Intelligent System for Adhesion Control of Universal Robotic Platform

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Abstract

The paper is devoted to modern aspects of mobile robotics, namely to the universal robotic platforms that can be used in various technological environments and conditions to perform different technical tasks at industrial facilities and enterprises. These platforms are capable of moving on horizontal surfaces with complex terrain as well as climbing vertically on sheer walls and ceilings and are the universal autonomous means of carrying out complex operations in hard-to-reach and dangerous places for humans. One of the biggest challenges in operating these robotic platforms is proper adhesion control when moving on inclined planes. In this study, the authors performed the design and study of the intelligent adhesion control system that provides efficient and reliable fastening and movement of the platform on inclined surfaces of various types. This system is based on fuzzy control principles that allows determining the necessary adhesion force of the robotic platform for its safe and efficient use at various angles of the surface inclination. The system's performance is verified by computer simulation.

Keywords

Mobile robotics, universal robotic platform, intelligent adhesion control, fuzzy control system, computer simulation

1. Introduction

In recent years, the introduction of robotic systems and complexes in various spheres of human activity has become increasingly widespread [1-3]. In modern life, different types of robots are involved in a huge number of processes, ranging from closed production cycles of heavy industry and metallurgy to customer service and cargo delivery. The use of various robotic solutions provides enormous benefits, in particular, eliminating expensive human labor, significantly increasing productivity, accuracy and speed of technological operations, reducing risks to the life and health of people when performing tasks in hazardous and harmful environments, eliminate errors caused by the human factor and operator fatigue, etc. [4, 5].

A separate fairly widely used class of robotic systems are mobile robots (MR) and robotic complexes [6, 7]. They allow performing the tasks of monitoring, inspection, reconnaissance, the movement of equipment and tools to perform complex labor-intensive technological operations in hard-to-reach places, and are especially effective at functioning in the fully automatic mode [8, 9]. For example, at the moment, the mobile welding robot has been developed and successfully applied, that can achieve automatic large fillet welding seam tracking in narrow spaces [10]. In turn, MRs for painting [11] and removing paint [12] from various surfaces are quite effective. Also, widespread are robots for inspection [13] and complex cleaning [14] of the bodies of various objects, and others. Universal mobile robotic platforms (UMRP) have even greater efficiency [15]. Due to the modular structure, these robotic objects can simultaneously have different types of propulsion devices and different sets of technological tools.

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This allows them to be used to perform a wide range of diverse tasks in various environments and conditions, for example, on a horizontal surface with complex terrain, above and below water, on vertical and inclined surfaces of various types, etc. [16]. As a result, due to such versatility, the speed of performance is significantly increased and the cost of performing various technological operations is reduced.

However, at the same time, the creation of such types of UMRPs also poses rather difficult tasks for developers to design highly efficient intelligent control systems. These control systems should also have a modular structure to automate the control processes of various types of propulsion devices (for moving on a horizontal and inclined surface, underwater and above water) and various working tools (for monitoring, inspection, painting, cleaning, welding, etc.). It is most expedient to develop such control systems based on the principles of artificial intelligence [17], which is confirmed by a number of published studies [18, 19]. So, fuzzy control is used quite effectively for mobile robot navigation in an unknown environment when avoiding random obstacles [20] and for a caterpillar robot capable of moving along inclined ferromagnetic surfaces [21]. Neural network control is also widely used, for example, for inspection mobile robots [22] and others.

Of particular note is the adhesion force control system (AFCS) when the platform moves on various types of inclined surfaces. This system is very important since the safety of movement on inclined and vertical surfaces directly depends on it, which is confirmed by a number of recent studies [23, 24]. Moreover, the correct control of the adhesion force can significantly increase the efficiency of the entire motion control system due to the rational distribution of loads. In particular, the adhesion force control systems for various robots have been developed based on advanced control principles, namely predictive [25] and fuzzy [26], neuro-fuzzy [9]. The systems in [25, 26] make it possible to implement smooth adhesion control in various conditions (when changing the driving torque and surface friction), however, do not take into account the simultaneous uncertain change in the inclination angle of the working surface. In turn, the system in paper [9], on the contrary, takes into account the uncertain change in the angle of inclination and the friction coefficient of the surface, but does not consider the different values of the driving torques of the propulsors. At the same time, to achieve high adhesion efficiency, it is necessary to implement flexible determining and automatic control of the adhesion force depending on the coefficient of friction, driving torque and the angle of inclination of the working surface.

Thus, the main purpose of this study is the development and research of the intelligent system for adhesion automatic control of the universal mobile robotic platform with flexible determining the adhesion force taking into account the main parameters (coefficient of friction, driving torque, inclination angle of the working surface).

