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FEATURES OF KINEMATICS AND CONTROL OF MULTI-LINK MANIPULATOR ROBOTS

Abstract. The subject of research is multi-link manipulators, their kinematics and methods of controlling multi-link manipulator robots. To improve the accuracy of movement of each link and their synergy of work with each other during operation. In addition, the subject of the research is the analysis of the requirements for multi-link robot manipulators and the improvement of the kinematics of the robot-manipulator movements based on the comparison of mathematical methods in operating conditions. In different operating conditions manipulators and the automation of the production line is a big step for industry. Instead of a traditional industrial robot, a multi -link manipulator robot can be a good intermediate solution. It is more maneuverable, flexible, and has more complex movements for working on serial production. Multi-link robots provide a quick replacement of skilled labor in case of a shortage of employees or when production needs to be accelerated. As with any revolutionary technology, it is necessary to be critical of its implementation. The most decisive advantage of a robot over a single-link industrial robot is flexibility. Especially since the production environment needs to be able to adapt to handle the work with small volumes and a large number of different tasks. Such robots are more mobile and take up less space than traditional industrial robots. They are easier to reprogram to perform different jobs or product variants. However, it is worth noting that programming a traditional robot, which in its specialized environment requires deep knowledge and endless settings. When using a robot, the entry barrier for operators is significantly reduced, while deployment and ROI are accelerated. **The aim of** the work is to determine how the project context affects the choice of motion techniques and to determine the dependencies between requirements discovery methods. The article solves the following tasks: to study the trajectory of robots and compare mathematical control methods. Requirements in industry, create and draw a parallel regarding the practice of using demonstration robots and requirements in real conditions of using multi-link structures, determine the preferences of practitioners regarding detection methods and determine how the project context affects the choice of requirements detection techniques, determine dependencies between requirements detection methods. **The task** using such a method as a parametric form of the task is to prove that: the mathematical model of motion trajectories is the most reliable. Development and improvement of kinematic movements of manipulators with synergy of movements between manipulators. The following results were obtained: The best detection **methods** were identified and compared with other comprehensive studies. **Conclusion**: It was concluded that the choice of the shape of the wave-like trajectory of the movement; a traveling wave in a coordinate system moving along this sine wave form should be used as a control program for an automatic drive system. The assignment of a form in the form of a sine wave appears unsuitable for this task, because the obvious disadvantage of the sine wave is a continuous change in curvature and greater curvature at the peaks at large amplitudes.

Keywords: manipulators, mechanisms, movement trajectory, snake robots, trunk bending, movement phases, angular deviation.

Introduction

Reports of automatic technical devices with more or less complex mechatronics for production, festive events, or demonstration models that have appeared in recent decades and at the very beginning of the nineties are designed to perform the same type of monotonous work and to simplify and optimize the production process. It is worth noting that it is recognized that demonstration robots are an independent class of robots with their own distinctive types and features. Demonstration robots include movable manipulators with component parts or moving robotic machines with automatically controlled drives that do not perform any production functions but demonstrate themselves or other objects [1,2,3]. Demonstration robots are widely used to attract attention at exhibitions, in advertising, in entertainment, on theater stages [2], during holidays and in processions in parks and attractions. Competitions are organized for some types of demonstration robots (e.g., for culinary robots that compete with each other in cooking battles). Manually operated mini robot spies have become very popular. Demonstration robots primarily involve an element of initiative and invention, but many demonstration robots, drives, and their mechanisms and control systems deserve serious scientific consideration.

Various aspects of industrial robots are usually considered within the framework of typical industrial production projects: based on the existing requirements, the optimal option is selected, which specifies the type of robots required for a given task, their number, and also addresses the issues of power supply infrastructure (power supply, coolant supply - in the case of liquid cooling of equipment elements) and integration into the production process (provision of blanks/semi-finished products and return of the finished product to the automatic

Small demonstration robots can be considered reptilian robots (spies) with rather complex control systems. Also, demonstration robots for games (p1au game). Currently, most reports on the Internet refer to such robots. According to the geometry of their mechanisms, kinematics and appearance, they can be anthropomorphic, android or simply androids (imitating humans) or zoomorphic (imitating animals, such as dogs). There are also unique discoveries. One of the most sophisticated and advanced demonstration robots is the bipedal anthropomorphic robot Azino from Honda, which is capable of not only walking on the floor but also climbing stairs, communicating with people, and gesturing meaningfully.

