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DESIGN AND OPERATIONAL PECULIARITIES OF FOUR-DEGREE-OF-FREEDOM DOUBLE-LEGGED ROBOT WITH PNEUMATIC DRIVE AND TURNING MECHANISM

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Abstract. *Problem statement.* Mobile robots are of significant interest among scientists and designers during the last several decades. One of the prospective drives of such robots is based on pneumatically operated walking (stepping) system with no use of electric, heat, magnetic or other types of energy. This allows the use of pneumatically-driven robots in the cases when the use of other energy sources is prohibited (e.g., in some gaseous or fluid mediums). At the same time, the walking (stepping) type of moving increases the manoeuvrability and cross-country capability of the mobile robot, and decreases the harmful effect of its interaction with the supporting surface (e.g., the fertile soil surface) in comparison with wheeled or caterpillar drives. *Purpose.* The main purpose of this research consists in substantiation of structure and parameters of pneumatic system of four-degree-of-freedom mobile robot with orthogonal walking drive and turning mechanism. *Methodology.* The research is carried out using the basic laws and principles of mechanics, pneumatics and automation. The numerical experiment is conducted in MathCAD software; the computer simulation of the robot's motion is performed using SolidWorks software; the modelling of the pneumatic system operation is carried out in Festo FluidSim Pneumatic software. *Findings (results) and originality (novelty).* The improved structure of the mobile robot with orthogonal walking drive and turning mechanism is proposed. The pneumatically operated system ensuring the robot's curvilinear motion is substantiated. *Practical value.* The proposed design of walking robot can be used while designing industrial (production) prototypes of mobile robotic systems for performing various activities in the environments that are not suitable for using electric power or other types of energy sources. *Scopes of further investigations.* While carrying out further investigations, it is necessary to design the devices for changing motion speed of the robot and the height of lifting of its feet.

Keywords: structural analysis, kinematic analysis, pneumatic drive, degree of freedom, mobile robot, simulation, robotic system, operational parameters.

Introduction

Automation and robotization of industrial and technological processes in different branches of human activity is a leading and long-term trend of development of modern society [1]. Nowadays, industrial robots have become quite widespread and have formed the main technological base of the machine-building, instrument-making, electrical and electronic fields of the world's industry [1], [2].

Over the last decades, a new direction of robotics related with autonomous mobile robots equipped by onboard control systems has been formed [1]–[11]. In many developed countries, companies with advanced information and production technologies aspire to develop industrial prototypes of competitive mobile robots for various purposes, in particular, for performing military, technological and exploratory operations. However, the processes of development and improvement of these significantly complicated robotic devices are constrained because of the lack of an open-access comprehensive scientific and theoretical framework for calculating and designing of autonomous mobile robotic systems, taking into account the latest developments in the areas of navigation systems, systems of technical vision, systems of environmental analysis and decision-making, etc. [1].

Problem Statement

The walking type of motion along the cross-country terrain is especially actual in those cases when the use of wheeled or caterpillar drives is impossible or unjustified for technical and operational reasons [1], [2], [3]. In particular, walking machines can be effectively used while performing technological operations on soils with low bearing capacity, in oil and gas industries, while introducing new soil-saving technologies in forestry and agriculture, for emergency rescue operations under extreme conditions, and for eliminating the consequences of natural and man-made disasters, hostilities, etc. [1], [2], [3].

Among the wide variety of walking movers of mobile robotic systems with different drives and control systems, one of the simplest and the most commonly used ones are cyclic orthogonal-rotary stepping mechanisms. They provide a predetermined trajectory of the supporting foot and significantly simplify the control system ensuring the prescribed movement of the machine [1]–[11].

The tasks of improving the design and reducing the cost of mobile robotic systems with simultaneous preservation of their technical and operational capabilities are considerably urgent nowadays. In particular, in this paper it will be substantiated the possibility of implementing a system of changing the direction of motion of the mobile robotic system designed on the basis of a double-legged structure with a pneumatically operated orthogonal stepping drive.

Review of Modern Information Sources on the Subject of the Paper

The use of an orthogonal walking drive ensures the motion of a mobile robot during which its weight is supported by the structure (frame), while the motors are not loaded. The driving links of the legs of such a machine, as a rule, have linear movements relative to each other in mutually perpendicular directions. The vertical drive, which ensures adaptation and supporting of the machine's weight, becomes turned off when the foot touches the ground, and the vertical position of the machine is fixed by the brake. This allows adaptation to unevenness of a terrain due to different lengths of extension of vertical links of legs, and supporting the weight of a machine without the use of a drive [4]. The disadvantages of the orthogonal scheme consist in relatively large sizes of the legs with two or more degrees of freedom in relation to the sizes of the machine's body; the complexity of the constructive implementation of a leg designed on the basis of an orthogonal scheme, which is due to the presence of translational pairs and the need to change the orientation of the stepping planes to make a turn [4].

One of the possible principal diagrams of walking machines, which is designed using two platforms with orthogonal drives, is presented in Fig. 1 [4]–[10]. In this design, the movements of the legs are characterized by cyclic (periodical) repetition: when one of the platforms rests on the ground, the other one moves relative to it. Then the cycle repeats with another platform. Such a scheme, provided the use of self-braking gears (e.g., "screw-nut" gears driven by electric motors), does not require energy consumption to support the weight of the machine. However, the additional energy losses arise due to periodical acceleration and deceleration of each platform, and due to increased friction losses in self-braking gears. The other drawback of orthogonal walking drives consists in complexity of constructive implementation of turning mechanisms of moving platforms used for changing the direction of movement of a mobile robot. Nevertheless, there exist a great variety of designs of turning mechanisms which can be used taking into account the "price-efficiency" ratio adopted by the consumer. Talking about the increased energy consumption for keeping the machine's body in a stable vertical position, for orthogonal cyclic walking mechanisms, numerous methods of improving their effectiveness are proposed (e.g., by using self-braking gears in machine drives, special friction-type braking mechanisms, hydraulic or pneumatic drives etc.).

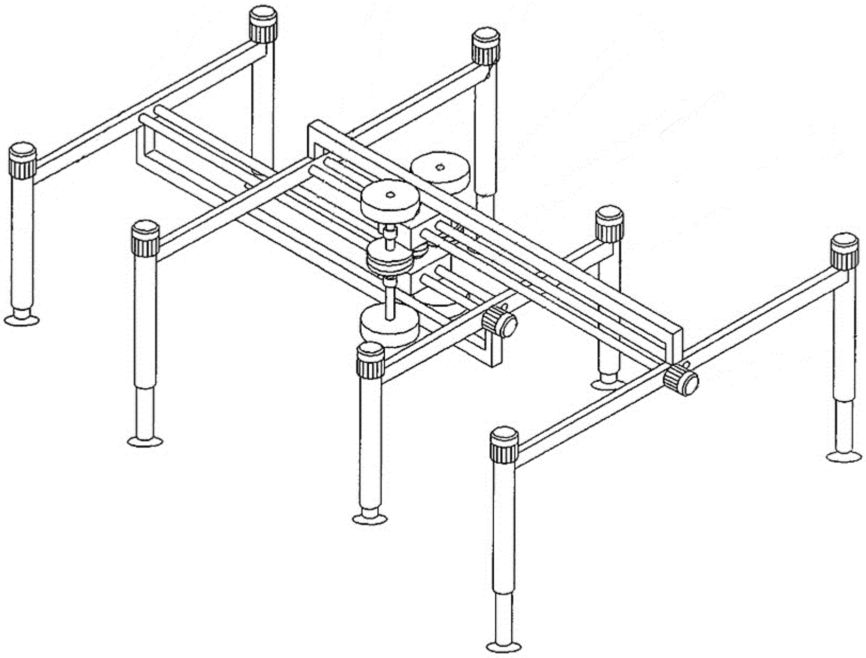
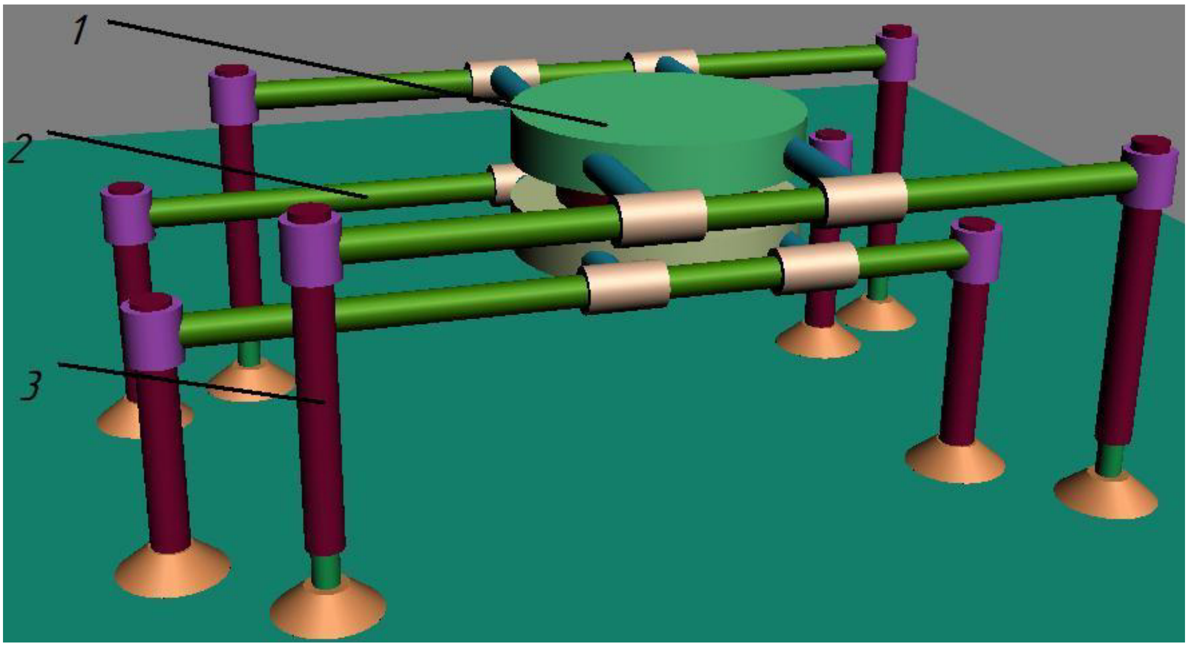