The main contribution of the authors is as follows:

a) design of the functional structure of the two-level intelligent system for the adhesion automatic control of the UMRP;

b) development of the tactical-level fuzzy subsystem for determining the necessary adhesion force of the UMRP considering the coefficient of friction, driving torque and the inclination angle of the working surface.

2. Generalized Structure of the Hierarchical Control System for the Universal Mobile Robotic Platform

Since the universal mobile robotic platform is a complex multi-component control plant, its control system must have a multi-level hierarchical structure. In turn, the principle of hierarchical multi-level control implies the presence of the highest, strategic, tactical and executive levels of control. The highest level represents the human operator and the human-machine interface (HMI) [27]. At this level of the control system, the human operator must make a decision on the implementation of a particular technological operation, task, movement, or maneuver of the UMRP based on the analysis of the environment and the situation, assessment of current operating conditions, external disturbances, etc. [28].

Moreover, to make such decisions the operator may implement preliminary simulations of certain situations based on the embedded simulation models to predict the UMRP’s behavior and the state of the environment. At the strategic level of control, after receiving certain commands (control goals) from the highest level it is necessary to plan technological operations, tasks, or movements and their transformation into certain sequences of elementary actions (subtasks) [28-30]. At this level, various control algorithms can be used depending on the specific technological operation being performed. Therefore, the strategic level forms the commands for the tactical level to perform specific actions or basic operations. In turn, the main task of the tactical control level is to transform the control commands of the strategic level into the control programs that define the laws of coordinated functioning or movement of executive mechanisms and actuators of the executive level of control. The given programs define sequences of the set values of the generalized controlled coordinates of the UMRP's main executive mechanisms [28]. As for the executive level of control, it consists directly of executive mechanisms and actuators, sensory system (SS), as well as of automatic control subsystems, which due to the corresponding control impacts work out the set values of the platform's generalized controlled coordinates, that come from the tactical level [28]. In turn, the SS is used to receive feedback and to obtain all available information about the state of the UMRP and the environment.

The generalized functional structure of the hierarchical control system for the UMRP is presented in Fig. 1, where the following notations are adopted: CATO1, CATO2, …, CATO*l* are the control algorithms of the 1st, 2nd, …, *l*th technological operations; CMPD1, CMPD 2, …, CMPD*n* are the control modules of the 1st, 2nd, …, *n*th propulsion devices; CMTT1, CMTT 2, …, CMTT*m* are the control modules of the 1st, 2nd, …, *m*th technological tools; $\mathbf{U}_{SL}$ is the vector of control signals for the strategic level; $\mathbf{U}_{TL}$ is the vector of control signals for the tactical level; $\mathbf{U}_{EL}$ is the vector of control signals for the executive level; $\mathbf{U}_{SS}$ is the vector of sensory system outputs; $\mathbf{X}_R$ is the vector of controlled and technological coordinates of the UMRP.

