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ELLIPSOIDAL TONTOR STEP MODEL OF SENSORS FOR AUTOMATED MECHATRONIC SYSTEMS

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Modern medicine widely uses mechatronic modules in systems of various purposes, such as automated systems of diagnostics, scanning, irradiation. Recently, mechatronic modules in robotic surgical complexes are gaining importance. Thus, with the use of integrated sensors in mechatronic modules, executive manipulators of automated systems, positioning accuracy in defined spatial coordinates can be maintained. This data helps the medical staff to diagnose, monitor the patient's condition and make treatment decisions. The main purpose of sensor support in mechatronic systems is to ensure the accuracy and reliability of the system's functioning. Sensors must be sensitive and stable enough to provide measurements with high accuracy and respond to changes in real time. In addition, similar mechatronic modules are combined with sensors to create bionic limb prostheses, to restore human movement functions in various orthopedic diseases.

At the same time, the trajectory of the movement of the executive bodies of the mechatronic medical system, regardless of its purpose, during spatial transformations of searching for the coordinates of a real object, must be determined taking into account possible deformations.

Therefore, the accuracy of real-world displacement in space is determined by sensors that measure the parameters of physical objects. Thus, real transformations can be defined by spatial deviations that can be described using an ellipsoidal model. Accuracy, like the strength of the mechatronic module of a robot arm, is a variable value. They depend not only on the number of joints and the mobility of the hinges, but also on the position of the manipulators in space. At one point of coordinates, the module can apply more force than at another. The same is true for positioning accuracy, where the positioning error is greater at some points than at others. Therefore, an important actual problem in the creation of medical robotic systems is to determine the step-by-step movement of such a module in the workspace.

Therefore, the purpose of this work is to determine the ellipsoidal TONTOR step model of sensors for automated mechatronic systems, as the motion of the executive manipulators and sensors of the system during transformations from imaginary coordinate space to real space determines trajectory errors. Based on the existing opportunities analyzed in the work application of mechatronic modules in automated medical systems, relevant tasks related to maintaining the positioning accuracy of diagnostic manipulators and sensors are defined. The importance of sensory complexes in measuring various biological parameters that determine the patient's condition is noted. And this involves the application of models of spatial movement of the sensor in the working space of automated equipment, in particular, a robotic mechatronic complex.

In the work, it is proposed to use the TONTOR step model to increase the accuracy of the realization of the movement trajectory of the sensors of the mechatronic automated system. The results of creating an ellipsoidal model of the TONTOR step, which most accurately reflects the features of moving an object in space during transformations of the transition to real space, are given.

***Keywords**: TONTOR step; sensor; mechatronic systems; vector model; transformation; distance.*

Introduction

Modern medicine widely uses mechatronic modules in systems for various purposes. So, in this way, under the condition of using integrated sensors, automated diagnostic systems, scanning of human body organs, and robotic surgical complexes are created [1, 2].

Integrated sensors have found wide application, in particular in medical mechatronic systems. Integrated sensors are used to measure physiological parameters such as body temperature, pulse, blood pressure, blood oxygen level, and others. Thus, with the use of integrated sensors in mechatronic modules, executive manipulators of automated systems, positioning accuracy in defined spatial coordinates can be maintained.

This data helps the medical staff to diagnose, monitor the patient's condition and make treatment decisions. The main purpose of sensor support in mechatronic systems is to ensure the accuracy and reliability of the system's functioning [3 - 5]. Sensors must be sensitive and stable enough to provide measurements with high accuracy and respond to changes in real time.

In addition, similar mechatronic modules are combined with sensors to create bionic limb

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prostheses, to restore human movement functions in various orthopedic diseases [6].

In general, mechatronic modules and systems with executive bodies have wide applications in various industries where precise control of movement, performance of operations and manipulations is required [6 - 8]. They help to improve productivity, efficiency and quality of work in various spheres of life, contribute to automation and the development of new technologies.

At the same time, the trajectory of the movement of the executive bodies of the mechatronic medical system, regardless of its purpose, during spatial transformations of searching for the coordinates of a real object, must be determined taking into account possible deformations.

Therefore, the accuracy of real-world displacement in space is determined by sensors that measure the parameters of physical objects. Thus, real transformations can be defined by spatial deviations that can be described using an ellipsoidal model. In this case, we will rely on previous physical and mathematical models [9 - 11].

