Cable-driven parallel robot (CDPR) has the great potential for various applications in industry and in everyday life. They consist of an end effector and a base, which connected by several cables. CDPRs have a large workspace compared to the workspace of classic parallel robots. CDPR have a simpler structure have good dynamic properties, high carrying capacity, mobility and low cost. The only drawback is that the CDPR cables can only work for retraction and cannot push. This article presents the design of a prototype of a planar CDPR with four cables for practical use in the educational process. This prototype of a planar CDPR is necessary for a better understanding of the design features, structure, kinematics, statics and dynamics of the CDPR by students. The planar CDPR performs two translational motions, due to the controlled 4 cables, and one rotational motion of the end effector. The research of the kinematics and statics of the planar cable-driven parallel robot is carried out. Simulation of the motion of a planar cable-driven parallel robot in the Python programming language has been carried out. A design was developed and a prototype of the planar cable-driven parallel robot was manufactured. Experimental researches of a prototype of the planar cable-driven parallel robot have been carried out. The results of experimental researches have shown that the CDPR works well enough. During the tests of the prototype of the planar cable-driven parallel robot, it was found that the distortions of the trajectory of the end effector depend on the tension of the cables. It is necessary to monitor the tension level using strain gauges. Based on the analysis of the results obtained, the effectiveness of the use of the prototype of a planar CDPR in the educational process of the robotics course has been confirmed

Keywords: cable-driven parallel robot, planar, design, kinematics, statics, tension, end effector, prototype, control, encoder

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DEVELOPMENT OF A PLANAR CABLE PARALLEL ROBOT FOR PRACTICAL APPLICATION IN THE EDUCATIONAL PROCESS

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1. Introduction

Cable-driven parallel robots (CDPR) are a type of parallel robot, in which the link of the working body is supported in parallel by m cables with n drives. Unlike classic parallel robots, cable-driven parallel robots are powered by flexible cables.

CDPR in comparison with conventional parallel robots have lower inertial characteristics, which provides high speeds and acceleration of the working body. Due to the flexibility of the cables, CDPR can be used to solve complex tasks with a large workspace. However, the use of CDPR in existing production workshops and closed storage facilities is limited, which is caused by a sharp increase in the tension forces of the cables with an increase in the lifting height of the load. A feature of CDPR is that their flexible links can only work in positive tension, and lose their performance when compressed. This feature severely limits the development and use of CDPR and requires further development of the development of new structural schemes.

Due to the fact that CDPRs are relatively new robots that fundamentally differ from classical parallel robots, problems arose in teaching students. Studies have shown that the presentation and video of the structures and operation of existing CDPRs is not enough to understand the features of their structure, kinematics, statics and control systems. Here it turned out that lecturing and showing video of the work of existing CDPRs is not enough for students to acquire sufficient competence. Planar cable-driven parallel robots are a new type of parallel robots, and its research is currently relevant in the world. The research of the structure, kinematics and statics of the CDPR in order to create a prototype of a planar CDPR, simple in design, with a convenient control algorithm and with the possibility of practical application in the educational process are relevant.

2. Literature review and problem statement

One of the first CDPR was the Robocrane, developed in 1989 in the United States by the National Institute of Standards and Technology (NIST), for use in cargo handling in ports, bridge construction and other areas [1, 2]. The CDPR Robocrane is a six-cable-suspended Stewart platform with six degrees of freedom. Here, cables are used instead of hydraulic cylinders, and gravity is an implicit auxiliary drive.

A typical CDPR consists of three parts, including a fixed platform, a mobile platform, and multiple cables that are used to connect the fixed platform to the mobile platform

CDPR [3]. The length of the cable can be changed by means of winches driven by motors mounted on a fixed platform as shown in Fig. 1 [4, 5].

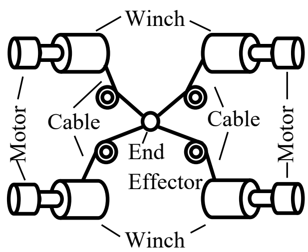

Fig. 1. Scheme of CDPR with $m=4$ cables

CDPR is an under-constrained, when the position and orientation of the end effector of CDPR is determined only by its gravity. In the case when the position and orientation of the end effector are completely determined by the lengths of the cables, the CDPR is fully-constrained or redundantly constrained. CDPR with n degrees of freedom and controlled by m cables can be classified into three types [6]:

– CDPR with the under-constrained $n+1>m$;

– CDPR with the fully-constrained $n+1=m$;

– CDPR with redundantly constrained $n+1<m$.

For fully-constrained or redundantly constrained CDPR, the position and orientation of the end effector depends only on kinematics and statics.

