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Development of a manipulator for fully automated the process of charging electric vehicles

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Electric cars are gradually gaining popularity both in the world and in Ukraine. But in order for them to be freely used throughout the country, an appropriate infrastructure is needed. Unlike traditional cars with internal combustion engines, electric cars can be refuelled anywhere there is access to an electrical outlet. The main problems of electric cars during their operation over long distances are related to the duration of the journey on one charge and the low development of the infrastructure for them. Systems of automated charging stations are also gradually developing. There are already terminals of charging stations with payment by bank card and other payment systems, but they work on the principle of self-service. For full automation of the charging process, connecting the charging station to the electric car without human intervention is not enough. Wireless charging can solve this problem, but at this stage of development, the power transferred in this way is not always enough. To solve this problem, a combination of a manipulator arm and a typical charging station was proposed. The manipulator will determine the vehicle's position and insert the charging station's socket into the car's plug using sensors and machine vision. As part of this work, we made a conceptual project of a manipulator that will automatically connect the connector of the charging station to the car. Also, for this charging complex, a system of monitoring and protection of the electrical connection of the charger with the consumer against short circuit, overheating, sparking and arcing connector was developed, taking into account various interchangeable connectors. When developing the manipulator's arms, the following tasks were taken into account: ensuring sufficient kinematic freedom of movement to cover the working area of the charging station service and maximally simplifying the design. To reliably ensure access to any point of the working space, a kinematic scheme with two translational and three rotational links was used. Next, to determine the position of the manipulator in the workspace, the direct and inverse kinematics problems for this scheme were solved. The physical model of the manipulator along with servomotors, PID controllers and control system based on the equations of kinematics problems was simulated in the Matlab application software package. The implementation of a machine vision system and a switching device protection system is proposed for a full-fledged control system of the automated charging station. The resulting design of the automated charging station is experimental and does not have many analogues in the world. The modularity of the design ensures the versatility of its use at other types of charging stations, as well as the possibility of its modernization.

Key words: electric vehicles, charging station, manipulator, direct and inverse kinematics problems, control system, protection system of switching devices.

Introduction

Electric cars are considered the most promising technologies in the automotive market. Despite the fact that all developed countries at the legislative level are trying to switch to "green" electric vehicle systems, interest in these vehicles, compared to gasoline and diesel cars, is still quite low around the world [1]. An important issue for electric cars is the availability of adequate charging infrastructure, since waiting at charging stations due to the lack of chargers can discourage owners from using electric cars [2, 3].

With each month, the number of electric vehicles both in the world [4] and in Ukraine is increasing [5, 6], which brings the development of charging infrastructure to the fore. According to the marketing agency IRS Group, as of September 2020 alone, there were 8,529 electric charging stations in Ukraine [6]. The ratio of the number of electric cars to the number of connection points is 4.2. This is a very good indicator, at the level of the best European countries (the same index in the Netherlands) [7].

As we can see from the above, currently most of the leading countries of the world are actively developing and expanding the infrastructure network for electric vehicles. The need for automation of charging stations for electric vehicles grows with the increase in their number [5, 6]. And although technologies for automation are becoming more accessible and cheaper [7,8], developments in the field of automation of charging stations for electric cars are not being conducted actively enough, while they remain within the framework of expensive concepts and only a few companies. [8, 9]

Therefore, the development of a fully automated charging complex is very urgent. Our work is devoted to the development of a model of a fully automatic complex for servicing an electric vehicle.

1. The theoretical part

1.1. Statement of the research problem

As mentioned above, the design of a fully automated charging system for electric vehicles is a very urgent task [7, 10]. To make this task easier, let's break it down into a number of tasks: choosing a charging station, developing a conceptual model of the manipulator arm, and developing a general control system (machine vision to perceive external information, a controller and its software for general control). complex, as well as equipment and protection self-diagnosis systems).

There are already quite a few developed charging stations [3], therefore, for the implementation of our project, we will take the initial parameters of the Charge Complex-T charging complex from the AvtoEnterprise company [6]. As part of this work, we will make a conceptual project of a manipulator that will automatically connect the connector of the charging station to the car. Also, for this charging complex, we will develop a system for monitoring and protecting the electrical connection of the charger with the consumer against short circuit, overheating, sparking and arcing, taking into account various interchangeable connectors.

1.2. Manipulator development

When developing the arm of the manipulator, we will rely on the following tasks: ensuring sufficient kinematic freedom of movement [11,12] to cover the working area of the charging station service and maximum simplification of the design [13].

To reliably ensure access to any point of the workspace, let's take a kinematic scheme with two translational and three rotational links (Figure 1).

