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Mobile Systems with Vertical Displacement Robots*

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This paper concerns the study of the problem of fabricating mobile systems having vertical displacement robots. Methods of facilitating robot motion along vertical surfaces, and the advantages and drawbacks of each method are examined. Results are given of modelling the orientation and locomotion of the transport module of a vertically mobile robot. Fuzzy model theory is used as the mathematical apparatus for modelling. An analysis is given of the mechanical system of the vertically mobile robot for a variety of industrial applications. Cleaning, painting, cutting, and inspection operations are considered as possible industrial applications. Robot designs that permit moving from one surface to another are given. Results are also provided from research on grippers used in vertically-mobile robots.

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INTRODUCTION

Extensive research has been conducted in recent years in developed countries for the purposes of fabricating mobile tele-controlled or remote-controlled robots capable of moving along horizontal, inclined or vertical surfaces. Such robots must be capable of overcoming or avoiding obstacles encountered in their path, of returning to the required initial (start) position, set up to execute the required industrial operations and to perform such execution [1–4]. Such robots and robotics complexes are needed because of increasing demands on industrial operation performance, accident and emergency conditions, and conditions that are hazardous or difficult for a human operator. Emergency conditions or environments may have elevated levels of radioactivity, high temperatures, high gas concentrations, etc. It may, for example, be necessary to decontaminate facilities, including walls and floors, to initiate emergency operations in atomic power plants, to fight fires, work in construction, assembly, or paint structures at high elevations or construct a variety of structures, repair ship hulls in dock, etc. [5–9].

In many cases it is sufficient to use vertically- and horizontally-mobile robots. However, there are often problems such as those in the case of facility decontamination when the automation equipment must have a higher degree of mobility and be capable of carrying out the required industrial operations by moving both along horizontal and vertical surfaces as well as floors.

Research and development of high-mobility robots, including vertically mobile robots (VMR),have been progressing rapidly over the last several decades in support of national and international programs in Japan, the USSR, the US, Great Britain, France, and other nations. Universal vacuum devices (independent of the surface material) are widely used as grippers for gripping vertical surfaces and floors; the robots also use controlled magnetic grippers designed for robot gripping of ferromagnetic surfaces [10–14].

Foreign companies have also had significant results with industrial applications of vertically mobile robots, including Tokyo Gas Limited, Hitachi (Japan), International Robotics Technology (USA), Portsmouth Polytechnic (Great Britain), etc. As demonstrated by the First International Robot Olympiad [15] held in September of 1990 in Glasgow

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(Great Britain), the USSR achievements in this field are at a level comparable with that found internationally: two vertically mobile robots manufactured by the Institute of Problems in Mechanics of the USSR Academy of Sciences were awarded medals in this Olympiad.

Further development of this new field in robot engineering has required research aimed at improving robot mobility and maneuverability, as well as robot intelligence and expanding technological capabilities and effective fields of application.

Mobility and maneuverability can be improved by allowing robots to advance from the floor to walls and from walls to ceiling, etc., during movement. This is a very difficult problem, with certain achievements accomplished to date that, however, require their own further development. One of the methods that yields improved mobility involves installing a vertically mobile robot on a mobile carrier-robot (dolly or carriage) capable of moving along horizontal surfaces. The vertically mobile robot attaches itself to vertical surfaces automatically in response to corresponding control commands. The Institute of Problems in Mechanics of the USSR Academy of Sciences and the Institute of Engineering Physics of the USSR Academy of Sciences have jointly developed a high mobility and reliability robotics complex. The results of this design development will be discussed in this paper.

The intelligence of the complex is improved by installing corresponding sensors (radar, ultrasound, tactile, industrial vision, etc.), by establishing feedback, developing special scene analysis algorithms, developing databases on external environments and automatic decision-making. The significant advantages provided by the future development of such complexes include the possibility of using them in working environments and in emergencies where it is hazardous or difficult for humans (high radiation, high temperature, toxic or poisonous gases, high elevations for industrial operations as well as other emergency situations).

This paper presents results from research devoted to the problem of fabricating vertically-mobile robots: specifically, the realization of mechanical motion along vertical surfaces by various means, modelling of motion, investigation of maneuverability and locomotion, analysis of mechanical systems for effective execution of different industrial operations including moving from one surface to another at right angles, investigation and development of vacuum grippers.

To improve maneuverability and extend functional capabilities, the mobile robotics complex includes an automatically controlled horizontally-mobile robot, a connected vertically-mobile robot, and a manipulator for providing adhesion of the vertically-mobile robot to the surface (Fig. 1). The complex can be controlled from a single control panel in an autonomous, supervisory, or automatic mode. The control panel is located in a separate facility at a safe distance from the operations site of the robot in a certain emergency environment.

1. Methods of Realizing VMR Mobility Along Vertical Surfaces

The following methods are used to realize mechanical motion of the transport module along a vertical surface.

The first is a discrete step method. In this method, the robot platform travels in discrete steps, with one group of grippers clamping in the interval between the steps and the other group releasing contact in this interval. Variants of this method include a discrete step method with uncontrolled locomotion speed, and a discrete step method with controlled

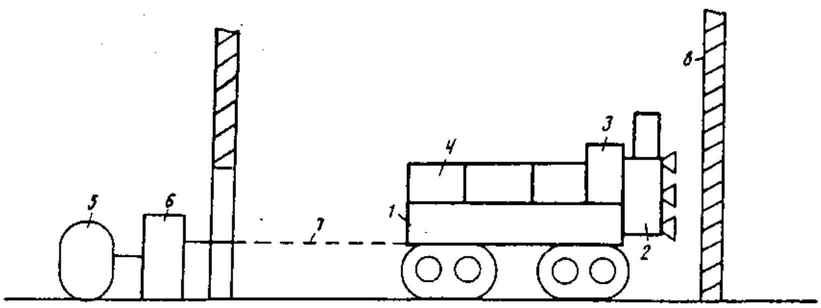


Fig. 1. High mobility robotic system: *1*) horizontally-mobile robot; *2*) vertically-mobile robot containing industrial equipment; *3*) interface between vertically and horizontally mobile robots; *4*) power source; *5*) operator; *6*) control panel; *7*) control channel; *8*) working surface.

locomotion speed within each individual step. The advantages of this method include easy realization and performance reliability. The drawbacks include low speed and limited functional capabilities. A continuous speed of the robot platform cannot be achieved using this method.

The second method of locomotion along a vertical surface is the continuous step method. This method makes possible continuous locomotion of the robot platform in a step mode, whereby one group of grippers initiate gripping and the other group is released without interrupting platform motion. This method extends the functional capabilities of the robot by achieving a continuous speed of the robot platform, and hence the industrial equipment mounted on the platform. However, the algorithm and the control system are more complex.

The third method is the crawler method. This method makes it possible to obtain a continuous robot platform speed by employing a crawler mechanism. The varieties of this method include a method using internal grippers in the crawler mechanism and the crawler method utilizing independent grippers. In the latter case, the crawler mechanism is used only to initiate robot translational motion within the free range of the drive when the grippers are fixed. The primary advantage of the gripper method of locomotion is a high degree of locomotion and reliability. The drawbacks include increased complexity and weight.

The fourth locomotion method is the anthropomorphic method. In this method, motion is initiated by means of multilink support members that simulate the motion of living organisms, specifically insects [15]. This method requires a large number of degrees of freedom and a developed control system. The complexity of the structural realization in this case reduces the performance reliability of the complex as a whole. However, this method yields the best flexibility for overcoming a variety of obstacles.