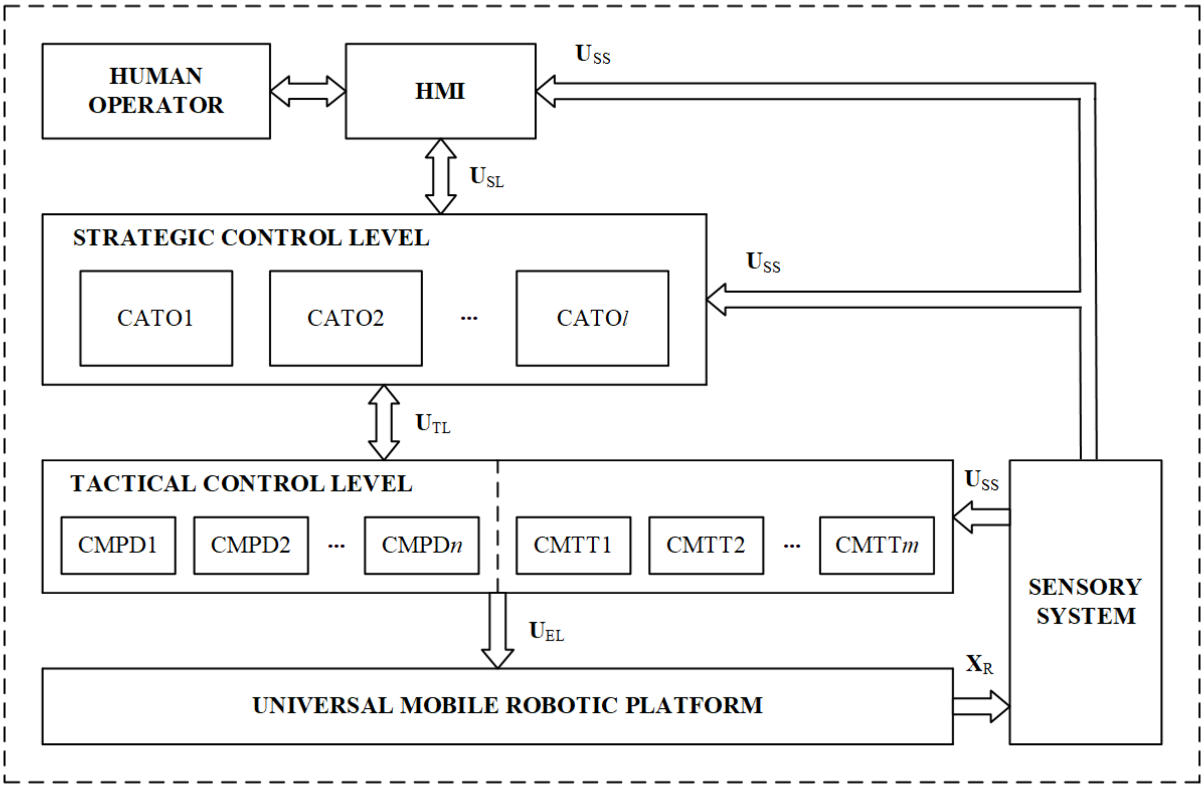


Figure 1: Generalized functional structure of the hierarchical control system for the universal mobile robotic platform

In this control system the operator uses a specialized HMI to transmit the control signals $\mathbf{U}_{SL}$ to the strategic control level and receive signals $\mathbf{U}_{SS}$ about the state of the platform and the environment from the sensory system.

The strategic level has a set of *l* control algorithms (CATO1, CATO2, …, CATO*l*) for implementing the control of a number of technological operations (inspection, welding, painting, ultrasonic diagnostics, rust removal, cleaning, etc.) that can be performed using this robotic platform. In turn, various combinations of propulsion devices and technological tools of the mobile platform can be used to perform these technological operations. Moreover, to perform new types of technological operations, appropriate new control algorithms can be added in this system to the strategic level of control.

For direct control of the different propulsion devices (wheeled, caterpillar, walking, propeller, gravity type, etc.) and technological tools (video cameras, welding machines, cleaning cutters, manipulators and others) in the process of performing various operations, there are corresponding control modules (CMPD1, CMPD2, …, CMPD*n*, CMTT1, CMTT2, …, CMTT*m*) at the tactical control level in this system. When adding new types of propulsion devices or technological tools to the UMRP, the appropriate control modules must be previously designed and added to the tactical control level of the system. In turn, these control modules are control systems with a complex structure and carry out the coordinated control of all executive mechanisms, drives and actuators that are parts of certain propulsion devices and technological tools.

Finally, to control the variables of individual drives and actuators at the executive level (located directly on the UMRP in Fig. 1) of this system, there are separate stabilization and automatic control subsystems, which are slave control systems for the tactical-level control modules.

Among the many working tools and propulsion devices of the mobile robotic platform, the adhesion device (AD) deserves special attention. The use of this device gives the opportunity to significantly expand the range of tasks and technological operations, as it becomes possible to perform various work in hard-to-reach places on inclined and vertical surfaces (sheer walls and ceilings). In turn, the adhesion device, depending on the tasks and operating conditions, can be implemented on the basis of various physical principles, for example, propeller type, vacuum, magnetic, electromagnetic, and others. Thus, for the effective application of the adhesion devices of various types on the UMRP in various operating modes, it is necessary to develop an appropriate universal control module.

Next, we consider the development of a functional structure, control algorithms and the main components of the AD control module in the form of a specialized adhesion force control system.