The most large-scale demonstration robots in demand are those based on long, bendable shells or multi-link chains. Flexible long body parts with similar properties include the trunks and long necks of some animals (giraffe, Chinese dragon), and possibly larger wings (albatross). As for the theatrical stage, a transformed figure of a ten-meter giant, whose design included a multi-link mechanism of a bending spinal column, and a dragon structure, was developed and realized [3]. Technogenic fantasies based on self-modified geometric shapes depicting stylized technical objects and even moving compositions. The development of this area allowed us to outline some ways to further develop this idea with prospects for technical implementation

Analysis of recent research and publications

The analysis of current robots has shown that today the problem of controlling robots with complex control kinematics is being acutely analyzed. When analyzing risks, the causes of their occurrence are considered. Methods of risk analysis have been developed: risk assessment depending on the characteristics of the robot control method, the degree of innovation novelty, analysis of innovation risk at certain phases of the robot life cycle, with a scale for assessing the effectiveness of mathematical modeling of each of the mathematical models and a proposed analysis and their effectiveness [9, 3].

There are works on theoretical and practical issues of risk management, in which one of the important stages is the task of choosing a way to reduce risks and increase efficiency. The author identifies the sequence of risk management processes according to this sine wave shape and describes ways to minimize risks. The main attention is paid to the principles of phasing and a large deviation tolerance based on concrete examples. The issues of minimizing the risky outcome are considered with a detailed consideration of the risk-forming factors, taking into account the degree of uncertainty of the environment [5, 7].

In foreign publications, considerable attention is paid to the development of standards for managing kinematics, required deviation tolerances, and management risks on different surfaces. Innovation risks are often defined as the probability of loss arising from different weather conditions. In foreign publications, considerable attention is paid to the development of standards for kinematic control, required deviation tolerances, and risks of control on various surfaces. However, little attention has been paid to the issue of risk selection methods and risk pairing mechanisms. The decision to choose a method does not take into account all the factors of influence in real operating conditions. One of the effective ways is to increase the risk factors for the robot during the operation period and calculate these risks by mathematical modeling. This method is mainly used for the final commissioning of any mechanical device [11,12]. Let us first consider the general problem of creating a mechanical system of the torso, taking into account its large size. The article considers snake robots of variable geometry, serpentine or serpentine demonstration robots, which are characterized by the presence of a long main bending body. The head may have independent degrees of freedom, but it may represent the last link of the body; Chinese dragons also have legs. It is known that the serpentine dragon is an indispensable participant in festivities in a number of countries in Southeast Asia. Interest has been expressed in creating a controlled (on cables) flying dragon for China, about 100-200 meters long. There is no doubt that moving snakes and dragons of smaller, but rather large sizes will find their place in the productions (primarily with fairy tales and theatrical plots) of many large theaters in Ukraine. The authors' proposed classification of variants of designs similar to demonstration robots with variable geometry, as well as their components, by several features is shown in fig. 1.

The structures of demonstration robots of variable geometry and their components can be built as multi-link mechanisms, deformable elastic bearing elements along the entire length, or as a sequential structure with rigid links. It is even possible to combine these principles.

In most cases, larger demonstration works are built on non-existent structures, as on internal skeleton frames, with a light decorative outer shell, cladding. If the shell that forms the appearance is rigid, then its attachment to the core or company frame is usually carried out at many points; during bends, it is necessary to ensure mobility, against slipping without jamming or touching adjacent fragments. However, it is possible that flexible (in particular, corrugated) cladding can be used not only as an appearance forming, but also as a load-bearing material. So far, load-bearing plastic cladding without frame structures has been used exclusively in small-scale works.

A large number of publications have been devoted to deciphering and explaining the mechanisms of snake movement, developing their mathematical models, and creating moving models that copy the principles laid down by wildlife (e.g., [4, 5]). It is recognized that the very principle of movement only by bending the body without limbs is based on the use of differences between the friction coefficients in transverse and longitudinal movements.