The work [7] presents the results of researches of the architecture of new parallel robots with a cable drive, using cable loops to improve accuracy. First, the winch system is replaced by a cable loop driven by a slider: the movement of the implement can be controlled by the movement of the slider. The disadvantage of this architecture is that the mechanism works with redundancy. In addition, to eliminate redundancy, additional springs are introduced, which complicates the design of the CDPR as a whole. In [8], the results of researches of CDPRs with a simpler structure are presented than in [7]. The paper proposes theorems characterizing the poses of the wrench-closure workspace. These theorems are then used to reveal the parts of the reachable workspace that belong to wrench-closure workspace. Finally, an efficient algorithm is presented that determines the achievable workspace for the subsequent synthesis of CDPRs. In work [9], a method of optimal dimensional synthesis of CDPR is proposed, namely, the search for the geometry of a planar CDPR with a given workspace. The disadvantage of this work is the lack of accounting for the CDPRs control system. The work [10] presents the design and kinematic characteristics of an inexpensive, planar CDPR with 4 controllable cables. An easy algorithm for programming its work is proposed. A prototype was built and tests confirmed the feasibility of the system design and operation. The disadvantage of this work is the lack of detailed test results of the prototype of the planar CDPR. In work [11], the design and kinematic analysis of the CDPR with four cables was carried out. CDPR performs a plane motion, including two translational and one rotational motion. Experimental tests on the implemented prototype have shown the performance of the CDPR. The disadvantage of this work is the lack of a CDPR control system. These shortcomings of work [11] are eliminated in work [12], here a simple and convenient algorithm is proposed for controlling a planar CDPR. The works [11–14] show the development of prototypes of planar CDPR. The disadvantages of these works are the complexity of the application of methods for the design of planar CDPR. There is no clear algorithm for development prototypes of planar CDPR. The work [15] considers the application of robotics in the practice of higher education from the point of view of both teachers and students. In [16], a robot prototype and a module for STEM programs were developed by interviewing STEM teachers in schools in Malaysia. The main aim of this research is to develop an inexpensive robot prototype and module to increase interest of Malaysian students in STEM based on the Malaysian school curriculum. The work [17] presents the application of the prototype of the mobile robot «Robotino» on various examples in education. Some examples are shown here: studying the components, structure and modeling of mechatronic systems, studying automatic control, studying the collection, processing and application of data from different sensors, programming in different programming tools, studying methods of image processing and object detection.

An analysis of the literature shows that the development and research of parallel cable robots is receiving a lot of attention in the world. A large number of works are devoted to the practical designs of CDPRs and their use in various fields of industry. In this regard, let's believe that it is expedient to continue the development of a planar CDPR with a simple design and a convenient control algorithm with the possibility of practical application in the educational process.

3. The aim and objectives of the study

The aim of this article is to develop an inexpensive prototype of a planar CDPR for practical use in the educational process.

To achieve the aim, the following tasks were set:

– kinematic and static analysis of a planar CDPR;

– development of a control system for the motion of a planar CDPR;

– build of the prototype planar CDPR;

– experimental research of the prototype planar CDPR.

4. Materials and methods

The study used the methods for solving problems of the theory of mechanisms and machines and numerical methods.

CDPRs are relatively new types of parallel robots. The main difference from conventional parallel robots is the replacement of their rigid links with flexible ones (cables). A feature of the CDPRs is that their flexible links can only work in tension, and lose their performance when compressed. This feature severely limits the students' understanding of the structure, structure, kinematics, statics and dynamics of the CDPR. Here it turned out that lecturing and showing video of the work of existing CDPRs is not enough for students to acquire sufficient competence. The development of a planar CDPR for practical use in the educational process is currently relevant due to the fact that working with a prototype of a planar CDPR, students study its structure, kinematics, statics and control and gain real practical knowledge in the field of robotics.

To develop a prototype of a planar CDPR, for practical use in the educational process, it is necessary to select the CDPR structure, conduct a kinematic and static study of a planar CDPR, which performs only translational motion, and only the end effector of the working body has rotational motion. The next stage consists in the development and manufacture of a prototype of a planar CDPR. Carrying out tests of planar

CDPR under various operating modes and analyzing the results obtained. Based on the analysis of the results obtained, consider the possibilities of the practical application of a planar CDPR in the educational process of the robotics course.

To select the structure of a planar CDPR, let's use the method proposed in [6]. Fig. 2 shows the kinematic scheme of the chosen structure of a planar CDPR consisting of a working body with an end effector, which is connected in parallel with 4 cables with a fixed frame, the cables are controlled by 4 actuators. Here, only the translational motion of the planar CDPR is considered, and only the end effector has rotational motion. The planar CDPR scheme shown in Fig. 3 has a torque-free configuration around the Z-axis at the attachment point of the end effector implement pivot. A planar CDPR has $m=3$ degrees of freedom, and $n=4$ controllable cables. Then, according to the formula [6] $n+1<m$. CDPR has 2 redundant constrains, and the forces must be distributed between the cables. This CDPR has only one solution to the inverse kinematic problem. The redundancy of the CDPR refers to the number of kinematic constraints and therefore static forces are usually not unambiguously determined.

To solve the direct and inverse kinematic analysis of the translational motion of the plane CDPR, let's use the geometric method. The solution of the inverse kinematic task is necessary to control the planar CDPR. Direct kinematics is necessary to simulate the motion and control the planar CDPR using sensors. The CDPR cables are attached at one end to the fixed frame and at the other end to the hinge of the end effector. The CDPR cables are in a taut position. Under the assumption that all cables, in any position, are always in a taut state, the kinematics of the CDPR is similar to the kinematics of parallel robots with one-sided constraints.

Fig. 2 shows a kinematic scheme of a planar CDPR, where the following are indicated: x, y – coordinates of the point of the CDPR end effector; L_i – length of the i-th cable; θ_i – angles of inclination of the i-th cable, A_i – points of attachment of the i-th cable to a fixed square frame with side L_B.

To solve the inverse kinematic task, it is necessary to determine the lengths of the i-th cables L_i relative to the attachment points $\boldsymbol{A}_i=\{A_{ix}\,A_{iy}\}^T$, for the given coordinates of the point of the end effector of the CDPR $\boldsymbol{X}=\{x\,y\}^T$, from Fig. 2 there is:

$$L_i=\sqrt{\left(x-A_{ix}\right)^2+\left(y-A_{iy}\right)^2}\;i=1\ldots,4. \tag{1}$$

The angles θ_i are determined:

$$\theta_i=\tan^{-1}\left(\frac{y-A_{iy}}{x-A_{ix}}\right)i=1\ldots,4\;. \tag{2}$$

To solve the direct kinematics of a planar CDPR, it is necessary to determine the coordinates $\boldsymbol{X}=\{x\,y\}^T$ of the CDPR end effector, for the given cable lengths L_i. Consider cables 1 and 2 (Fig. 2) with the coordinates of the attachment points to the fixed frame $\boldsymbol{A}_1=\{0\;0\}^T$ and $\boldsymbol{A}_2=\{L_B\;0\}^T$.

