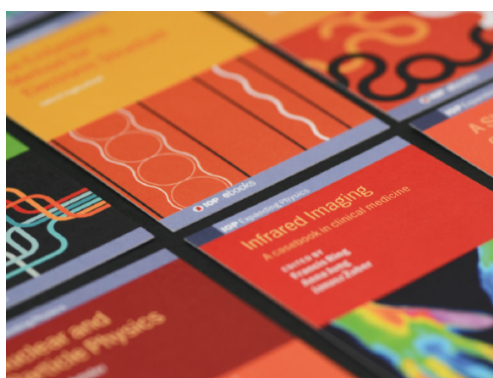


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Tool positioning device of a surgeon for the low-invasive surgery

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Abstract. The article considers the technical features of a digitizer which is to be used as a part of the system of intraoperative navigation. To reduce the costs for the manufacturing of a 3D-digitizer, we have shown the advantages of the special bench which provides the check of the values obtained by the shaft encoders used to record the positions of the manipulator depending on the actual dimensions of the basic elements of the device. The results of the mathematical experiment have shown that the calibration algorithm of the 3D-digitizer is fully functional and provides the opportunity to measure the actual dimensions of the basic elements of the device; to record the values of the shaft position encoder; to calibrate the values of the shaft position encoder taking into account the actual dimensions of the basic elements of the device.

1. Introduction

Nowadays due to the increase of the number of low-invasive surgery, there is a need for advanced technical tools which can be used in the endoscopy procedure. The main requirements which are specified for this equipment are informational support of the surgeon while preparing and carrying out low-invasive surgery [1], high fidelity for positioning of a surgical instrument [2, 3], opportunity to prepare and carry out the surgery in the existing procedure without significant changes of the methodology, etc. It is specially required to comply the obtained during the preoperative stage data about the patient with his real condition [4, 5, 6, 7].

In this regard we observe a raise of interest towards the tools used for measuring and control which are applied in other fields. One of them is a 3D-digitizer used in machinery production. This device provides three-dimensional digitizing of an investigated object and is in full compliance with the requirements to be used in surgery.

The major constraint for the direct use of the existing 3D-digitizer models in surgery is the necessity to refine their design to install them on the existing platforms used in surgery rooms (surgery tables, surgical consoles, carts, etc.) and change linear dimensions of the basic parts to comply with the location of the patient during the surgery.



2. Materials and methods

To solve the mentioned above tasks, we performed an experiment using a 3D-digitizer model installed on the track of the surgery table. The most “demanding” position of the patient is shown in figure 1.



Figure 1. Defining the basic dimensions of the construction using a 3D-digitizer model.

The experiment was performed with the help of the practitioner and it was found out that the most desirable construction of the 3D-digitizer must have an extension at least 1.5 m long. In this case the required accuracy for the tool positioning must be no more than 1 mm. Moreover, it is necessary to take into account the use of the basic surgery casing with the sticky edges which is necessary to protect the surgical equipment.

Taking into account all the specific features, we designed models of the surgery rooms shown in figure 2.

