

SELECTION OF A KINEMATIC MODEL AND DESIGN FEATURES OF A 3D SCANNER

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Abstract: The paper examines the selection of a conceptual diagram for a 3D scanner of free form objects. A structure has been chosen that meets the design requirement for scanning accuracy of 25µm for parts of dimensions 500x500x350 mm. The choice of mechanical elements has determined the scanning accuracy, mechanical characteristics, as well as the required electric drive. Conclusions have been drawn about the accomplishment of precise digital images of mechanical parts ready to be used in a computer medium.

Keywords: 3D scanning, positioning mechanical system.

1. INTRODUCTION

Engineering requirements have determined the increasing popularity of the reverse engineering approach, which involves the acquisition of the part shape by means of unconventional measurement (scanning) and subsequent generation of a 3D file suitable for computer processing. The devices that perform this function are called 3D scanners. The advantages in using these scanners are the rapid digitization of the part shape, design of matrices and their replicas, restoration of unique parts and much more.

The first step in designing the mechanical system of a 3D scanner generating a precise digital copy of the object being scanned is to determine the following elements of the device:

- type of the measuring instrument;
- mechanical structure that meets the scanning requirements.

The choice of a measuring instrument is determined by the way of capturing the points on the object surface – contact or non-contact.

The contact methods of measurement use a special touch probe consisting of an arm and an optical system. The physical touch causes the arm to deviate from its position, whereby the optical system responds and performs the measurement.

Non-contact methods are mainly based on the triangulation method and the method of laser light dephasing. They have the important advantage of being able to measure objects having a delicate or elastic structure.

The mechanical structure of the measuring system should meet the accuracy requirements and be capable of scanning objects of specific geometric dimensions.

The purpose of the present paper is the design and development of a scanning device for parts having dimensions 500x500x350 mm and measurement accuracy of 25µm.

2. DEVELOPMENT

1. Requirements to the measuring instrument.

The main requirements to the measuring instrument are the scanning speed and accuracy. For the purposes of the present paper a laser head for non-contact measurement has been chosen, manufactured by Wolf&Beck and having the following characteristics:

- measurement range – 140 ± 25 mm;
- resolution – $5 \mu\text{m}$;
- scanning speed – 3500 pps;
- detection threshold on inclined surfaces – 80° .

2. Requirements to the mechanical system.

The choice of a mechanical diagram involves performing a sufficient number of basic movements of the measuring instrument relative to the object being scanned, so that its shape would be recorded with as few scans as possible.

The mechanical structure to be designed must not permit vibrations affecting the accuracy of measurement, nor linear thermal expansions of materials exhibiting different temperature coefficients.

If the object to be scanned is assumed, very roughly, to be cylindrical, then the surfaces developing vertically can be captured by the measuring instrument in horizontal position, which moves in vertical direction. When scanning rectangular objects, all of its horizontal or near-horizontal surfaces will be scanned by a vertical laser beam performing a plane motion.

To achieve this purpose, the mechanical diagram should have five degrees of freedom. These include three linear displacements along axes X , Y and Z , one rotary motion of object W and positioning of the laser head in horizontal and vertical positions. The linear motions have to provide horizontal linear motion of the laser head (X and Y) and vertical displacement (Z), which will be independent of one another or in a synchronous mode. The mechanical system has to provide for displacements along the axes with integral accuracy of $\pm 5 \mu\text{m/m}$. The rotary motion (W) ensures the primary motion when scanning the curved surface of rotary bodies. It should provide information about initial and angular position of the object to be scanned. The fixed positions of the laser scanning head guarantee rotary and vertical scanning of surfaces.

The overall structure will be based upon a solid working plane, which will absorb the vibrations and have minimum linear deformation.

3. Design versions for realization of a 3D positioning system.

Two major versions of mechanical systems have predominantly been used in practice. The first one is a cantilever beam that supports the measuring instrument. The degrees of freedom vary from 3 to 8. These systems are most commonly driven manually and perform control functions in the precise manufacturing of parts. The second type is a portal system which provides three degrees of freedom. These are the portal displacement, a motion in the direction of the portal beam and a vertical motion perpendicular to the machine fundament. Additional degrees of freedom are the positioning of the measuring instrument and the object rotation. The main difference in these systems lies in the choice whether the portal should be a moving element or the object being scanned should perform a motion relative to it. The choice is reduced to determining what the mass and dimensions of the object to be scanned are. In the case of great dimensions and mass it is recommended to use a positioning system with a moving element and a fixed portal. This is necessary in order to reduce the vibrations in the mechanical system due to the increase in the portal height and length. In the case of limited dimensions and mass it is advisable to use a mechanical system with a moving portal.