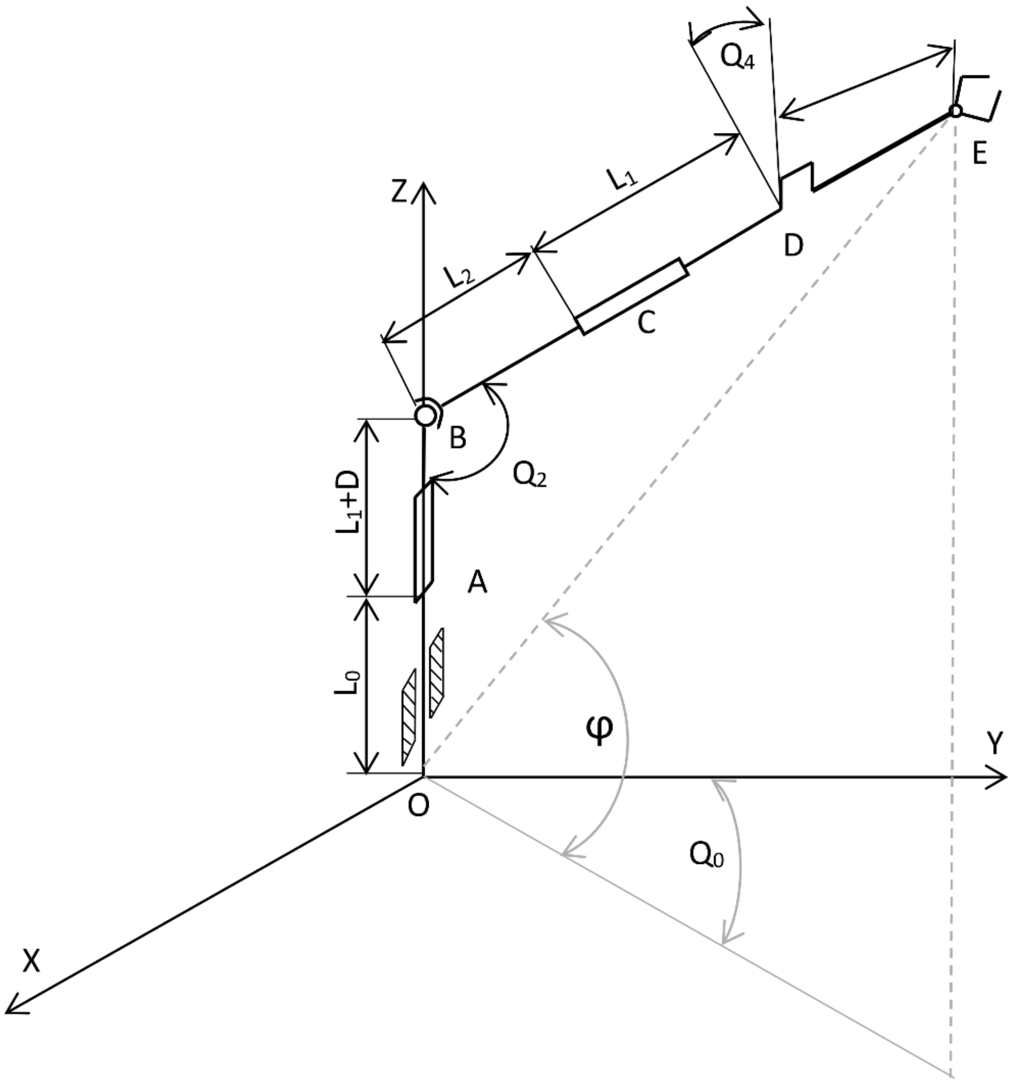

Fig. 1. Kinematic diagram of the manipulator

To find the position and orientation of the manipulator links, we will use the coordinate system proposed by Denavit and Hartenberg [12]. The construction of the coordinate system for the proposed manipulator scheme will be described in the form of the algorithm shown in Table 1.

Table 1

Parameters of the kinematic scheme of the manipulator

Link/parameter	c	d	α	q
0	0.8	-	0	q_0
1	0.8	d_1	π/2	-
2	0.8	-	0	q_2
3	0.8	d_3	0	-
4	0.8	-	0	q_4

Further, in order to determine the position of the manipulator in the working space, we will solve the tasks related to the determination of the relations between the coordinates of the grip of the manipulator, given in different forms: on the one hand, the position of the working body (grip) is uniquely determined by the generalized coordinates of the multi-link mechanism, and on the other - by with numbers that specify the position and orientation of the coordinate system associated with it.

The direct positional problem is formulated as follows: based on the given vector of generalized coordinates q = (q1, q2, ..., qN)t find the position and orientation of the grip s = (f). We will look for the position and orientation of the grip in the form of the homogeneous transformation matrix (1)

$$T = \begin{pmatrix} R & p \\ 0\,0\,0 & 1 \end{pmatrix} \tag{1}$$

Let A, i = 1,2, ..., N be the matrices that determine the transition from the coordinate system of the i-th link to the coordinate system of the (i-1)th link. Then, obviously, matrix (1) is a solution to the given problem.

$$T_N = A_1 A_2 \ldots A_N \tag{2}$$

We enter the matrix:

$$T_i = A_1 * A_2 \ldots A_i \tag{3}$$

We obtain the following recurrence relation:

$$T_i = T_{i-1} A_1, i = 1{,}2 \ldots N \tag{4}$$

$$T_0 = E \tag{5}$$

Ratio (4) allows not only to write down the solution of the direct problem about the position of the grip in a compact form, but also to determine the location and orientation of all links of the manipulator, since the matrix T determines the position and orientation of the i-th link. Ratio (5) unit matrix.