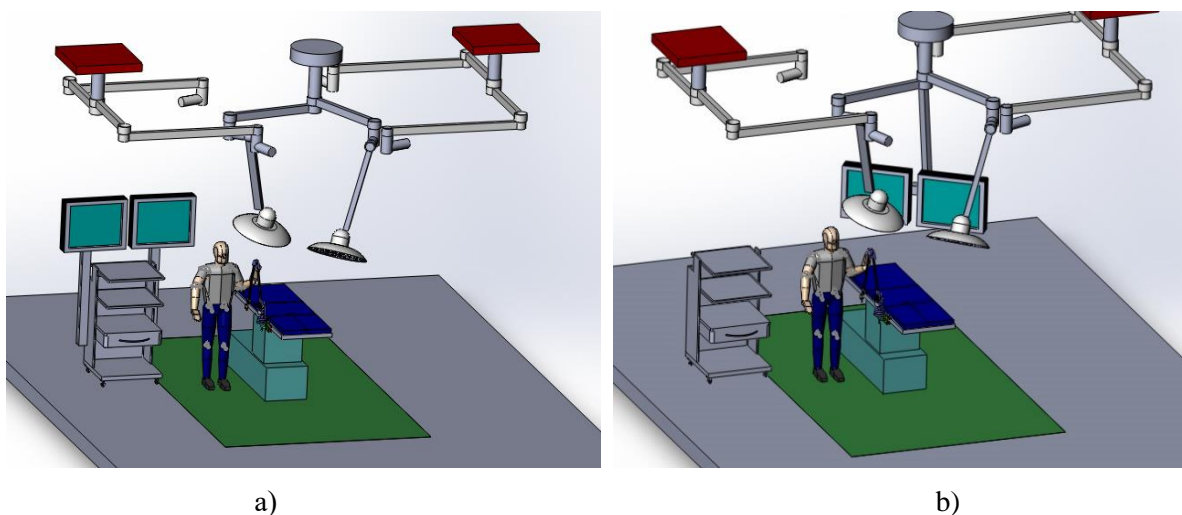


Figure 2. Model of the surgery room with the installed 3D-digitizer on the surgery table and with monitors set: a) on the medical stand and b) on the hanger.

To prepare the manufacturing of the 3D-digitizer, we designed its rotary joint, see figure 3. The base of the construction is made of levers 1 and 2 placed on the console. In the body of lever 2 there is a step motor 4 of SHD-86 (Step Motor – 86) type (a hybrid two-phase step motor with IP 65 produced by research and production company “Electroprivod”). This motor sets in motion the lock-out mechanism 3 of the levers movement relative to one another. The lock-out mechanism 3 locks or releases the wedge-shaped blade 5 in the spline groove of lever casing 1.

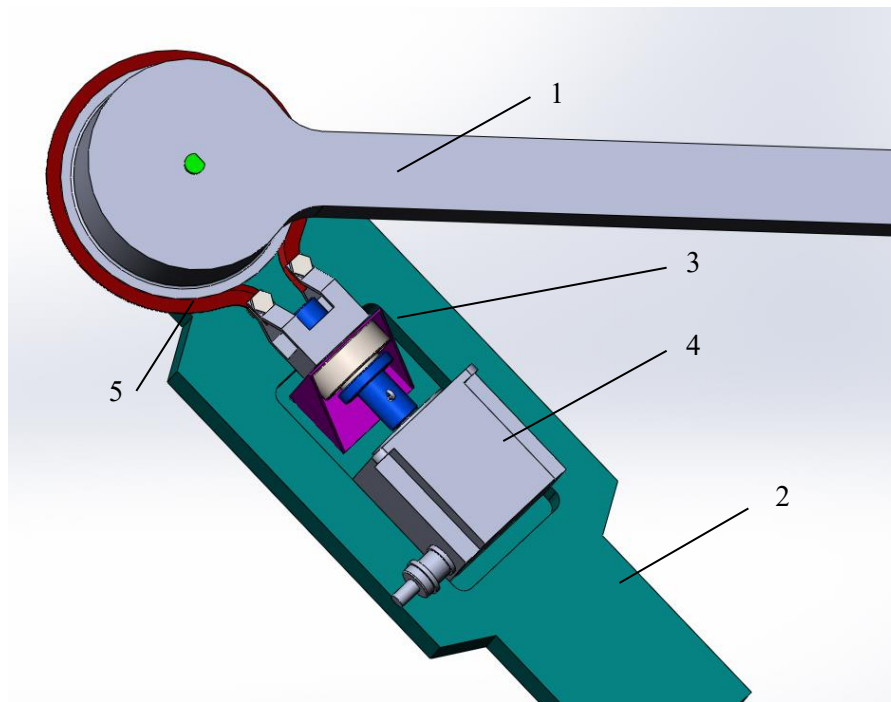


Figure 3. Layout of the rotary joint of a 3D-digitizer.