The fifth method of moving along vertical surfaces is the parallelogram method. This method is named after the features of its realization, which utilizes the property of a parallelogram which allows alternate motion of its parallel, hinged sides. In this case, there is no need to use two platforms which, in combination with the absence of gripper elevation and descent drives, make this design simple and light [5]. When grippers on one side of the parallelogram are used for clamping, the second side moves in a given direction, moving the attached free grippers by sliding along the surface. This method is the fastest, although it has a comparatively low reliability and limited capabilities with respect to industrial applications, since there is no working support platform. Moreover, this design is insufficiently rigid and has limited lift capacity.

2. Modelling the Orientation and Locomotion of the VMR Transport Module

The correct synthesis of VMR structure to account for the specific nature of the problem addressed, which includes advancing the industrial equipment along a selected trajectory, specifically, under conditions of uncertainty with regard to the external situation, requires preliminary modelling of the orientation and locomotion of the VMR transport model.

There are a number of special features of employing models in the control of a complex multilink system such as a mobile VMF. The primary difficulty lies in insufficient correlation between events in the external environment and the model representation of these events accessible to the robot's artificial intelligence. Moreover, there are many variables in a multiply-coupled system, and therefore when generalized model concepts are used it involves reduction of data and fuzziness in model descriptions. The representation of the external environment in the knowledge base of an autonomous mobile robotics system using visual information is purely of a natural-language descriptive nature. Therefore, the linguistic description of events in the knowledge base must be translated into an adequate analytic form. This creates certain difficulties in the analysis and simulation of mobile robot systems.

Fuzzy set theory [16–18] has therefore been valuable in the development of a model of VMR orientation and locomotion. This theory makes it possible to use nonfuzzy solutions ("defuzzifiers") with fuzzy raw data. The model can take into account both the descriptive (generalized) nature of input data and uncertainty in robot behavior and perception associated with the insufficient correlation between external events and their subjective representations. Various possible approaches to describing such fuzzy models of autonomous robot motion can be found in [16–20].

Fuzzy model theory [17] and, specifically, the modified moving object model proposed in [16] is used as the mathematical apparatus for modelling the orientation and motion of VMRs.

The procedural rules of a fuzzy controller are postulated as linear equations with variable coefficients.

As in [16], the procedural i-th control rule ($i = 1, 2, \ldots, m$) is written as

$$R^i : x_1 \text{ is } A_1^i, \quad x_2 \text{ is } A_2^i, \ldots, x_n \text{ is } A_n^i,$$

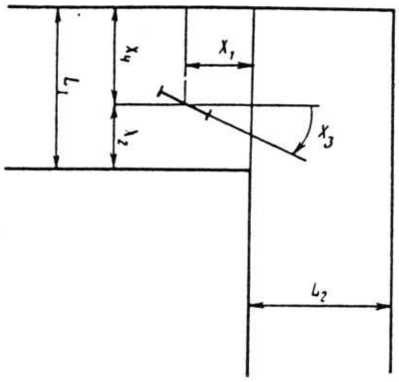


Fig. 2. Determination of the input variables X_1–X_4.

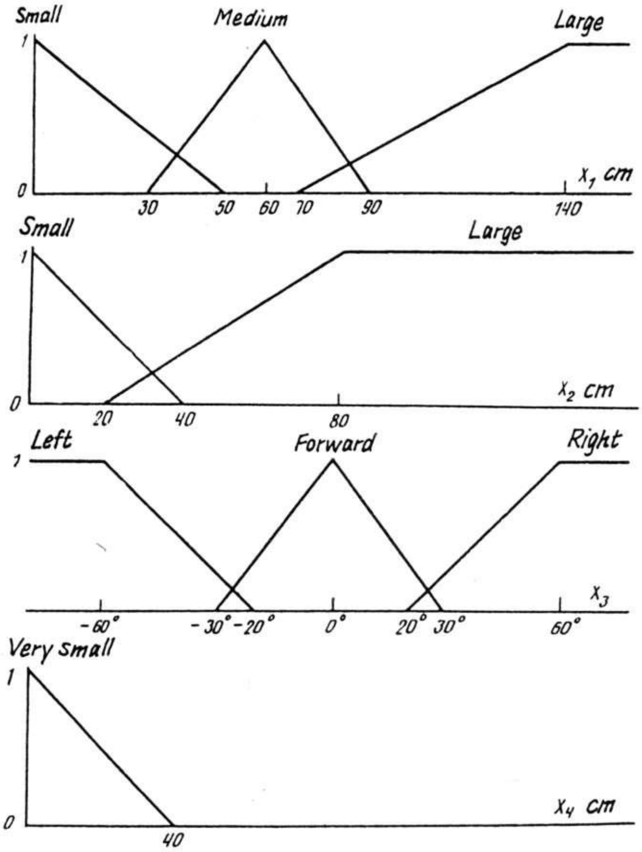


Fig. 3. Membership function for the fuzzy variables.

$$\to y^i = P_0^i + P_1^i x_1 + \ldots + P_n^i x_n, \quad j = 1, 2, \ldots, n,$$

where A_j^i are the fuzzy variables that characterize the x_j input variables in linguistic form; P_j^i are the coeffi[illegible] equation for the rule R^i; y^i is the turning angle of the VMR relative to its preceding position. The [illegible] of the fuzzy set X is written as $\mu(X)$ and is approximated by $(R-L)$-type functions [16]. The variables A_j^i [illegible] in each specific case by the subject domain and are described below for a VMR (Fig. 2). Based [illegible]

$x_1^0, \ldots, x_n^0$ the output (the turning angle of the VMR through y^0 degrees) is determined by averaging the weights of the variables: y^i:

$$y^\circ = \sum_{i=1}^{m} W^i y^i \Big/ \sum_{i=1}^{m} W^i, \tag{2.2}$$

$$W^i = \bigwedge_{j=1}^{n} \mu_j^i (x_j^\circ), \quad j=1, 2, \ldots, n. \tag{2.3}$$

The number of fuzzy rules m in the control algorithm will correspond to the number of combinations of linguistic variables A_j^i ($j = 1, \ldots, n$; $i = 1, \ldots, m$) that can be used to describe the given robot position ($x_1^0, \ldots, x_n^0$).

Identification of the rules of the fuzzy control algorithm involves, in accordance with [16, 18], defining:

—the number of fuzzy spatial gradations at the input (such as small, medium, and large for x_1, small and large for x_2, etc.);

— the membership functions μ (x) of these fuzzy linguistic variables;

— the coefficients in the deductions of the logic control rules.

The operator can monitor the rotation and trajectory of the VMR output to the monitor screen. The VMR has a constant speed and therefore only its rotation is monitored.

The fuzzy control rules are determined, in accordance with [16,18], to minimize the output error (which is equal to the difference of the results at the output of the model and the output of the process). After the membership functions are selected in accordance with (2.2), the coefficients $P_0^i - P_n^i$ are determined in a manner that minimizes the resultant error. Since the latter is nonlinear with respect to the parameters of the membership function, the process of identifying the coefficients is repeated in conjunction with optimization of the membership functions [17].

Control is therefore realized in the model as twenty control rules. Consistent with [16, 18], four variables x_i, i = 1, 2, 3, 4 are selected at the input (Fig. 2), where x_1 is the distance from the VMR to the first rotation angle (see Fig. 2); x_2 is the distance from the floor; x_3 is the direction of robot motion; and x_4 is the distance from the ceiling. The value x is obtained as the output as the output result: the turning angle of the VMR.