Let's determine the type of matrices in the case of using the Denavit-Hartenberg representation. According to the method of constructing coordinate systems, the following operations may be necessary to combine the (i-1)-th coordinate system $O_{i-1}X_{i-1}Y_{i-1}Z_{i-1}$ with the i-th coordinate system $O_iX_iY_iZ_i$.

a) Rotation around the Z_{i-1} axis by an angle qi. (X_{I-1} and X_i axes are parallel);

d) Displacement along the Z_{i-1} axis by di (X_{i-1} and x_i axes coincide).

Each of these operations can be represented by a correspondingly homogeneous matrix:

$$Rot(z, q_i) = \begin{pmatrix} & & & 0 \\ & R_{z,q_i} & & 0 \\ & & & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{6}$$

$$Rot(y, a_i) = \begin{pmatrix} & & & 0 \\ & R_{y,a_i} & & 0 \\ & & & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{7}$$

$$Trans(z, d_i) = \begin{pmatrix} & & & 0 \\ & E & & 0 \\ & & & d_i \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{8}$$

where the rotation matrices RYa, RZq have the form:

$$R_{z,q_i} = \begin{pmatrix} c_{qi} & -s_{qi} & 0 \\ s_{qi} & c_{qi} & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{9}$$

$$R_{y,a_i} = \begin{pmatrix} c_{qi} & 0 & s_{qi}0 \\ 0 & 1 & 0 \\ -s_{qi} & 0 & c_{qi} \end{pmatrix} \tag{10}$$

Further, we find the solution of the direct problem using the Matlab software package (Fig. 5) [12, 15].

The inverse problem of kinematics can be formulated as follows: the given kinematic diagram of the manipulator and the known position and orientation of the grip in the coordinate system of the first link (rack). It is necessary to determine the value of the generalized coordinates that will ensure the given position of the grip. You can set the grip position, like any solid body, using six values. Usually, three of them are the coordinates of the grip centre, two more are the direction cosines of one of the coordinate axes of the grip, and the last one is one of the direction cosines of the other coordinate axis of the grip. Given the known geometric parameters of the links, find all possible vectors of the attached variables of the manipulator, which ensure the specified position and orientation of the grip relative to the absolute coordinate system. We formulate the task as follows: given the position and orientation of the grip s = s* or $T_N = T^*_N$, find the generalized coordinates q* = (q^*_1, q^*_2 ... q^*_N) т.

If marked:

$$s = f_s(q) \tag{11}$$

Or:

$$T_N = f_T(q) \tag{12}$$

Hence, the sought angles q* will be given by the ratio

$$q *= f^{-1}{}_T(T^*{}_N) \tag{13}$$

Thus, the solution of the inverse positional problem is reduced in the general case to the solution of nonlinear trigonometric systems of six equations with N unknowns. It is known that this type of system can:

a) have no decision. This means that the given position and orientation of the grip of the system cannot be achieved by any choice of angles (movements) in the articulations;

b) have a single decision;

c) have more than one solution. This means that there are several (or infinitely many) manipulator configurations that provide a given grip position.

Solving the inverse positional problem is extremely important for manipulator control. Indeed, if the program movement of the manipulator is specified in the form of the trajectory of its grip s(t) (or T_N(t), which is equivalent), then for the control of the links it is necessary to provide such q(t) that at each moment of time the relation (11) is fulfilled. However, unfortunately, there is no general method of solving this system in an explicit form, which is precisely what is desirable, since the control of the manipulator is carried out in online mode. (However, the use of numerical methods is also associated with a number of difficulties associated with the possible divergence of the corresponding iterative schemes) [12].

From the analysis of three methods of the inverse positional problem [12]: the method of inverse transformations is suitable for solving our problem.

Using the method of inverse transformations, we will solve our problem according to the following algorithm.

The T_N matrix, which determines the position and orientation of the grip, has the form:

$$T_N = A_1 A_2 \dots A_{N-1} A_N \tag{14}$$

Where A = $A_i(q_i)$ – are transition matrices from the i-th to the (i-1)th manipulator coordinate system..

Then, multiplying the relation (3.14) by ${A_i}^{-1}$ (since the matricesA_i are nondegenerate), we have:

$${A_i}^{-1}(q_i) T_N = A_1 A_2 \dots A_{N-1} A_N \tag{15}$$

Due to the fact that the matrix T_N is known, it was possible to solve relation (12) with respect to q_i. If the structure is such that it is possible to find q_1, then this process is repeated for $q_1, q_2, \dots q_N$.t is clear that after multiplying (13) on the right by ${A_N}^{-1}$, we will similarly find q_N.