3. Functional Structure of the Adhesion Force Control System for the Universal Mobile Robotic Platform

The main task of the adhesion device of the mobile robotic platform is to create the necessary adhesion force to an inclined or vertical surface for the safe and efficient movement of this platform while simultaneously performing the necessary technological operation. To safely hold the UMRP on an inclined or vertical surface, the maximum possible adhesion force could be provided in all operation modes, however, in this case, there will be a maximum energy consumption of the adhesion device and a sufficiently large additional resistance to the propulsion devices. Together, this will significantly reduce the overall efficiency of the UMRP and the performance of a particular operation. Thus, for the most efficient use of the adhesion device with energy saving, it is necessary to provide flexible control of the adhesion force depending on the various modes of movement of the platform and the performance of various technological operations, as well as on many other factors. At the same time, the AFCS must determine the required (set) value of the adhesion force and ensure its automatic maintenance (stabilization). In turn, the set value of the adhesion force is significantly affected by such parameters as the angle of inclination and the friction coefficient of the working surface, the total mass of the robotic platform together with the technological tools, as well as the traction force of the propulsion devices. Moreover, the structure of this control system must be universal for any type of the adhesion device. Taking into account the above conditions and particular features, as well as the complexity of the mathematical description of the processes of the platform moving along inclined surfaces of various types, it is advisable to develop the adhesion force control system based on the principles of artificial intelligence [31, 32]. In addition, this system should consist of two levels of control: tactical and executive. At the tactical level, the set value of the adhesion force of the platform to the surface should be determined based on the values of the angle of inclination of the working surface, the coefficient of friction and the traction force of the propulsion devices. In turn, at the executive level, the automatic control of the adhesion force should be performed, that is, the stabilization of the set value under the influence of various disturbances. Analyzing various methods and approaches of artificial intelligence, it can be concluded that it is most expedient to develop the tactical-level subsystem for determining the set value of the adhesion force on the basis of fuzzy logic [33, 34]. Fuzzy systems make it possible to effectively generalize expert information and experimental data, formalize the mechanisms of human thinking, form linguistic models of complex processes, and approximate nonlinear multidimensional dependencies [35, 36]. In turn, the executive-level subsystem for the adhesion force automatic control can be designed based on different types of intelligent controllers, in particular, neural network [37, 38], fuzzy [39] or neuro-fuzzy [9].Taking into account all of the above, the functional structure of the two-level adhesion force control system for the UMRP is formed, which is shown in Fig. 2.

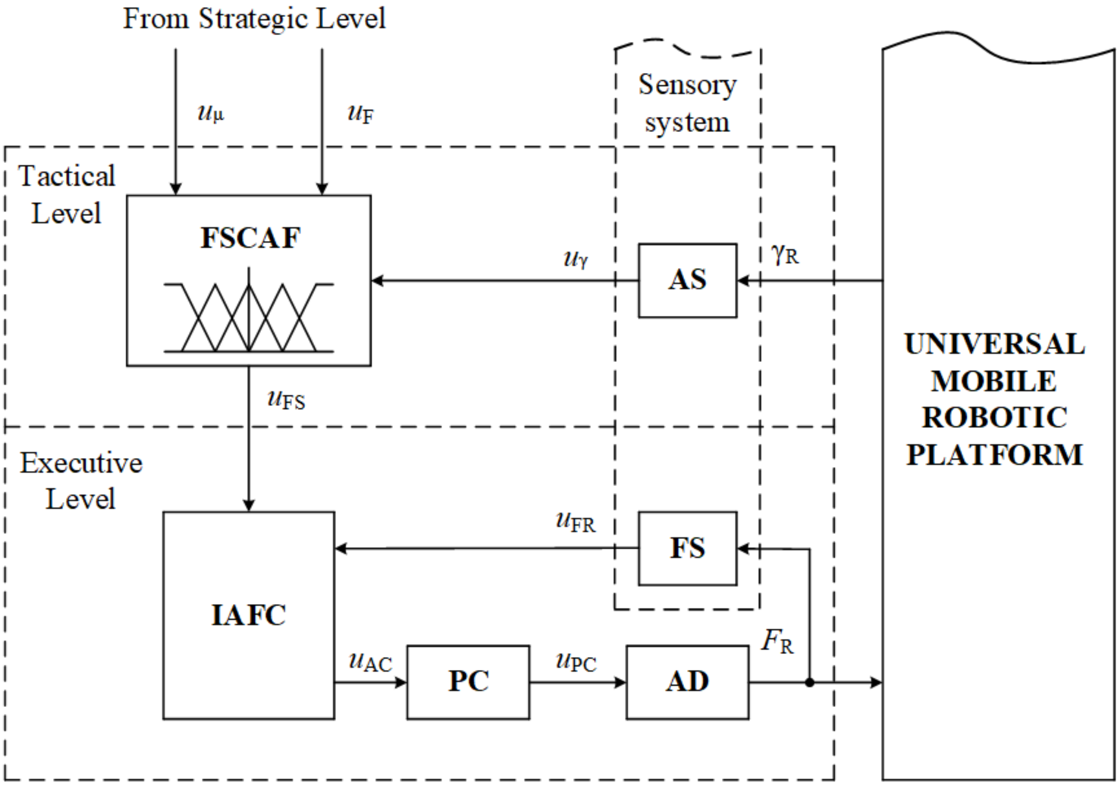


Figure 2: Functional structure of the two-level adhesion force control system for the universal mobile robotic platform

In Fig. 2, the following designations are adopted: FSCAF is the fuzzy subsystem for calculating the adhesion force set value; IAFC is the intelligent adhesion force controller; AS is the angle sensor; FS is the force sensor; PC is the power converter; u_μ is the signal corresponding to the current value of the coefficient of friction of the contact parts of the platform and the working surface; u_F is the signal corresponding to the current value of the traction force of the UMRP propulsion devices; u_γ is the signal corresponding to the current value of the angle of inclination of the working surface; u_{FS} is the FSCAF output signal which corresponds to the set value of the adhesion force; u_{FR} is the FS output signal which corresponds to the real value of the adhesion force; u_{AC} is the IAFC output control signal; u_{PC} is the PC output signal; γ_R is the current value of the angle of inclination of the working surface; F_R is the real value of adhesion force.