Then the direct kinematics of the planar CDPR is solved as the intersection of two circles [12], one centered at point $\boldsymbol{A}_1$ with radius L_1 and the other centered at $\boldsymbol{A}_2$ with radius L_2. Let's solve the equation of intersection of two circles and get the following result:

$$x=\frac{L_B^2+L_1^2-L_2^2}{2L_B},\;\;y=\pm\sqrt{L_1^2-x^2}. \tag{3}$$

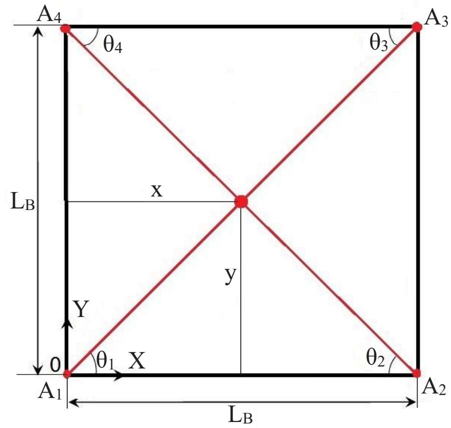

Fig. 2. Kinematic scheme of a planar CDPR

Here, a positive solution for y in (3) is chosen to ensure that the solution of the direct kinematics lies within the fixed frame. After solving (3), it is possible to determine the lengths of 3 and 4 cables from (1), to control the correctness of the obtained solution.

To determine the velocity of the cables, consider the equations of the closeness of the i-th cable [12]:

$$\{x\,y\}^T=\left\{A_{ix}+L_i\cos(\theta_i)\;\;A_{iy}+L_i\sin(\theta_i)\right\},\;i=1,\ldots,n. \tag{4}$$

Differentiate (4) by time:

$$\begin{Bmatrix}\dot{x}\\ \dot{y}\end{Bmatrix}=\begin{bmatrix}\cos(\theta_i) & -L_i\sin(\theta_i)\\ \sin(\theta_i) & L_i\cos(\theta_i)\end{bmatrix}\begin{Bmatrix}\dot{L}_i\\ \dot{\theta}_i\end{Bmatrix},\;i=1,\ldots,4. \tag{5}$$

Invert in (5) the Jacobi matrix of i-cables:

$$\begin{Bmatrix}\dot{L}\\ \dot{\theta}_i\end{Bmatrix}=\begin{bmatrix}\cos(\theta_i) & \sin(\theta_i)\\ \dfrac{-\sin(\theta_i)}{L_i} & \dfrac{\cos(\theta_i)}{L_i}\end{bmatrix}\begin{Bmatrix}\dot{x}\\ \dot{y}\end{Bmatrix},\;i=1,\ldots,4. \tag{6}$$

To determine the velocity of the cables, from the first line (6) let's obtain:

$$\begin{Bmatrix}\dot{L}_1\\ \dot{L}_2\\ \dot{L}_3\\ \dot{L}_4\end{Bmatrix}=\begin{bmatrix}\cos(\theta_1) & \sin(\theta_1)\\ \cos(\theta_2) & \sin(\theta_2)\\ \cos(\theta_3) & \sin(\theta_3)\\ \cos(\theta_4) & \sin(\theta_4)\end{bmatrix}\begin{Bmatrix}\dot{x}\\ \dot{y}\end{Bmatrix}. \tag{7}$$

In general form (7) can be written as:

$$\dot{\boldsymbol{L}}=\boldsymbol{M}\dot{X}, \tag{8}$$

where $\dot{\boldsymbol{L}}$ is the velocity vector of the cables, M is the inverse Jacobi matrix of the CDPR, and $\dot{X}=\{\dot{x}\dot{y}\}^T$ is the vector of the velocity of the end effector of the CDPR.

The inverse task of determining the CDPR velocity, result (7), is solved directly, here the inversion was performed symbolically from (5) to (6) with little calculations and there is no singularity problem. However, in order to solve the direct problem of determining the CDPR velocity, it is necessary to invert (8):

$$\dot{\boldsymbol{X}}=\boldsymbol{M}^{-1}\dot{\boldsymbol{L}}.$$

Due to redundant constraints, M is not a square matrix, but has a size of $n\times2$ for the plane case; therefore, it is not possible to invert M, but there are two options for solving the direct task of determining the velocity [12]:

1) choose only two cables to obtain a reduced square inverse Jacobi matrix. For example, as in the case of solving the direct problem, choose cables 1 and 2. Then the direct solution to the problem of determining the velocity of the CDPR with 4 cables will be:

$$\dot{\boldsymbol{X}} = \boldsymbol{M}_{12}^{-1} \cdot \dot{\boldsymbol{L}}_{12},$$

where $\boldsymbol{M}_{12}$ is the matrix $\boldsymbol{M}$ with rows 3,4 removed, and $\dot{\boldsymbol{L}}_{12}$ is the velocity vector 1 and 2 of the cable. After determining the velocity, it is necessary to verify that the input data $\dot{\boldsymbol{L}}$ was correct by evaluating the ignored rows by equation (8);