So, finding the matrix $T_5 = A_1 A_2 A_3 A_4 A_5$, and taking its last column as a vector, we get:

$$\begin{gathered}
P_{x5} = \cos q_0 \cdot \cos q_2 \cdot (d_3 + l_2 + l_3 + l_4) \\
P_{y5} = \cos q_2 \cdot \sin q_0 \cdot (d_3 + l_2 + l_3 + l_4) \\
P_{z5} = d_1 - \sin q_2 \cdot (d_3 + l_3 + l_4) + l_0 + l_1
\end{gathered} \tag{16}$$

These relations are a system of three trigonometric equations with five unknowns q_0, q_2, q_4, d_1, d_3 and the lengths of the links, which are known l_0, l_1, l_2, l_3, l_4.

So, this system has no solution. More equations need to be used. We take the equation from the rotation matrix:

$$\begin{gathered}
Yy = \cos q_0 \cdot \cos q_4 + \sin q_0 \cdot \sin q_2 \cdot \sin q_4 \\
Zz = -\sin q_2
\end{gathered} \tag{17}$$

Let's solve the system of equations (16 – 17). Dividing P_{y5} by P_{x5}, we get:

$$\begin{gathered}
\frac{P_{y5}}{P_{x5}} = \frac{\sin q_0}{\cos q_0} \\
q_0 = \tan^{-1}\left(\frac{P_{y5}}{P_{x5}}\right)
\end{gathered} \tag{18}$$

And from the equation Zz, we get:

$$\begin{gathered}
Zz = -\sin q_2 \\
q_2 = \sin^{-1}(Zz)
\end{gathered} \tag{19}$$

We take the equation Yy and divide it by $\cos q_4$ and express q_4:

$$\begin{gathered}
Yy = \cos q_0 + \sin q_0 \cdot \sin q_2 \cdot tg\, q_4 \\
tg\, q_4 = \frac{Yy - \cos q_0}{\sin q_0 \cdot \sin q_2} \\
q_4 = \tan^{-1}\left(\frac{Yy - \cos q_0}{\sin q_0 \cdot \sin q_2}\right)
\end{gathered} \tag{20}$$

We find d_3 from the equation Py5:

$$\begin{gathered}
P_{y5} = \cos q_2 \cdot \sin q_0 \cdot (d_3 + l_2 + l_3 + l_4) \\
d_3 = \frac{P_{y5}}{\cos q_2 \cdot \sin q_0} - (l_2 + l_3 + l_4)
\end{gathered} \tag{21}$$

And we also find d_1 from the equation Pz5:

$$\begin{gathered}
P_{z5} = d_1 - \sin q_2 \cdot (d_3 + l_3 + l_4) + l_0 + l_1 \\
d_1 = P_{z5} + \sin q_2 \cdot (d_3 + l_3 + l_4) - l_0 + l_1
\end{gathered} \tag{22}$$

In the future, the solution of the proposed equations is found using the Matlab software package [12, 16].

Using the general principles of designing industrial manipulators [13, 14], the physical model of the manipulator together with servomotors, PID controllers and a control system based on the equations of kinematics problems was simulated in the Matlab application software package. The result of the simulation was a block diagram (Figure 2, 3) and a test simulation of the operation of the manipulator (Figure 4, 5)