Fig. 1. Principal diagram of mobile robot with orthogonal walking drive

Another design of a mobile robot with orthogonal walking drives is presented in Fig. 2 [4]–[10]. The robot consists of three basic modules: of vertical movement of supporting feet; of horizontal movement of movable platforms; of turning platforms relative to each other. All modules are equipped with controlled electromechanical drives (stepper motors with worm gearboxes and screw-nut transmissions). The robot's body 1 consists of the upper and the lower parts, on each of which there are fixed the pairs of guides. The movable platforms 2 are driven by the corresponding motors and can move along the guides in any horizontal direction. At the ends of each platform there are mounted retractable (telescopic) vertical supporting struts 3 connected to the drives of vertical movement (Fig. 2).

a

Fig. 2. Design (a) and principal (b) diagrams of mobile robot with orthogonal walking drives



b

Fig. 2. (Continuation). Design (a) and principal (b) diagrams of mobile robot with orthogonal walking drives

While performing the stepping process, four supports of one platform are in contact with the supporting surface, while the other four supports are raised and move horizontally with another movable platform in the direction of the robot's course movement (Fig. 2). The total number of controlled drives is 11 (8 vertical drives of supporting legs, 2 drives of movable platforms, and 1 drive of the turning module).

The improved model of the walking machine considered above is given in Fig. 3 [4]–[10]. On the frame of the machine there is mounted the cabin with a workplace of the operator-driver and the control systems. A small gasoline generator is mounted behind the cabin, which supplies the machine with electrical power. In the lower part of the frame there are four modules of orthogonal walking drives, each of which consists of three basic elements: mechanism of vertical movement, mechanism of horizontal movement, and mechanism of turning. The first mechanism is equipped by an electric motor actuating a vertical self-braking “screw-nut” transmission; the mechanism is responsible for raising and lowering the round support mounted on the sliding rod. The robot has eight supports. Horizontal movement mechanism, which consists of electromechanical drive (also designed on the basis of “screw-nut” transmission), is designed to move the supporting platforms in the horizontal direction (back and forth). Each chassis unit has two sets of drives for horizontal movements. The turning mechanism consists of two electromechanical modules, one of which (central one) raises the entire structure with the supporting feet above the supporting surface, and the other one rotates the raised frame around the vertical axis [4]–[10].

The machine’s motion along a flat surface is performed as follows: the machine lifts four supports of one movable platform and pushes them forward using the mechanism of horizontal movement. Then the raised supports are lowered until their feet becomes in contact with the supporting surface. Then the walking cycle is repeated, but this time the other four supports are raised and moved forward [4]–[10].

Based on a similar design diagram, the mobile robot “RTS” equipped by an orthogonal pneumatic walking drive was developed at Lviv Polytechnic National University in 2019 (Fig. 4) [11]. The robot consists of two movable platforms 1 and 2, which are able to move relative to the frame 10 along the horizontal guides 11 and 12, respectively. The rectilinear cyclic motion of platforms 1 and 2 is provided by two pneumatic cylinders 3 and 4, respectively. Such design of the horizontal drive of the platforms provides an increase in the length of one step of the robot (i.e., its displacement during 1 cycle of operation of the pneumatic drive). At the four ends of the load-carrying platforms 1 and 2 there are mounted four vertical synchronized pneumatic cylinders 5 and 6, respectively (thus, the total number of vertically operating pneumatic cylinders is 8; the cylinders of each platform work synchronously).

Fig. 3. Design diagram of the improved robot with orthogonal walking drives

The rods of the pneumatic cylinders 5 and 6 are connected to the supports 7 and 8, which interact by their feet with the supporting surface along which the robot moves (Fig. 4). To move the platforms relative to each other, the supporting feet of one platform are placed at a greater distance from each other (looking in the direction of the robot's motion). The width of the "track" of another platform is narrower, which allows its supports to move between the supports of the outer platform [11].

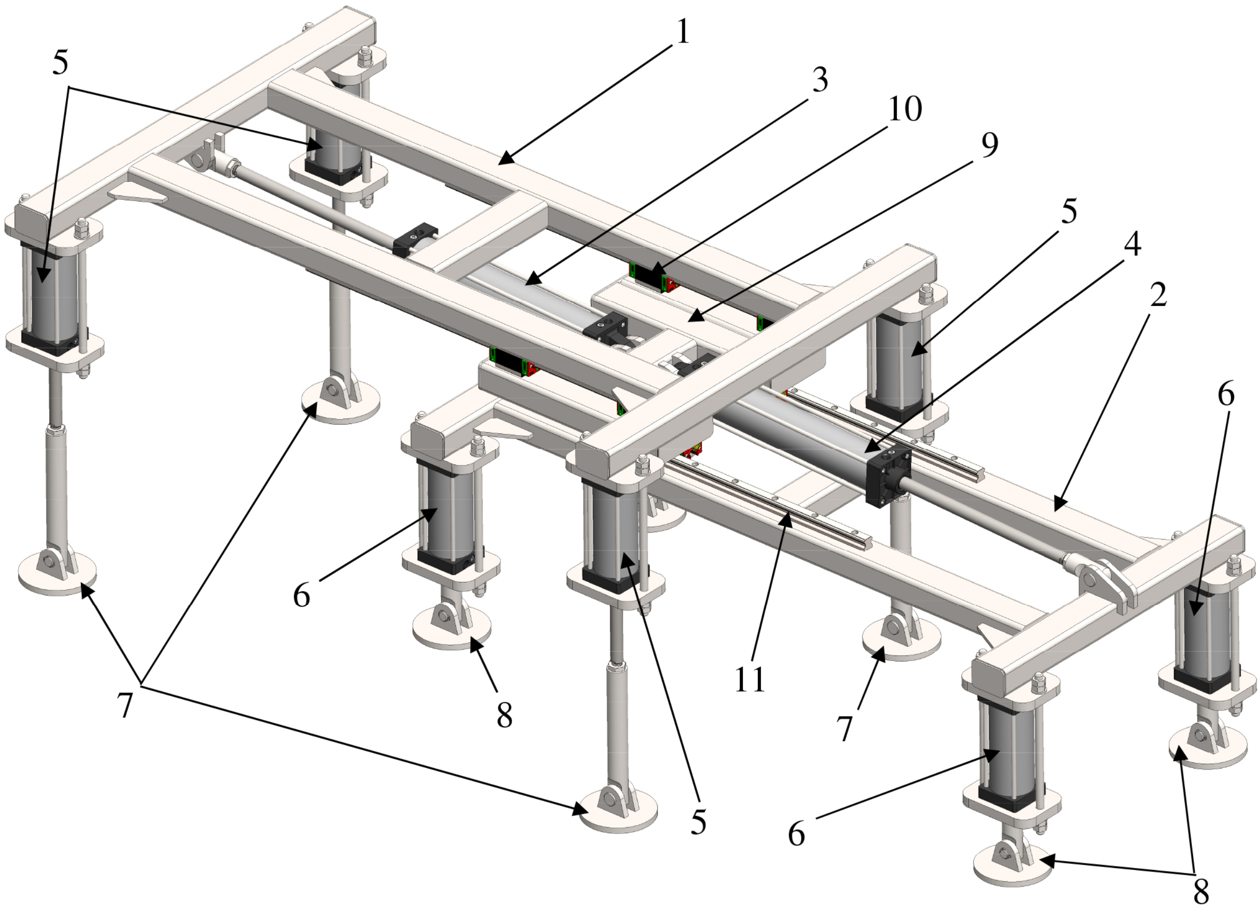


Fig. 4. Design diagram of the "RTS" robot developed at Lviv Polytechnic National University

Objectives and Problems of Research

The disadvantages of the robots considered above (Figs. 1–4) include the lack of ability to change the direction of their course motion by turning the load-carrying platforms relative to each other. Therefore, in this paper there is set the task of improving the existing design of the robot with orthogonal walking drive by equipping it with a special turning mechanism driven by a pneumatic system.