In relation to the general ideology of demonstration robotics, this article is about different, perhaps completely different, but adapted for technical implementation ways of building mechanisms and reproducing geometric shapes typical of snakes in motion. This means dividing the tasks of movement into the tasks of movement itself to follow a certain trajectory. It is assumed that the movement can be set by wheels with drives that may be uncontrollable either in terms of rotation angles or in terms of speed.

Regardless of the design, the desired laws of variable geometry and kinematics of serpentine robots are determined by the following basic requirements: the points of the midline of the sections must move along the same fixed wave-like trajectory when coiling [6];

- Restrictions are imposed on the curvature of the cross-sectional midline from above, due to structural constraints; however, curvature continuity is not required [6-8];
- Programmability and adaptability of the software, reproduction of motion by means of a drive system should be ensured [10-13].
- Movement in the coordinate system moving with the snake is represented by a sinusoid running from head to tail [7];
- It should be possible to change the lateral deviations from a straight line within a wide range to ensure balance [5-6];

To begin with, we will not take into account the natural constructive discretization of the snake's body along the lengths. The most important starting point is the choice of the shape of the wave trajectory; a traveling wave in the coordinate system moving along this sinusoidal shape should be used as a control program for an automatic drive system.

Setting the shape in the form of a sinusoid seems to be unsuitable for this task, because the obvious disadvantage of a sinusoid is a continuous change in curvature and greater curvature at the vertices at large amplitudes [7].

Purpose of the article – Analyzing and improving the kinematic motion of manipulators with synergistic movements with each other. As well as the development of a more, perfect bending torso, and the robot's head and its degrees of freedom in movement.

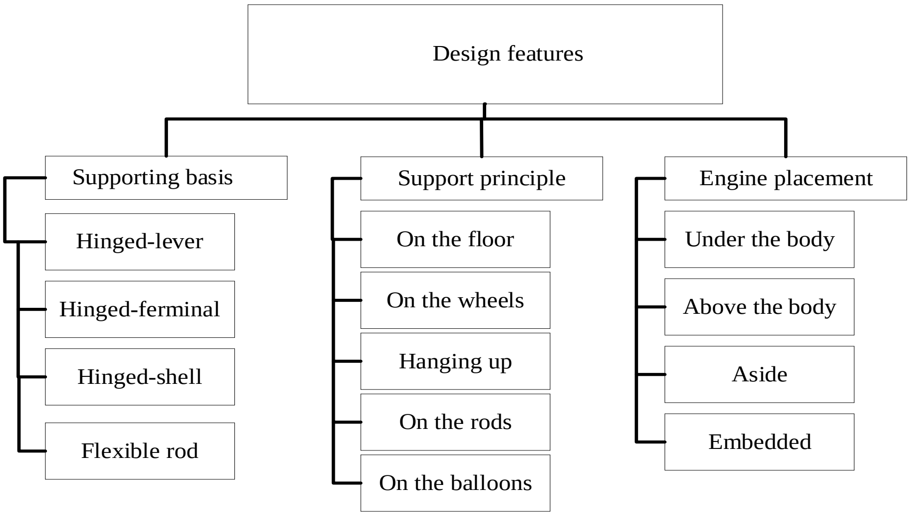

Fig. 1. Qualification of the design of demonstration robots with variable geometry and their components

Solving the problem

With the above requirements, only the parametric form of the trajectory in the form of *x(s)* and *y(s)* can be used. As an argument *s*, it is advisable to take the length of the arc *s* of the trajectory section from the selected starting point. Then, for the movement of a snake with a speed *V*, the determination of the coordinates of the points of its midline of sections along the length is carried out directly by replacing the argument *s* with $(\mathrm{l} + Vt - \mathrm{l}0)$.

In the program movement, the velocity vector of each point of the snake along the length is directed along the trajectory. This greatly facilitates the possibility of various schematic, fundamental and constructive solutions, and even the implementation of such movements on controlled drives. For example, rolling bearings with axes perpendicular to the centerline of the cross-sections can be placed along the length of the body. For a stage demonstration robot, it is possible to lay a track along the entire length of the railroad track, and then movement along it will occur without slippage [8].

