

APARATURA BADAWCZA I DYDAKTYCZNA

A new alternative polar positioning system for cartesian positioning system used in laser engraving device

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ABSTRACT

A novel conception of the construction of mechanical actuator system – polar positioning system which is an alternative to classic Cartesian cross table of laser device for engraving glass and other transparent dielectrics is presented in the work. Sample scenarios of movements of the working arm and the glass workpiece in polar positioning system are discussed. A preliminary analysis of the stiffness of the proposed solution which allows evaluation of machining accuracy (the quality of positioning the laser beam) is presented as well. A novel solution presented in this article of positioner may contribute to the new quality in techniques of laser glass engraving.

Alternatywny pozycjoner biegunowy dla klasycznego kartezjańskiego aparatu ruchowego laserowego urządzenia grawerującego

Słowa kluczowe: pozycjonowanie, pozycjoner biegunowy, laserowa obróbka szkła

STRESZCZENIE: W pracy przedstawiono koncepcję mechanicznego systemu wykonawczego nowego pozycjonera biegunowego, który jest alternatywą dla klasycznego rozwiązania aparatu ruchowego urządzenia grawerującego opartego na kartezjańskim stole krzyżowym. Omówiono przykładowe scenariusze przemieszczeń ramienia obróbczego oraz obiektu obrabianego w pozycjonerze biegunowym. Przeprowadzono wstępną analizę sztywności proponowanego rozwiązania, która przekłada się na ocenę dokładności obróbki (jakości pozycjonowania laserowej wiązki obróbczej). Prezentowane w pracy rozwiązanie przyczynić się może do wprowadzenia nowej jakości w technikach laserowego grawerowania szkła.

1. INTRODUCTION

An interesting and increasingly developed direction of using lasers among the glass decorative techniques is the subsurface laser engraving. An object modeled in the computer (two – or three dimensional) is performed by laser in the space of workpiece – glass as a point structure (example – Fig. 1) [1]. The main parameters defining this type of mechatronic processing systems are their efficiency and high quality of object surface forming by laser.



Figure 1 Example of 3D object engraving in glass (dimensions: 40 x 40 x 40 mm, 15777 points)

Implementation of the prescribed requirements can be ensured by increasing the laser parameters (processing instrument) or changing the control algorithms of the positioning system. One can also modify the structure of the laser beam positioning system [1]. The quality of laser engraved object inside the glass, thus the quality of the final product (glass cube), depends primarily on how it will be positioned. Among many factors affecting the quality of positioning you can identify primarily: smooth movement, speed and accuracy [1, 2]. These factors significantly contribute to the market competitiveness of manufactured product, due the fact of the final quality of the final product and the same production capacity which can meet the needs of the market. Due to non-smooth positioning, i.e. movement from one point to another successively engraved (forming) with different and significant velocities and acceleration of the positioning system in processing system generates considerable forces of inertia. This results in faster wear of mechatronic components of the engraving system and affects the surface quality of the formed object. From the point of view of the machining of laser engraving system it becomes important to maximize the operating characteristics

of the processing instrument. In the case of this type of device it is most often creating a maximum number of points of structure formed in glass within the prescribed period of time (in constant cycle of pulsed laser – 50 Hz, 100 Hz or more). Therefore, the positioning should be sufficiently fast so that each of the generated laser pulses could be used to forming a single point of three-dimensional object structure. In case when positioning is not accurate enough each point of the formed structure can overlap or will be located at different distances from each other. As a result the structure of the forming object will be destroyed by the occurring crack deviating significantly in size and form from the other points of structure or the form of the object engraved inside glass will be distorted.

2. TRADITIONAL POSITIONING SYSTEM WITH A CARTESIAN POSITIONER

Analyzing the laser beam positioning system used in currently available on the market laser glass engraving systems one can unequivocally state that actually most of them are based on Cartesian positioner [1]. This is due, among other things, to the fact that traditional solutions used in the current generation of processing system are often designed on the solution from the times when computer technology of device control was not used. Technical solutions impossible to implement from the past several or dozens of years can be successfully introduced today to the engineering practice in the form of a uniform mechatronic device, thanks to the combination of mechanical, electronic and information technology in one product. Commonly used in laser engraving system is Cartesian cross table [1]. It is usually built from the drives and spindle-nut transmission system. Here it is used to move the workpiece and the laser beam. In the XY plane workpiece is moved (the main displacements of the processing of the single object layer are performed here). The Z axis is used to focus of laser beam engraving object inside the glass (a transition between object layers appears here). However, this type of solution have some disadvantages [3]. The main one should be classified that with the increasing range of movements and the increasing of the maximum speed and acceleration, the next in the series drive has a greater global dimensions. Increasing the size of the positioning system results in increased di-