Table 1

Fuzzy variables in the control rules

Rule	X_1	X_2	X_3	X_4
R^1	-	-	L	VL
R^2	-	-	F	VL
R^3	S	S	L	-
R^4	S	S	F	-
R^5	S	S	R	-
R^6	S	L	L	-
R^7	S	L	F	-
R^8	S	L	R	-
R^9	M	S	L	-
R^{10}	M	S	F	-
R^{11}	M	S	R	-
R^{12}	M	L	L	-
R^{13}	M	L	F	-
R^{14}	M	L	R	-
R^{15}	L	S	L	-
R^{16}	L	S	F	-
R^{17}	L	S	R	-
R^{18}	L	L	L	-
R^{19}	L	L	F	-
R^{20}	L	L	R	-

S — small, M — medium, L — large, VL — very large, L — left, R — right, F — forward.

Table 2

The coefficients in Eq. (2.1) for logic control rules $R^1 - R^{20}$

Rules	P_0	P_1	P_2	P_3	P_4
R^1	3.000	0.000	0.000	−0.045	−0.004
R^2	3.000	0.000	0.000	−0.030	−0.090
R^3	3.000	−0.041	0.004	0.000	0.000
R^4	0.303	−0.026	0.061	−0.050	0.000
R^5	0.000	−0.025	0.070	−0.075	0.000
R^6	3.000	−0.066	0.000	−0.034	0.000
R^7	2.990	−0.017	0.000	−0.021	0.000
R^8	1.500	0.025	0.000	−0.050	0.000
R^9	3.000	−0.017	0.005	−0.036	0.000
R^{10}	0.053	0.038	0.080	−0.034	0.000
R^{11}	−1.220	−0.016	0.047	−0.018	0.000
R^{12}	3.000	−0.027	0.000	−0.044	0.000
R^{13}	7.000	−0.049	0.000	−0.041	0.000
R^{14}	4.000	−0.025	0.000	−0.100	0.000
R^{15}	0.370	0.000	0.000	−0.007	0.000
R^{16}	−0.900	0.000	0.034	−0.030	0.000
R^{17}	−1.500	0.000	0.005	−0.100	0.000
R^{18}	1.000	0.000	0.000	−0.013	0.000
R^{19}	0.000	0.000	0.000	−0.006	0.000
R^{20}	0.000	0.000	0.000	−0.010	0.000

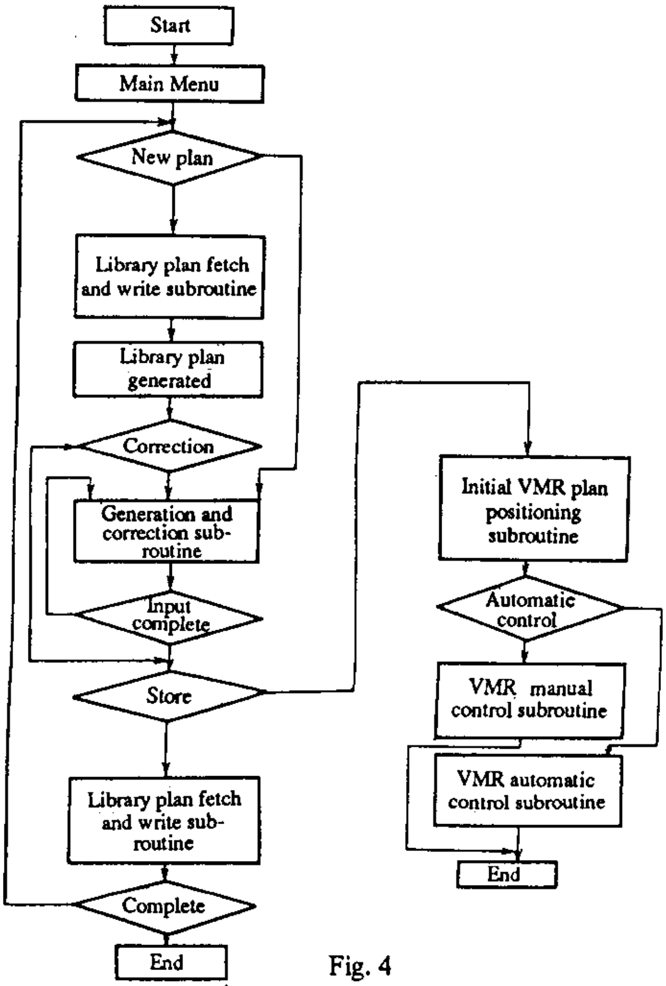


Fig. 4

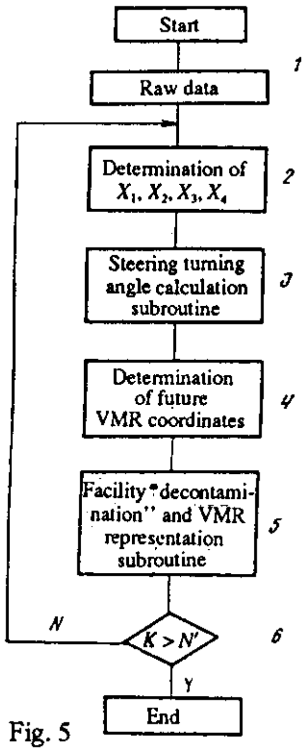


Fig. 5

Fig. 4. Flow chart of the robot orientation and locomotion simulation program.

Fig. 5. Flow chart of the robot fuzzy algorithm control subroutine.

Three fuzzy variables are taken for fuzzy separation of the input space for x_1, two for x_2, three for x_3 and one for x_4. The membership functions and coefficients P_j^i are determined in [16] based on an analysis of approximately 500 standard "input-output"cases obtained for the specific selected 18 motion trajectories. Figure 3 shows the identified functions associated with the linguistic levels of the input variables of the VMF. Tables 1 and 2 provide the logic control rules and the coefficients P_j^i.

The program that simulates on-screen VMR motion in various aspects was developed by O.I. Vasil'yeva and V.N. Raldugin.

The program:

—makes it possible to initiate manual and automatic control of the VMR;

—can be used to develop and use a library of standard positional plans;

—makes it possible to display new plan scenarios by means of a cognitive graphics (CG) block and to correct library plans during operation when new information is obtained from the VMR.

A flow chart of the program is given in Fig. 4.

A flow chart of the subroutine initiating automatic control of VMR motion is given in Fig. 5. The subroutine makes it possible to initiate automatic VMR motion along the perimeter of a facility with a given layout based on the fuzzy logic algorithm and the procedural control rules.

Block 1 generates the following raw data:

1) the initial VMR coordinates;

2) Tables 1 and 2 of the coefficients P_j^i and the procedural rules;

3) the membership function for the variables x_1, x_2, x_3, and x_4, in accordance with Fig. 3;

4) the set of linguistic variables A_j^i.

Block 2 which generates the values of x_1, x_2, x_3, and x_4 (the input variables characterizing the position of the VMR) operates on the basis of knowledge of the VMR coordinates and information on the facility plan. In practice, this is equivalent to the VMR measurement of the distances to the floor and obstacles by means of sensors.

