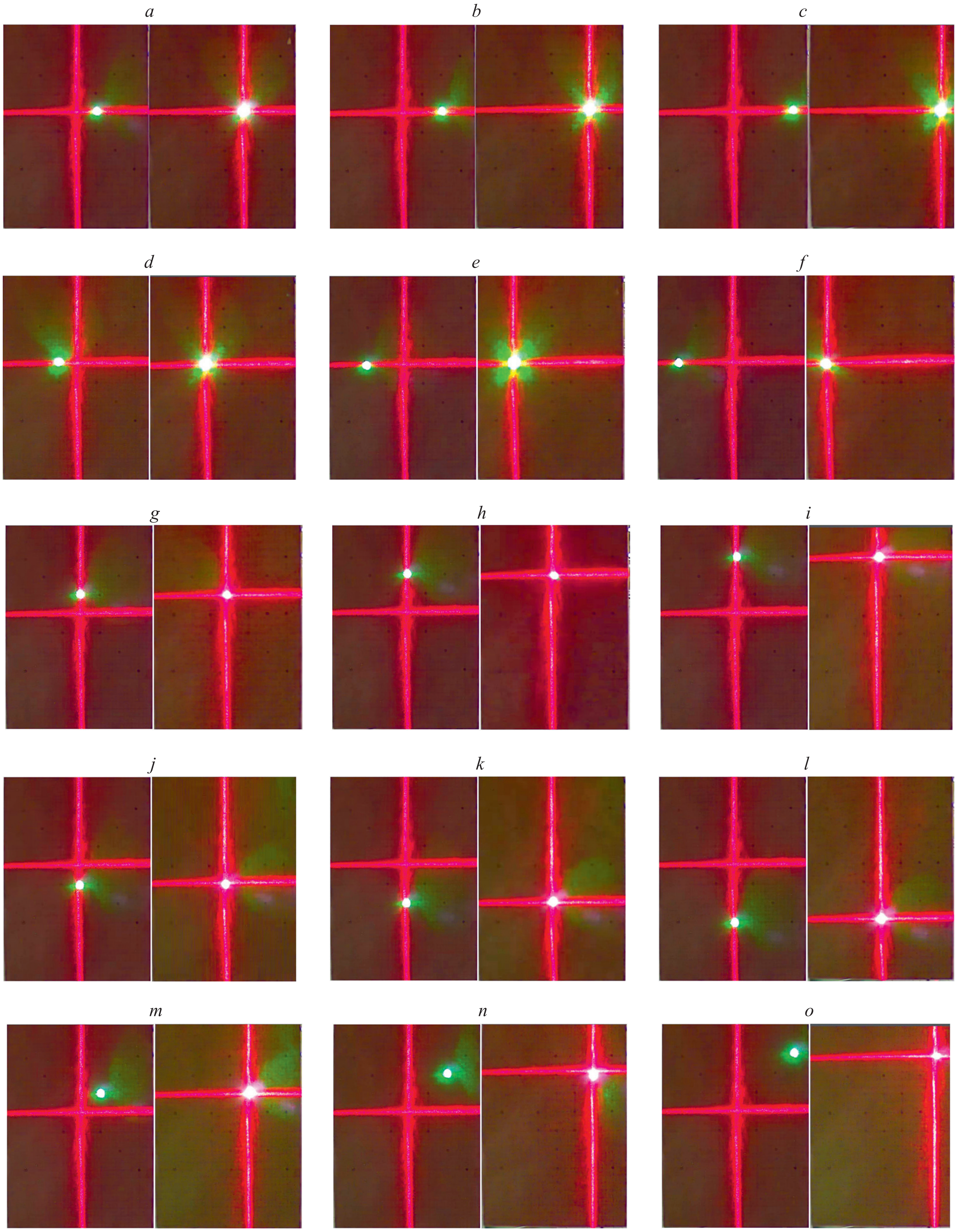

Fig. 12. Experiment results on the movement of the position error compensation device on the laser target coordinates *X*, *Y*, mm: (25, 0) (*a*); (50, 0) (*b*); (75, 0) (*c*); (–25, 0) (*d*); (–50, 0) (*e*); (–75, 0) (*f*); (0, 25) (*g*); (0, 50) (*h*); (0, 75) (*i*); (0, –25) (*j*); (0, –50) (*k*); (0, –75) (*l*); (25, 25) (*m*); (50, 50) (*n*); (75, 75) (*o*); (25, –25) (*p*); (50, –50) (*q*); (75, –75) (*r*); (–25, 25) (*s*); (–50, 50) (*t*); (–75, 75) (*u*); (–25, –25) (*v*); (–50, –50) (*w*); (–75, –75) (*x*)