mensions of the engraving system also resulting in an increase in the level of forces of inertia. The resulting inertial forces due to mechanical vibrations affect the increase in the noise level at the same time causing premature wear of the system components and strongly affect the quality of the formed object. Because drives link in XY plane (one drive carries the second drive) the main inconvenience arises because of large moving masses and the resulting restrictions of the drive dynamics, which carries another drive. Discussed further in the work developed by the author novel polar positioning system is devoid of the mentioned drawbacks. With a simple design, low manufacturing cost and computer control polar positioning system can provide an alternative to conventional, commonly used traditional Cartesian positioners [2, 3]. The main assumptions made in the development of the proposed solution included [1-3]:

- the column of the working arm should allow free movements above the workpiece;
- rotating column of the working arm should be closer to the working table; the length of the working arm should be as short as possible and the construction of the arm should be light and stiff – this primarily will reduce positioning errors and reduce inertia forces;
- the drive parameters relating to the accuracy will depend on the length of the working arm.

To fulfil the condition of the lowest possible mass of working arm a physical separation of the working arm from the laser emitter by virtue of his dimension and mass is necessary. Fixing it on the rotary working arm in the form of a laser head would significantly increase the size and mass of the arm which due to the inertia of such system could not exist.

3. STIFFNESS OF THE STRUCTURE POSITIONING SYSTEM VS. ACCURACY OF LASER PROCESSING

One of the important factors affecting directly the accuracy laser processing by using positioning system is the stiffness of the structure [1, 2, 5]. A deflection (deformation) of the structure as a result of affecting forces of inertia will be a measure of accuracy. Therefore it can be assumed that accuracy will be greater, the greater the rigidity of the present structure.

The classic Cartesian positioner (stationary system of laser beam – moveable workpiece) is usually based on a cross XY table – created with connect-

ed single axis positioners. The drive is transmitted from the stepping motor through a transmission coil for the positioning table. The connection of movements in two axis allows to move workpiece in a plane and thus for forming single layers of the object structure. This system is a series where apart from stiffness and damping additional mechanical backlash in the whole structure is assumed [1, 2, 5] (Fig. 2A). This is due to the method of modelling multibody systems adopted widely in the literature in the fields of mechatronics and robotics. The overall stiffness of this solution can thus be expressed by the following formula:

$$C = \frac{C_1 C_2}{C_1 + C_2}, \quad (1)$$

where:

- C_1 – stiffness of X axis of positioning system,
- C_2 – stiffness of Y axis of positioning system.

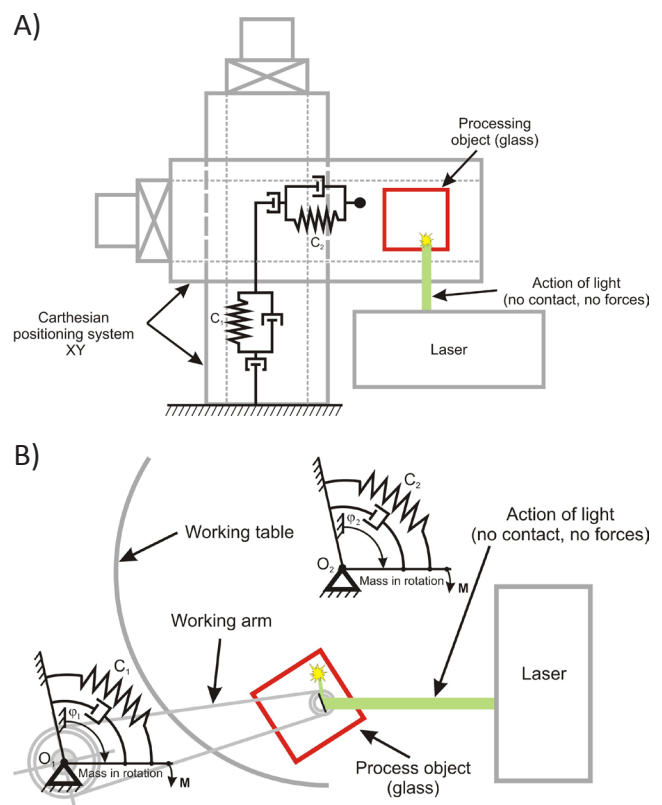


Figure 2 Stiffness modeling in: A) Cartesian positioning system, B) polar positioning system