Fig. 2 shows only one period of such a wave - the *i*-th section of length $\triangle \mathrm{l}$ starts from the centerline. It is proposed to form a formula for a trajectory in a fixed coordinate system (or a traveling wave in a moving coordinate system) by combining the arcs of circles of radius *R* with displaced centers [10].

Both the shape and the length of the arc on the period are determined by two parameters: the radius *R* and the angle *a*. The analytical representation of this shape by halves of the period: when $0 < s < \mathrm{R}(\pi + 2\mathrm{a})$,, i.e., for the first half of the period,

$$\mathrm{x} = \triangle \mathrm{s}_2 = \mathrm{R}[\cos\ \mathrm{a} - \cos\ (\triangle \mathrm{s}_1 / \mathrm{R} - \mathrm{a})];$$

$$\mathrm{x} = \triangle \mathrm{s}_2 = -\mathrm{R}[\sin \mathrm{a} + \sin\ (\triangle \mathrm{s}_1 / \mathrm{R} - \mathrm{a})]. \quad (1)$$

at $\mathrm{R}(\pi + 2\mathrm{a}) < \mathrm{s} < 2\mathrm{R}(\mathrm{p} + 2\mathrm{a})$, i.e., for the first half of the period,

$$\mathrm{x} = \triangle \mathrm{s}_2 = \mathrm{R}[\cos\ \mathrm{a} - \cos\ (\triangle \mathrm{s}_2 / \mathrm{R} - \mathrm{a})];$$

$$\mathrm{x} = \triangle \mathrm{s}_2 = -\mathrm{R}[\sin \mathrm{a} + \sin\ (\triangle \mathrm{s}_2 / \mathrm{R} - \mathrm{a})]. \quad (2)$$

In these expressions, the increase in the length of the arc $s1$ is counted from the beginning of the period (from the point Ai), and the increase in the length of the arc $s2$ is counted from the middle of the period (from the point $\mathrm{B}i$) [9].

This results in the following relationships between the length $S0$ of the arc on the period, radius *R*, angle *a*, arc length *L*, along the centerline of the cross-sections, transverse span *B* (i.e., overall size), and the elimination of *h* centers of circular sections:

$$\mathrm{S}_0 = 2\mathrm{R}(\pi + 2\mathrm{a}); \mathrm{L} = 4\ \mathrm{R} \cos \mathrm{a};$$

$$\mathrm{h} = \mathrm{R} \sin \mathrm{a}; \mathrm{B} = 2\ \mathrm{R}(1 + \sin \mathrm{a}). \quad (3)$$