As can be seen from Fig. 2, at the tactical level, the FSCAF determines the required (set) value of the adhesion force based on the signals corresponding to the current value of the coefficient of friction u_μ, the current value of the traction force of the UMRP propulsion devices u_F and the current value of the angle of inclination of the working surface u_γ. In turn, the signals u_μ and u_F are given from the strategic level of control, and the signal u_γ comes from the sensor for measuring the angle of inclination of the working surface. The current value of the coefficient of friction of the contact parts of the platform and the working surface is determined experimentally or pre-set by the operator depending on the type and material of the working surface. The current value of the traction force of the UMRP propulsion devices comes from the control system of the platform propulsion devices. As a result, the signal which corresponds to the set value of adhesion force u_{FS} is determined by the FSCAF based on fuzzy inference engine and a pre-designed rule base.

At the executive level, the stabilization of the set value of the adhesion force is performed using the intelligent adhesion force controller. In turn, the IAFC the compares the signal u_{FS} from the FSCAF with the force sensor signal u_{FR} and, using the embedded intelligent algorithm, performs automatic control of the UMRP's adhesion force. The IAFC output control signal u_{AC} is amplified by a power converter and directly fed to the adhesion device. Moreover, the intelligent controller must be previously adjusted or trained for a specific adhesion device based on the simulation or experimental models.

Next, we consider the development of the tactical-level fuzzy subsystem for determining the necessary adhesion force of the UMRP in more detail.

4. Development of the Fuzzy Subsystem for Calculating the Adhesion Force Set Value

The fuzzy subsystem for calculating the set value of the adhesion force (Fig. 3) has three inputs (u_γ, u_μ, u_F) and one output (u_{FS}). It is advisable to develop this fuzzy system on the basis of a Mamdani-type fuzzy inference mechanism. In turn, Mamdani's fuzzy inference mechanism includes sequential execution of the following stages: fuzzification, aggregation, activation, accumulation and defuzzification [40-42].

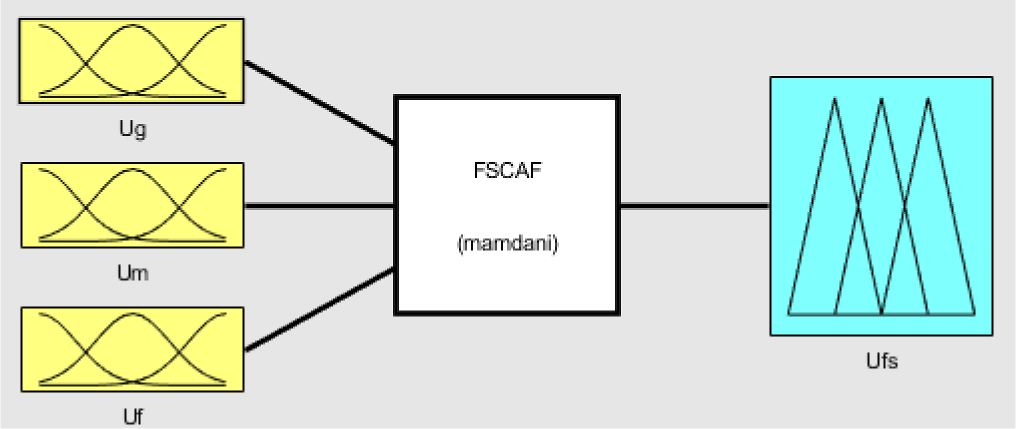


Figure 3: Structure of the FSCAF

At the stage of fuzzification, the instantaneous numerical values of the input variables are mapped to the corresponding fuzzy term sets with the calculation of the membership degree values. In this case, for the variable u_γ, corresponding to the angle of inclination of the working surface, it is advisable to choose 6 linguistic terms with triangular-type membership functions: Z – zero; S – small; LM – less than middle; M – middle; L – large; VL – very large. Also, this variable can vary in the range from 0 to 180 degrees. Moreover, the variable u_γ is defined by the value of angle γ'_R that is determined by the current value of the angle of the working surface inclination γ_R using the following dependency

$$\gamma'_R = \begin{cases} \gamma_R, \text{ at } \gamma_R \le 180°; \\ 360° - \gamma_R, \text{ at } \gamma_R > 180°. \end{cases} \quad (1)$$

The appearance of the linguistic terms of the variable u_γ with the set parameters is shown in Fig. 4.