4. Definition of the design solution.

Considering the proposed versions of mechanical driving systems for the 3D scanner, a diagram has been chosen that meets the requirements for the motions of the object being scanned and the laser head (Fig.1).

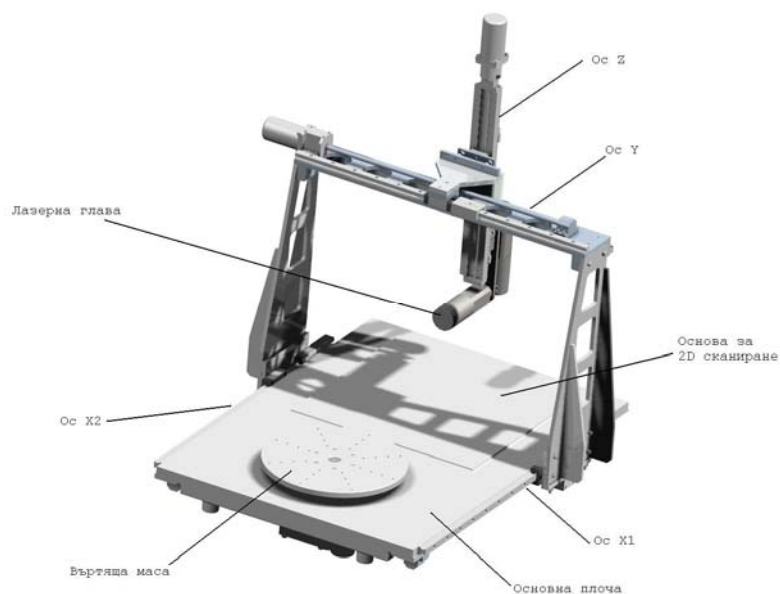


Figure 1: General view of the mechanical structure of a 3D scanning device

It is a device with five degrees of freedom, portal-type, performing three linear displacements along axes X , Y and Z , one rotary motion of object W and horizontal and vertical positioning of the laser head. The measurements taken will be recorded as points in an orthogonal system of three coordinates.

5. Meeting the technical requirements.

In order to achieve the required accuracy of the parts to be scanned, a positioning system has been proposed consisting of:

- guide rails with built-in incremental lines – the resolution of the embedded linear encoders enables the positioning of the mechanical system with accuracy of $1\ \mu\text{m}$;
- runner blocks for linear guidance along axes X , Y and Z with lower coefficient of friction (Fig.2);
- screw drives with zero clearance (gap). This drive transforms the rotary motion of the electric motor into rectilinear motion of the coordinate module (X , Y , Z) with a high ratio between the speeds of the two motions and a high ratio between the axial force and the force of periphery (Fig.3). The screws along axes X and Y have been chosen of diameter $\varnothing 12 \times 2$, while along axis Z the chosen diameter is $\varnothing 8 \times 2.5$.

All mechanical elements have been selected from leading manufacturers who guarantee the fulfillment of the accuracy requirements set to them.

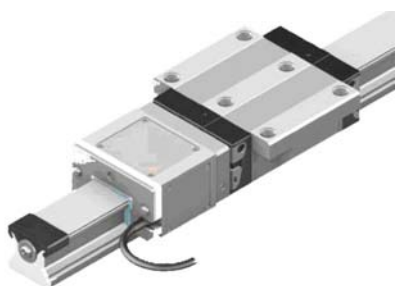


Figure 2: Guide line with a measuring runner block

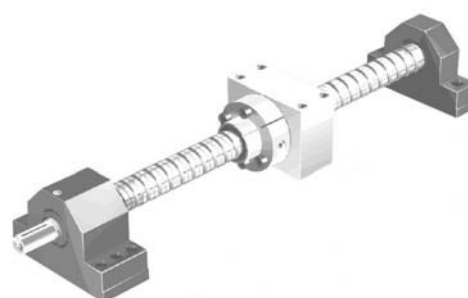


Figure 3: Screw drive

6. Determining the masses of the moving elements required for choosing the driving system.

The moment applied on the screw or the nut is directly proportional to the mass of the moving elements in the mechanical system. Its function is to perform their relative displacement and to overcome the axial force acting

on the screw. The force identification will determine precisely the required moment and power of the driven electric motor.

The mechanical diagram determined for the product includes components that are unified for ensuring the motions along the three axes. Therefore the moment of motion applied to the screws has to be determined for the one that is most unfavourably loaded. This refers to the two screws located along axis X , which displace all moving masses of the product. The most infavourable diagram for them is the position in which the vertical module (axis Z) is positioned on axis Y in such a way that it is in the end positions (Fig.4).