The subroutine used to calculate the turning angle of the VMR (Block 3) uses the fuzzy logic scheme and the procedural control rules previously given. The linguistic gradation and membership functions of the variables x_1–x_4 shown in Fig. 3 are used. The Block 3 subroutine includes the following component parts: 1) conversion of the input variables $x_1 - x_4$ into linguistic form A_j^i ($j = 1, \ldots, 4$; $i = 1, \ldots, 20$); 2) determination of the sets $A_1^i - A_4^i$ and the membership functions $\mu_j^i(x_j)$ for the given variables x_1–x_4 with the correspondence conditions $x_1^i \rightarrow A_1^i$, $x_2^i \rightarrow A_2^i$, x_3^i, $\rightarrow A_3^i$, $x_4^i \rightarrow A_4^i$; 3) identification of the number i of the control rule R^i in fuzzy control procedure; 4) calculation of the value of the turning angle y_n for each given step in the cycle statement.

The future VMR coordinates (Block 4) are determined based on recurrent equations that include the step, the current coordinates of the VMR and the turning angle y_n for the given step in the cycle.

The VMR generation and facility "decontamination" subroutine (Block 5) is used to generate an image of the robot on a screen and to eliminate spots: domains that characterize radioactive contamination (if the VMR route passes through them). This produces a graphical representation of the purification of the contamination zone after the VMR has passed through.

The conditional jump (Block 6) monitors the completion of the route. Here K is the number of the wall along which the VMR is moving; N' is the total number of obstacles.

The proposed modelling scheme allows automatic VMR locomotion facilities within a variety of layouts and different obstacles with virtually no operator participation. The necessary condition for this operating mode is availability of the information regarding the location of the robot relative to the floor of obstacles (x_1–x_4). In practice, this is achieved by mounting a sensor on the VMR that measures the required distances.

Figure 6 shows the route covered by the VMR from modelling of the robot motion in the automatic control mode. Note that the results from simulating obstacle avoidance and VMR travel along the perimeter of a nuclear power plant service facility demonstrated the accurate performance of the proposed fuzzy VMR robotics control algorithm.

3. Analysis of the VMR Mechanical System for Application to a Variety of Engineering Problems

The structure of the VMR may vary depending on the task executed by the robot while the modular design of the overall complex is retained.

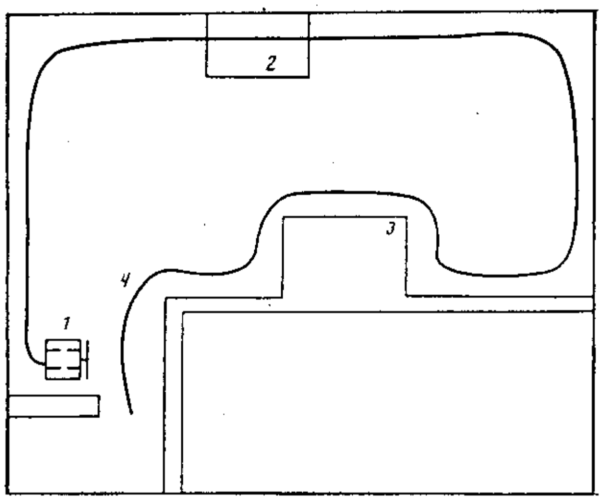


Fig. 6. Simulation of robot motion on the computer screen: *1*) robot; *2*) radioactive contamination zone; *3*) obstacles; *4*) robot route in automatic control mode.

The primary principles used in modifying the VMR structure can be determined by analyzing realizations of the complex for such applications as cleaning, painting, cutting, and inspection.

Vertical surface cleaning operations are required in a variety of industrial applications such as window washing of high-rise buildings, decontamination of structural surfaces in atomic power plants, and other applications. The structural features of the transport module are determined by the requirements for improved robot maneuverability to achieve coverage of the entire surface area independent of its configuration. Therefore, on the one hand, the transport module must be comparatively small in size and, on the other, must provide a sufficient cargo-carrying capacity to support the weight of the cleaning systems mounted on the transport module and the weight of the detergent containers as well as the weight of the associated pipes and tubes. This problem is solved by further developing the gripper system while maintaining the overall size of the robot platforms. When cleaning fragile surfaces such as glass, the metallic elements of the working surface are removed from the grippers, at the same time that such elements are commonly necessary when cleaning concrete surfaces with significant irregularities. The specific nature of cleaning radioactive contamination from surfaces is the requirement for complete automation. This means that the VMR design must include an additional automatic interface between the transport module and the horizontally-mobile transport system. This interface delivers the robot to the working area, places it on the surface to be cleaned, removes it after the completion of the operation and returns it to its initial position in an automatic mode. Figure 7 shows a photograph of an experimental complex that executes the described operational algorithm. This complex, which was developed at the Institute of Problems in Mechanics in conjunction with the Institute of Engineering Physics Problems, contains a self-centering automatic interface in the VMR transport module, which guarantees a reliable link between the module and the horizontally-mobile transport system when there are deviations from the initial problem position of ± 3 mm when removed from a vertical surface. In this case the detergent containers and the vacuum used to run the brushes mounted on the VMR are placed on the horizontally mobile transport robot. This relieves the VMR transport module of the additional weight and thereby improves its mobility. Improved noise immunity in the communications units of the complex control system is important for this application; such improved noise immunity is achieved by using available fiber-optic communications equipment.

When the VMR is used for painting, it is possible to simplify the transport module design by constructing the operational module with an independent manipulator. The manipulator holds a paint sprayer whose trajectory is not only determined by the transport module as it moves, as in the cleaning case described above, but also by manipulator motion. Figure 8a shows the resulting trajectory of such combined motion. When a constant speed of the transport module is necessary for uniform painting, drives that are synchronized through the control system are installed on each of the robot platforms. One VMR design version for painting operations is shown in Fig. 8b. It is characterized by a compact design and a relatively high speed. The paint is fed by means of an ejection pump installed on the robot.