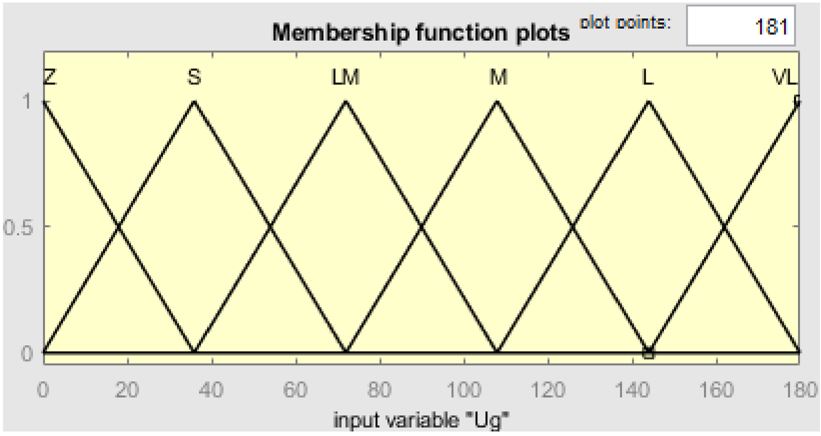


Figure 4: Linguistic terms of the variable u_γ with the set parameters

The membership function of linguistic terms of triangular type on the example of this variable is represented by the expression (2)

$$\mu(u_\gamma)=\begin{cases} 0, \text{ at } u_\gamma \le a \text{ or } u_\gamma \ge c; \\ \dfrac{u_\gamma - a}{b-a}, \text{ at } a < u_\gamma \le b; \\ \dfrac{c-u_\gamma}{c-b}, \text{ at } b < u_\gamma < c; \end{cases} \qquad (2)$$

$$a \le b \le c,$$

where a, b and c are the customizable parameters of the membership function.

In turn, for the variables u_μ and u_F, that correspond to the current values of the friction coefficient and traction force of the propulsion devices, 3 linguistic terms with triangular-type membership functions are chosen: S – small; M – middle; L – large. The appearance of the linguistic terms of these variable with the set parameters is shown in Fig. 5, *a*, *b*.

The variable u_μ can vary in the range from 0.15 to 0.8, and the variable u_F is set in relative units (from 0 to 1) from the maximum value of the traction force.

As for the system's output variable u_{FS}, it is advisable to use 9 linguistic terms with triangular-type membership functions for it. They are: Z – zero; S – small; LM – less than middle; M – middle; MM – more than middle; L – large; VL – very large; E – extreme. In turn, this variable is set in relative units (from 0 to 1) from the maximum value of the adhesion force developed by the adhesion device. As a rule, the maximum adhesion force value is defined as 7...10F_P, where F_P is the total UMRP weight with equipment. The appearance of the linguistic terms of this output variable with the set parameters is shown in Fig. 6.

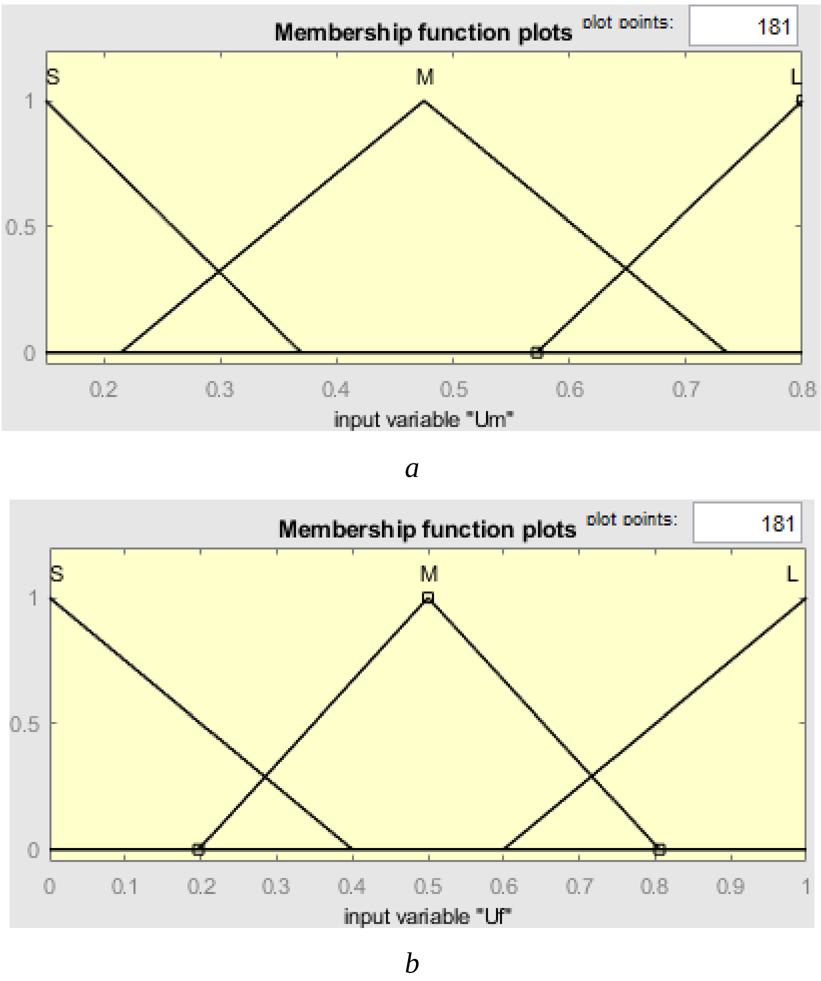
The production rules of the rule base (RB) for the given Mamdani-type system are given as follows:

$$\text{IF “}u_\gamma = A_1\text{” AND “}u_\mu = B_1\text{”AND “}u_{\mathrm{F}} = C_1\text{” THEN “}u_{\mathrm{FS}} = D_1\text{”,} \qquad (3)$$

where A_1, B_1, C_1 and D_1 are certain linguistic terms of the given variables.

The developed rule base of the fuzzy subsystem for determining the necessary adhesion force of the UMRP is presented in Table 1.

The Mamdani-type fuzzy inference engine consists of sequential execution of the stages of aggregation, activation and accumulation [40, 41]. At the aggregation stage, the degree of truth of the conditions for each of the rules of the fuzzy inference system is determined [43]. For this, the values of the membership functions of the linguistic terms of the variables obtained at the stage of fuzzification, which make up the antecedents of fuzzy production rules, are used. In turn, finding the degrees of membership of antecedents is done using the t-norm based on the "min" operation.



a

b

Figure 5: Linguistic terms with the set parameters of the variables: a) u_{μ}; b) u_F

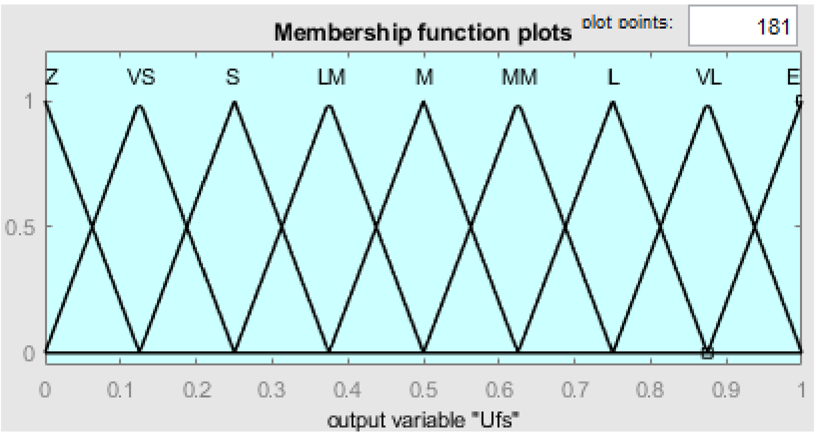


Figure 6: Linguistic terms of the output variable u_{FS} with the set parameters

The activation stage is the process of finding the degree of truth of each of the elementary logical subconclusions (expressions) that make up the consequents of all fuzzy production rules [44]. In turn, for the output signal of the system, at this stage, truncated membership functions for subconclusions of the rules are found based on the "min" operation. At the accumulation stage, the truncated membership functions found at the previous stage are combined to obtain the final fuzzy subset of the output variable based on the "max" operation.