Structural and Operational Peculiarities of the Basic Design of Mobile Robot

The basic design of the mobile robot developed on the basis of the orthogonal walking drive actuated by a pneumatic system was implemented as the laboratory-scale plant at the Department of mechanics and automation engineering of Lviv Polytechnic National University. The general design of the robot is presented in Fig. 5. It consists of two movable platforms 1 and 2 able to move relative to each other along horizontal guidelines using one double-acting pneumatic cylinder 3. The platforms are equipped with pneumatic cylinders 4, 5, whose piston rods move vertically and are connected with feet 6. In order to ensure the static stability of the robot's structure, the supporting feet 6 are designed in the form of U-shaped plates. The distance between the opposite sides of the foot is equal to the robot's step length.

The considered laboratory-scale robot was carefully tested, and its basic operational peculiarities were analyzed. Based on the performed experimental investigations, there were substantiated the prospects of improvement of the existent robot's design.

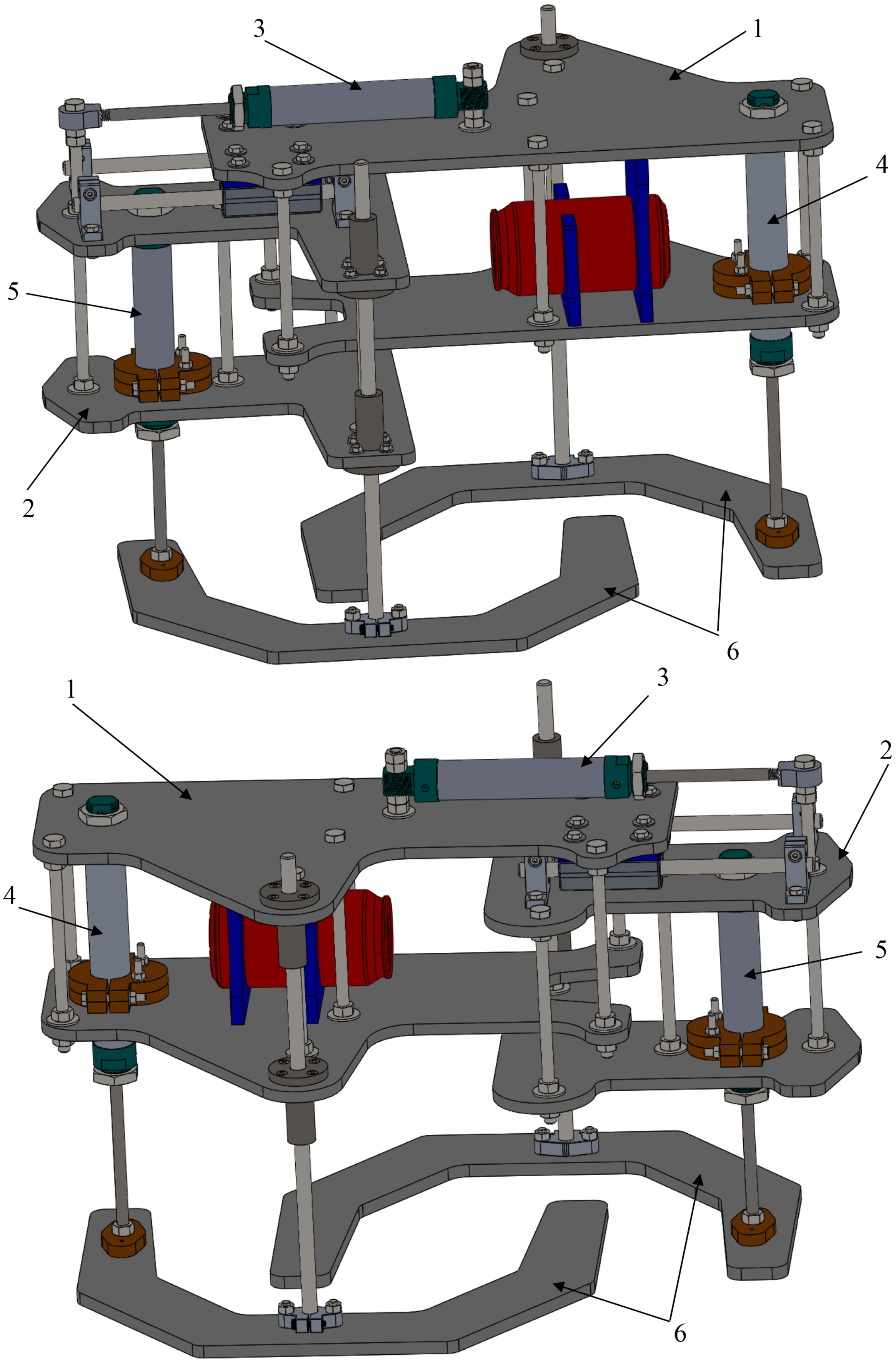


Fig. 5. Basic design of laboratory-scale mobile robot

Improved Design of Mobile Robot

The improved design of mobile robotic system with orthogonal walking drive is presented in Fig. 6. The robot consists of two movable platforms 1 and 2, which are able to move relative to each other along the horizontal guides 9 fixed on the supports 13 of the lower movable platform 2. Rectilinear horizontal cyclic movement of platforms 1 and 2 is provided by the pneumatic cylinder 6. Such design of the horizontal drive of platforms 1 and 2 provides the required length of one step of the robot (i.e., its displacement after one operational cycle of the actuating pneumatic system). On each movable platform, by means of clamps 12, there are vertically mounted pneumatic cylinders 4 and 5. To the piston rods of the pneumatic cylinders 4 and 5, there are connected supports that interact by their feet 3 with the supporting surface along which the robot moves. To increase the rigidity of the supports and, correspondingly, the stability of the robot's structure, the supporting feet are additionally joined by guides 7 and 8, which pass through linear bearings 10 fixed on movable platforms 1 and 2. For mutual movement of platforms relative to each other and for ensuring the static stability of the robot's structure, the supporting feet 3 are made in the form of U-shaped plates. The distance between the opposite sides of the U-shaped plates corresponds to the length of the robot's step (the maximum displacement of the rod of the pneumatic cylinder 6 of horizontal movement of movable platforms).

The cyclic rectilinear motion of the robotic system is carried out as follows. The supporting foot 3 of one of the movable platforms is in contact with the supporting surface. In this state, the piston rod of the corresponding pneumatic cylinder 5 is extended as much as possible. The rod of the vertical pneumatic cylinder 4 of the other movable platform is retracted, i.e., the foot of the other platform is raised above the supporting surface. At this time, the extended rod of the pneumatic cylinder 6 of the horizontal movement of the platforms 1 and 2 begins to retract causing the movement of the platform 2 to the left relative to the platform 1. When this movement ends, the foot 3 of the platform 2 is lowered until it begins to contact with the supporting surface. The piston rods of the pneumatic cylinder 6 of horizontal movement and of the pneumatic cylinder 5 of vertical movement remain at rest. After the foot 3 reaches the supporting surface, the feet of the first platform begin to rise due to retraction of the piston rod of the pneumatic cylinder 5, and the piston rod of the pneumatic cylinder 6 of horizontal movements of the platforms begins to extend causing the movement of the platform 1 to the left relative to the platform 2. Then the stepping (walking) cycle is similarly repeated.