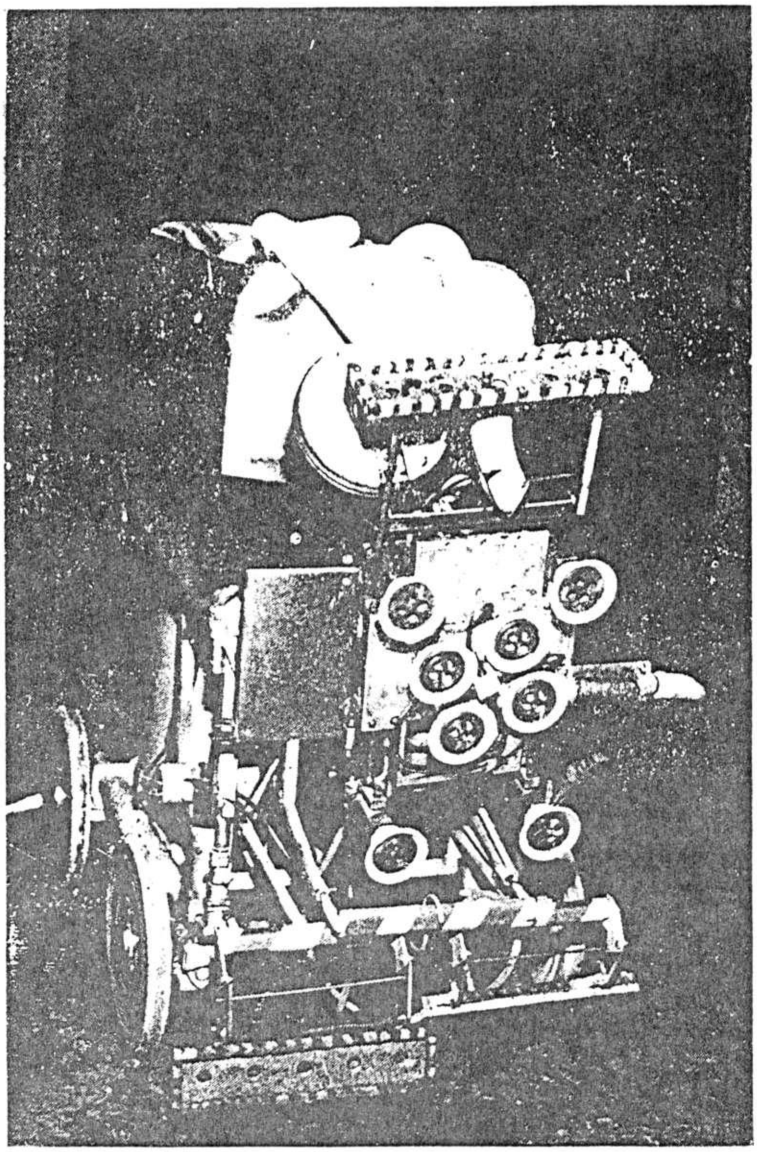
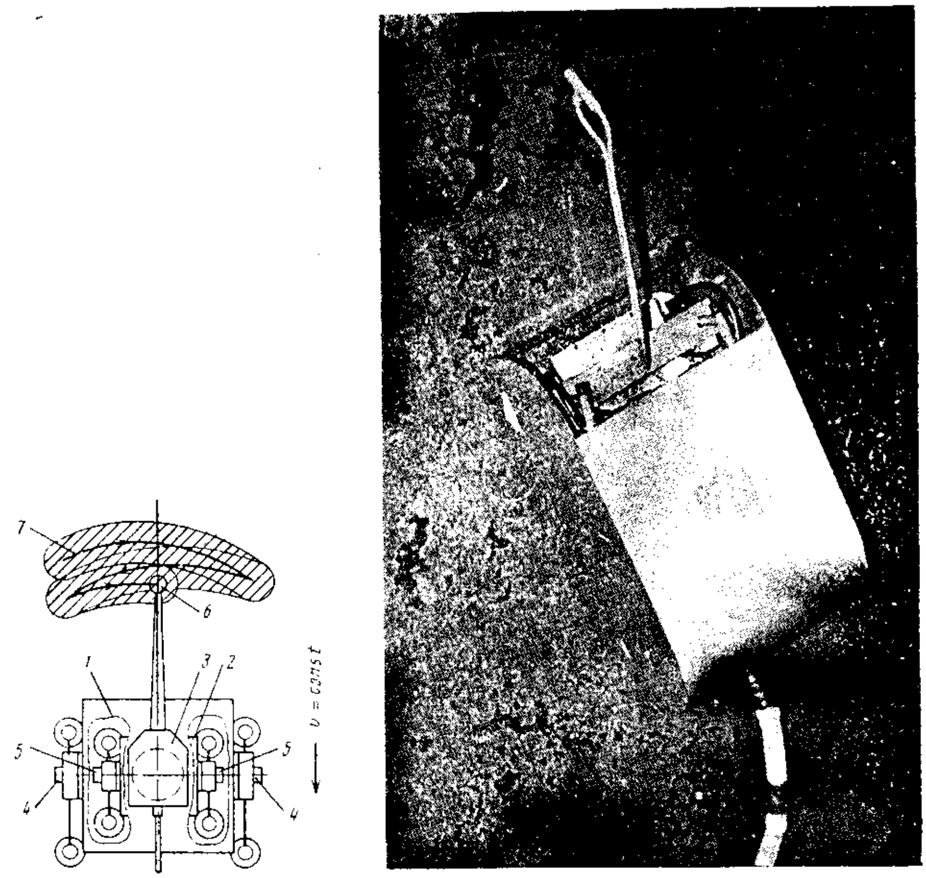


Fig. 7. Remote-controlled robotics cleaning complex.

The problem of cutting metallic surfaces by means of a VMR involves certain difficulties in the implementation of the transport module and the operational module. For example, to cut a hole in a reservoir wall (in fire-fighting operations) it is necessary to lift heavy machinery up to 40 kg in weight to a height of up to 20 m, and to allow the cutter to run along the hole contour over a total length of up to 10 m within a given period. The optimum method of solving this problem is to employ two tools, in this case two cutters. A robot with such a structural design is shown in Fig. 9. Two operational module cutters are mounted to be fixed relative to the robot center, which follows a trajectory that allows the cutters to cut along the contour of the hole. In this case the control system must be capable of realizing five switching points in accordance with the operational cycle diagram of the robotic equipment shown in Fig. 10. An overall view of the robot containing the cutting module is shown in the photograph (Fig. 11). When the robot is used in fire-fighting applications, the chassis is manufactured with a casing fabricated from TK-11-TOA heat-resistant metal-coated silica fiber to provide thermal protection, thereby allowing the robot system to retain functional capacity at temperatures to 300°C. In this case, the transport module includes an air-conditioning unit that should be installed using the output lines of the pneumatic actuator mechanisms employed in the robot drive devices and grippers [9].



a b

Fig. 8. Painting VMR. a: Configuration for executing painting operation: *1*) external platform; *2*) internal platform; *3*) rotator; *4, 5*) speed regulators; *6*) paint sprayer; *7*) paint sprayer trajectory. b: Overall view of painting VMR.

Surface inspection by means of a VMR that involves, aside from direct monitoring and measurement operations, such operations as surface quality diagnostics using a remote camera, also makes it possible to employ input information for robot navigational purposes. Test results for the robot shown in Fig. 2, which was equipped with an ultrasonic sensor, have demonstrated that it is capable of detecting obstacles at distances up to 2 m. Therefore the system is capable of timely transmission of feedback signals to the control system, which compensates the robot trajectory in order to bypass a detected obstacle. This property is particularly important when the robot travels under uncertain terrain conditions using remote control. Another example where measurement information is used is automatic searching for a reliable surface grip site for the robot. When the robot supports make contact with the surface, the surface quality sensor will, upon detecting defects below the support that will interfere in gripping, transmit a signal to the control system to move the supports to another position. The robot structure therefore includes an adaptation unit that expands its functional capabilities. This permits the construction of more flexible systems, one of which includes an inspection system for vertical piping with local joints. Figure 13 shows a VMR design for moving inside jointed piping. Diagnostic equipment can be installed on the robot. Robot motion is initiated by means of a power cylinder and uses alternate adhesion of the supports on the support tracks. When no joints (bends) are present in the pipeline, the sensors do not make contact with its surface, and the robot travels rectilinearly. In this mode, the correction valves open to the outside atmosphere; there is no control signal at the output of the "OR" element and the power valve connects the empty cavity of the power cylinder to the sealed chamber. Upon approaching a pipe bend, one or two sensors make contact with the internal surface of the pipe and transmit signals to the corresponding correction valves. These valves control the correction cylinders to advance the front belt around the cylinder in the direction that breaks sensor contact with the pipe surface. Three sensors arrayed in increments of 120° in the pipe cross-section can be used spatially to track an arbitrary bend in the pipe axis. When at least one sensor makes contact with the pipe surface, robot

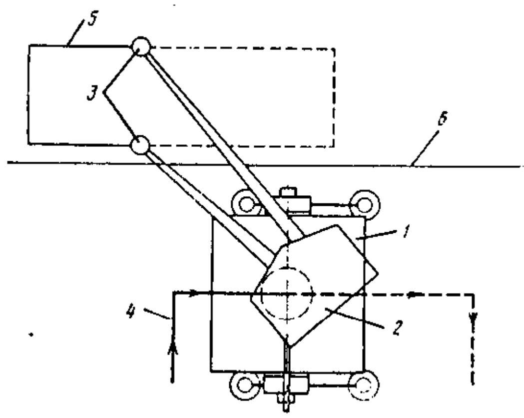


Fig. 9. Design for executing a hole cutting operation: *1*) transport module; *2*) industrial module; *3*) cutters; *4*) trajectory of robot center; *5*) contour of cut hole; *6*) boundary of travel surface.