2) an alternative approach to the direct problem of determining the velocity of the CDPR is to use the limited Moore-Penrose pseudo-inversion [12]:

$$\dot{\boldsymbol{X}} = \boldsymbol{M}^{\#} \cdot \dot{\boldsymbol{L}},$$

where

$$\boldsymbol{M}^{\#} = \left(\boldsymbol{M}^{T}\boldsymbol{M}\dot{\boldsymbol{L}}\right)^{-1} \cdot \boldsymbol{M}^{T},$$

when using any of the approaches, the solution to the direct task of determining the velocity is subject to singularities. The singularity conditions are derived from the determinants of four possible square 2×2 submatrices of the matrix $\boldsymbol{M}$:

$$\begin{aligned} &\sin(\theta_2-\theta_1)=0 \quad \theta_2-\theta_1=0,\pi,\\ &\sin(\theta_3-\theta_2)=0 \quad \theta_3-\theta_2=0,\pi,\\ &\sin(\theta_4-\theta_3)=0 \quad \theta_4-\theta_3=0,\pi,\\ &\sin(\theta_1-\theta_4)=0 \quad \theta_1-\theta_4=0,\pi. \end{aligned} \qquad (9)$$

Singularities arise when two cables are in one straight line; this is only possible at the edge of the theoretical kinematic workspace, that is, at the edges of the fixed frame. (9) gives the singularities of the planar CDPR with 4 cables.

To simulate the statics of the CDPR, let's use the equilibrium equations. A workspace in which all cables are under positive tension, with all possible forces applied in Cartesian coordinates, is called a static workspace. For static equilibrium, the sum of the forces applied by the cables to the moving point should be equal to the resulting external forces acting on the end effector of the CDPR.

Fig. 3 shows a scheme of the forces acting at the point of the end effector of the CDPR [12].

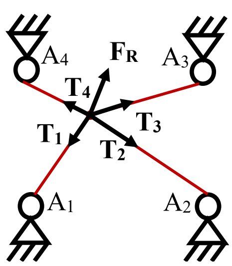

Fig. 3. A scheme of the forces acting at the point of the end effector of the CDPR

Statics equations:

$$-\sum_{i=1}^{4} T_i \hat{\boldsymbol{L}}_i = \boldsymbol{F}_R. \qquad (10)$$

Here, gravity is ignored because it is assumed to be perpendicular to the plane of the CDPR. In (10) T_i – the tension of the i-th cable, (opposite to the direction of the unit length of the cable) $\hat{\boldsymbol{L}}_i=\{\cos\theta_i \sin\theta_i\}^T$, $\boldsymbol{F}_R=\{f_x\, f_y\}^T$ – the resulting vector force of external forces acting on the end effector of the CDPR. Let's write (10) in the form:

$$\boldsymbol{ST} = \boldsymbol{F}_R,$$

where

$$\boldsymbol{S} = \left[-\hat{\boldsymbol{L}}_1 \ldots -\hat{\boldsymbol{L}}_4\right],$$

$\boldsymbol{S}$ is a static Jacobi matrix of 2×n size, and $\boldsymbol{T}=\{T_1 \ldots T_4\}^T$ is the vector of scalar tensions of the cables T_i.

For planar CDPR with 4 cables:

$$\begin{bmatrix} -\cos\theta_1 & -\cos\theta_2 & -\cos\theta_3 & -\cos\theta_4 \\ -\sin\theta_1 & -\sin\theta_2 & -\sin\theta_3 & -\sin\theta_4 \end{bmatrix} \begin{Bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{Bmatrix} = \begin{Bmatrix} f_x \\ f_y \end{Bmatrix}. \qquad (11)$$

There is a special duality between force and velocity: the corresponding Jacobi matrices are related by the relation from (7) and (11) $S=-M^T$.

The kinematic and static calculation of the planar CDPR was carried out in the Python programming language. To develop the system configuration of the prototype of a planar CDPR, let's use the method proposed in [11]. To develop a control system for a planar CDPR, let's use the method proposed in [12]. Testing a prototype of a planar CDPR will be carried out by drawing a circle with the end effector of the CDPR. Next, a check will be carried out for the coincidence of the trajectory drawn by the end effector of the CDPR with the circle.

5. Results of researching the planar cable-driven parallel robot

5. 1. Kinematic and static analysis of a planar CDPR

To simulate the motion of a planar CDPR, let's take the dimensions of the side of the square of the fixed frame L_B=1000 mm. The end effector of the planar CDPR $\boldsymbol{X}=\{x\, y\}^T$ makes a circular motion under the action of a constant external force $\boldsymbol{F}_R=\{1\, 1\}^T$. The calculations of the planar CDPR model were carried out in the Python programming language [18] for two types of trajectory of the end effector – circle and four-petal flower:

1) The trajectory of motion of the end effector of a planar CDPR in the form of a circle is shown in Fig. 4 and is described by the equations:

$$\begin{cases} x = 200\cos 0.5\pi t, \\ y = 200\sin 0.5\pi t, \\ 0 \le t \le 6. \end{cases}$$

The calculation of the change in the lengths of the cables L_i, i=1,...,4 by the (1), for the trajectory of the end effector of the planar CDPR in the form of a circle, in Fig. 5 shows their graphs.

A static analysis of the planar CDPR was carried out according to (11), with a constant external force $\boldsymbol{F}_R=\{1\, 1\}^T$. Calculations have shown that with such a force, let's obtain that the tension of cables 3, 4 is zero, and cables 1 and 2 have non-zero tension. In Fig. 6 shows the tensions in the cables for the trajectory of the end effector of a planar CDPR in the form of a circle.