In contrast to the prototypes of the mobile robots presented in Figs. 4 and 5, the proposed (improved) robot's design also provides the ability to change the direction of the course motion of the robot due to the fact that the upper movable platform 1 is structurally made of two parts 1 and 13 hingedly connected with each other. Thus, the pneumatic cylinder 4 of the vertical movement of the foot 3, as well as the entire supporting mechanism of the foot 3 are placed on a turning platform 13, which has the ability to turn around the platform 1 by means of the vertically placed cylindrical hinge 14. In this case, the platform 13 (and therefore the foot 3) has the ability to move orthogonally (back and forth) together with the upper platform 1 relative to the lower platform 2, which provides a cyclic stepping (walking) of the robot. On the other hand, by using an additional pneumatic cylinder 15 it is possible to change the angular position of one foot of the robot relative to the other foot, i.e., it is possible to turn the platform 13 relative to the platform 1 and to change the direction of the robot's motion.

In this section of the paper, the preconditions for further substantiation of possibilities of use of the considered way of movement of mobile robotic systems and other types of technological transporting equipment are considered. In particular, the following chapters will analyze in detail the processes of moving and changing the direction of motion of the improved design of the mobile robot with an orthogonal stepping (walking) drive. In addition, there will be constructed a cyclogram (timing diagram) of operation of the pneumatic actuating system and will be proposed a scheme of connecting and controlling the corresponding pneumatic cylinders providing horizontal movements of the platforms 1, 2, vertical movements of the feet 3, and rotary movements of the turning platform 13. After this it is necessary to construct the calculation diagram of the robot's mechanical system, to perform the kinematic and dynamic analysis of the robotic system, and to analyzed the main characteristics of its translational motion and turning process.

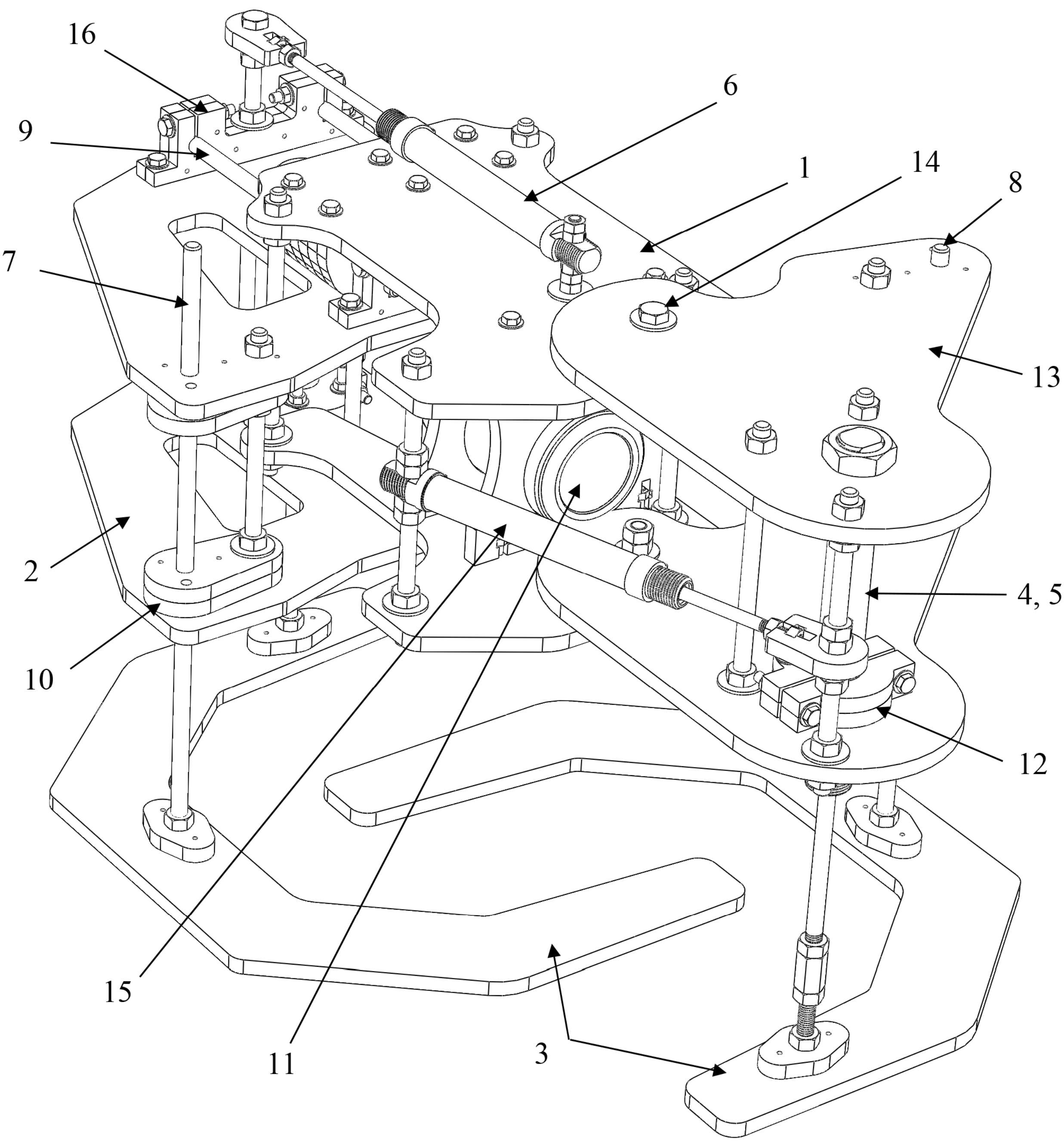


Fig. 6. Improved design of laboratory-scale mobile robot

Analysis of the Rectilinear Walking Process

Let us consider the main cycles of the walking process of the mobile robotic system with an orthogonal stepping drive. The first cycle (Fig. 7, a) begins when the supporting foot of one of the platforms is in contact with the supporting surface, and the foot of the other platform begins to descend. At the same time there is a movement of one platform to the left relative to another platform due to operation (retraction) of the pneumatic cylinder of horizontal movement of platforms.

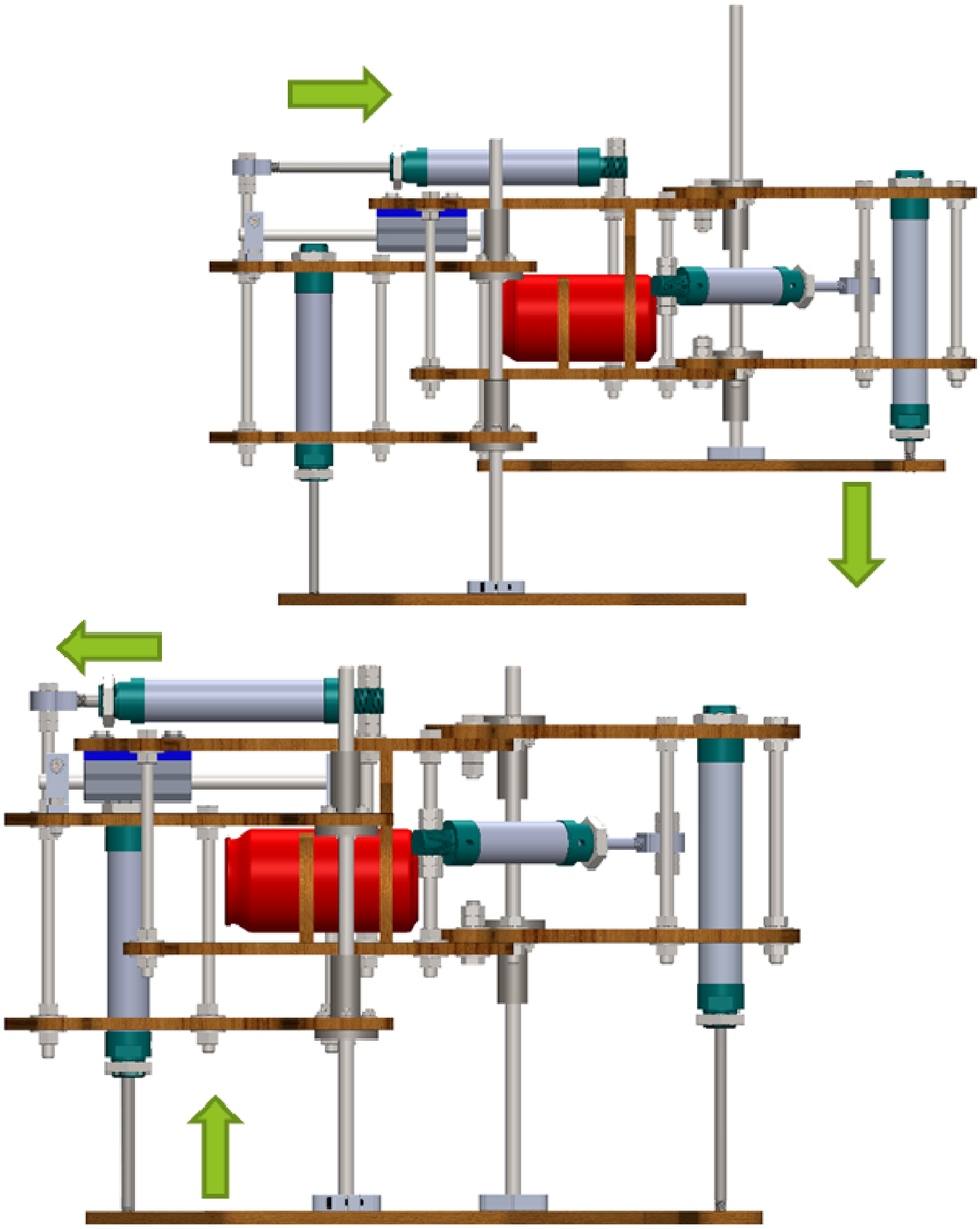
The second cycle (Fig. 7, b) of the stepping process begins when the foot of the second platform reaches the lower end point, i.e. begins to rest on the supporting surface. At this moment of time, there begins the lifting of the foot of the first platform, which until now has supported the body of the robot. The lifting process is accompanied by the movement of the free foot relative to the supporting platform due to the operation (pulling) of the pneumatic cylinder of horizontal movement of the platforms.