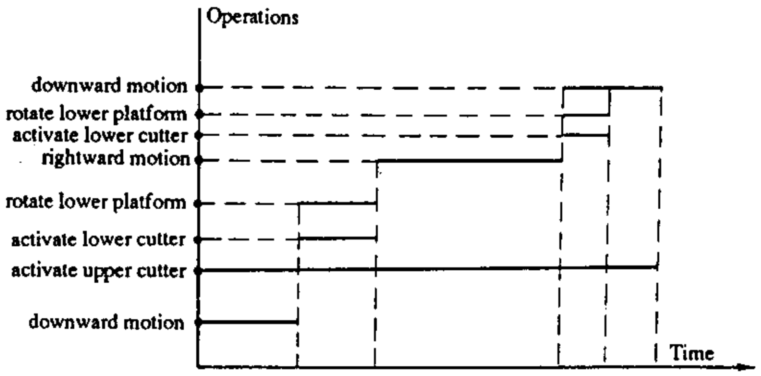


Fig. 10. Operational cycle diagram of industrial equipment for cutting an enclosed contour.

translational motion is halted, since a signal that connects the empty cavity of the power cylinder to the outside air through the power valve appears at the output of the "OR" element. After the position of the front belt is corrected, translational motion of the robot resumes until the power cylinder has completed its cycle. In the case of significant bends in the piping there will be several corrections to the position of the front belt per power cylinder cycle. After this process, the front belt attaches to the pipe surface, while the rear belt is tightened against the front belt. This motion cycle then repeats.

One promising direction for VMR development is to construct robots that are capable of automatic transmission from one surface to another. This class of robots in some sense integrates the capabilities of all VMR designs examined here. Figure 14 shows the design of a robot capable of crossing over to a surface at any angle of inclination with respect to the direction of motion (both in sign and magnitude). This design contains an intergrated drive for two platforms containing a tracking mechanism with internal grippers, and an automatic platform direction corrector for use when the robot crosses from one surface to another. Robot rectilinear motion is initiated by a power drive that advances the tracking mechanism containing the grippers. In this case the power drive must be capable of separating only a single gripper at each time from the travel surface, while the device is held by the sum of all grippers in contact with this surface. To make it possible to pass through surface irregularities during robot motion, the rod end cavities of the correction cylinders are coupled to the external air through corresponding valves, which imparts the necessary flexibility to the design. When crossing to a surface that forms an angle of up to 90° or greater with the initial surface (a leftward turn in Fig. 14) the obstacle sensor makes contact with this surface and, through the probe, activates a switch, which in turn initiates the corresponding correction cylinder. Since the correction cylinders are connected to the front platform, it crosses over to the new surface. If this surface has an inclination exceeding 90°, the obstacle sensor will depress the spring-loaded element of the probe during the crossing without imparting mechanical drag and, at the same time, hold the vertical switch in the closed position. The signal from

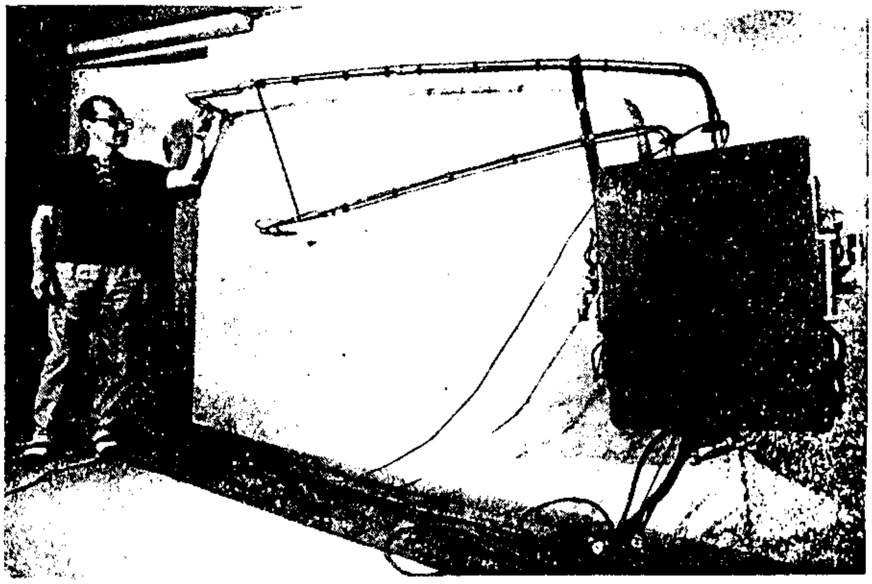


Fig. 11. An overall view of robot with cutter module.

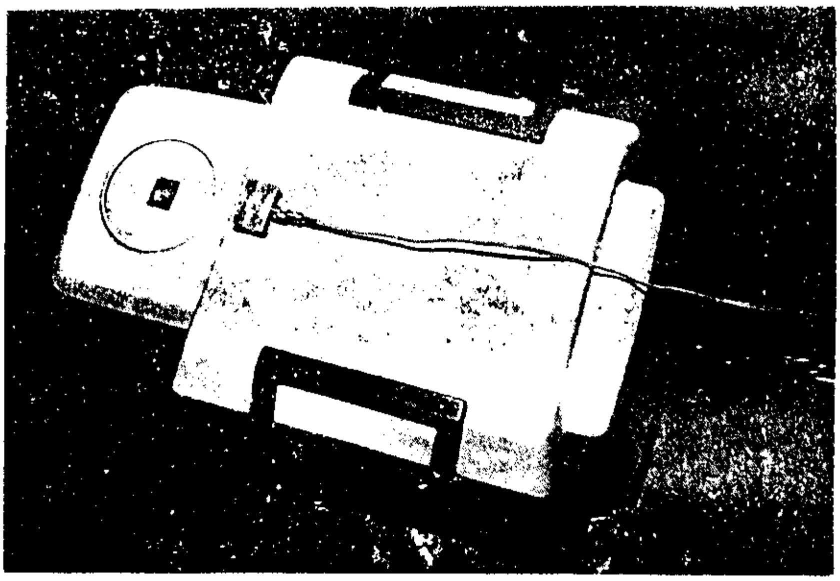


Fig. 12. Diagnostic robot with ultrasonic sensor.

the vertical switch to the relay element disables the control circuit of the corresponding correction cylinder before the support sensor loses contact with the surface, thereby allowing the robot to move across the ceiling. When reaching a new surface, contact between the surface and the obstacle sensor is broken and the vertical switch opens the rod end cavity of the corresponding correction cylinder to the outside air through the valve. In this case, the relay element recloses. When located on an even surface, the tracking mechanism automatically equalizes the position of the platforms. When crossing to a surface that forms a negative angle with the initial surface (a rightward turn in Fig. 14) the support sensor breaks contact with the surface, and the support switch closes. This activates the corresponding correction cylinder, and the rear platform moves downward until the support sensor makes contact with the new surface in a manner analogous to that described above. Symmetrical units on the rear platform are activated for reverse motion. The robot can be turned by duplicating this design on a common chassis and employing independent speed control over each tracking mechanism. This function is realized by the robot control system.