The conducted analysis of positioning systems including possible laser beam and workpiece positioning systems [1] led the author to propose a different approach to the positioning than traditional Cartesian positioning system. It is modelled on positioning system in hard drives. This approach, according to the author knowledge, is not applied

in the practice of designing devices for laser glass engraving. In the case of the novel polar positioning system (Fig. 2B) as a modification of traditional structure of positioning system individual stiffness occur in the parallel [1, 2, 5]. The overall stiffness of the device comes down to the sum of the working arm stiffness and the rotary working table, which can be written as a formula:

$$C = C_1 + C_2, \quad (2)$$

where:

C_1 – stiffness of working arm,
 C_2 – stiffness of working table.

Processing of the three-dimensional laser forming object inside glass is layer performed, starting from the lowest stacked layers proceeding in succession to layer lying above. This is due to the fact that local micro crack could “override” the area which a focused laser beam should reach. Imposing at this point micro cracks would cause the previously mentioned micro-destruction of the structure of the formed object. Due to the layered nature of processing in both cases the analysis comes down only to movements of positioners in the XY plane – hence Z axis which is used to move to the next layer is not considered here [2, 6].

Favorable stiffness of structure argument and the argument associated with lower manufacturing cost of the proposed solution in relation to precise Cartesian axes led the author to develop its own design polar positioning system (a more detailed description, item 5). In developing the concept of the positioner the argument of increased productivity and speed of working of polar device was also taken into consideration. Another, equally important argument, is the lower cost of manufacturing simple rotatable pairs relative to precise linear axis. In Cartesian XY – positioning system accuracy of displacement will depend largely on the accurate manufacturing of axis and on ensuring perpendicularity of axes relative to each other. This factor considerably increases the cost of the structure, and thus affects the growth of the price of the whole engraving system.

4. MOVEMENT SCENARIOS OF WORKING ARM AND WORKPIECE

For a more complete description of the concept of polar positioning system a laser beam and workpiece type of processing the following point of structure of the forming object should be ana-

lyzed. The laser forming object structure can be carried out according to two assumed scenarios [1, 7, 8]. The first scenario assumption is that the working arm takes the main displacement and directs laser beam in the space of the workpiece (Fig. 3A). The same operation is carried out to all the objects on the working table. Then the working arm is moved by a predetermined angle to create another “path”. In this case the inertia forces are eliminated by providing a constant rotary speed of working table. The working arm is moved by a slight angular value after moving over successive object. The third dimension of the forming object is created by changing a focal length with the special lens system of working arm. In this scenario it is easier to ensure equal distance between points of structure formed after each pass of the laser. The analogy to the previously-cited example of the hard drive can be indicated. The rotational speed of working table is constant (in hard drive – drive platter) and the working arm (in hard drive – magnetic head) is slightly moved. Such system provides a constancy of inertia forces arose from the working table (after the achievement of the assumed speed). In the second scenario (Fig. 3B) the working arm moves oscillating above the workpiece on the working table. The object is moved by predetermined angular value of working table after processing the first “path”. In this scenario points of the structure formed in the first cycle will be away at equal distance. But when we move to the next cycle of object processing we will not able to provide in a single pass equidistance between forming points of structure. In one extreme position the distance between points will be different than in the second position [4]. This case shows that despite more favorable from the point of view of dynamics of the device (smaller masses are moved) and limitation of inertia forces associated in processing it would necessary to ensure special control software. This software would allow selecting the points on feasible path. Consequently this would not necessarily increase efficiency of the laser engraving system.

5. PROPOSED SOLUTION OF POLAR POSITIONING SYSTEM

To form the point of the object at any point in the working space, angular positioning of working table is necessary. The working table is rotated around an axis O_2 by a specified angle φ_2 (Fig. 4B). The general and main objective in developing