The layout of the rotary joint of 3D-digitizer with taken apart elements is given in figure 4. Fixed on the console levers 1 and 2 are interconnected with the help of bearings 3 and 4. A rotary encoder 6 (of E50S Series with the diameter $\varnothing 50\text{mm}$, Shaft type Incremental Rotary Encoder produced by Autonics) is fixed in lever 2 with screws 17 to provide data collection using the position of one lever in relation to the other. The shaft of the rotary encoder 6 is fixed in the lever casing 1 and provides the mechanical connection of the rotational position.

Step motor 4 is connected with the help of shaft 11 via shaft bearing 13 with lock-out mechanism 3 which blocks the movement of the levers relative to one another. There is an opening for spline 12 on the output shaft of step motor 4 to fix shaft 11. On the free end of shaft 11 there is a screw thread which is necessary for axial movement of lever lock-out mechanism 3.

Shaft bearing 13 gets the axial load and transfers it via mechanical stop 16 to lever casing 2.

Lock-out mechanism 3 of the movement of the levers relative to one another via bolted joint 15 locks and releases (depending on the direction of the output shaft rotation of step motor 4 wedge-shaped blade 5 in groove 18 of lever casing 1).

To provide the safety use of such a construction of a 3D-digitizer in medical institutions, open elements (step motor, lock-out mechanism, wedge-shaped blade) and the gap between the levers are covered with safety shells (as it is shown in the figures).

To calculate the position of the tool's probe it is necessary to calculate the coordinate of point E (see figure 5). To complete this task it is necessary to calculate the coordinates of the passing points which are in the joints between the levers (points B and C).

To perform calculation we use the formulae for calculation of the sides of a triangle and trigonometric functions. The point B coordinates are calculated in the following way:

$$x_B = d_1 \cdot \sin(\alpha_0);$$

$$y_B = d_1 \cdot \cos(\alpha_0);$$

$$z_B = l_1,$$

where x_B, y_B, z_B are coordinates of point B , d_1 is a shift between levers 1 and 2, l_1 is the lever 1 length.

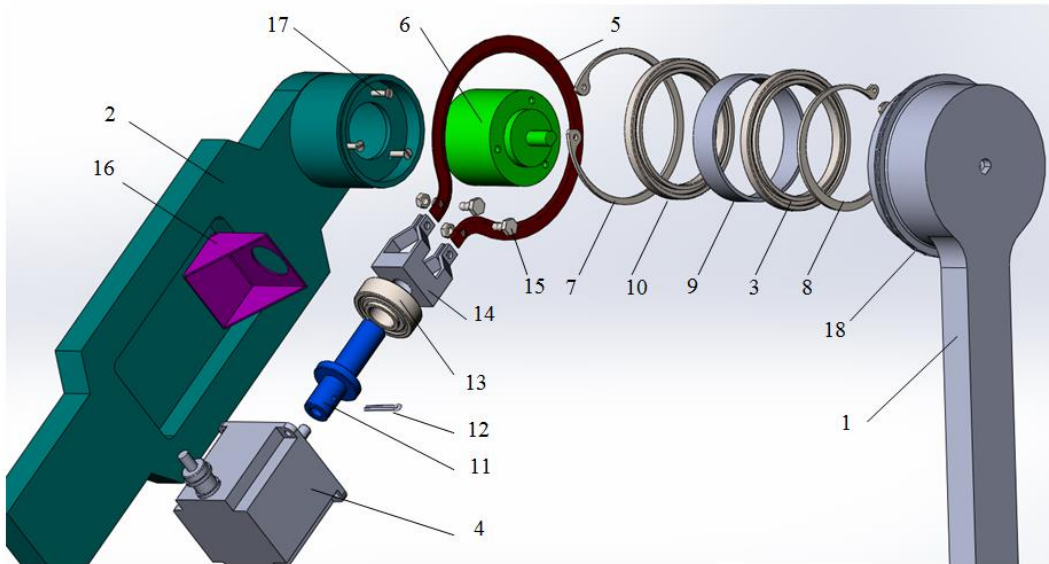


Figure 4. Layout of the rotary joint of a 3D-digitizer with taken apart elements.