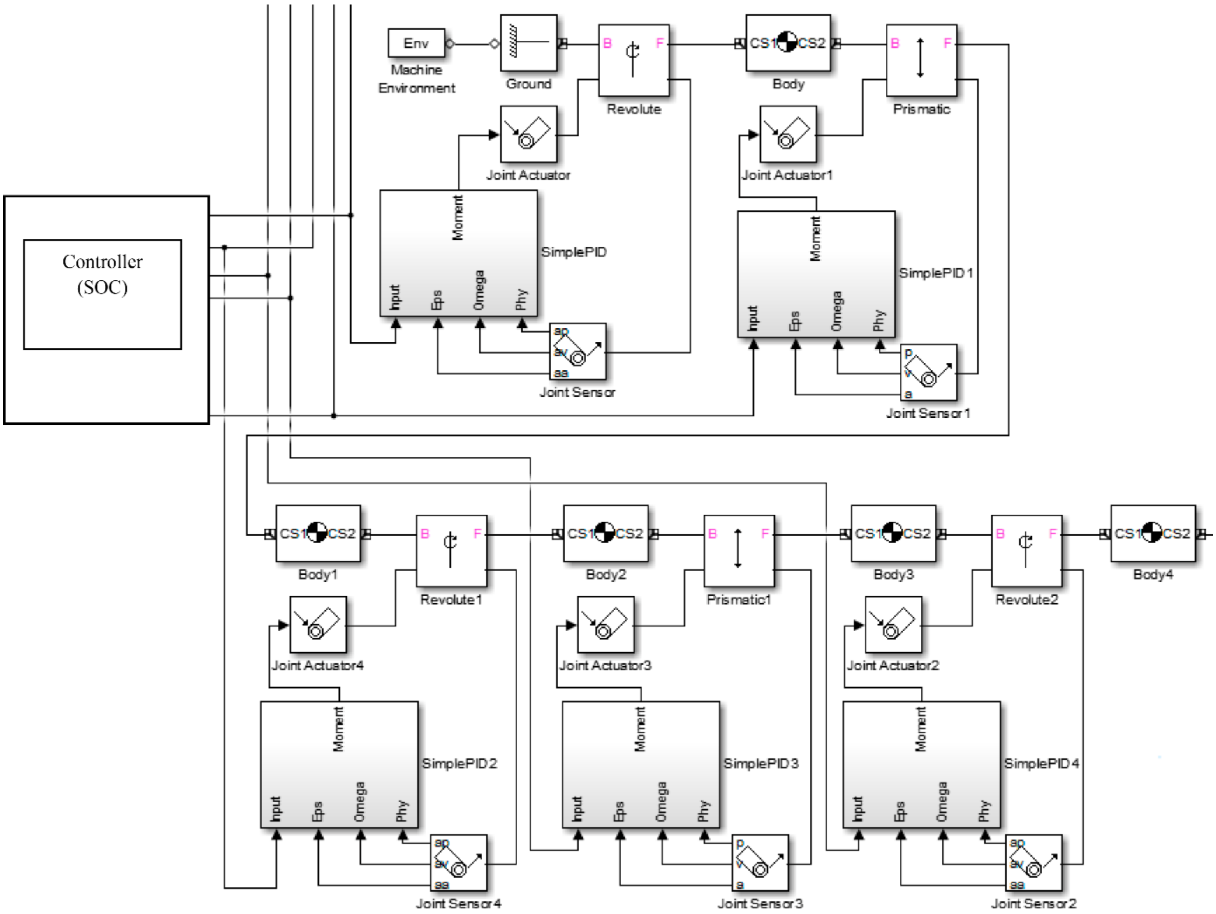

Fig. 2. The diagram of the connection of servomotors and PID controllers with links of the manipulator and the control unit

2. The result and their discussion

For a full-fledged control system of the work of an automated charging station, it is necessary to implement machine vision systems and a protection system. For machine vision, we will use Raspberry Pi Zero, Pi camera, camera cable, microSD card, USB power supply, USB-micro-USB cable. The machine vision system will ensure that the car's charging connector is located in the working area of the station. Pulse distance sensors (RPT) and a TL725 "MEMS" gyroscope with a built-in three-axis accelerometer will provide accurate position tracking and control of the charger's movement [16].

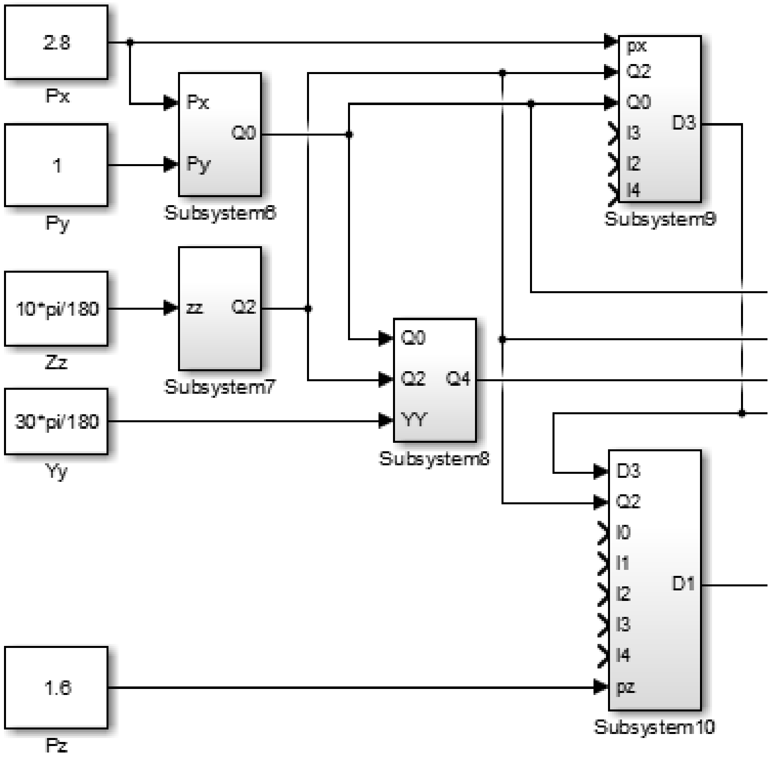

Fig. 3. Block diagram of the manipulator control unit (Controller)