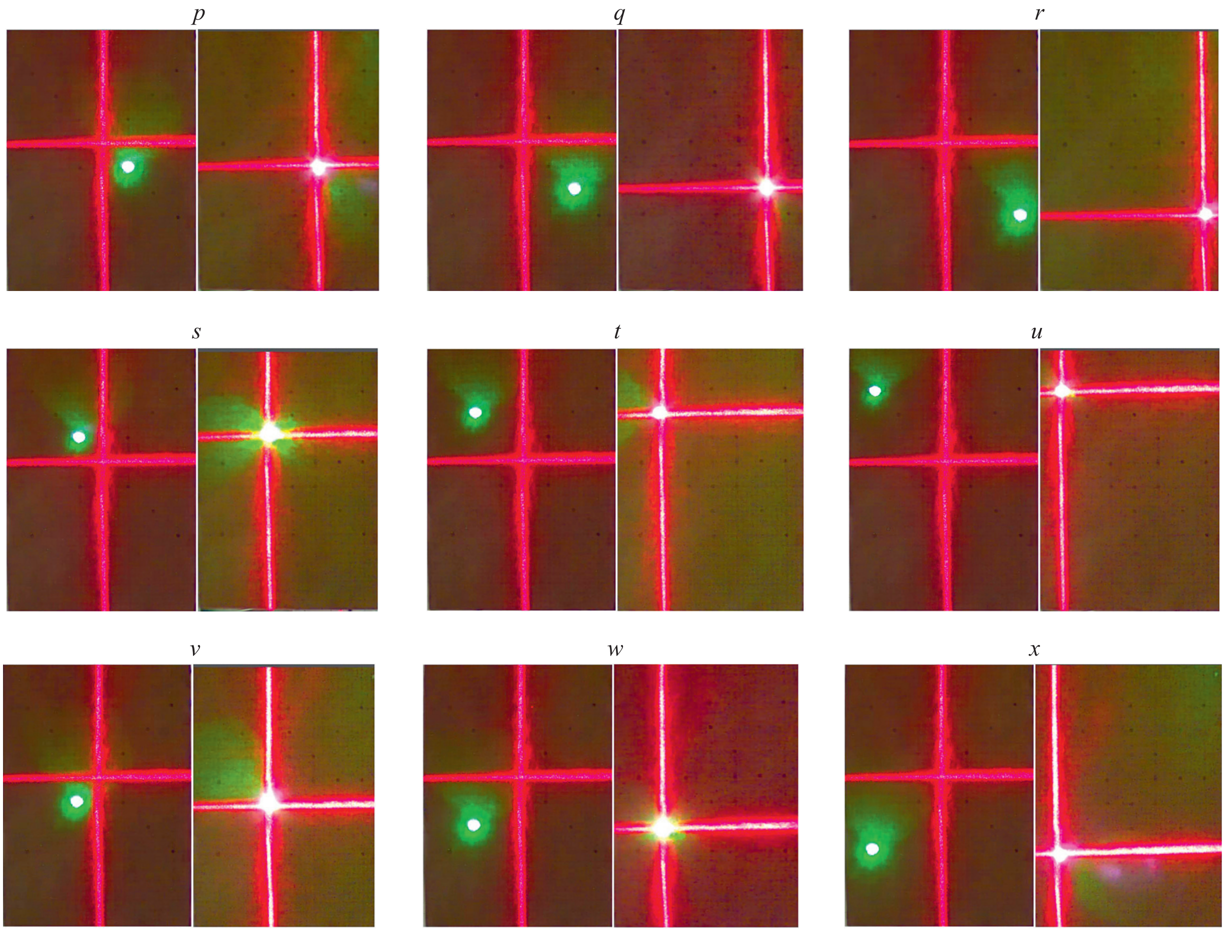

Fig. 12. Continuation

the target, and the red dot is the coordinate point where the red laser beam moved during the experiment.