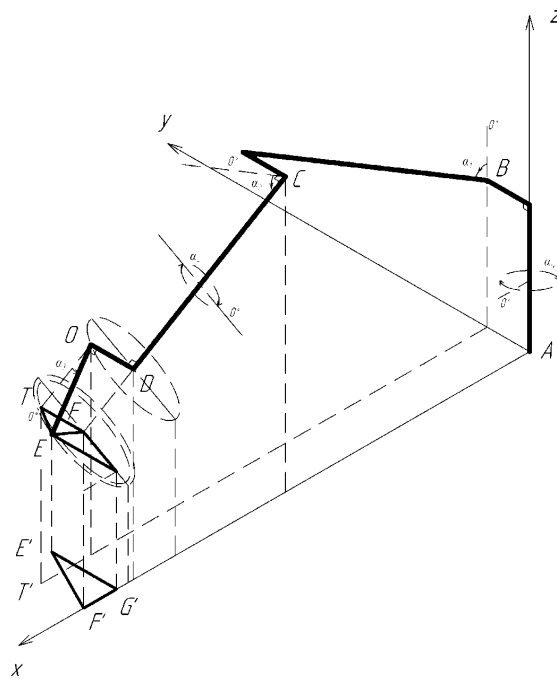


Figure 5. Calculation of the point of coordinates of digitizer’s tip.

To calculate the coordinates of point C , the following ratios should be used:

$$x_C = l_2 \cdot \sin(\alpha_1) \cdot \cos(\alpha_0) + (d_1 - d_2) \cdot \sin(\alpha_0);$$

$$y_C = l_2 \cdot \sin(\alpha_1) \cdot \sin(\alpha_0) + (d_1 - d_2) \cdot \cos(\alpha_0);$$

$$z_C = z_B + l_2 \cdot \cos(\alpha_1),$$

where x_C, y_C, z_C are coordinates of point C, d_2 is a shift between levers 2 and 3, l_2 is the lever 2 length.

The calculation of the coordinates of point D:

$$x_D = (l_2 \cdot \sin(\alpha_1) + l_3 \cdot \sin(180 - \alpha_1 - \alpha_2)) \cdot \cos(\alpha_0) + (d_1 - d_2) \cdot \sin(\alpha_0);$$

$$y_D = (l_2 \cdot \sin(\alpha_1) + l_3 \cdot \sin(180 - \alpha_1 - \alpha_2)) \cdot \sin(\alpha_0) + (d_1 - d_2) \cdot \cos(\alpha_0);$$

$$z_D = z_C + l_3 \cdot \cos(\alpha_1 + \alpha_2),$$

where x_D, y_D, z_D are coordinates of point D, d_2 is a shift between levers 2 and 3, l_3 the lever 3 length.

The calculation of the coordinates of point E:

$$x_E = x_D + l_4 \cdot \cos(\alpha_3) \cdot \cos(\alpha_0) + \sin\left(\alpha_4 - a \tan\left(\frac{l_4 \cdot \sin(\alpha_3)}{d_3}\right)\right) \cdot \cos(180 - \alpha_1 - \alpha_2) \times \\ \times \sqrt{d_3^2 + (l_4 \cdot \sin(\alpha_3))^2} \cdot \cos(\alpha_0) + \cos\left(\alpha_4 - a \tan\left(\frac{l_4 \cdot \sin(\alpha_3)}{d_3}\right)\right) \cdot \sqrt{d_3^2 + (l_4 \cdot \sin(\alpha_3))^2} \cdot \sin(\alpha_0);$$

$$y_E = y_D + l_4 \cdot \cos(\alpha_3) \cdot \sin(\alpha_0) + \sin\left(\alpha_4 - a \tan\left(\frac{l_4 \cdot \sin(\alpha_3)}{d_3}\right)\right) \cdot \cos(180 - \alpha_1 - \alpha_2) \times \\ \times \sqrt{d_3^2 + (l_4 \cdot \sin(\alpha_3))^2} \cdot \sin(\alpha_0) + \cos\left(\alpha_4 - a \tan\left(\frac{l_4 \cdot \sin(\alpha_3)}{d_3}\right)\right) \cdot \sqrt{d_3^2 + (l_4 \cdot \sin(\alpha_3))^2} \cdot \cos(\alpha_0);$$

$$z_E = z_D + \sqrt{d_3^2 + (l_4 \cdot \sin(\alpha_3))^2} \cdot \sin(\alpha_4) + a \tan\left(\frac{l_4 \cdot \sin(\alpha_3)}{d_3}\right) \cdot \sin(180 - \alpha_1 - \alpha_2)$$

where x_E, y_E, z_E are coordinates of point E, l_4 is the length of lever 4.