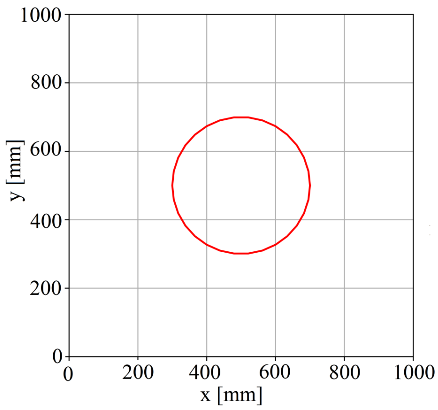

Fig. 4. The trajectory of motion of the end effector of a planar CDPR in the form of a circle

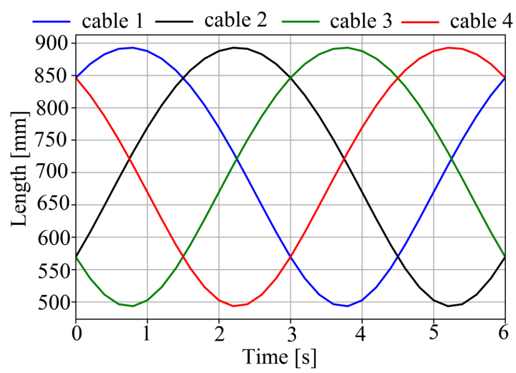

Fig. 5. The graph of the change in the lengths of the cables L_i, $i=1,..,4$

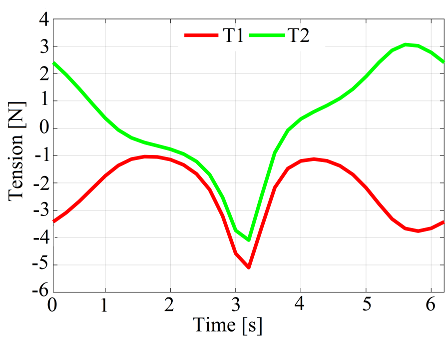

Fig. 6. Tensions in the cables for the trajectory of the end effector of a planar CDPR in the form of a circle

2) The trajectory of motion of the end effector of a planar CDPR in the form of a four-petal flower is shown in Fig. 7 and is described by the equations:

$$\begin{cases} x = 50 + 20\sin(2t)\cos(t), \\ y = 50 + 20\sin(2t)\sin(t), \\ 0 \le t \le 6. \end{cases}$$

The calculation of the change in the lengths of the cables L_i, $i=1$, ..., 4 by the (1), for the trajectory of the end effector of the planar CDPR in the form of a four-petal flower, in Fig. 8 shows their graphs.

A static analysis of the planar CDPR was carried out according to (11), with a constant external force $\boldsymbol{F}_R=\{1\ 1\}^T$. Calculations have shown that with such a force, let's obtain that the tension of cables 3, 4 is zero, and cables 1 and 2 have non-zero tension. In Fig. 9 shows the tensions in the cables for the trajectory of the end effector of a planar CDPR in the form of a four-petal flower.

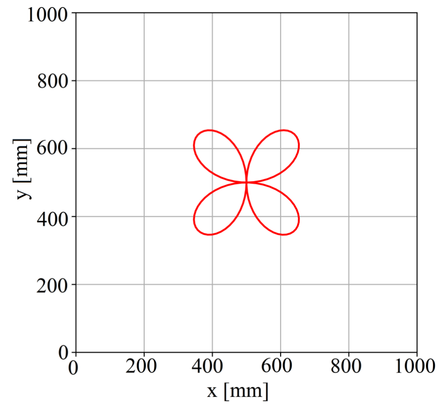

Fig. 7. Trajectory of motion of the end effector of a planar CDPR in the form of a four-petal flower

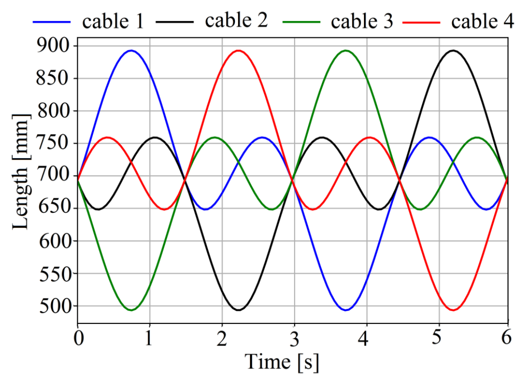

Fig. 8. The graph of the change in the lengths of the cables L_i, $i=1,..,4$

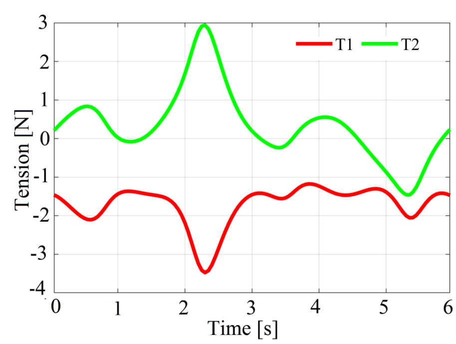

Fig. 9. Tensions in the cables for the trajectory of the end effector of a planar CDPR in the form of a four-petal flower

The results of static calculations showed that some cables have zero tension when the end effector of the planar CDPR moves under load.