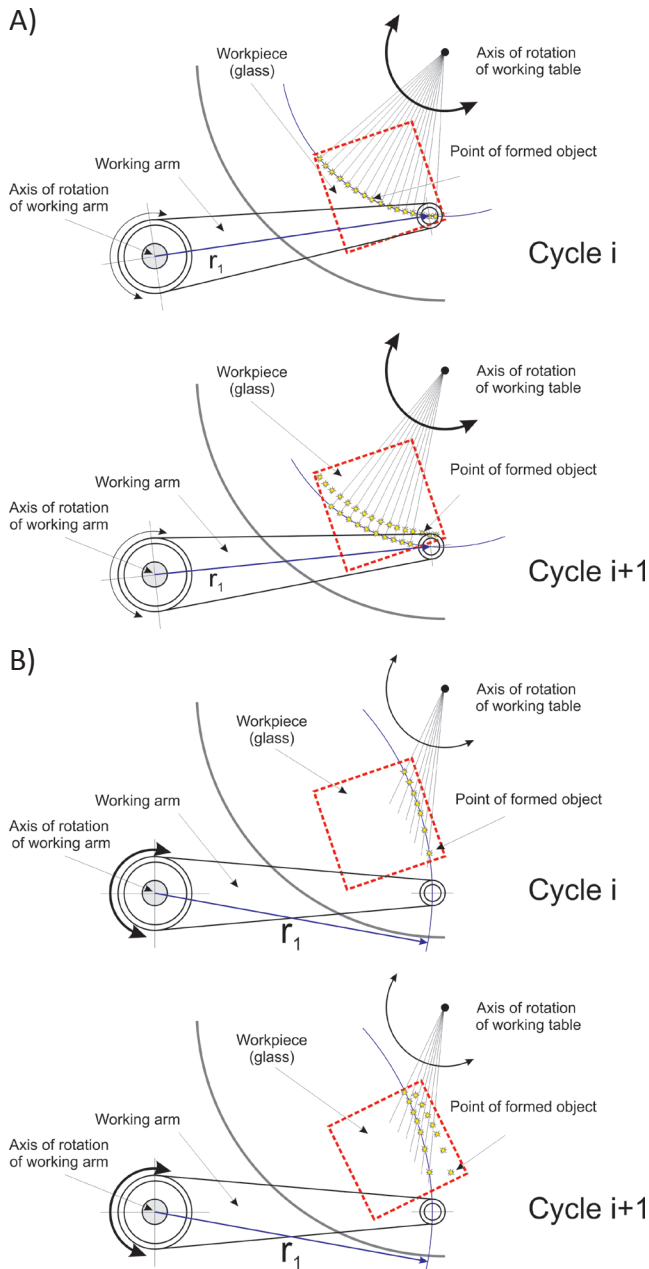


Figure 3 Two scenarios of filling the object point of structure

the novel concept of working table was primarily that it enables secure the workpiece mounting (glass cube) [2, 3]. This requirement stem from the fact that the processing workpiece will move at a predetermined, constant speed. Apart from this requirement using rotary device can reduce the space of loading material to be processed and thus isolate more the sphere of laser light influence reflected from the external surfaces of glass. The control system of the rotation of the working table should also ensure smooth speed control. In order to fully exploit the capability of the laser it is necessary to ensure such movements so that you can use 100, 200 or more laser pulses generated during 1 second.

The duration of a single laser pulse is in the range from 4 ns to 6 ns and the next pulse, for example in the case of laser 200 Hz, is generated every 5 ms. Accordingly the transition to the next formed point of object should be specified in mentioned above time period. At the time when there will not be a need to place the point of object in local area of formed object, a special mechanical system overshadows the laser beam and thus it will not affect on the workpiece (glass). For the purpose of designing a device assumed that the maximum size of the workpiece should close in size 100 x 100 x 100 mm and it is the developed device should ensure simultaneous attachment of four processed objects. This condition mainly ensures an increase in capability of laser engraving system which in the case of commercial use is a significant argument. The proposed conceptual solution of the rotary working table shown in Fig. 4 A. According to the assumption the glass blocks (glass cubes – marked in Fig. 4 as 1) are mounted on the rotary working table 2 using special fasteners 4. These fasteners allow to adjust the size of the mounting area to the size of the glass cube.

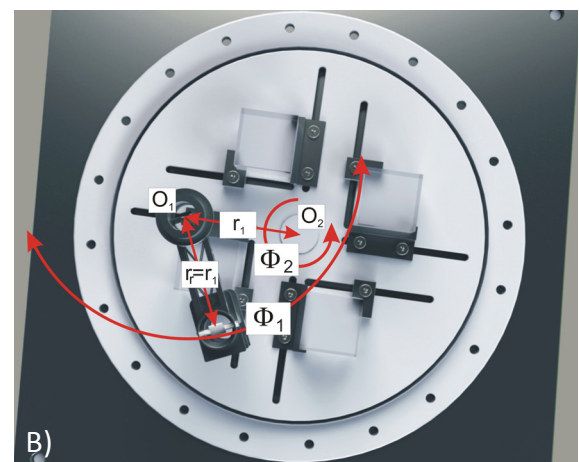
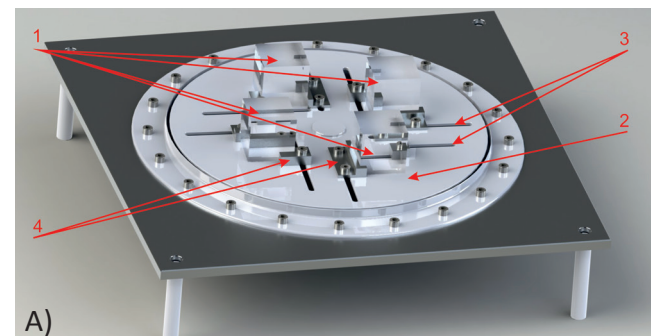