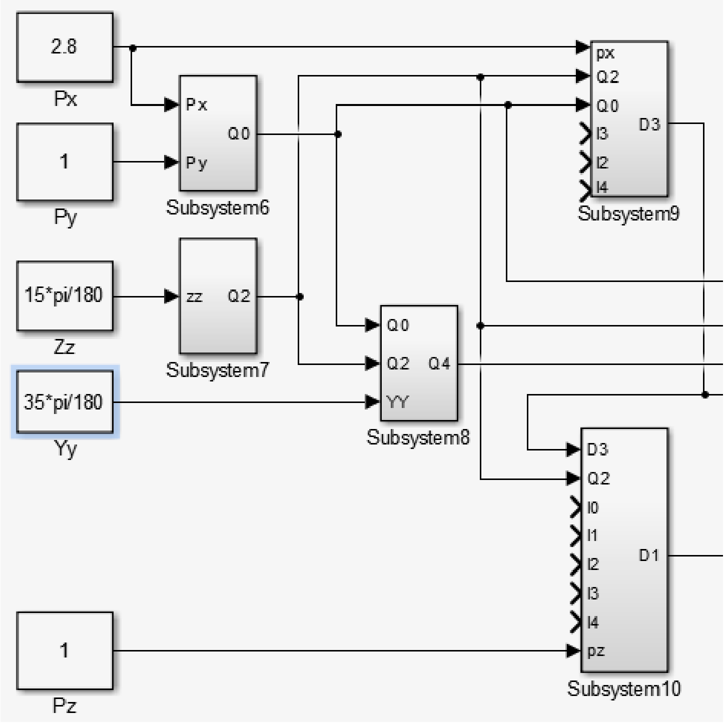

Fig. 4. Modelling the assignment of coordinates to the manipulator control unit in the Matlab environment

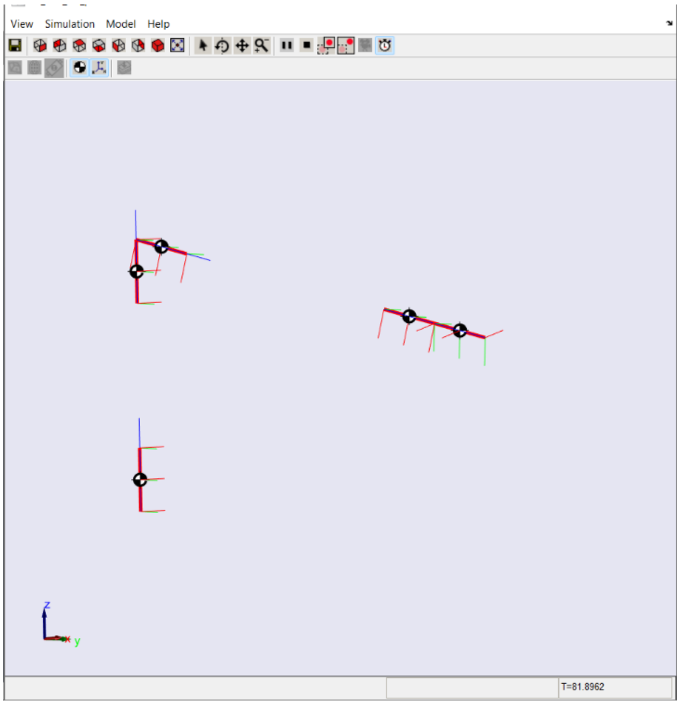

Fig. 5. Visualization of the operation of the manipulator with the given input parameters in the Matlab environment

The integrated CPSH servo drive combines in one compact case everything necessary to control the movement of the motor rotor in various operating modes.

A PID controller is used to control the actuators of the manipulator. It forms a control signal, which is the sum of three terms, the first of which is proportional to the difference between the input signal and the feedback signal (misalignment signal), the second - the integral of the mismatch signal, the third - the derivative of the mismatch signal. The model of the PID controller was built using the MATLAB software package (Figure 6).

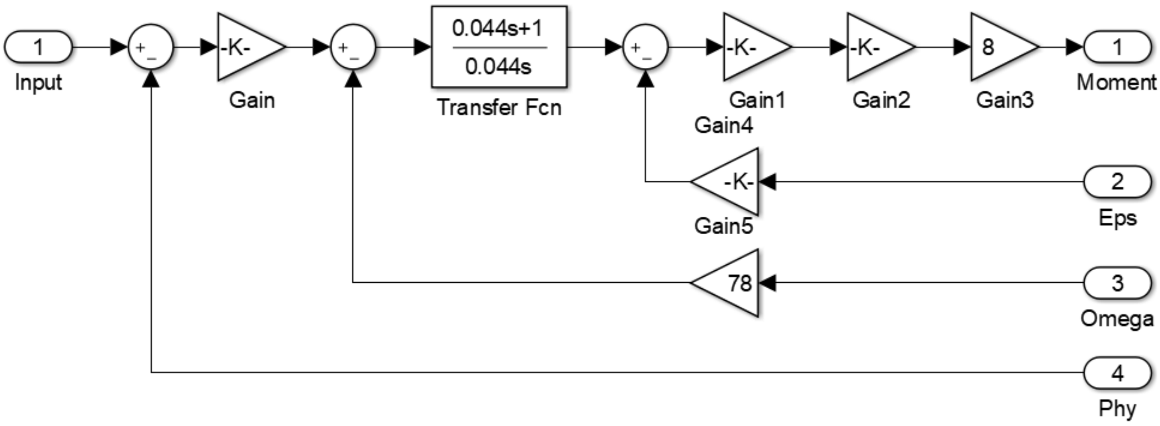

Fig. 6. Block diagram of the PID controller

As a system of protection of the switching device, a proprietary designed design of the arc-break protection device (PZDP) was used (Figure 7). The scheme of the control system will be based on the PZDP scheme with a two-pole automatic switch mechanism.