The VMR control system coordinates the operation of several robots simultaneously performing the same technological operation. This process may involve both distributing parts of the same equipment to achieve a common high cargo-carrying capacity of the VMR complex and the use of different industrial equipment on different robots performing the same complex operation.

One promising version of interaction between multiple robots involves the use of a single transport VMR with multiple industrial VMRs installed on the transport VMR.

After the industrial robots are delivered to the operating area by the transport robot, they begin independent operation, and, after executing their assigned operations, return to the transport robot. This process serves to increase the operational capacity of the industrial VMR and improves mobility and flexibility of the overall complex.

4. Grippers on Vertically-Mobile Robots

Grippers are the components that determine the robot performance reliability on vertical surfaces.

Vacuum grippers (VG) have the greatest flexibility in terms of gripping capacity on both metallic and nonmetallic surfaces. One feature of VGs for vertically mobile robots is the combination of vacuum and mechanical clamping to achieve the maximum possible surface adhesion in all possible directions of detachment forces acting on the robot during its motion in the vertical plane.

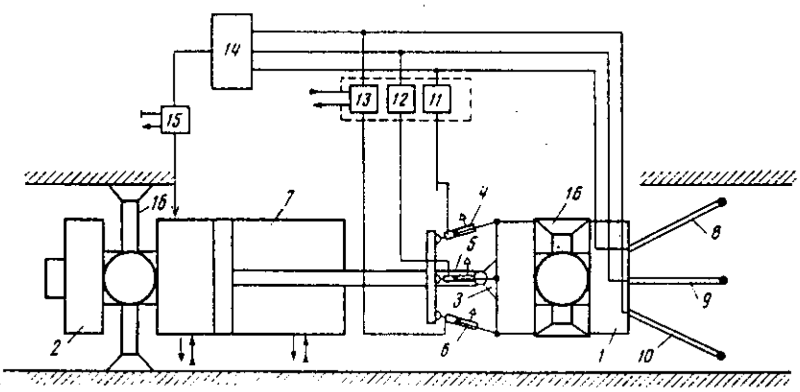


Fig. . VMR design for travel within bent piping: *1*) front support belt; 2) rear support belt; *3*) hinge; *4, 5, 6*) correction cylinders; *7*) power cylinder; *8, 9, 10*) sensors; *11, 12, 13*) correction valves; *14*) OR element; *15*) power valve; *16*) supports.

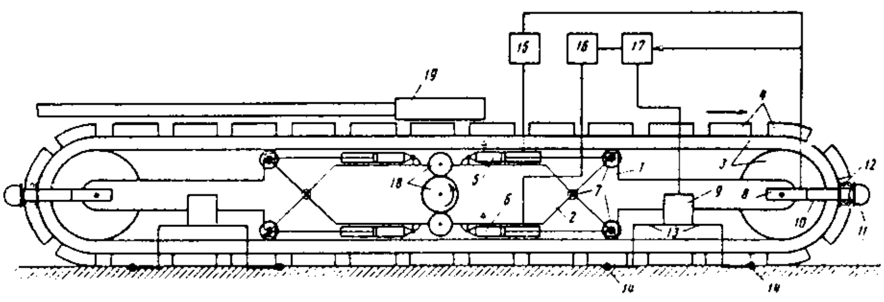


Fig. . Design of a VMR capable of crossing from one surface to another: *1*) platform; *2*) chassis; *3*) track mechanism; *4*) grippers; *5, 6,*) correction cylinders; *7*) hinges; *8, 9*) switches; *10*) probe; *11*) obstacle sensor; *12*) spring; *13*) support sensor; *14*) supports; *15, 16*) valves; *17*) relay element; *18*) reduction gear; *19*) feed channel.

Structurally the VG includes an elastic grip which holds a clamping support connected to the up-down drive. The grip is fitted with a position sensor that initiates feedback with the control system. The elastic grip cavity is connected to an ejector. The elastic grip performs the function of a vacuum sealing element to seal the VMR during clamping. The adhesion support, besides functioning as the support for the VG structure, also provides mechanical clamping due to the surface adhesion forces that arise simultaneously with the evacuation of the elastic grip cavity due to pressing of the support against the surface. To increase the adhesion forces, it is convenient in a number of cases to include tapered protrusions on the adhesion support. The up-down drive, which is connected to the robot chassis, brings the elastic grip connected to the adhesion support into contact with the clamping surface and returns the VG to its initial position after ejector release to execute the next robot step. Ejectors are used as vacuum sources in VGs since they operate independently in each robot VG, which is important for their operational reliability. The significant advantages of ejectors in this case include compact size and low weight, as well as the elimination of the requirement that the vacuum channel be at the robot travelling height. The vacuum sensor monitors the minimum tolerable evacuation in the grip cavity [21].

The VG test method involves determining the fundamental operating specifications which include changes in detachment and shear forces in the VGs as a function of feed pressure at the ejector input for different types of adhesion surfaces.

Figure 15 shows the calculated dependences of the separation forces on input pressures to the ejector for different effective working surface diameters of the vacuum grippers with no looseness in surface gripping.

VG tests for an actual vertically-mobile robot design are of greatest practical interest. The parameters of this design were optimized based on theoretical calculations to achieve a given support capacity of the transport module with a limited module size. The diameter of the VG working surface is 128 mm. The elastic grip is fabricated from VIKSINT U2-28 sealant. At working pressure, this material seals the microirregularities on the adhesion surface and has elevated heat resistance, which is required for such applications of vertically mobile robots as fire-fighting operations [9]. The quality of adhesion surfaces during tests corresponded to surface purity classifications ranging from 3.2 to 50, which encompasses a broad range of actual surfaces for such practical applications as, for example, inspection of metallic reservoirs as well as testing of surfaces with irregularities up to 0.3 mm in size.

Figure 16 gives results from studies to determine the detachment and adhesion forces of a VG as a function of the ejector supply pressure. The tests were carried out both for dry surfaces and surfaces covered in machine oil, which simulates actual robot operating conditions, specifically in reservoirs containing fuels and lubricants.

In Fig. 16, curves *1* and *2* characterize the detachment of a VG from a dry and a lubricated surface, respectively, while curves *3* and *4* characterize the shear of the VG on these same surfaces. Curve *5* was obtained under combined detachment and adhesion forces on the VG from a dry surface at 20°C.

These results suggest that the maximum detachment (separation) force arises at a feed pressure in the range (0.3–0.4) MPA. This is due to the functional features of the ejector. For a lubricated surface (Fig. 16, curve *2*) the detachment force drops by 7%. The maximum shear force on a dry surface is 5% lower than the corresponding maximum detachment force, although the characteristic is flatter, which expands the range of working supply pressures by 25%. For a lubricated surface, the shear force deceases by more than 10%. Therefore, under shear, the decease in the friction coefficient is more critical than under detachment. As a rule, under actual operating conditions, the detachment and shear forces act simultaneously on the VG. Results from simulating such a case are reflected by curve *5* (Fig. 16). A comparison of the characteristics for individual and combined detachment and shear forces clearly indicates that the actual adhesion reliability margin can be determined by modelling individual detachment and adhesion effects corrected to account for a 30% increase in the reliability margin from the force obtained in the optimum supply pressure zone, which lies between 0.3 and 0.4 MPa.