Figure 4 The solution of rotary working table: A) general view, B) view of the arm under the rotary table

This is due to the fact that glass blocks may be of various sizes. Fitting to size occurs due to the shift to the desired position fasteners in special hollow tubes 3 on the working table. The final position occurs after pressing the fastener to the working table and the workpiece and screwing it with a hexagon socket.

When designing the control system of movements of rotary working table the fact that it is important to maintain constant speed of working table and possible to adjust speed within the range must be taken into account. This is due to assumption that at given constant radius r_1 the working table rotates at a speed that provides the exploitation of the maximum number of laser pulses. It also assumed that the radius is half of the radius of the working area of the rotary working table. The values of angular velocity for selected radius can be calculated by using the overall formulas for the angular velocity ω . Presuppose for Δt – the time of generating of another laser pulse; and changing the value of angle $\Delta\alpha$ can be calculated by using the formulas for the length of the arc of a circle, which for the first calculation may be taken as the minimum distance between formed points of object. Providing constant speed of the working table with the mounted glass cube on it will reduce generated inertial forces in the system. Stepper motor with precise harmonic gear with ratio greater than 1:2000 will provide the drive of the working table. An additional subdivision of steps will be accomplished through the use to control the motor driver a card with micro stepping operating mode.

The working arm and the rotary working table with workpiece will comprise polar positioning system. The working arm design should allow an orientation of the laser beam at any point of processing the glass cube. At the same time the optical system associated with the working arm should ensure the changing of the focused laser beam position to the extent that one can form any points of spatial object of the assumed maximum size. The working arm should also ensure the resolution of displacement focused laser beam from one point to another point approx. 200 micrometers. The material used for designing of the working arm must be rigid and lightweight. The length of the working arm should be up to the shortest (the final length will depend on the dimension of working table) and at the same time should be such as to be able to provide coverage

for working area of the working table. This factor will limit the negative impact of interacting forces of inertia [2]. To meet such requirements the working arm was designed in the form as shown in Figure 5. A treatment laser beam 10 is directed by the optical system in case 1 marked in Figure 5. The case is used to attach the working arm to the positioning system body and provides the possibility for rotation by a specific angle. Additionally the case was made of a toothed ring 2, which in combination with harmonic gear allows for additional gear ratio for a single step (displacement). A mirror 4 reflecting the laser beam and orienting it toward the second mirror 4 is also mounted there whose task is to direct the beam to the focusing optics system 5.