The most appropriate model for determining the spatial displacements of an object is the TONTOR step model [11].

Accuracy, like the strength of the mechatronic module of a robot arm, is a variable value. They depend not only on the number of joints and the mobility of the hinges, but also on the position of the manipulators in space [3].

At one point of coordinates, the module can apply more force than at another. The same is true for positioning accuracy, where the positioning error is greater at some points than at others. Therefore, an important actual problem in the creation of medical robotic systems is to determine the step-by-step movement of such a module in the workspace.

Therefore, the purpose of this work is to determine the ellipsoidal TONTOR step model of sensors for automated mechatronic systems, as the motion of the executive manipulators and sensors of the system during transformations from imaginary coordinate space to real space determines trajectory errors.

Ellipsoidal TONTOR step model at sensors

In our research [9, 10, 11], we determined the features of the transition from imaginary spatial coordinates to real ones when measuring the parameters of objects with integrated sensors, which is necessary for specifying the trajectories of movement of mechatronic modules.

Let's use the model created by the authors in the work [11]. In this case, the curvature of real vector [11, Fig. 2, p. 103] is determined by angles ψ_0 and ψ_1, which are only indirectly related by the torsion coefficient of space. Therefore, let's imagine the problem in a slightly different way. We will assume that distortions in space represent elliptical deformation. In the basics of this theses, situation is considered in [11], where it is shown that the deformation of one half of the step space during the movement of the mechanisms of equipment can be described by a parabolic law.

Thus, let's consider the previous drawing at [11, Fig. 2, p. 103] with the new coordinate system as in (Fig. 1) of this work. Of course, we have a number of simplifications here, but nevertheless the whole situation has a more visual character.

So, if we consider the sum of two parabolas, the branches of which to meet each other are directed, then as a result we get an ellipsoidal geometry of this figure.

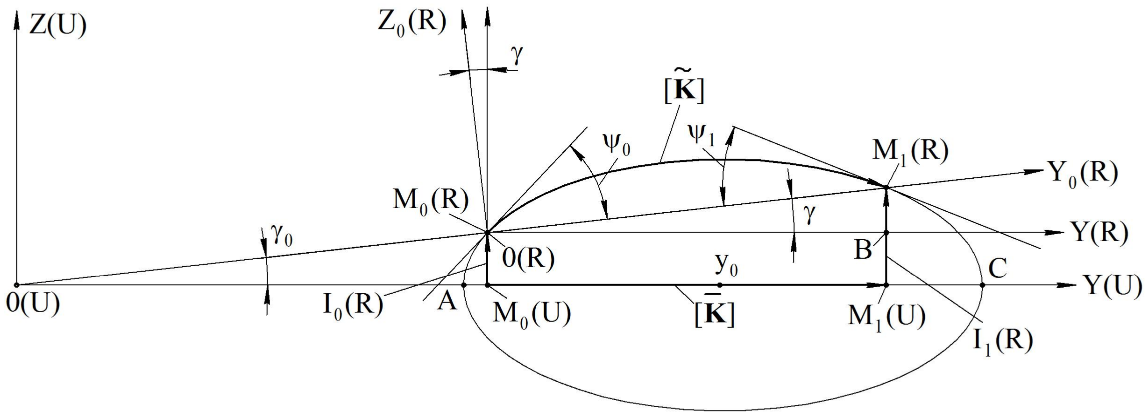

Fig. 1. Ellipsoidal model of TONTOR step

So, in a general form, we have an ellipse with a central focus, which is located on a plane $X(U), O(U), Y(U)$ at a distance y_0 from the origin of coordinates $O(U)$. Thus, its description in its current form will be as follows

$$\frac{(y-y_0)^2}{a^2}+\frac{z^2}{b^2}=1, \quad (1)$$

where *a, b* are the parameters, which defined in [12].

The size of vector $\left[\bar{\mathbf{K}}\right]$ will be on axis $\mathrm{O(U)\,Y(U)}$ between the $\mathrm{M_0(U)\,M_1(U)}$ points. Projection of this vector on to the curve of ellipse gives us a curvilinear vector $\left[\tilde{\mathbf{K}}\right]$ between the points $\mathrm{M_0(R)}$ and $\mathrm{M_1(R)}$ with the corresponding angles ψ_0 and ψ_1.