The third cycle (Fig. 7, c) of the stepping process begins when the foot of the first platform has reached the uppermost position, and the pneumatic cylinder of horizontal movement of the platforms has moved the movable platform to the left relative to the supporting (stationary) platform. At this moment of time, there begins the lowering of the foot of the first platform until it comes into contact with the supporting surface.

The fourth cycle (Fig. 7, d) of the stepping process begins when the foot of the first platform reaches the lowest position (i.e., begins to contact with the supporting surface). In this case, the movement of one platform relative to another does not occur, and the foot of the second platform begins to rise.

After the fourth cycle, the system takes the initial position (Fig. 7, e) and the walking cycles begins to repeat (the final position of the piston rods of the pneumatic cylinders in the fourth cycle corresponds to the initial position of the rods in the first cycle).

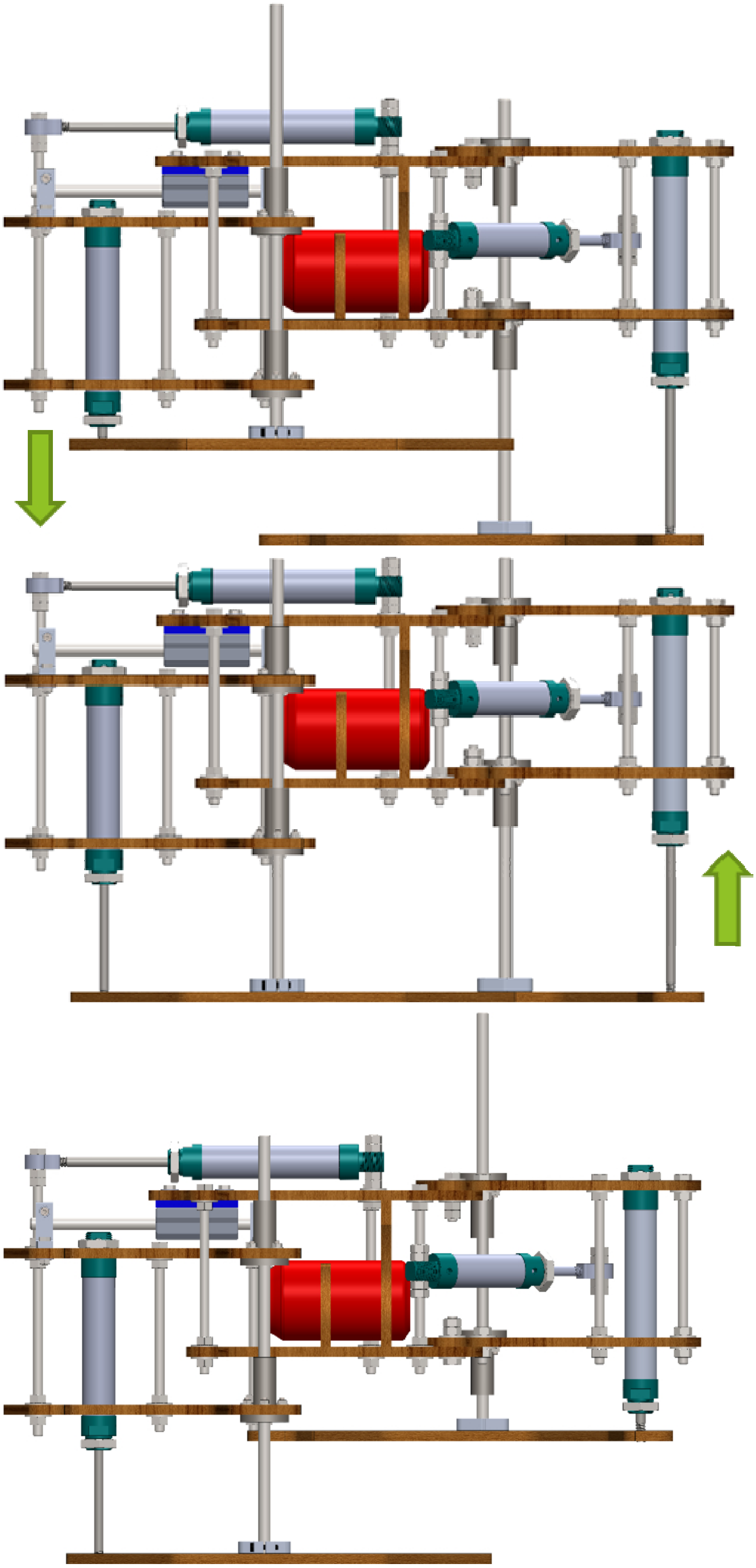
Therefore, the rectilinear walking process of the proposed mobile robotic system is characterized by cyclic (discrete-periodic) movements of the platforms and feet, which should be programmed and controlled.