One of the determining factors in using a VG robot for fire-fighting operations is its capacity to operate at elevated temperatures. The primary requirement for VGs in this case is heat resistance of the elastic grip. Curves *6* and *7* represent results from temperature tests obtained from combined loading of VGs. As we see from these graphs, for every 100°C heating of the adhesion surfaces, the adhesion forces rise by ~ 5%. This is due to the fact that the VG gripper becomes more elastic with rising temperature and, consequently, the sealing conditions of its vacuum cavity are improved. This effect is observed up through the temperature values corresponding to the thermal expansion of the material from which the working surface of the VG grip was fabricated.

The characteristics given in Fig. 16 remain virtually unchanged for adhesion with surface irregularities up to 50 μm in size. Figure 17 shows the dependences on input ejector pressure of the decrease in vacuum resulting from the presence

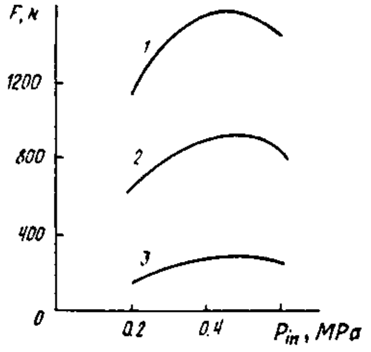


Fig. 15. Calculated dependences of the VG detachment forces on ejector input pressures: *1*) for a grip 150 mm in diameter; *2*) for a grip 128 mm in diameter; *3*) for a grip 64 mm in diameter.

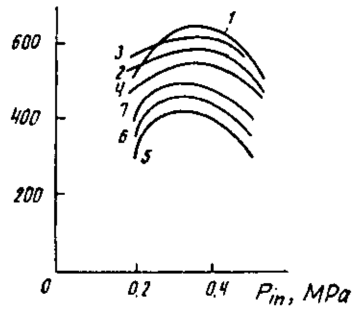


Fig. 16. Experimental dependences of the VMR detachment and adhesion forces on ejector input pressures: *1*) detachment from a dry surface; *2*) detachment from a lubricated surface; *3*) shear on a dry surface; *4*) shear on a lubricated surface; *5*, *6*, *7*) combined effect of detachment and shear at 20°C, 150°C,and 300°C on a dry surface.

of surface irregularities up to 300 μm in size (graph *1*) as well as for the case where isolated seal-breaking holes appear in the vacuum channel of the VG with diameters of 0.9 mm (graph *2*) and 1.8 mm (graph *3*), respectively. These diameters correspond to the diameters of the restrictors in the vacuum channels of the robot VGs and hence graphs *2* and *3*, aside from modelling the case of an increase in irregularity size, make it possible to evaluate the case in which several VGs are fed from a single vacuum channel. These data are important in designing a robot with external and internal VGs operating from a single up-down drive. The experimental results suggest that the vacuum of a VG grip on a surface with irregularities up to 300 μm in size drops by roughly 15% compared to the vacuum in the sealed ejector channel (graph *4*) at operating pressures at the ejector input, while with leaks simulated by restrictors 0.9 mm and 1.8 mm in diameter, respectively, the vacuum level drops by 40% and 70%, respectively.

The operational dynamics of VGs are characterized by the time required for the pressure level to reach certain vacuum in the grip cavity when in direct contact with the ejector. Figure 18 shows the dependences of this time on restrictor diameter in the ejector channel for different volumes of the grip cavity. A vacuum of 0.05 MPa with a restrictor diameter of 0.2 mm and volumes ranging from 10 cm^3 to 30 cm^3 is achieved over a time of the order of 8 s, while this same vacuum is achieved over a period of the order of 2 s for a diameter of 1.2 mm. These parameters must be taken into account when calculating delays in the motion control programs of robots, which determine the time interval between individual commands such as transfer of gripping from one group of VGs to another while maintaining adhesion reliability at the required speed. From the designer viewpoint, the graphs given in Fig. 18 can be used to determine the most suitable size of the restrictors used in the vacuum channel and the volume of the VG grip cavities.

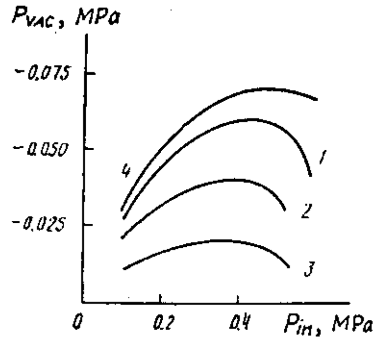


Fig. 17. Experimental dependences of the ejector channel vacuum level on the input ejector input pressure levels for different leakage source sizes: *1*) adhesion surface irregularities up to 300 μm in size; *2*) leakage source 0.9 mm in diameter; *3*) leakage source 1.8 mm in diameter; *4*) no leakage sources.

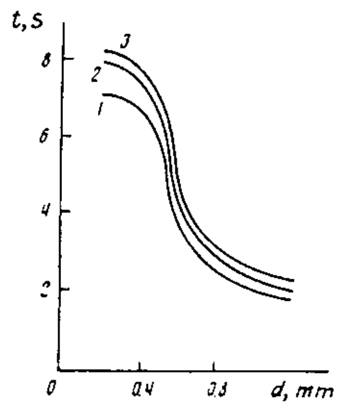


Fig. 18. Experimental dependences of the evacuation time of different grip cavity volumes on the diameter of the ejector channel restrictor: *1*) volume 10 cm^3; *2*) volume 20 cm^3; *3*) volume 30 cm^3.

Test results make it possible to choose optimum operating modes of the VGs depending on the specific operating conditions of the robot and to determine the necessary number and combination of robots to achieve a given carrying capacity to transport industrial equipment along vertical surfaces.

CONCLUSION

Significant attention in many countries has recently been focused on the design of independent robotics systems capable of movement under complex conditions in the presence of obstacles. In this process the organization of robot motion along vertical or inclined surfaces with reliable adhesion to these surfaces represents one of the fundamental theoretical problems, since such surfaces represent an important part of many different structures. The capacity to travel along such surfaces requires the robot to maintain significant adhesion forces that must be rapidly and reliably controlled by the control system. A very important area in such research is modernization of grippers, particularly, vacuum grippers. For moving on surfaces of complex configuration, which include horizontal and vertical sections, it is more important to develop conbined mobile systems that contain vertically- and horizontally-mobile robots with linkages. The wide variety of possible mobile systems is due both to the extensive range of travelling surfaces and the variety of industrial problems requiring specific equipment. Combining such equipment, as well as the required sensors, with a mobile transport system also represents a serious problem. In this light, the development of mobile robots capable of climbing vertical or other complex surfaces represents a fundamental theoretical problem with a wide variety of applications.

The development of the scientific field concerned with the construction of integrated vertically- and horizontally-mobile robots with an advanced sensor system will yield additional capabilities including automatic descision-making on advancement in vague environments under extreme conditions. In these cases, complex mobile robotics systems have elements of artificial intelligence. Hence supervisory control used today will, as robot sensor systems advance, be gradually replaced by more complex control that will be capable of solving such problems in changing or extreme conditions.

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