According to the problem we are solving, it is possible to accept the condition that the points $\mathrm{O(U)}$, $\mathrm{M_0(R)}$ and $\mathrm{M_1(R)}$ are on the same straight line. This line is at an angle γ relative to the imaginary coordinate plane $\mathrm{X(U), O(U), Y(U)}$.

We tie the local coordinate system [11, Fig. 2, p. 103] with its origin to a point $\mathrm{M_0(R)}$ and get a real coordinate system $\mathrm{X(R), O(R), Y(R)}$. Points of the vector $\left[\tilde{\mathbf{K}}\right]$ rest with their ends on the ends of the realization vectors $\mathbf{I}_0\mathrm{(R)}$ and $\mathbf{I}_1\mathrm{(R)}$.

So, in order to decide on the given task, we need to decide on the coordinates of the points $\mathrm{M_0(R)}$ and $\mathrm{M_1(R)}$, length of the vector $\left[\tilde{\mathbf{K}}\right]$, magnitude of the vectors $\mathbf{I}_0\mathrm{(R)}$ and $\mathbf{I}_1\mathrm{(R)}$. To begin with, let us consider the equation of a straight line $\mathrm{O(U)\ M_0(R)}$ in the form

$$z = tg\gamma \cdot y\ . \quad (2)$$

If we transform the equation of the ellipse (1) to the imaginary form, we get

$$z^2 = b^2\left(1-\frac{(y-y_0)^2}{a^2}\right). \quad (3)$$

By substituting z from equation (2) to equation (3), we have the opportunity to obtain the coordinates of the points $\mathrm{M_0(R)}$ and $\mathrm{M_1(R)}$

$$tg^2\gamma \cdot y^2 = b^2\left[1-\frac{(y-y_0)^2}{a^2}\right],$$

From here

$$\left(1+\frac{a^2}{b^2}\mathrm{tg}^2\,\gamma\right)\mathrm{y}^2-2y_0y+y_0^2-a^2=0\ . \quad (4)$$

Solving (4) with respect to y, we obtain the coordinates of the points $\mathrm{M_0}$ and $\mathrm{M_1}$, accordingly of the imaginary coordinate system.

So,

$$y\left(\mathrm{M_0}\right)=\frac{y_0-\sqrt{y_0^2-\left(1+\frac{a^2}{b^2}\mathrm{tg}^2\,\gamma\right)\left(\mathrm{y_0^2-a^2}\right)}}{1+\frac{a^2}{b^2}\mathrm{tg}^2\,\gamma} \quad (5)$$

$$y\left(\mathrm{M_1}\right)=\frac{y_0+\sqrt{y_0^2-\left(1+\frac{a^2}{b^2}\mathrm{tg}^2\,\gamma\right)\left(\mathrm{y_0^2-a^2}\right)}}{1+\frac{a^2}{b^2}\mathrm{tg}^2\,\gamma} \quad (6)$$

and on the z coordinate

$$\mathrm{z}\left(\mathrm{M_0}\right)=\mathrm{tg}\,\gamma\cdot y\left(\mathrm{M_0}\right)$$
$$\mathrm{z}\left(\mathrm{M_1}\right)=\mathrm{tg}\,\gamma\cdot y\left(\mathrm{M_1}\right) \quad (7)$$

The length of the $\left[\tilde{\mathbf{K}}\right]$ vector will be determined by a known equation $y\left(\mathrm{M_1}\right)$

$$\left[\tilde{\mathbf{K}}\right]=\int\limits_{y(M_0)}^{y(M_1)}\sqrt{1+[z'(y)]^2}\,dy\ , \quad (8)$$

where

$$z'(\mathrm{y})=\left[\frac{b}{a}\sqrt{a^2-\left(y-y_0\right)^2}\right]'= \\ =\frac{b}{a}\frac{(y-y_0)}{\sqrt{a^2-\left(y-y_0\right)^2}} \quad (9)$$

The integral (8) cannot be solved in the usual way, because it is a transcendental function. To do this, we expand the integrand into a series using Newton's binomial

$$\sqrt{1+[z'(y)]^2}=1+\frac{1}{2}[z'(y)]^2-\frac{1}{8}[z'(y)]^4+ \\ +\frac{1}{16}[z'(y)]^6-\ldots-\mathbf{[S]}\ . \quad (10)$$

To facilitate mathematical operations, let's ignore the last member of the series, considering it equal to **[S].**