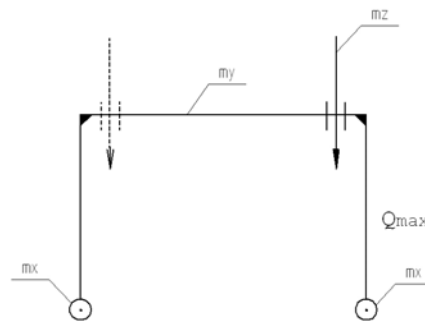


Figure 4: Loading of axis X when axis Z is in end position

The subsequent calculations will focus on the most unfavourable cases of loading, which will determine the drives along the remaining axes.

Distribution of the components masses according to their drive along the coordinate axes:

- distributed mass of the moving parts of one X guide and half of the mass of the Y guide - $m_{xy} = 36,422 \text{ kg}$;
- the moving masses of axis Z - $m_{z,mov} = 6,124 \text{ kg}$;
- the fixed elements of axis Z - $m_{z,stat} = 7,683 \text{ kg}$.

7. Choice of electric motors.

The calculations for choosing an electric motor involve determining the resisting moment reduced to its shaft.

The maximum resisting moments that have to be determined are:

7.1. One of the X axes when axis Z is in the end right-hand position (Fig.4). Then there is maximum load from masses m_x ; m_y and m_z and a maximum resisting moment, respectively – $M_{cnp,x}$. The resisting moment is limiting for determining or checking of the chosen electric motor.

The force on the runner blocks for the X axes is determined using the formula:

$$Q_{max,x} = g \left(m_{z,mov} + m_{z,stat} + \frac{m_{xy}}{2} \right), \quad N \quad (1)$$

$$Q_{max,x} = 9,81 \left(6,124 + 7,683 + \frac{36,422}{2} \right) = 314 \text{ N} .$$

The axial force on the screw drive along axis Z is determined using the formula:

$$Q_{max,z} = g \cdot m_{z,mov}, \quad N \quad (2)$$

$$Q_{max,z} = 9,81 \cdot 6,124 = 60 \text{ N} .$$

The axial force generated in the nut of the guide screw is:

$$F_x = \mu Q_{max,x} = 0,01.314 = 3,14 N ,$$

where g is the gravitational acceleration ($9,81 \text{ m/s}^2$), $\mu = 0,01$ – friction coefficient during rolling in the screw drive.

The resisting moment of the screw drive will be:

$$M_x = F_x \cdot \tan \gamma \cdot \frac{d_{B,x}}{2} = 3,14 \cdot \tan 3^\circ \cdot \frac{0,012}{2} = 9,87 \cdot 10^{-4} \text{ Nm} , \quad (3)$$

where γ is the inclination angle of the helical line:

$$\gamma = \arctg \left(\frac{p_x}{\pi \cdot d_{B,x}} \right) = \arctg \left(\frac{0,002}{3,14 \cdot 0,012} \right) = 3^\circ ;$$

$d_{B,x} = 0,012 \text{ m}$ - screw diameter;

$p_x = 0,002 \text{ m}$ - screw pitch.

The moment applied to the axle of the electric motor is:

$$M_{oe,x} = \frac{M_x}{\eta_1^k \cdot \eta_2^m} = \frac{0,000987}{0,95 \cdot 0,98^2} = 10,817 \cdot 10^{-4} \text{ Nm} , \quad (4)$$

where η_1 is the efficiency of the screw drive ($\eta_1 = 0,95$), η_2 - the efficiency of the roller guides ($\eta_2 = 0,98$), k and m - the number of the respective elements.

7.2. Axis Z, since the masses of the electric motor, the mechanical elements and the laser head generate an axial force in the screw drive and determine the maximum resisting moment – $M_{cnp,z}$.

The load on the screw includes the weight of the module, laser head, electric motor and the masses of the mechanical elements.

The resisting moment along axis Z is:

$$M_z = m_{z,mov} \cdot g \cdot \tan \gamma \cdot \frac{d_{B,z}}{2} = 6,124 \cdot \tan 5^\circ 41' \cdot \frac{0,008}{2} = 23,58 \cdot 10^{-4} \text{ Nm} , \quad (5)$$

where γ is the inclination angle of the helical line:

$$\gamma = \arctg \left(\frac{p_z}{\pi \cdot d_{B,z}} \right) = \arctg \left(\frac{0,0025}{3,14 \cdot 0,008} \right) = 5^\circ 41' ;$$

$d_{B,z} = 0,008 \text{ m}$ - screw diameter;

$p_z = 0,0025 \text{ m}$ - screw pitch.

The moment applied to the axle of the electric motor is:

$$M_{\partial\theta,z} = \frac{M_z}{\eta_1^k \eta_2^m} = \frac{0,002358}{0,95 \cdot 0,98^2} = 25,84 \cdot 10^{-4} \text{ Nm.} \quad (6)$$

Providing the required speed of the electric motor for scanning:

$$n_{\partial\theta} = \frac{60V}{p}, \text{ min}^{-1},$$

where V is the maximum conveying speed of the laser in m/s , p - pitch of the guide screw in m .