a

b

Fig. 7. Graphical representation of the robot's walking process



c

d

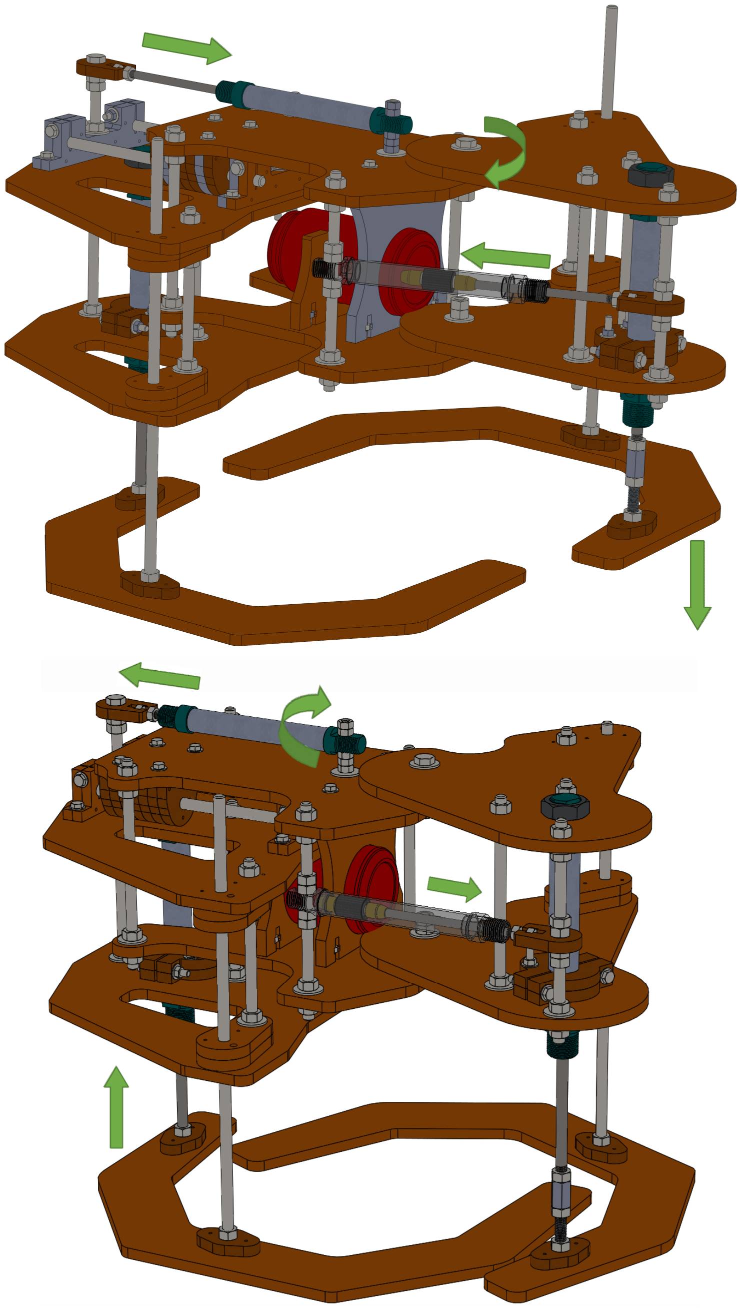
e

Fig. 7. (Continuation). Graphical representation of the robot's walking process

Analysis of the Turning Process

The change of direction of the robot's course motion (i.e., the turning process) is performed starting from the first walking cycle (Fig. 8, a). When one of the supporting feet is raised and the other is in contact with the supporting surface, the platforms are translationally moved relative to each other in the horizontal direction with simultaneous turning of the rotary part of the upper platform around the corresponding hinge. Thus, the raised supporting foot is lowered and at the same time changes its angular position relative to another supporting foot, which is currently in the phase of contact with the supporting surface (Fig. 8, a).

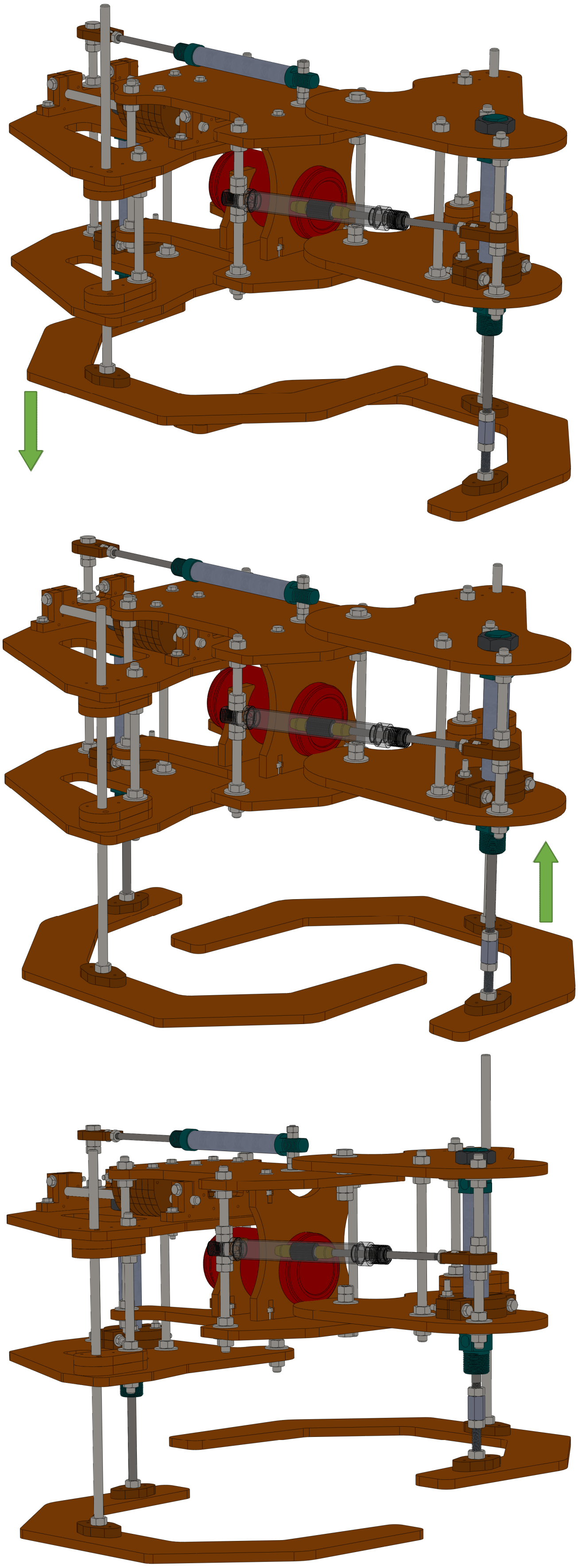
In the second walking cycle (Fig. 8, b), there begins to rise the second supporting foot, which during the first cycle was in contact with the supporting surface. At the same time, there is a horizontal movement of one movable platform relative to another one with simultaneous turning of the "free" platform around the supporting one (Fig. 8, b). As a result of this turning, the angular position of the raised foot relative to the lowered foot, which is in contact with the supporting surface, changes.



a

b

Fig. 8. Graphical representation of the robot's turning process



c

d

e

Fig. 8. (Continuation). Graphical representation of the robot's turning process

After the second walking cycle, the robot's feet occupy the same angular position relative to each other as at the beginning of the stepping cycle (i.e., the corresponding surfaces of the feet become parallel). The next three stepping cycles (Figs. 8, c, d, e) are completely similar to the usual stepping algorithm considered in the previous section of the paper (see Figs. 7, c, d, e). Thus, during one step, the robot has the possibility to change the direction of its course motion at an angle α (where α is the maximum angle of turning of the rotating platform 13 around the hinge 14, provided by extending-retracting of the piston rod of the pneumatic cylinder 15 (see Fig. 6)).

Formation of Timing Diagrams of Operation of Pneumatic Cylinders

The case of straight-line (rectilinear) motion of the mobile robot.

On the basis of the previously considered motion process of the mobile (walking) robot (Fig. 7), let us form timing diagram (cyclogram) of operation of its pneumatic drive. The pneumatic drive consists of three pneumatic cylinders. Two pneumatic cylinders are used for lifting/lowering of supporting feet. The other one is used for horizontal displacement of the movable platforms.

The first cycle of operation of pneumatic drive should provide the following operations (Fig. 9): a) "delay" ("stoppage") of the vertical pneumatic cylinder of the robot's active platform (this means that one platform is immovably staying on the supporting surface); b) motion (reverse run, retracting, back stroke) of the rod (pin) of the horizontal pneumatic cylinder; c) going down (forward stroke, direct run) of the rod of the vertical cylinder of the passive platform (which does not act upon the supporting surface).

The second cycle of operation of pneumatic drive should provide the following operations (Fig. 9): a) "delay" ("stoppage") of the vertical pneumatic cylinder of the robot's platform, which became active after the first cycle (this means that the second platform is immovably staying on the supporting surface); b) lifting (reverse run, back stroke) of the rod of the vertical pneumatic cylinder of the other platform, which became passive after the first cycle (which acted upon the supporting surface in the first cycle); c) motion (forward stroke, extending, direct run) of the rod of the horizontal pneumatic cylinder in the opposite direction to the one made in the first cycle.

The third cycle of operation of pneumatic drive should provide the following operations (Fig. 9): a) "delay" ("stoppage") of the vertical pneumatic cylinder of the robot's platform, which became active after the first cycle and remained active during the second cycle (this means that the second platform is immovably staying on the supporting surface); b) lowering (forward stroke, direct run) of the rod of the vertical pneumatic cylinder of the platform, which became passive after the first cycle and remained passive in the second cycle (this platform did not act upon the supporting surface in the second cycle); c) "delay" ("stoppage") of the rod of the horizontal pneumatic cylinder (because the passive platform has already moved relative to the active one at the distance that is equal to the length of one step).

The fourth cycle of operation of pneumatic drive should provide the following operations (Fig. 9): a) "delay" ("stoppage") of the vertical pneumatic cylinder of the robot's platform, which became active after the third cycle (this means that the first platform is immovably staying on the supporting surface); b) lifting (reverse run, back stroke) of the rod of the vertical pneumatic cylinder of the second platform, which became passive after the third cycle (this platform does not act upon the supporting surface in the fourth cycle); c) "delay" ("stoppage") of the rod of the horizontal pneumatic cylinder (because the passive platform has already moved relative to the active one at the distance that is equal to the length of one step).

The case of curvilinear motion of the mobile robot.