Substituting (9) into (8) and using (10), we obtain the following result

$$\int\limits_{y(\mathrm{M_0})}^{y(\mathrm{M_1})}\sqrt{1+\frac{b}{a}\cdot\frac{(y-y_0)^2}{a^2-(y-y_0)^2}}dy= \\ =\int\limits_{y(\mathrm{M_0})}^{y(\mathrm{M_1})}dy+\frac{1}{2}\int\limits_{y(\mathrm{M_0})}^{y(\mathrm{M_1})}\frac{(y-y_0)^2\,dy}{a^2-(y-y_0)^2}+ \\ +\frac{1}{8}\int\limits_{y(\mathrm{M_0})}^{y(\mathrm{M_1})}\frac{(y-y_0)^4\,dy}{[a^2-(y-y_0)^2]^2}+\mathbf{[S]} \quad (11)$$

We solve each integral, separately using and the following equation (12)

$$\int\limits_{y(\mathrm{M_0})}^{y(\mathrm{M_1})}dy=y(\mathrm{M_1})-y(\mathrm{M_0})=\frac{y_0+\sqrt{y_0^2-\delta^2(\mathrm{y}_0^2-a^2)}}{\delta^2}- \\ -\frac{y_0-\sqrt{y_0^2-\delta^2(y_0^2-a^2)}}{\delta^2}=\frac{2}{\delta^2}\sqrt{y_0^2-\delta^2(y_0^2-a^2)} \quad (12)$$

where

$$\delta^2=1+\frac{a^2}{b^2}tg\gamma.$$

$$\frac{1}{2}\int_{y(M_0)}^{y(M_1)}\frac{(y-y_0)^2\,dy}{a^2-(y-y_0)^2}=\frac{1}{2}\left\{\frac{1}{2}\left[a^2-(y-y_0)^2\right]^2-\right.$$
$$\left.-2a\left[a^2-(y-y_0)^2\right]+a^2\ln\left|a^2-(y-y_0)^2\right|\right\}\Bigg|_{y(M_0)}^{y(M_1)}= \quad (13)$$
$$=\left(\frac{1}{4}u^2-au-\frac{a^2}{2}\ln|u|\right)\Bigg|_{y(M_0)}^{y(M_1)}$$

where $u=a^2-(y-y_0)^2$.

We define

$$\frac{1}{8}\int\frac{(y-y_0)^4\,dy}{\left[a^2-(y-y_0)^2\right]^2}=\frac{1}{8}\left\{\frac{\left[a^2-(y-y_0)^2\right]^3}{3}-\right.$$
$$-\frac{4a^2\left[a^2-(y-y_0)^2\right]^2}{2}+6a^2\left[a^2-(y-y_0)^2\right]- \quad (14)$$
$$\left.-4a^2\ln\left|a^2-(y-y_0)^2\right|-\frac{a^4}{a^2-(y-y_0)^2}\right\}.$$

After substituting the values from (12), (13) and (14) into (11), we obtain the following result

$$\left[\tilde{\mathbf{K}}\right]=\int_{y_1}^{y_2}\sqrt{1+[z'(y)]^2}\,dy=\frac{2}{\delta^2}\sqrt{y_0^2-\delta^2\left(y_0^2-a^2\right)}+$$
$$+\left[\frac{u^3}{24}-\frac{1}{4}u^2(1+a)+ua\left(1+\frac{6}{8a}\right)-\right. \quad (15)$$
$$\left.-\frac{1}{2}a^2(1-a)\ln|u|-\frac{a^4}{4}\right]+[\mathbf{S}],$$

given certain boundaries

$$y_1=\frac{y_0+\sqrt{y_0^2-\delta^2(y_0^2-a^2)}}{\delta^2};\; y_2=\frac{y_0-\sqrt{y_0^2-\delta^2(y_0^2-a^2)}}{\delta^2}.$$

The length of the chord M_0M_1 is defined as

$$\left[\bar{\mathbf{K}}\right]=L(M_0M_1)=$$
$$=\sqrt{\left[y(M_1)-y(M_0)\right]^2+\left[z(M_1)-z(M_0)\right]^2}.$$

Or, after a number after following transformations, using equations (5), (6), (7), we obtain

$$\left[\bar{\mathbf{K}}\right]=\frac{y_0^2-\left(1+\frac{a^2}{b^2}tg^2\gamma\right)\left(y_0^2-a^2\right)\sqrt{2\left(1-tg^2\gamma\right)^2}}{1+\frac{a^2}{b^2}tg^2\gamma}+$$
$$+[\mathbf{S}]$$