5. 2. Development of a control system for the motion of a planar CDPR

To control the stepper motors of CDPR, it is necessary to determine the angles of rotation of the drums of the winches

β_i, i=1,...,4 expressed as a function of the end effector, position $\boldsymbol{X}=\{x\ y\}^T$. Let's take r as the radius of the winch drum. Let's assume that all 4 winches have the same radii. Let's define all β_i equal to zero when the end effector is located in the geometric center of a square fixed frame. Let's determine the initial lengths of the cables equal to $L_{0i}=\sqrt{2}L_B$, the change in the length of the i-th cable $\Delta L_i=L_{0i}-L_i$. The angles β_i are determined by the formula $\beta_i=\Delta L_i/r$.

Consequently:

$$\beta=\begin{Bmatrix}\beta_1(\mathbf{X})\\ \cdot\\ \cdot\\ \beta_4(\mathbf{X})\end{Bmatrix}=\frac{1}{r}\begin{Bmatrix}L_{01}-\sqrt{\left(x-A_{1x}\right)^2+\left(y-A_{1y}\right)^2}\\ \cdot\\ \cdot\\ L_{04}-\sqrt{\left(x-A_{4x}\right)^2+\left(y-A_{4y}\right)^2}\end{Bmatrix}. \qquad (12)$$

Due to the complexity of installing the position sensor of the end effector, which is needed to create position feedback, let's use stepper motor encoders.

Fig. 10 shows a block diagram of a planar CDPR control system. This feedback circuit will only work well if sufficient tension is maintained on all cables at all times.

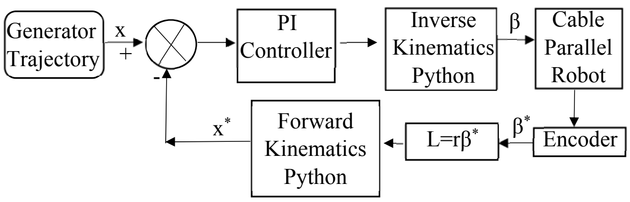

Fig. 10. A block diagram of a planar CDPR control system

Let's define the angles β_i^*, i=1, ..., 4 through the encoders of the motors, and then let's find the corresponding cable lengths L_i. Solving the direct task of the CDPR kinematics, let's find the position of the end effector $\boldsymbol{X}^*$. Next, let's use the PI-controller to reduce the trajectory error $e=X^*-X$.

5. 3. Build of the prototype planar CDPR

For the build of a prototype of a planar CDPR, a configuration of its system was developed, taking into account the convenience and clarity when demonstrating its work to students. The configuration of the system of the prototype of the planar CDPR is shown in Fig. 11. Here the following initial data are selected: dimensions of the fixed frame 1×1×0.2 m, payload 0.5 kg, maximum end effector velocity 1.5 m/s.

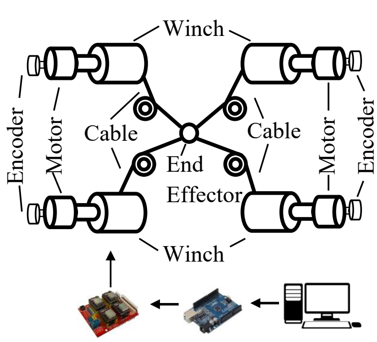

Fig. 11. The configuration system of the planar CDPR

According to the configuration of the planar CDPR system shown in Fig. 11, four winches need to be developed.

Fig. 12 shows the design of the developed CDPR winch, which consists of a drum mounted on a shaft with two bearings at both ends. The drum is connected to the Nema17-17HS8401S stepper motor through a coupling. An encoder is attached to the end of the drum.

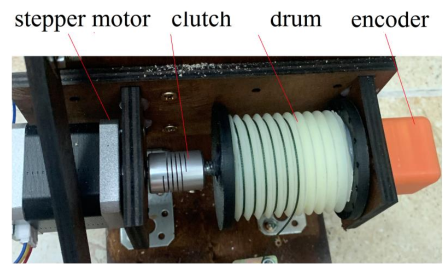

Fig. 12. Design of the CDPR winch

The stepper motor controller (Fig. 13) is based on the Arduino Uno controller with a CNC Shield v3 expansion board and stepper motor drivers using the Arduino GRBL software. With the help of the Arduino controller, the CDPR is controlled by the computer via the USB port.

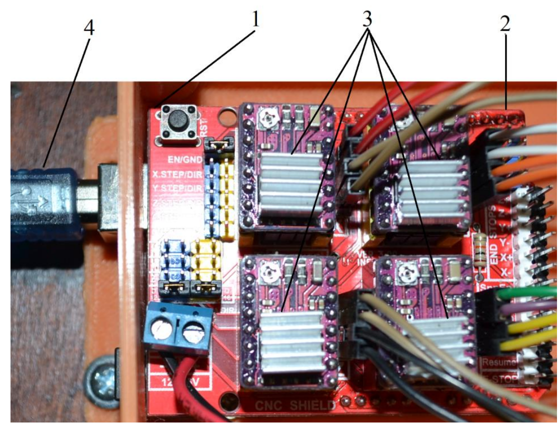

Fig. 13. Stepper motor controller:
1 – Arduino Uno controller; 2 – CNC Shield v3 expansion board; 3 – stepper motor drivers; 4 – USB cable

Fig. 14 shows a general view of connecting stepper motors to the CDPR control controller.

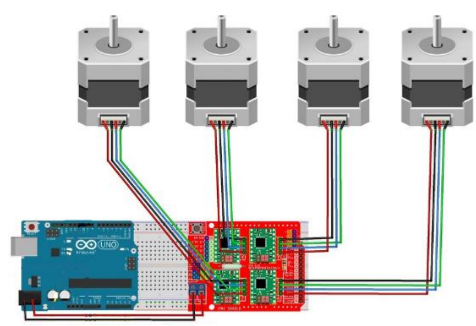

Fig. 14. A general view of connecting stepper motors to the CDPR control controller

The prototype of the planar CDPR is shown in Fig. 15.