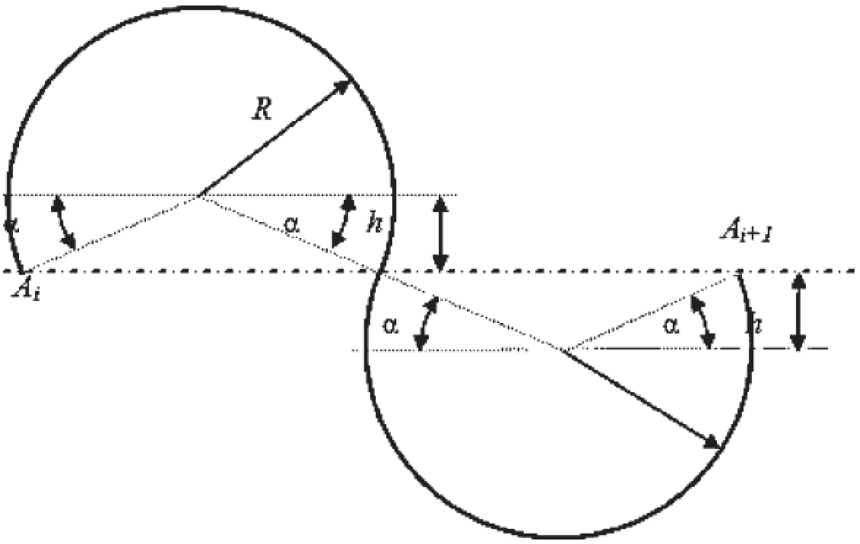

Fig. 2. Forming a trajectory by combining circles

The characteristic shapes of the three variants of the curves with the adopted analytical method of representation for the same value of the radius *R* are shown in fig. 3, a, b, c. The simplicity of these relations determines the good adaptability of the proposed form for programming movements. Here, the values of the parameter a are respectively $\mathrm{a} = 0, \mathrm{a} = -30\,°, \mathrm{a} = +30\,°$. At the same value of the radius *R*, a shorter wave resembles a sinusoid, while negative values of the angle a correspond to a smoother wave [15,14].

As it will be shown below, this allows to create a wave that runs by relay control of drives along sections. With regard to shape control tasks, it is important that in this representation the curvature and radius of curvature are piecewise constant and change sign twice per wave period.

Three consecutive phases of such a movement, in which all points of the snake move along the same periodic trajectory (dashed), are shown in fig. 4.

Without discussing the issue of removing the overturning, we assume that the modules are single-wheeled. Let us first consider a method of constructing snake-like robots on chain mechanisms, the rigid links (modules) of which, bogies on wheeled chassis, are connected in a pivotal series. The module body is a rigid drum. Vertical-axis hinges, in which successive modules are connected to each other, are extended at equal distances forward and backward along the longitudinal axis. Fig. 5 shows such a single-wheeled module [10].

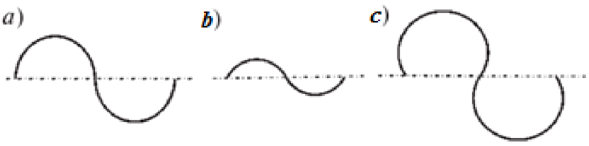

Fig. 3. Variants of movement trajectories based on obtaining arcs of circles of the same radius

The design of the module with three independently rotating wheels forming a platform support triangle generally provides stability on the horizontal plane. However, for a three-wheeled chassis, the ability to move with rolling wheels without slipping laterally depends on the mobility of the wheel axles relative to the platform. Naturally, an independent one-wheeled or two-wheeled module is not able to maintain a vertical position, only the connection of modules by movable joints can give a stable configuration of the snake as a whole with sufficient rigidity of the hinge joints. It is assumed that the chain of such drums has a single flexible (e.g., corrugated) covering (fabric or plastic). This covering should have an appropriate texture that forms the overall appearance of the snake's body. A two-wheeled module with sufficient wheel spacing on the sides will not allow you to roll over just on one side. Let's first assume that the triangular platform is rigidly connected to the drum of the module. Then, if two wheels rotate freely around the same axis, and the third wheel is an autonomous self-mounted wheel with an independent vertical axis, the properties with respect to trajectory movement are the same as for a three-wheeled and two-wheeled wheel [12].

In particular, all or only some modules can have wheel drives. In the following, when considering the tasks of moving along a given trajectory, the modules are depicted as single-wheeled, but the conclusions are valid for other, more complex options.

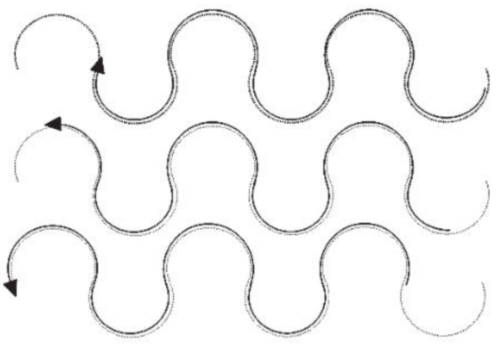

Fig. 4. Phases of movement along a periodic trajectory

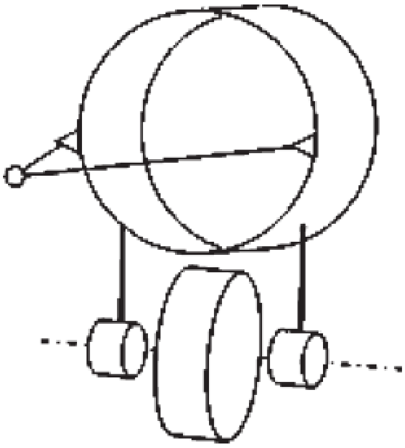

Fig. 5. Single-wheeled module of a snake-like robot with a hinged connection with vertical axes

If all three wheels are self-setting, the properties are completely different: rolling movement in any direction is possible without lateral wheel slippage. Modules with different numbers of wheels and non-driven, controlled by turning angles or uncontrolled) have the right to exist and be used in practice.