In contrast to the variant of rectilinear motion of the robot considered above, the proposed mechanism for changing the course motion of the robot involves the use of an additional pneumatic cylinder that rotates (changes the angular position) of one movable platform relative to the foot of another platform (Fig. 6). The robot turning process was described in detail in the previous section of the paper (Fig. 8). All walking cycles (raising and lowering the feet, relative movements of the platforms, etc.) for the cases of rectilinear motion (Fig. 7) and of turning process (Fig. 8) are similar. The only difference is the need to actuate the turning pneumatic cylinder, which must work synchronously with the pneumatic cylinder for horizontal movement of movable platforms. The updated cyclogram of operation of the robot's pneumatic system in the case of changing of its course motion is given in Fig. 10.

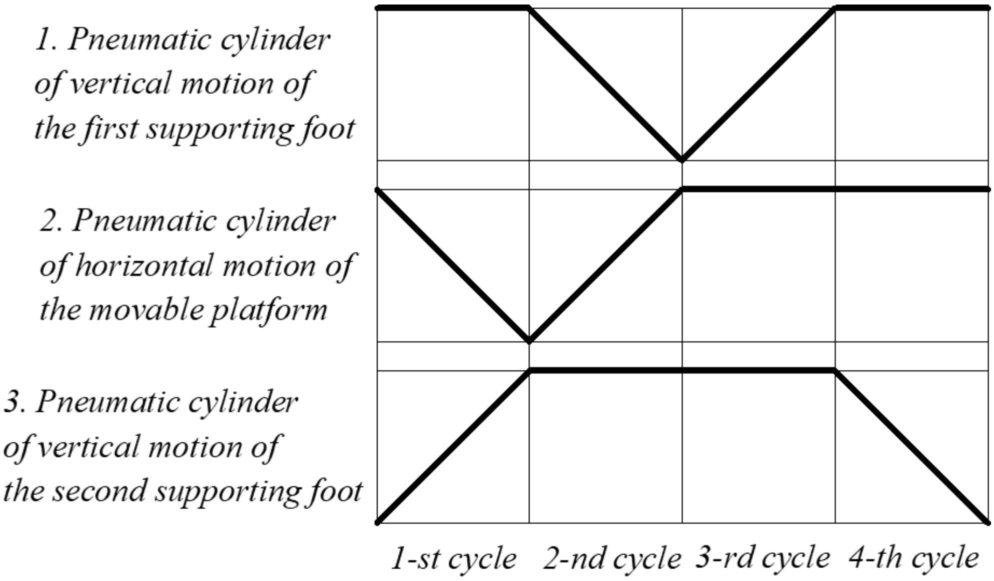


Fig. 9. Timing diagram of operation of the robot's pneumatic system during its rectilinear motion

During the first cycle of the stepping process (Fig. 10), the retraction (reverse run, back stroke) of the rod of the turning pneumatic cylinder must be ensured (i.e., the change of the angular position of the raised foot relative to the supporting foot). During the second cycle, there must be ensured the extending (forward stroke, direct run) of the rod of the turning pneumatic cylinder (i.e., the change of the angular position of the foot, which had been acting upon the supporting surface during the first cycle, and began to rise in the second cycle) causing the "alignment" of the moving platforms of the robot. During the third and fourth cycles there is provided the "delay" ("stoppage") of the turning pneumatic cylinder with the extended rod.

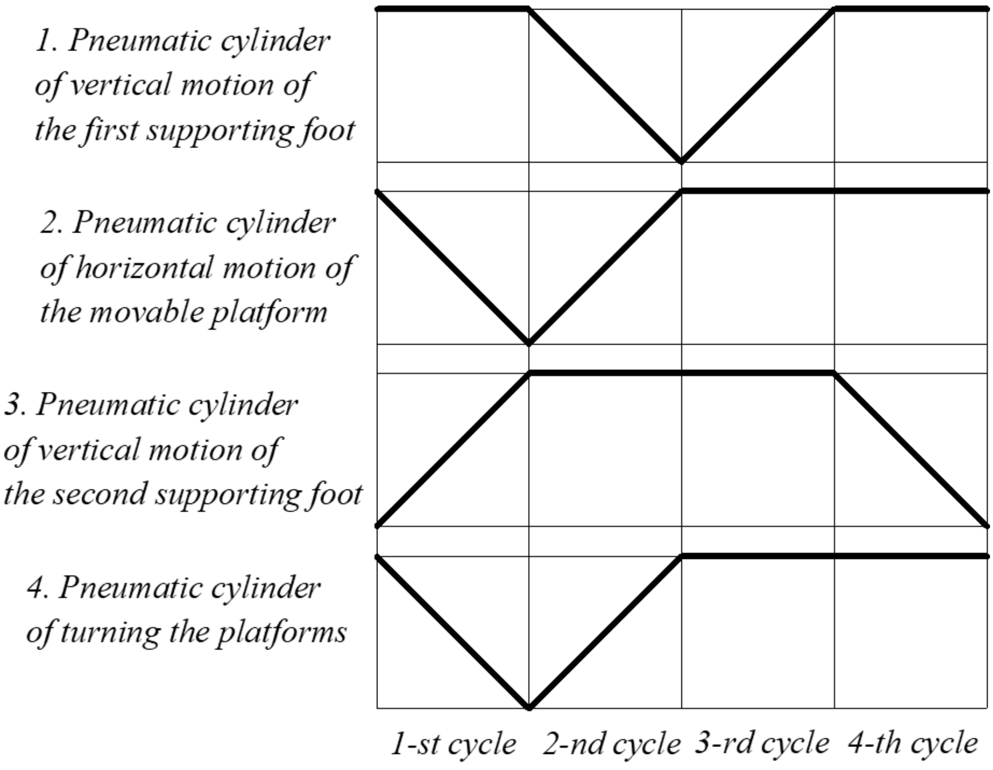


Fig. 10. Timing diagram of operation of the robot's pneumatic system during its turning (curvilinear motion)

Constructing Pneumatic Circuits of the Robot's Drive

The case of straight-line (rectilinear) motion of the mobile robot.

On the basis of the considered timing diagram of operation of pneumatic cylinders of the mobile robot (Fig. 9), let us construct the corresponding pneumatic circuit of the robot's drive (Fig. 11). The principal pneumatic circuit consists of the following components: three double-acting (two-way) cylinders providing direct and reverse run ($Д_1$, $Д_2$, $Д_3$); three two-position four-linear pneumatic control distribution valves (P_1, P_4, P_7), six two-position four-linear pneumatic distribution valves with end-sensors (P_2, P_3, P_5, P_6, P_8, P_9), two logical adding (summing) elements (I_1, I_2), starting distribution valve ("Start" button, P_{10}), and six regulating (pilot) air-flow constrictor with check (non-return) valves for providing the possibility of changing the intensity of air-consumption.

The proposed pneumatic circuit ensures the operation of the pneumatic cylinders in accordance with the prescribed program (timing diagram, Fig. 9). After pushing the "Start" button, the air flows through the ports (passages) of the distribution valve P_{10} if the piston of the cylinder $Д_3$ is located in the left end position. The air flows from the air-supply system to the control distribution valves P_4, P_7 providing the reverse run (back stroke) of the rods of the pneumatic cylinders $Д_2$ and the direct run (forward stroke) of the rod of the cylinder $Д_3$. Taking into account the necessity to ensure the simultaneous operation of two pneumatic cylinders during the first cycle, one logical adding (summing) element I_2 were used for registering the positions of the corresponding piston-rods with tappets of the pneumatic cylinders $Д_2$ and $Д_3$ during the stroke 1. The output signal from the adding (summing) element I_2 switch the control distribution valves P_1 and P_4. This provides the direct run (forward stroke) of the piston of the cylinder $Д_2$ and the reverse run (back stroke) of the piston of the cylinder $Д_1$.