The technical parameters of the prototype of the planar CDPR are shown in Table 1.

Table 2 shows the technical parameters of the planar CDPR stepper motor

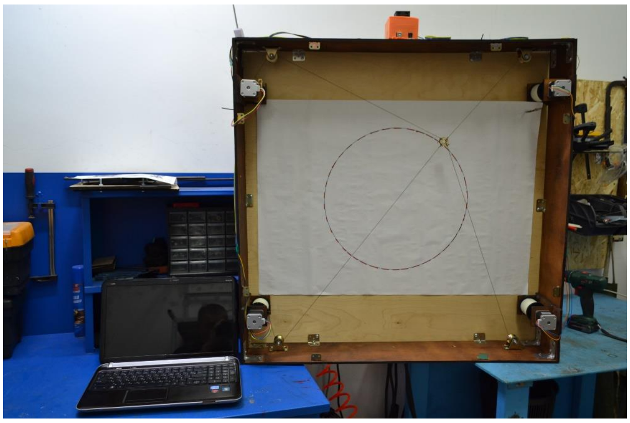

Fig. 15. The prototype of the planar CDPR

Table 1

Technical parameters of a planar CDPR

Length of planar CDPR	1 m
Height of planar CDPR	1 m
Payload	0.5 kg
Pulley radius	0.02 m
Drum diameter	0.05 m
Stepper motor	Nema17-17HS8401S
Speed	0.5 m/s
DOF	3 DOF
Settling Time	4 sec

Table 2

Technical parameters of the planar CDPR stepper motor

Step angle (deg)	1.8
Motor length (mm)	48
Rated current (A)	1.7
Phase resistance (ohm)	1.8
Phase inductance (mH)	3.2
Holding torque (N·cm Min)	52
Detent torque (N·cm Max)	2.6
Rotor inertia (g·cm^2)	68
Lead wire (No.)	4
Motor weight (g)	350

Fig. 16 shows the program interface for controlling a planar CDPR.

Here it is possible to manually control the planar CDPR end effector. Students can make translational motions of the end effector: forward-backward, left-right. It is possible to reproduce two preset trajectories of the planar CDPR end effector: a circle and a four-petal flower (Fig. 16).

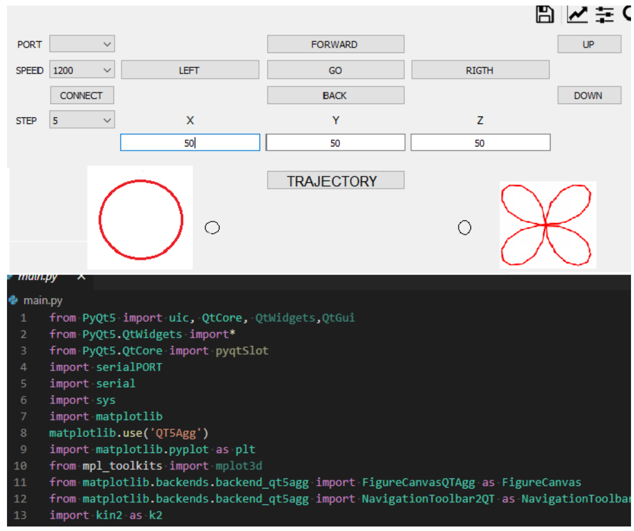

Fig. 16. Program interface for controlling planar CDPR

For testing, the design of the prototype planar CDPR has a back wall (Fig. 15), on which white paper is attached, for drawing the specified trajectories with the end effector.

5. 4. Experimental research of the prototype planar CDPR

Checking the work of the prototype of the planar CDPR was carried out when the end effector was drawing the trajectory of a circle with a radius of r=200 mm, the equation of which looks like:

$$\begin{cases} x(t) = 200\cos 0.5\pi t, \\ y(t) = 200\sin 0.5\pi t, \\ 0 \le t \le 6. \end{cases}$$

To draw this trajectory, a blue marker was attached to the end effector of the planar CDPR prototype. A total of three tests were carried out. In Fig. 17 shows in three colors (blue, black, green) the trajectories of the circle drawn by the end effector of the planar CDPR, and the red color shows a perfect circle.

Let's determine the maximum deviations of the radii of the circles from the radius of the ideal circle by the formula:

$$\Delta r_i^{\max} = \left| r - r_i^{\max} \right|,$$

$\Delta r_1^{\max} = 27$ mm, $\Delta r_2^{\max} = 21$ mm, $\Delta r_3^{\max} = 17$ mm. To evaluate the work of the prototype of a planar CDPR, let's determine the degree of repeatability of the trajectories. Let's determine the average value of the maximum deviations of the radii of the circles from the radius of the ideal circle by the formula:

$$\overline{\Delta r_{av}^{\max}} = \frac{1}{3}\sum_{i=1}^{3} \Delta r_i^{\max} = 21.67 \text{ mm}.$$

The average value of the maximum deviations of the radii of the circles from the radius of the ideal circle is 10.8 % of the length of the radius of the ideal circle, which indicates the insufficient accuracy of the work of the planar CDPR.