In undisturbed motion, the chain of modules reproduces a running wave, the planes of the wheels are almost everywhere close to the tangents to the programmed wave-like trajectory, which means that the wheels can rotate almost without lateral slippage, while the centers of the hinges are significantly offset from the specified trajectory to the side opposite to the center of curvature. A chain of hinged modules following a wave-like trajectory is shown in fig. 6. It is assumed that the centers of the contact spots of the wheels with the reference plane are on the program curve. Holonomous (geometric) connections reflect the constancy of the distances between the hinges of each module, and non-holonomous connections reflect the absence of lateral slippage in each of the unicycle modules [11].

Of course, the distances of both hinges from the vertical axis of the wheel are the same, i.e.,$\eta = 1$. It turns out that it is very important to choose a dimensionless parameter - the ratio $\eta = l1/l2$ of the distances $l1$ and $l2$ from the hinges (counting from the head) before and after the point where the wheel touches the plane. Fig. 7, a shows that in this case, at a precisely specified angular position, pairs of adjacent or any number of modules connected in series can move along a circular path of any radius without slipping, since the wheel planes will be tangent to the same circular path. It turns out that when moving, it is enough to set the correct initial position of all modules along a circular trajectory of a given (any) radius, use any module as a master, and there is no need to control the rotation of the modules' wheels; the movement will be in a circle without any guides.

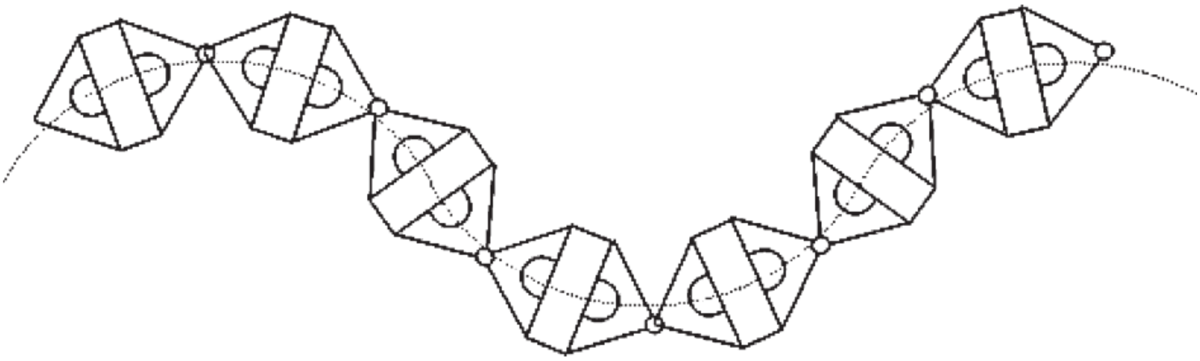

Fig. 6. Movement of hinged modules along a wave-like trajectory

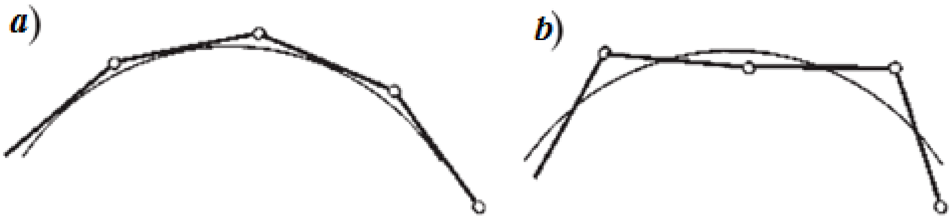

Fig. 7. The effect of setting the angular position of a pair of adjacent hinged modules on the movement along a circular trajectory

This seems to imply that if the program trajectories are formed from sections of circles, as in fig. 2, then in most of each of these sections, the constant curvature will fully correspond to the kinematics of the module connection, but it should be borne in mind that at $\eta = 1$, the angular deviation of one module (it can be considered the leading one) leads to a wave that does not fade away (fig. 7, b) and to further distortion of the trajectory shape. It can be shown that when $\eta < 1$, the deviations along the chain of modules will decrease (which can be qualified as kinematic stability), and when $\eta > 1$, they will increase.