- for $V_{max} = 0,2 \text{ m/s}$:

$$n_{\partial\theta,x} = \frac{60V}{p} = \frac{60 \cdot 0,2}{0,002} = 6000 \text{ min}^{-1}; \quad (7)$$

$$n_{\partial\theta,z} = \frac{60V}{p} = \frac{60 \cdot 0,2}{0,0025} = 4800 \text{ min}^{-1}. \quad (8)$$

Providing the required rotation of the axle of the electric motor for moving the laser head with $1\mu m$ along axes X and Y will be determined by the angular displacement $\alpha_{\partial\theta,x,y}$.

$$\alpha_{\partial\theta,x,y} = \frac{360^\circ \cdot 60 \cdot 1\mu m}{p_{x,y}},$$

where $p_{x,y} = 0,002 \text{ m}$ is the screw pitch along axes X and Y .

$$\alpha_{\partial\theta,x,y} = \frac{360^\circ \cdot 60 \cdot 10^{-6}}{0,002} = 10'48''. \quad (9)$$

for $p_z = 0,0025 \text{ m}$ the displacement of $1\mu m$ will be:

$$\alpha_{\partial\theta,z} = \frac{360^\circ \cdot 60 \cdot 10^{-6}}{0,0025} = 8'38''. \quad (10)$$

An encoder of the servomotor after the respective signal processing generates 20480 electric pulses for one revolution, or this corresponds to $\frac{360^\circ}{20480} = 1'05''$. This means that for $1\mu m$ the electric motor has approximately 10 pulses for positioning. Taking into consideration that the resolution of the measuring heads for linear displacement along the axes is $1\mu m$, it is obvious that the servomotor control is capable of responding precisely to a displacement of $1\mu m$.

After the conducted analysis it is possible to make a selection of driving electric motors. The selected electric motors have the following characteristics:

- rated moment - $M_n = 1,13 \text{ Nm}$;

- rated power - $P = 0,57 \text{ kW}$;

- rated revolutions - $n_n = 6000 \text{ min}^{-1}$.

It follows from the selection made that the mechanical modules selected in this way, in combination with the selection of servomotors will guarantee reliable operation of the scanning device.

8. Force characteristics of the driving modules.

The selection of servomotors has been made in such a way that the rated torque is several times higher than the torque required for driving the mechanical system. Therefore it is necessary to check what forces the screw drive guides would generate when the electric motors operate at a rated torque.

8.1. Drive along axis X.

Axis X is driven by two parallel screw drives that will develop the following axial force:

$$F_{x,max} = 2F_x = 2 \cdot \frac{2000 \cdot M_n \cdot \pi \cdot \eta}{p} = 2 \cdot \frac{2000 \cdot 1,13 \cdot \pi \cdot 0,9}{2} = 6390 \text{ N}, \quad (11)$$

where M_n is the rated torque of the electric motor in Nm, η - efficiency ($\eta = 0,9$), p – screw pitch in mm.

8.2. Drive along axis Y.

Axis Y is driven by one screw drive that will develop the following axial force:

$$F_{y,max} = \frac{2000 \cdot M_n \cdot \pi \cdot \eta}{p} = \frac{2000 \cdot 1,13 \cdot \pi \cdot 0,9}{2} = 3195 \text{ N}. \quad (12)$$

8.3. Drive along axis Z.

Axis Z is driven by a precise guide module consisting of a case with guides, two runner blocks and a screw drive that will develop the following axial force:

$$F_{z,max} = \frac{2000 \cdot M_n \cdot \pi \cdot \eta}{p} = \frac{2000 \cdot 1,13 \cdot \pi \cdot 0,9}{2,5} = 2556 \text{ N}. \quad (13)$$

It follows from the check conducted that the torque reserve in electric motors results in a possibility of developing considerable axial forces in screws. To achieve reliable operation of the device, the generated forces should be reduced by means of the torque developed by the electric motors, so that it would only provide smooth motion along the coordinate axes.

3. CONCLUSION

The study of the proposed kinematic model of a 3D scanning device has demonstrated the following advantages:

- maximum accuracy of the positioning device of 1 μm ;
- a rigid mechanical system has been created by incorporating gapless guides and screw drives;
- smoothness of operation determined by the selection of servomotors as a result of the calculations done concerning the required torque;
- high resolution - 5 μm ;
- non-contact laser measurement;
- universality of the product allowing scanning of objects made of different materials and having complex shapes.

The examined structure of the 3D scanner enables the conduction of precise comparison of real objects with their CAD models for the purposes of quality control, as well as for tracing the wear, corrosion and deformation of parts and components in the course of time.

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