Let us assume that angle α_0 (the angle of the rotation of the device) is equal to zero. Then, it is necessary to take into account the coordinates of point D as well as the lengths of segments FE and OT to calculate the coordinates of point E. We can calculate the length of the segment OT through the hypotenuse (the length of lever 4) and angle α_3 . To calculate the length of the segment FE, we shall construct a triangle TEF in the base of the cone which is formed by the rotational motion of lever 4. Having triangle TEF, we can calculate the length of segment FE (the radius of the cone base) as a square root of sides TF (the circle radius formed by the rotation of lever OD) and TE (the projection of lever 4 onto the cone base). To construct the projection of segment FE on axes X and Y, we shall calculate the sides of the triangle GEF formed by segments FG (which is the part of the straight line located in the plane perpendicular to plane XOY) and EG (which is perpendicular to segment FG).

The option which has been offered has a significant drawback – when producing and assembling the components, accurate production of manipulator sections of the 3D-digitizer is required. To reduce the costs for the use of high-fidelity processing equipment while producing the elements of the 3D-digitizer, it is considered reasonable to use a calibration bench.

The main task of the bench is to correct the values of the free end of the manipulator of the 3D-digitizer according to the actual linear levers dimensions and readings of the rotary encoder.

The construction of the bench shown in figure 6 includes a table with a firmly fixed guide-track-and-stop. The 3D-digitizer’s manipulators levers are fixed in the control points (0; 1; 2; 3; 4 and 5) in the set order.

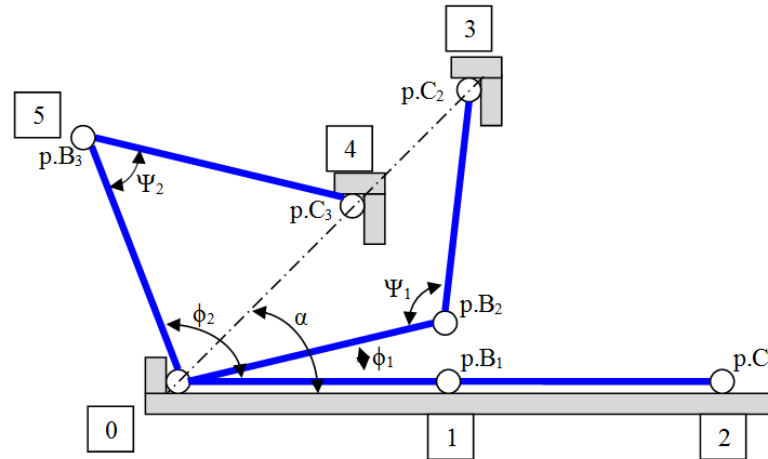


Figure 6. Calibration bench.

The calibration algorithm of the 3D-digitizer is the following:

- 1) Installation and fixing of the joint in point A into the guide-track-and-stop (0).
- 2) Setting levers of the 3D-digitizer manipulator along the guide-track-and-stop (0); (1) and (2). The values of the rotary encoders are fixed in points A and B. The obtained values are considered to be zero values.
- 3) Point C is fixed and moved into the guide-track-and-stop (3). It is shown in figure 1a as point c_2 . In this case the middle joint of the 3D-digitizer manipulator must be set into position B_2 . We measure and note down the values of angles ψ_1 and ϕ_1 .
- 4) Point C is fixed and moved into the guide-track-and-stop (4). It is shown in figure 1a as point c_3 . In this case the middle joint of the 3D-digitizer manipulator must be set into position B_3 . We measure and note down the values of angles ψ_2 and ϕ_2 .