Fig. 13 presents the data obtained from the experiments in this study. From the comparison graph, it is found that the largest error value on the X axis is 2.6 mm at coordinates (–75, –75) and the largest error value on the Y axis is 3.8 mm at coordinates (50, 0) and (75, 0). As a result, it can be concluded that the errors contained in the coordinate position data are generally small. Based on analysis conducted, the errors that appeared in this experiment were partly related to the size of the laser spot. The spot formed by the projection of the laser beam on the target is quite large, about 5 mm in diameter. With this size of laser spot, the detection program cannot provide more accurate results. However, the difference between the data is still within the tolerance of the laser spot which is less than 5 mm. In addition to the position data, there is also inclination angle data in the experiment. It is known that the maximum absolute error, inclination angle along the φ and θ axes is 0°24′. It is known that the error comes from the mechanical part of the mockup modified Stewart platform. As explained in the previous section, the modified Stewart platform is a complex device where each part of the device interconnected. The complex mechanism slightly restricts in the movement of the platform, which leads to decrease in the accuracy of the platform. Nevertheless, the device developed in this research has high positioning accuracy. Based on the experiment results, it can be concluded that the laser beam positioning error compensation device can move and work according to the target and direction given by the control program which is by directing the laser beam projection of the moving platform (red laser) from

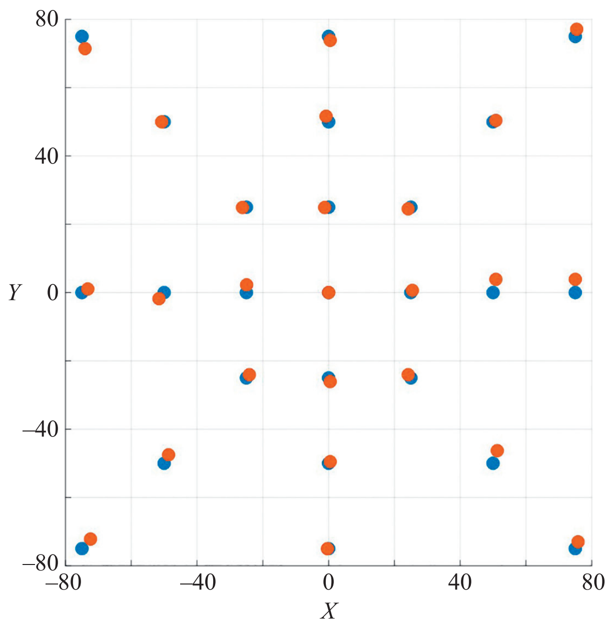

Fig. 13. Comparison graph of the laser spot position coordinates between reference position and experimental results

the origin coordinate (0, 0) mm to the specified point or predetermined position of the reference laser point (green laser) on the laser target.

Conclusion

In this research, a laser head is developed which has adaptive capabilities to the surface of the workpiece so that it can compensate for position error, stabilize the beam waist position, and reduce internal vibrations during processing of workpieces with uneven surfaces. A device called a modified Stewart platform was developed as the focusing and stabilization system of laser beam positioning error compensation device. The platform has the ability to move in 3 DOF, namely rotation along the φ and θ axes and movement along the *Z* axis. During the experiment, a program was developed to control the movement of the moving platform and detect the laser spot. The program allows the device to operate automatically, providing an automatic positioning system and automatic calibration. It was shown that the laser beam positioning error compensation device acts on the possible shift the laser spot and provides the displacement of laser beam (red laser) to the required point with sufficient accuracy. Further, such a device can move to the desired position or continuously ensure the position of the laser head is always perpendicular to the surface of workpiece with high degree of accuracy. From the experiment, it was found that there is a slight error in experimental data, which is explained by the imperfection of the mechanism of the modified Stewart platform. The imperfections of the spring elements and backlash at the joints cause a decrease in the positioning accuracy of the platform. Also, errors that occurred in this experiment were partly related to the size of the laser spot. The spot formed by the projection of the laser spot is quite large, about 5 mm in diameter. With this size of the laser beam, the detection program cannot provide more accurate results. However, the difference between the experimental data and the model is still within tolerance, which is less than 5 mm. In general, this device can be used and implemented as a laser beam positioning error compensation system during processing of workpiece. Thus, the laser head can change the focus distance to the surface, adapt to uneven workpiece surfaces, or compensate for vibrations. In future work, it is planned to continue to develop and study the model of the moving platform under dynamic conditions, as well as improve the mechanical parts and increase the level of laser beam positioning accuracy.

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