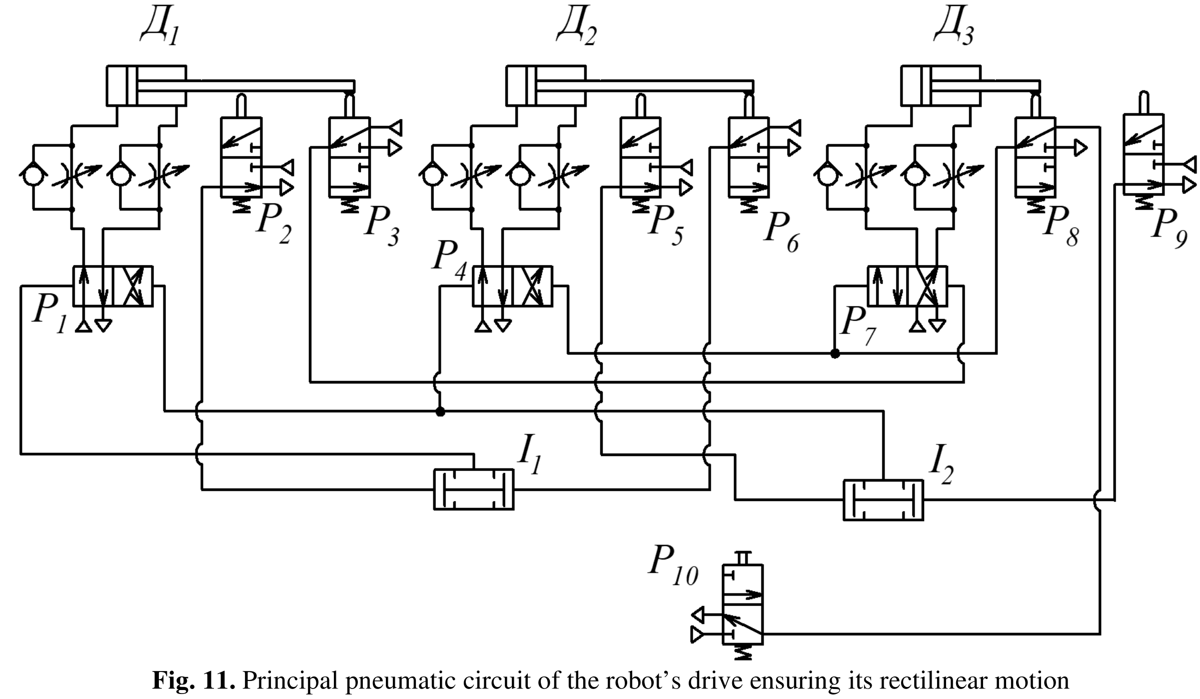


Fig. 11. Principal pneumatic circuit of the robot's drive ensuring its rectilinear motion

In order to start the stroke 3, it is necessary to register the end of performing the stroke 2. That is why the logical adding (summing) element I_1 is used in the pneumatic circuit. This element register the end of the stroke 2 (the end positions of the piston-rods with tappets of the pneumatic cylinders $Д_1$ and $Д_2$) due to adding (summing) the signals of the distribution valves with end-sensors P_2 and P_6. The logical adding (summing) element I_1 gives a command for performing the stroke 3 (the direct run (forward stroke) of the piston of the cylinder $Д_1$) by means of changing the position of the control distribution valve P_1. When the piston-rod of the cylinder $Д_1$ reaches its end-position, the distribution valve P_3 gives a command for performing the reverse run (back stroke) of the rod of the cylinder $Д_3$ by switching the distribution valve

P_7. At the end of the fourth stroke, the full cycle of the pneumatic system operation is performed. After this the following walking cycle is to be performed.

In order to stop the operation of the pneumatic system (and the cyclic stepping process of the robot) it is necessary to push the “Start” button (the starting the distribution valve P_{10}).

The case of turning (curvilinear motion) of the mobile robot.

According to the developed cyclogram (timing diagram) of operation of the driving pneumatic system of the mobile robot during its turning (curvilinear motion), the corresponding pneumatic scheme of connection and control of the pneumatic cylinders has been improved (Fig. 12). The principal pneumatic diagram consists of four double-acting (two-way) cylinders providing direct and reverse run ($Д_1$, $Д_2$, $Д_3$, $Д_4$); four two-position four-linear pneumatic control distribution valves (P_1, P_4, P_7, P_{11}), six two-position four-linear pneumatic distribution valves with end-sensors (P_2, P_3, P_5, P_6, P_8, P_9), two logical adding (summing) elements (I_1, I_2), starting distribution valve P_{10} (“Start” button for starting the rectilinear motion), starting distribution valve P_{12} (“Start-2” button for starting the turning process), and eight regulating (pilot) air-flow constrictor with check (non-return) valves for providing the possibility of changing the intensity of air-consumption to the corresponding cylinders (i.e., for changing the motion speeds of their piston-rods).

After pushing the “Start” button, while the “Start-2” button is not pushed, the compressed air is supplied from the pneumatic system and switches the control distribution valve P_{11}, as a result of which the rod of the pneumatic cylinder $Д_4$, which is responsible for turning the robot, is fixed in the extended position. This position of a rod of the turning pneumatic cylinder provides rectilinear motion of the robot. That is, when the "Start-2" button is not pushed, there takes place the stepping cyclogram shown in Fig. 9, and the pneumatic system operates similarly to the pneumatic system shown in Fig. 11. This stepping process has already been analyzed above.

When the “Start-2” button (starting distribution valve P_{12}) is switched on (pushed), the compressed air is supplied to the control distribution valve P_{11}, which controls the operation of the turning pneumatic cylinder $Д_4$. At the same time, the control distribution valve P_4 responsible for operation of the pneumatic cylinder $Д_2$ is supplied by the compressed air according to the same cyclogram as for the control distributor P_{11}. The pneumatic cylinder $Д_2$ sets into horizontal motion the movable platforms. Thus, due to the use of a two-position five-line starting distribution valve P_{12} it is possible to synchronize the operation of the pneumatic cylinders $Д_2$ and $Д_4$, and to implement the specified process of the robot stepping with the possibility of changing the direction of its course motion (turning).

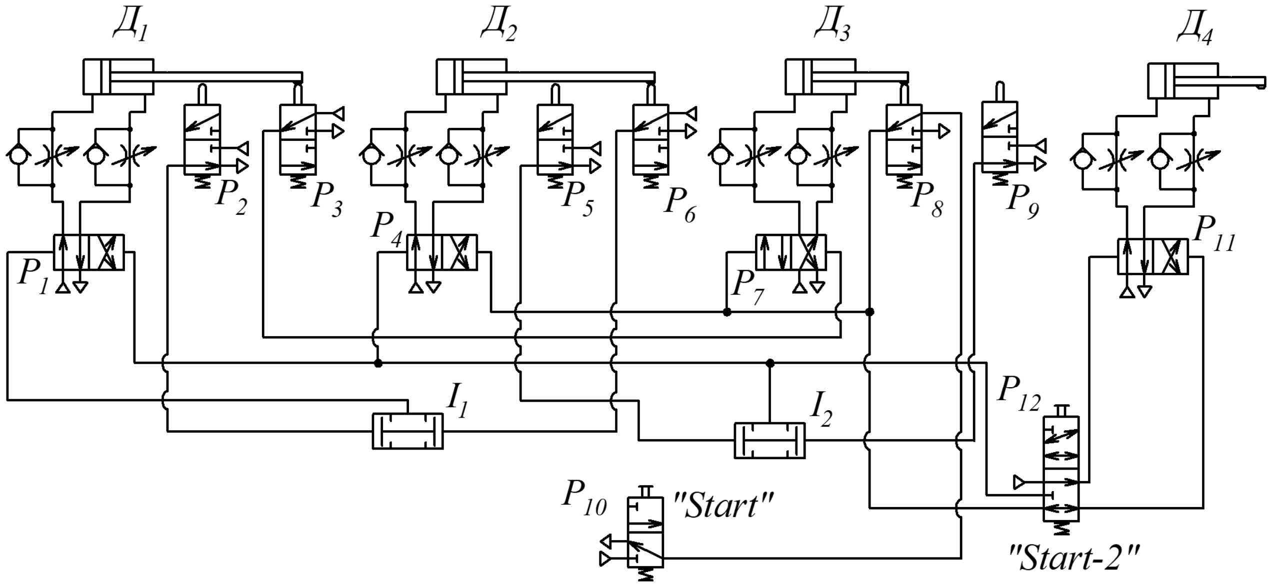


Fig. 12. Principal pneumatic circuit of the robot’s drive ensuring its curvilinear motion

Conclusions

In this paper, the improved design diagram of the mobile robotic system with orthogonal walking drive and pneumatic actuation system is proposed (see Fig. 6). The robot is equipped by two movable platforms and two feet. The basic peculiarities of its operation are considered, and the processes of the cyclic walking are described taking into account the possibilities of rectilinear (Fig. 7) and curvilinear (Fig. 8) motion of the robot. Based on the results of the performed analysis of the walking processes, the timing diagrams of operation of the actuating pneumatic cylinders were constructed (Figs. 9, 10) and the corresponding pneumatic circuits were developed (Figs. 11, 12).

While carrying out further investigations of the subject of the paper, it is necessary to derive the laws of motion of the robot's members, which provide its programmable cyclic walking motion in accordance with the substantiated timing diagrams of the pneumatic cylinders operation. In addition, it is necessary to perform the modelling of the robots motion using the derived motion equations and to simulate the robot's operation using its 3D-model designed in SolidWorks software. The simulation model of the robot's pneumatic system should be implemented in applied software FESTO FluidSim Pneumatics.

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