In this case, we have the previously considered case of $\eta = 1$ can be considered as corresponding to the limit of kinematic stability [13, 14].

Results

If in the proposed programmable motion the curvature of the sections takes only one of two values (positive and negative), then each linear actuator can be two-position and operate from stop to stop, which simplifies implementation. When moving along a piecewise circular trajectory, it should be borne in mind that there are local changes in geometry in areas close to the straight centerline, where the curvature must change sign, and this effect, taking into account lateral slippage, must be separately investigated by mathematical modeling. Consider the method of setting the relative angular position of two adjacent modules using a linear motor (Fig. 8).

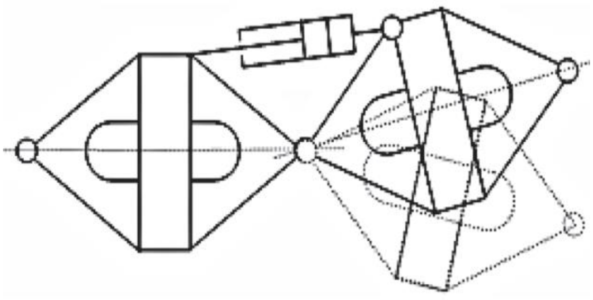

Fig. 8. Setting the angular position of adjacent modules using a linear motor

In particular, if the drive is pneumatic, then the motors can be pneumatic muscles, if the drive is electromechanical, then the motors can be of the solenoid type. When using the relay law of curvature control, it is for these zones that deviations from the program laws should be investigated, resistance forces should be estimated, etc. When moving, the control system should switch to the opposite position when a pair of modules passes the centerline. Thus, when the snake moves along the trajectory, the commands to switch the drives will follow several chains in parallel. The modules do not necessarily have the same dimensions, for example: at the tail, they may have smaller cross-sections and different distances between the connecting joints. For such a chain, the motion is realized in such a way that the tangents to the trajectory lie in the plane of the wheels or are close enough to them. In such cases, it is necessary to consider the choice of programmable trajectories separately. Mechanical manipulators are spatial mechanisms in the form of open, rarely closed kinematic chains of links forming kinematic pairs of one, rarely two degrees of mobility with angular or translational relative motion and a system of drives usually separate from each degree of mobility. At the end of the manipulator is the working body. The design of manipulators is determined primarily by their kinematic scheme. In addition, the type and location of the drives and mechanisms for transmitting motion from them to the manipulator's links are essential. Finally, manipulators often use balancing devices, which also have a significant impact on the design of manipulators.

Conclusions

Thus, based on the analysis of the material, it is possible to calculate the kinematics of each link of the manipulator quite accurately. In addition, a three-link manipulator based on the above formulas (1), (2), (3) or another multi-link manipulator. During the analysis of the robot, the problem of kinematics was solved, and it is possible to incorporate such a mathematical approach into the neural network approach. Based on the robot's training and automatic correction of the coordinate system, it is possible to move the robot in complex areas of movement. For a multi-link manipulator, the task becomes more complicated as the number of links increases due to the possibility of complex motion trajectories. To this end, the neural network will need to be further improved depending on the operating conditions. The input data for training the neural network can be solved using the parametric form of the motion trajectory because this method is accurate in calculations. Multi-link robot is a relatively new technology, but it is quite competitive compared to conventional robots. A multi-link robot is particularly well suited for large companies with a larger budget and a greater level of expertise.

Some disadvantages of multi-link robots are worth noting:

- they are not heavyweights, those models of robots that are very expensive to operate, and therefore are usually intended for light manufacturing and logistics tasks (15).
- traditional robots are more predictable and better suited for high-volume production. In addition, humans are still better at some complex tasks that require advanced pattern recognition using sensors or spatial awareness.