Taking into account the deviation of angle coordinates of guide-track-and-stops (0), (3) and (4) from the axes of the joints in points A, B and C, it is necessary to make some changes in the calculations:

- distance 0A: $\sqrt{2\left(\frac{D_A}{2}\right)^2}$ or $D_A/\sqrt{2}$;
- distance C4 or C3: $\sqrt{2\left(\frac{D_C}{2}\right)^2}$ or $D_C/\sqrt{2}$.

Taking into account the changes, we get an equation to define lever AB of the 3D-digitizer manipulator using the coordinates of the angles of guide-track-and-stops (0), (3) and (4):

$$AB = \frac{\left(04 - (D_A + D_C)/\sqrt{2}\right)^2 - \left(03 - (D_A + D_C)/\sqrt{2}\right)^2}{2\left[\left(04 - (D_A + D_C)/\sqrt{2}\right) \cdot \cos(\phi_2 - \alpha) - \left(03 - (D_A + D_C)/\sqrt{2}\right) \cdot \cos(\alpha - \phi_1)\right]} \quad (1)$$

As a consequence, the length of the lever BC of the 3D-digitizer manipulator can be calculated using the following formula:

$$BC = \sqrt{AB^2 + (03 - (D_A + D_C)/\sqrt{2})^2 - 2 \cdot AB \cdot (03 - (D_A + D_C)/\sqrt{2}) \cdot \cos(\alpha - \varphi_1)} \quad (2)$$

Furthermore, during the calibration process we can check the accuracy of the values of the rotational movement of the joint in point B received with the help of the encoder: ψ_1 и ψ_2 :

– to position the free end of the 3D-digitizer in point C₃:

$$AC_3^2 = AB^2 + BC^2 - 2 \cdot AB \cdot BC \cdot \cos\psi_2, \\ \psi_2 = \arccos\left(\frac{AB^2 + BC^2 - (04 - (D_A + D_C)/\sqrt{2})^2}{2 \cdot AB \cdot BC}\right); \quad (3)$$

– to position the free end of the 3D-digitizer in point C₂:

$$AC_2^2 = AB^2 + BC^2 - 2 \cdot AB \cdot BC \cdot \cos\psi_1, \\ \psi_1 = \arccos\left(\frac{AB^2 + BC^2 - (03 - (D_A + D_C)/\sqrt{2})^2}{2 \cdot AB \cdot BC}\right). \quad (4)$$

3. Results and discussion

We have defined the following data as the basic ones for the research:

- diameter of the joints of the 3D-digitizer manipulator is 80 mm;
- lever AB: 750 mm;
- lever BC: 750 mm.

Taking into account the probability of deviation of the joint diameter obtained during the manufacturing or measuring processes, the resulted accuracy of the linear dimensions of the 3D-digitizer manipulator is shown in the table 1.

Table 1. The resulted accuracy of the linear dimensions of the 3D-digitizer manipulator, taking into account the probability of deviation of the joint diameter obtained during the manufacturing or measuring processes.

| Joint diameter, mm | AB, mm | BC, mm | Overhang length, mm | Deviation, mm | | |
|--------------------|----------|----------|---------------------|---------------|----------|---------------------|
| | | | | AB, mm | BC, mm | Overhang length, mm |
| 80,01 | 749,9937 | 749,9904 | 1499,984 | 0,006337 | 0,009592 | 0,015929 |
| 79,99 | 750,0063 | 750,0096 | 1500,016 | -0,00634 | -0,00959 | -0,01593 |

In the relative expression, the accuracy of measurement of linear dimensions of the 3D-digitizer manipulator is shown in the table 2.

Taking into account the possible change of the encoder values in points A (angles φ_1 and φ_2) and B (angles ψ_1 and ψ_2), we have defined the accuracy (%) of the positioning of the free end of the 3D-digitizer if the joint diameter value has a $\pm 0,01$ mm deviation obtained during the manufacturing or measuring processes.