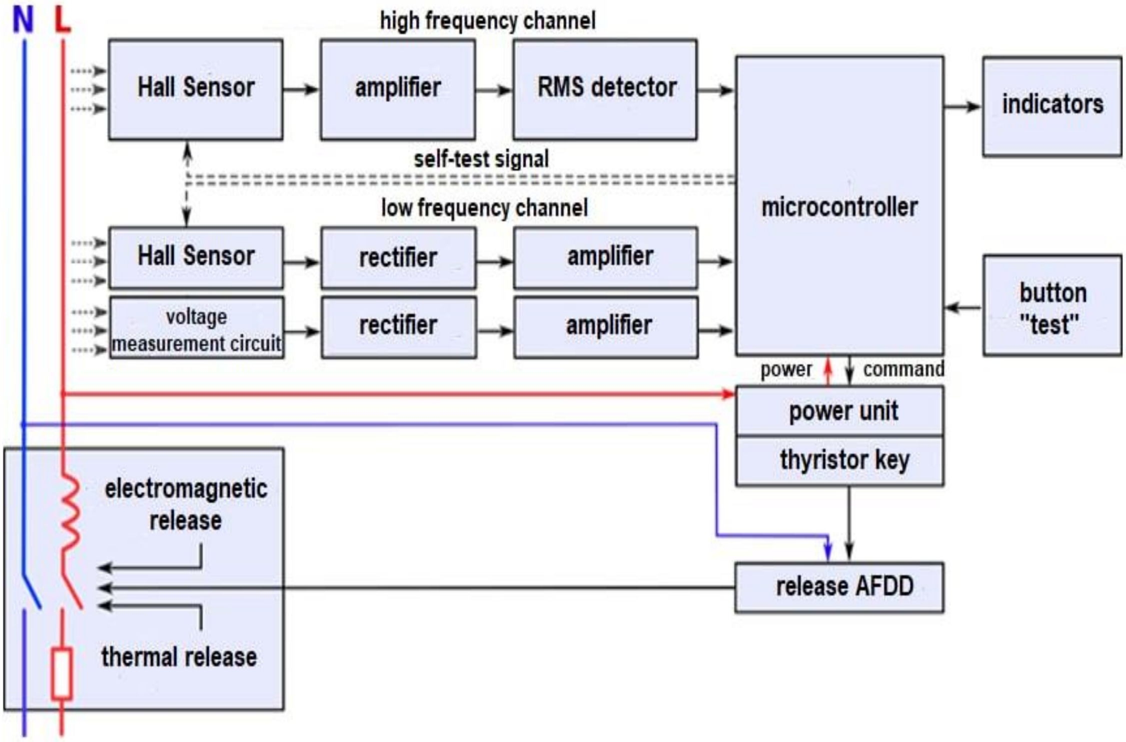

Fig. 7. Block diagram of PZDP with a two-pole mechanism automatic switch

To determine and control the parameters of the power supply circuit of the charging complex, we will use a circuit with current sensors (Hall sensor), to measure the current strength in the circuit due to a change in the magnetic field, and a temperature sensor (circuit with a thermoconformed) to measure the voltage in the circuit due to the temperature of the conductor (Figure 8) [16].

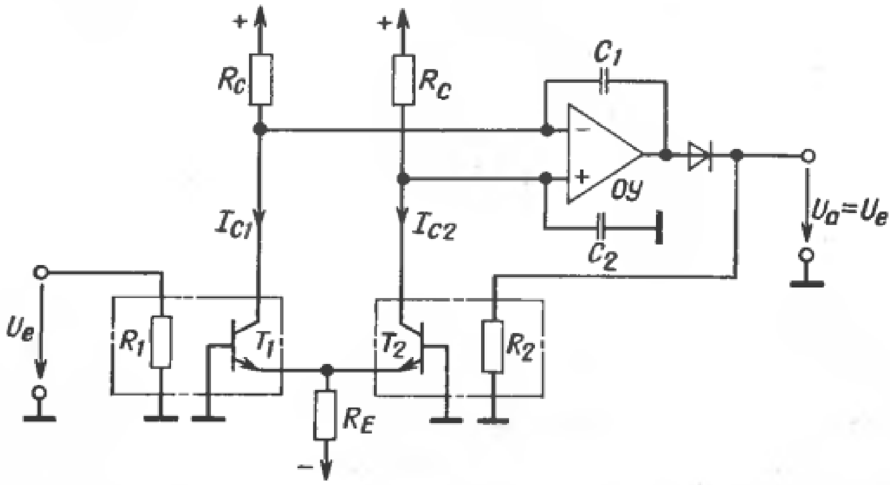

Fig. 8. Scheme of measurement of the effective voltage in the circuit

The sensors are connected to a microcontroller that is powered by a pulsed power supply. The microcontroller turns off the power circuit using a thyristor switch.

Similarly, electromagnetic and thermal disconnectors disconnect the power circuit when critical values are reached.