Effective operation of a multi-link robot depends on readiness:

- learn what is required to program, operate, and maintain it.
- avoid monotonous, repetitive work that causes injuries and move towards more interesting tasks.
- Specialists are needed for programmatic, mechanical, kinematic, and other adjustments (16, 17).
- When humans and robots occupy the same space, inherent safety issues arise. The danger can be minimized with the help of cameras, laser scanners, sensors, LED and audio feedback, and pattern recognition using machine learning. As before, each case requires a critical risk assessment, taking into account various factors.

However, despite all the difficulties in use, such robots are used for casting, stamping, welding, carrying loads, installing parts, assembling bodies, and other work to automate and speed up production processes. This can significantly reduce the time spent on production work and reduce the price of the service or product of the original product.

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Особливості кінематики та управління багатоланкових роботів маніпуляторів

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Анотація. Предметом дослідження багатоланкові маніпулятори їх кінематика та методи управління багатоланкових роботів маніпуляторів. Для покращення точності руху кожної ланки та їх синергія роботи один з одним під час роботи. Також предметом дослідження являться аналіз виявлення вимог до багатоланкових роботів маніпуляторів та покращення кінематики рухів робота-маніпулятора на основі порівняння математичних методів у умовах експлуатації. В різних умовах експлуатації маніпуляторів, автоматизація виробничої лінії – великий крок для промисловості. Замість традиційного промислового робота багатоланковий робот-маніпулятор може стати гарним проміжним рішенням. Він більш маневрений, гнучкий і відрізняється виконанням більш складних рухів для роботи на серійному виробництві. Багатоланковий робот забезпечують швидку заміну кваліфікованої робочої сили в разі нестачі співробітників або коли потрібно прискорити виробництво. Як і у випадку з будь-якою революційною технологією, необхідно критично ставитись до її реалізації. Найбільш вирішальною перевагою робота перед одноланковим промисловим роботом є гнучкість. Особливо з огляду на те, що виробниче середовище має вміти пристосовуватися, щоб справлятися з роботою з дрібними обсягами та великою кількістю різних завдань. Такі роботи є більш мобільні та займають менше місця, ніж традиційні промислові роботи. Їх простіше перепрограмувати до виконання різних робіт чи варіантів продукту. Але варто зазначити що від програмування традиційного робота, який у своєму спеціалізованому середовищі вимагає глибоких знань і нескінченних налаштувань. При використанні робота вхідний бар'єр для операторів значно знижується, при цьому прискорюється розгортання та рентабельність інвестицій. **Мета** роботи полягає в тому, щоб визначити, як контекст проекту впливає на вибір техніки руху, та визначити залежності між методами виявлення вимог. У статті вирішуються наступні завдання: вивчити траєкторію руху роботів та порівняння математичних методів управління. Вимог у діяльності на промисловості, створити та провести паралель щодо практики використання демонстраційних роботів та вимог в реальних умовах використання багатоланкових конструкцій , визначити переваги практиків щодо методів виявлення та визначити як контекст проекту впливає на вибір техніки виявлення вимог, визначити залежності між методами виявлення вимог. **Завдання:** використовуючи такий метод як параметрична форма завдання довести що: математична модель траєкторій руху є найнадійніша. Розробка та покращення кінематичної рухів маніпуляторів с синергією рухів між маніпуляторами. Були отримані такі результати: Найкращі **методи** виявлення були визначені та порівняні з іншими всебічними дослідженнями. **Висновок**: Зроблено висновок, що вибір форми хвилеподібної траєкторії руху; біжуча хвиля в системі координат, що рухається за цією формою синусоїди має бути використана як програма керування автоматичною системою приводів. Завдання форми у вигляді синусоїди стосовно даної задачі представляється непридатним, тому що явний недолік синусоїди - безперервна зміна кривизни і більша кривизна у вершинах при великих амплітудах.

Ключові слова: маніпулятори, механізми, траєкторій руху, роботи-змії, згинання тулуба, фази руху, кутове відхилення.