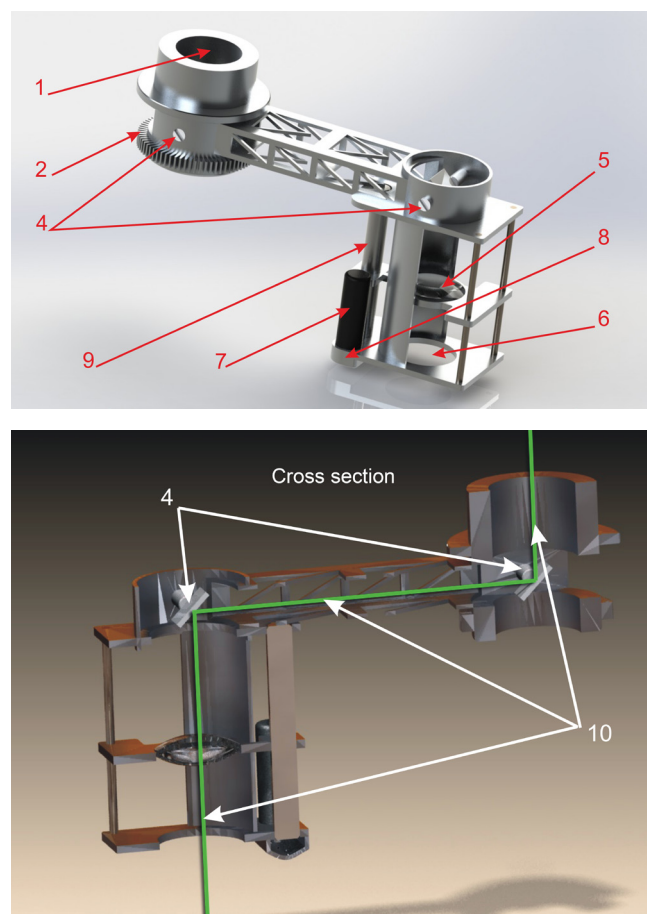


Figure 5 The solution of working arm of polar positioning system

This system provides the possibility of adjusting the height of focusing laser beam which is passing through the space, indicated in Figure 5 as 6, in space of glass cube. Height control of the focusing laser beam is achieved through the use of additional drive 7 with mechanical gear 8. It is used to move in the Z axis focusing lens 5 by the spindle-nut system 9.

The assumed movements of the working arm for angle φ_1 are foreseen for the interval $(0, \pi)$. The length of working arm r_r should correspond to the aforementioned radius r_1 of the working table. For the length of the working arm r_r should be taken not the size of the whole structure but the distance between laser beam inbound and outbound from the working arm. The axis of rotation of the working arm O_1 must be located at the intersection of the radius r_1 of the working table (Fig. 4B). Such adopted parameters of structure will ensure full impact of the laser beam on the glass cube mounted on the rotary working table and also maximally shorten the length of the working arm and reduce the value of the inertia forces. The proposed solution of polar positioning system consists of two main modules: one of them is related to the structural plate 4 and the working arm 7 (shown in Fig. 6) and the second module is associated with the plate 5 where the rotary working table 8 is mounted. As the drive of this components are used stepper motors with harmonics gear – 2, 6. Above the upper plate 4 a pulse laser emitter Nd:YAG – 1 is additionally fixed integrated with optical, control, power and cooling systems. The component that complement the concept of polar positioning system is a sensory system 3 (Fig. 6).

It is used to count the number of defects (cracks) formed in the workpiece. Its existence is due to the need to ensure a feedback loop, for example in case of an emergency resulting from power loss or emergency system stop by the user.

6. CONCLUSIONS

When we design an efficient mechatronic positioning system it becomes necessary to have a wider view at process and components associated with mechanical actuator system and also electronics information system and the feedback (relationship, flows) occurring between them. The product device should be reliable in the oper-

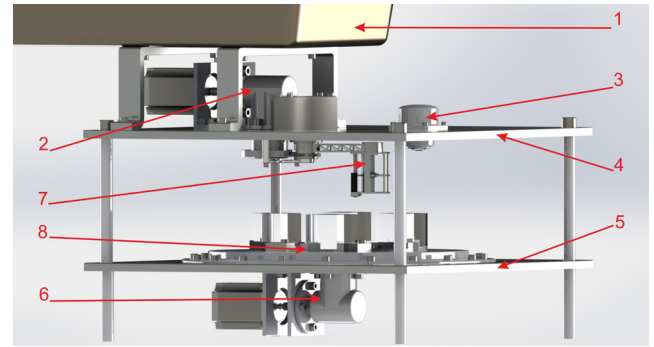


Figure 6 Polar positioning system of device for laser glass engraving

ation, inexpensive, functional and easy to use [2]. Do not forget that in addition to the integration of the various subsystems it is necessary to obtain the synergy effect. For the purposes of engineering the term of synergy means a new, unattainable characteristics of the device. Therefore the accuracy of positioning resulting from the stiffness and simplicity of the device structure and the ease to computer convert position, translate into low cost of the mechatronic laser engraving system production while maintaining high quality of processing. The analysis of the stiffness of polar positioning system provides a basis for adoption of the idea that the simple solutions can achieve accurate positioning of the laser beam. An increase in the accuracy of engraving device indirectly influences an increased productivity of the system and an increase in parameters of the process of laser glass processing. The synergy effect (it is defined as a new, previously unachievable characteristics of positioning system) in case of novel polar positioning system that i.e. another (not traditional) thinking process which has been made possible through the use of the computer control for the moving of the simple rotation mechanism [1, 3]. Presented in the work an alternative solution of polar positioning system will be used to carry out further computer simulation studies confirming the validity of the reasoning adopted and the development of a prototype and testing its usefulness on the workbench.

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