Two Huaibei huadian HD-T10IC3 Hall sensors, three normalizing amplifiers LM386 Arduino (11171), automatic disconnector ABB S803B-B80 type B, automatic circuit breaker BA88-35P 3P 125A 35kA, thyristor 70TPS12, pulse power supply 12 V were chosen for the implementation of the proposed scheme. and 5 A, Arduino Uno R3 CH340 microcontroller.

Fig. 9. General view of the experimental design of a fully automated charging station

3. Arrangement and principle of operation of an automated charging station

The Charge Complex-T charging complex from AvtoEnterprise [16] is connected to the manipulator developed by us. The manipulator is equipped with built-in sensors, a controller and a switching device protection system (Figure 9).

The system is aimed at automating the process of charging an electric car. The designed system is used according to the following principle: in the first step - the car approaches the working area of the charging station; in the second step - through the mobile application, we initiate the start of charging by making a payment. After payment, the general system of the charging station gives a command to start the charging process to the manipulator. Thanks to machine vision, the manipulator determines the position of the charging connector of the electric vehicle. Next, with the help of sensors and step-by-step changes in the position of the chains, the hand of the manipulator selects the required angle of insertion of the refuelling connector into the car connector and makes the connection. After a reliable connection, at the command of the charging station, the refuelling connector is blocked and the process of charging the electric vehicle begins. During the entire charging time, the PZDP protection system monitors the quality of the connection. In the third step, after the charging process is completed, the refuelling connector will be blocked and it will be removed from the electric vehicle connector, after which the manipulator will move to its initial position.

4. Conclusion

During the design of the complex of automatic charging of electric vehicles, a conceptual model of the manipulator was developed for automatic connection of the station connector with the electric vehicle. Also, this complex was equipped with a self-diagnosis and equipment protection module, which includes an arc flash device with a two-pole automatic shutdown mechanism. For safer operation, the charging complex is equipped with an arc fault detection unit. The operation of the device is based on monitoring the current in the phase conductor using two Hall sensors and a voltage meter.

The developed system is compatible with the Charge Complex-T "Automotive" complex and supports different types of standard charging connectors for each standard supported by the charging complex.

The resulting design of the automated charging station is experimental and does not have many analogues in the world. The modularity of the design ensures the versatility of its use at other types of charging stations, as well as the possibility of its modernization.

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Розробка маніпулятора для повної автоматизації процесу заряджання електромобілей

Електромобілі поступово набирають популярності як в світі так і в Україні, але щоб ними можна було вільно користуватися в масштабах країни, необхідна відповідна інфраструктура. На відміну від традиційних автомобілів з двигунами внутрішнього згоряння, електромобілі можуть заправлятися скрізь, де є доступ до електророзетки. Основні проблеми електрокарів при їх експлуатації на великі відстані, пов'язані з тривалістю ходу на одному заряді та невеликою розвиненістю інфраструктури під них. Системи автоматизованих зарядних станцій теж поступово розвиваються. Вже є термінали зарядних станцій з оплатою банківською карткою та іншими платіжними системами, але вони працюють за принципом самообслуговування. Для повної автоматизації процесу зарядки не вистачає підключення зарядної станції до електрокара без участі людини. Бездротова зарядка може вирішити цю проблему, але на даному етапі розвитку потужності, що передається таким чином, не завжди достатньо. Для вирішення цієї проблеми було запропоновано поєднання руки-маніпулятора та типової зарядної станції. Маніпулятор визначатиме положення автомобіля та вставлятиме розетку зарядної станції у вилку машини, використовуючи датчики та машинний зір. В рамках цієї роботи ми зробили концептуальний проект маніпулятора, який автоматично підключатиме роз’єм зарядної станції до автомобіля. Також для цього зарядного комплексу було розроблено систему моніторингу та захисту електричного з’єднання зарядного пристрою зі споживачем від короткого замикання, перегріву, іскріння та дугового роз’єму з урахуванням різноманітних змінних роз’ємів. При розробці руки маніпулятора спирались на наступні завдання: забезпечення достатньої кінематичної свободу рухів для покриття робочої зони обслуговування зарядної станції та максимальне

спрощення конструкції. Для впевненого забезпечення доступу в будь яку точку робочої простору було використано кінематичну схема з двома поступальними та трьома обертальними ланками. Далі для визначення положення маніпулятора в робочому просторі були вирішені пряма та обернена задачі кінематики для цієї схеми. У пакеті прикладного програмного забезпечення MATLAB була змодельована фізична модель маніпулятора разом з серводвигунами, ПІД-регуляторами та системою керування на основі рівнянь задач кінематики. Для повноцінної системи управління роботою автоматизованої зарядної станції запропоновано реалізацію системи машинного зору та системи захисту комутаційних пристроїв. Отримана конструкція автоматизованої зарядної станції є експериментальною і не має багато аналогів у світі. Модульність конструкції забезпечує універсальність її використання на інших типах зарядних станцій, а також можливість її модернізації.

Ключові слова: електромобілі, зарядна станція, маніпулятор, пряма та обернена задачі кінематики, система керування, система захисту комутаційних пристроїв.

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