Table 2. In the relative expression, the accuracy of measurement of linear dimensions of the 3D-digitizer manipulator.

| Joint diameter, <i>mm</i> | AB, <i>mm</i> | BC, <i>mm</i> | Overhang length, <i>mm</i> | Deviation, <i>mm</i> | | |
|---------------------------|---------------|---------------|----------------------------|----------------------|----------|--------------------|
| | | | | AB, % | BC, % | Overhang length, % |
| 80,01 | 749,9937 | 749,9904 | 1499,984 | 0,000845 | 0,001279 | 0,001062 |
| 79,99 | 750,0063 | 750,0096 | 1500,016 | -0,00084 | -0,00128 | -0,00106 |

Correlation of the accuracy of the positioning of the free end of the 3D-digitizer depending on the accuracy of the manufacturing and measuring of the joints and definition of the rotational position of the elements in the construction is shown in the figure 7.

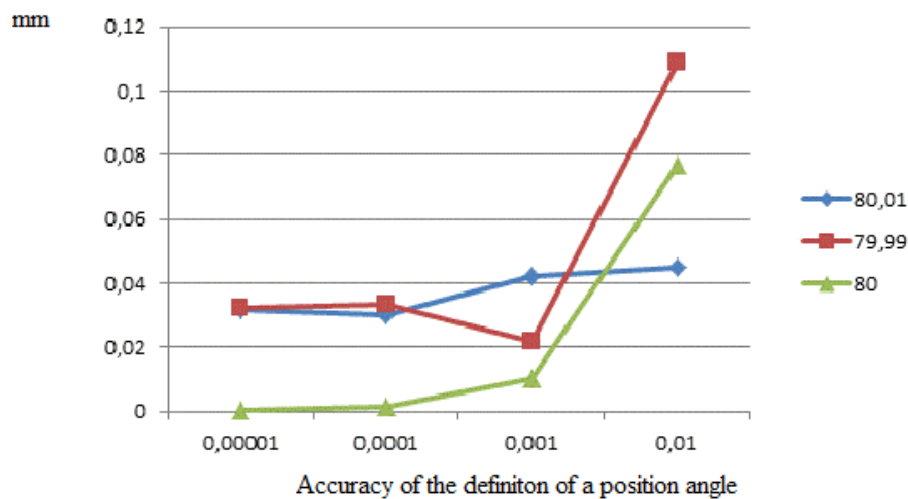


Figure 7. Correlation of the accuracy of the positioning of the free end of the 3D-digitizer depending on the accuracy of the manufacturing and measuring of the joints and definition of the rotational position of the elements in the construction.

If the accuracy of the rotary encoder values does not exceed 0.01 degree and the measuring and manufacturing of the joints have deviation values within ± 0.01 *mm*, we can assume that the design accuracy of the free end of the 3D-digitizer has the deviation within 0.045...0.11 *mm* which complies with the technical specifications.

4. Conclusion

The article considers the technical features of a digitizer which is to be used as a part of the system of intraoperative navigation.

To reduce the costs for the manufacturing of a 3D-digitizer, we have shown the advantages of the special bench which provides the check of the values obtained by the shaft encoders used to record the positions of the manipulator depending on the actual dimensions of the basic elements of the device.

The results of the mathematical experiment have shown that the calibration algorithm of the 3D-digitizer is fully functional and provides the opportunity to measure the actual dimensions of the basic elements of the device; to record the values of the shaft position encoder; to calibrate the values of the shaft position encoder taking into account the actual dimensions of the basic elements of the device.

The processing of the results of the mathematical experiment has shown that if the accuracy of the encoder values is within 0.01 degree and the accuracy of the measuring and manufacturing is within + 0.01 mm, the design accuracy of the free end position of the 3D-digitizer has the deviation within 0.045...0.11 mm which complies with the technical specifications.

Thus, the use of the calibration bench allows to reduce the costs for the high fidelity manufacturing of separate elements of the 3D-digitizer manipulator and perform the correction of the shaft position encoder values taking into account the actual length of the levers of the manipulator.

Acknowledgments

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