In order to determine the angles ψ_0 and ψ_1, we need to know the angles of inclination of the tangents at the points $M_0(R)$ and $M_1(R)$. Let's define these equations through the coordinates of the points. So, for a point $M_0(R)$ we have

$$\frac{y\cdot y(M_0)}{a^2}+\frac{z\cdot z(M_0)}{b^2}=1.$$

After the transformation, we get

$$z=\frac{b^2}{z(M_0)}\left[1-\frac{y\cdot y(M_0)}{a^2}\right] \quad (16)$$

Whence the derivative of the function (16), and therefore the tangent of the angle of inclination will be

$$z'=\frac{b^2}{a^2}\cdot\frac{y(M_0)}{z(M_0)}=\frac{b^2}{a^2}P_0,$$

where

$$P_0=\frac{y(M_0)}{z(M_0)}.$$

Similarly, we define the appropriate series of transformations for the $M_1(R)$ point

$$\frac{y\cdot y(M_1)}{a^2}+\frac{z\cdot z(M_1)}{b^2}=1$$
$$z=\frac{b^2}{z(M_1)}\left[1-\frac{y\cdot y(M_1)}{a^2}\right]$$
$$z'=\frac{b^2}{a^2}\cdot\frac{y(M_1)}{z(M_1)}=\frac{b^2}{a^2}P_1,$$

where

$$P_1=\frac{y(M_1)}{z(M_1)}.$$

Using the formula for determining the tangent of the angle of intersection of two straight lines on the plane and equation for the secant line [12], we find the corresponding angles ψ_0 and ψ_1.

So that will be it

- for ψ_0

$$\psi_0=arctg\frac{\frac{b^2}{a^2}P_0-tg\gamma}{1+\frac{b^2}{a^2}P_0tg\gamma}=arctg\frac{b^2P_0-a^2tg\gamma}{a^2+b^2P_0tg\gamma},$$

- for ψ_1

$$\psi_1=arctg\frac{\frac{b^2}{a^2}P_1-tg\gamma}{1+\frac{b^2}{a^2}P_1tg\gamma}=arctg\frac{b^2P_1-a^2tg\gamma}{a^2+b^2P_1tg\gamma}.$$

Finally, consider the radii of curvature, which directly relate to possible distortions. Thus, for both points we will have the following

$$R(M_0)=a^2b^2\left[\frac{y^2(M_0)}{a^4}+\frac{z^2(M_0)}{b^4}\right]^{3/2},$$

$$P(M_0)=a^2b^2\left[\frac{y^2(M_1)}{a^4}+\frac{z^2(M_1)}{b^4}\right]^{3/2}.$$

Now consider the realization vectors $\mathbf{I}_0(R)$ and $\mathbf{I}_1(R)$, which are in the error plane $P(x,y,z)=0$.

Since we have a direction of movement from the point $M_0(R)$ to $M_1(R)$, these vectors will be under the influence of deformation distortions. Thus, making the transition from the imaginary to the real, we always get distortions not less than the value of **[S].** So, according to the model of distortions that we are building, the $\mathbf{I}_0(R)$ vector cannot be smaller than **[S].** At the same time, the difference between the vectors $\mathbf{I}_0(R)$ and $\mathbf{I}_1(R)$ cannot be less than **[S].**

In fact, the values of these vectors are determined by the size of the angle γ and the geometric dimensions of the ellipse. If the angle γ is equivalent to the coefficient η (rotation of the space error), then the ratio of the semi-axes of the ellipse is the scaling factor (μ).

Since we considered the simplest case, the distortions are minimal, because this is the first stage of implementation. Under these conditions, for example, the duality changes from the dimensions $\mathbf{I}_0(R)$ to the value b (the semi-minor axis of the ellipse). However, this is the first distortion step that we encounter during the initial stage of obtaining the required step size of the sensor in the mechatronic system in space while performing medical manipulations. For the next stage of the displacement process of this defined object, the real coordinate system becomes imaginary relative to which its real system is developed.

At the same time, the angle γ (Fig. 1) can be both positive and negative depending on the type of process, that is, positive or negative.

In fact, the above is the analytical basis of the considered chain of processes of carrying out spatial movements in the mechatronic system working space from a vector point of view. Each subsequent spatial transition is accompanied by a new angle γ and ellipse in the coordinate y_0.