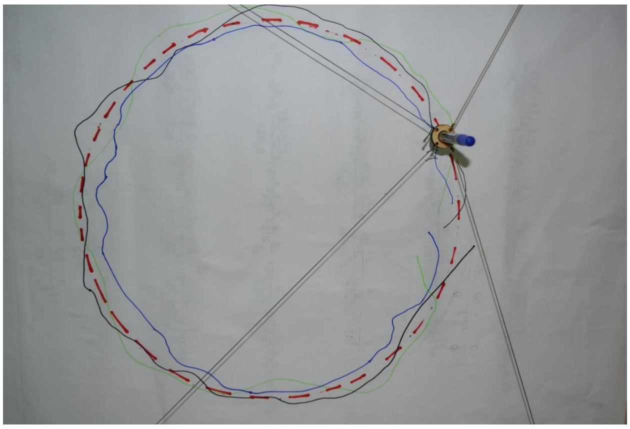

Fig. 17. Trajectories of the CDPR end effector are blue, black, green colors; reference trajectories is red

In the course of drawing the specified trajectories, it was found that the distortions (Fig. 17) of the trajectories occur as a result of a sudden loss of tension in any cable. It has been found that controlling sufficient cable tension is an important factor. When developing a planar CDPR control, it is necessary to include strain gauges to control the tension level in the cables.

6. Discussion of research results of the planar cable-driven parallel robot

The results of the kinematic and static analysis of the planar CDPR showed that the tension of the cables is highly dependent on the parameters of the trajectory of the end effector. Fig. 9 clearly shows that when the planar CDPR moves along the trajectory of the four-petal flower, the cables are subjected to significant variable tension in comparison with the usual circular motion (Fig. 6).

Fig. 10 shows the developed block diagram of the planar CDPR control system. Here, to simplify the control system, to create position feedback, stepper motor encoders are used. When analyzing the operation of the control system of the planar CDPR, it turned out that the feedback circuit will work well only if sufficient tension is constantly maintained on all cables.

A prototype of planar CDPR has been built, which consists of a fixed square frame, four winches, four stepper motors with encoders and four cables (Fig. 15). The CDPR winch (Fig. 12) consists of a drum attached to a Nema17-17HS8401S stepper motor and an encoder. The Arduino Uno stepper motor controller with the CNC Shield v3 expansion board (Fig. 13) is connected to a computer via a USB port.

The test of the work of the prototype of planar CDPR was carried out when the trajectory of a circle with a radius of r=200 mm was drawn by the end effector. The average value of the maximum deviations of the radii of the circles from the radius of the ideal circle is 21.67 mm, which is 10.8 % of the length of the radius of the ideal circle, which indicates the insufficient accuracy of the planar CDPR.

The obtained results of the work allow to solve the problem of creating planar CDPRs for teaching students, due to simple algorithms of kinematic and static analysis, a control system without complex sensors.

Compared to the prototypes of planar CDPRs developed in [11–14], our prototype does not have complex sensors included in the control system to maintain positive tension. In our case, this problem is solved by introducing a correction coefficients step motors that are determined experimentally.

The main limitations in this development of a planar CDPR is the control system of a planar CDPR, which requires the use of more advanced control algorithms, taking into account the dynamics of the planar CDPR.

The main disadvantage in the development of a planar CDPR is the insufficient consideration of the influence of the tension of the cables on the accuracy of the trajectory of the end effector. Further research is needed to improve the accuracy of the planar CDPR. For this, it is necessary to carry out the development of a planar CDPR, taking into account the sagging of the cables. In addition, it is necessary to consider the influence of external forces acting perpendicular to the plane of motion of the planar CDPR and which cause vibrations of the cables.

7. Conclusion

1. A kinematic analysis of a planar CDPR has been carried out, which performs only translational motion, and only the end effector has rotational motion. The graphs of the change in the lengths of the cables of the planar CDPR for circular motion and four-petal flower motion were obtained. The method of kinematic analysis of a planar CDPR is convenient and easy to calculate, unlike other methods. A static analysis of a planar CDPR was carried out, which performs only translational motion, and only the end effector has rotational motion. The graphs of the tensions of the cables of the planar CDPR for circular motion and four-petal flower motion were obtained. From the analysis of the results of modeling the kinematics and statics of the planar CDPR, it can be seen that the tension in the cables strongly depends on the parameters of the trajectory of the end effector. It is clearly seen here that when the planar CDPR moves along the four-petal flower trajectory, the cables are subjected to significant variable tension in comparison with the usual circular motion. This result is very important for students to understand that the kinematic and static of a planar CDPR strongly depends on the law of motion of the end effector, in contrast to parallel robots with rigid links.

2. A control system of a planar CDPR with position feedback through the encoders of stepper motors, assuming a constant sufficient tension of all cables is developed. This control system is convenient for students to use during the assembly and control of the planar CDPR and, unlike other control systems, does not contain complex sensors.

3. A prototype of a planar CDPR has been built. The configuration of the system of the prototype of the planar CDPR has been developed, which consists of a fixed square frame, four winches, four stepper motors with encoders and four cables.

4. Experimental researches of the prototype were carried out, which showed the efficiency of the planar CDPR design. Checking the work of the prototype of the planar CDPR was carried out by drawing the trajectory of a circle with the end effector. In the course of the experiment, it was found that the deviation of the trajectory from an ideal circle occurs as a result of a sudden loss of tension in any cable. The average value of the maximum deviations of the radii of

the circles from the radius of the ideal circle is 10.8 % of the length of the radius of the ideal circle. The use of a prototype of a planar CDPR in the educational process of a robotics course for students, gave the effect of a better understanding of the structure and features of the CDPR. In addition, the students developed a great interest in the production of new prototypes of the CDPR. In the course of independent work on the prototype of a planar CDPR, the students quickly learned how to control it and carry out kinematic and static calculations, which confirms the advantage of our prototype over other prototypes of the planar CDPR.

Acknowledgments

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