Conclusions

Based on the existing opportunities analyzed in the work application of mechatronic modules in automated medical systems, relevant tasks related to maintaining the positioning accuracy of diagnostic manipulators and sensors are defined.

The importance of sensory complexes in measuring various biological parameters that determine the patient's condition is noted. And this involves the application of models of spatial movement of the sensor in the working space of automated equipment, in particular, a robotic mechatronic complex.

In the work, it is proposed to use the TONTOR step model to increase the accuracy of the realization of sensors movement trajectory of the mechatronic automated system.

The results of creating an ellipsoidal model of the TONTOR step, which most accurately reflects the features of moving an object in space during transformations of the transition to real space, are given.

Further research in this direction involves the expansion of the proposed TONTOR step model in terms of additional parameters of the sensor movement trajectory during diagnostic and therapeutic manipulations by automated systems.

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ЕЛІПСОЇДНА МОДЕЛЬ КРОКУ ТОНТОР СЕНСОРІВ АВТОМАТИЗОВАНИХ МЕХАТРОННИХ СИСТЕМ

Сучасна медицина широко використовує мехатронні модулі в системах різного призначення, таких як автоматизовані системи діагностики, сканування, опромінення. Останнім часом все більшого значення набувають мехатронні модулі в роботизованих хірургічних комплексах.
Таким чином, за допомогою інтегрованих датчиків у мехатронних модулях, виконавчих маніпуляторах автоматизованих систем, можна підтримувати точність позиціонування в заданих просторових координатах. Ці дані допомагають медичному персоналу визначити діагноз, контролювати стан пацієнта і прийняти рішення щодо лікування. Основним призначенням сенсорної підтримки в мехатронних системах є забезпечення точності та надійності функціонування системи. Датчики мають бути достатньо чутливими та стабільними, щоб забезпечувати вимірювання з високою точністю та реагувати на зміни в реальному часі.
Крім того, подібні мехатронні модулі поєднуються з датчиками для створення біонічних протезів кінцівок, відновлення рухових функцій людини при різних ортопедичних захворюваннях.
Водночас, траєкторія руху виконавчих органів мехатронної медичної системи, незалежно від її призначення, при просторових перетвореннях пошуку координат реального об'єкта повинна визначатися з урахуванням можливих деформацій.
Тому точність реального переміщення в просторі визначається датчиками, які вимірюють параметри фізичних об'єктів. Таким чином, реальні перетворення можуть бути визначені просторовими відхиленнями, які можна описати за допомогою еліпсоїдальної моделі. Точність, як і міцність мехатронних модулів руки робота, є величиною змінною. Вони залежать не тільки від кількості шарнірів та їх рухливості, але й від положення маніпуляторів у просторі.
В одній точці координат модуль може прикладати більше сили, ніж в іншій. Те саме стосується точності позиціонування, коли помилка позиціонування в одних точках більша, ніж в інших. Тому важливою актуальною проблемою при створенні медичних роботизованих систем є визначення покрокового руху такого модуля в робочому просторі.
Тому метою даної роботи є визначення еліпсоїдальної моделі ТОНТОР кроку сенсорів для автоматизованих мехатронних систем, оскільки рух виконавчих маніпуляторів і сенсорів системи під час перетворень з уявного координатного простору в реальний простір визначає похибки траєкторії.
На основі проаналізованих наявних можливостей у роботі застосування мехатронних модулів в автоматизованих медичних системах визначено актуальні завдання, пов'язані з підтримкою точності позиціонування діагностичних маніпуляторів і датчиків. Відзначено важливість сенсорних комплексів у вимірюванні різних біологічних параметрів, що визначають стан пацієнта. А це передбачає застосування моделей просторового переміщення датчика в робочому просторі автоматизованого обладнання, зокрема роботизованого мехатронного комплексу.
У роботі запропоновано використовувати модель кроку ТОНТОР для підвищення точності реалізації траєкторії руху датчиків мехатронної автоматизованої системи. Наведено результати створення еліпсоїдальної моделі кроку ТОНТОР, яка найбільш точно відображає особливості переміщення об'єкта в просторі під час трансформацій переходу в реальний простір.

Ключові слова: крок ТОНТОР; датчик; мехатронні системи; векторна модель; перетворення; відстань.

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