Table 1
RB of the fuzzy subsystem for calculating the adhesion force set value

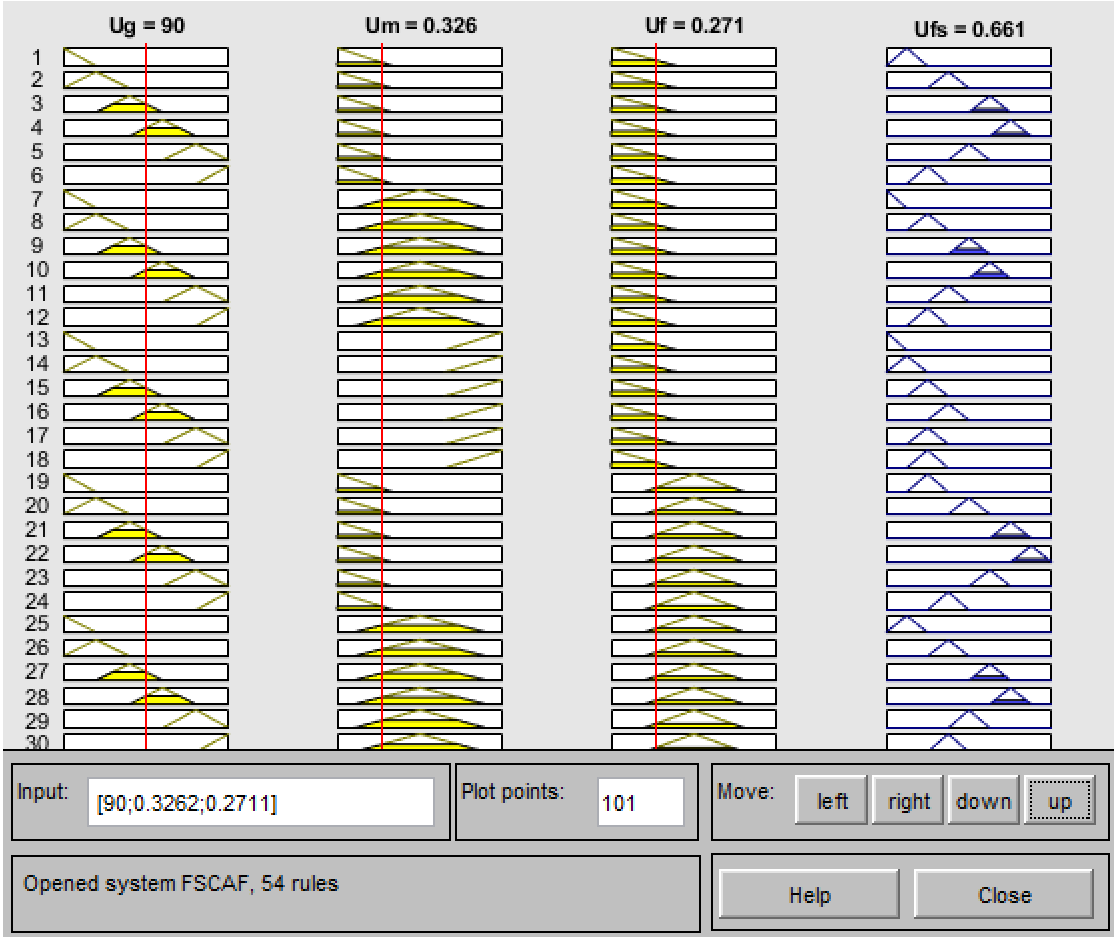
Rule number	Input variables			Output variable
	u_F	u_μ	u_γ	u_{FS}
1	S	S	Z	VS
2	S	S	S	LM
3	S	S	LM	MM
4	S	S	M	L
5	S	S	L	M
6	S	S	VL	S
7	S	M	Z	Z
8	S	M	S	S
9	S	M	LM	M
10	S	M	M	MM
11	S	M	L	LM
12	S	M	VL	S
13	S	L	Z	Z
14	S	L	S	VS
15	S	L	LM	S
16	S	L	M	LM
17	S	L	L	S
18	S	L	VL	S
19	M	S	Z	S
20	M	S	S	M
21	M	S	LM	L
22	M	S	M	VL
23	M	S	L	MM
24	M	S	VL	LM
25	M	M	Z	VS
26	M	M	S	LM
27	M	M	LM	MM
28	M	M	M	L
29	M	M	L	M
30	M	M	VL	LM
31	M	L	Z	VS
32	M	L	S	S
33	M	L	LM	LM
34	M	L	M	M
35	M	L	L	LM
36	M	L	VL	LM
37	L	S	Z	LM
38	L	S	S	MM
39	L	S	LM	VL
40	L	S	M	E
41	L	S	L	L
42	L	S	VL	M
43	L	M	Z	S
44	L	M	S	M
45	L	M	LM	L
46	L	M	M	VL
47	L	M	L	MM

48	L	M	VL	M
49	L	L	Z	S
50	L	L	S	LM
51	L	L	LM	M
52	L	L	M	MM
53	L	L	L	M
54	L	L	VL	M

In turn, the defuzzification stage is a process of transition from the membership function of the output linguistic variable $\mu_{\Sigma}\left(u^{*}_{\mathrm{FS}}\right)$ to its clear (numerical) value u_{FS} [42]. For fuzzy inference of the Mamdani type, the numerical value of the output signal is calculated by the center of gravity method based on the dependence (4)

$$u_{\mathrm{FS}} = \frac{\int u^{*}_{\mathrm{FS}} \mu_{\Sigma}\left(u^{*}_{\mathrm{FS}}\right) du_{\mathrm{FS}}}{\int \mu_{\Sigma}\left(u^{*}_{\mathrm{FS}}\right) du_{\mathrm{FS}}}. \tag{4}$$

The visualization of the calculation of the necessary adhesion force value using the developed fuzzy subsystem based on the available rules is shown in Fig. 7.



Input: [90;0.3262;0.2711]

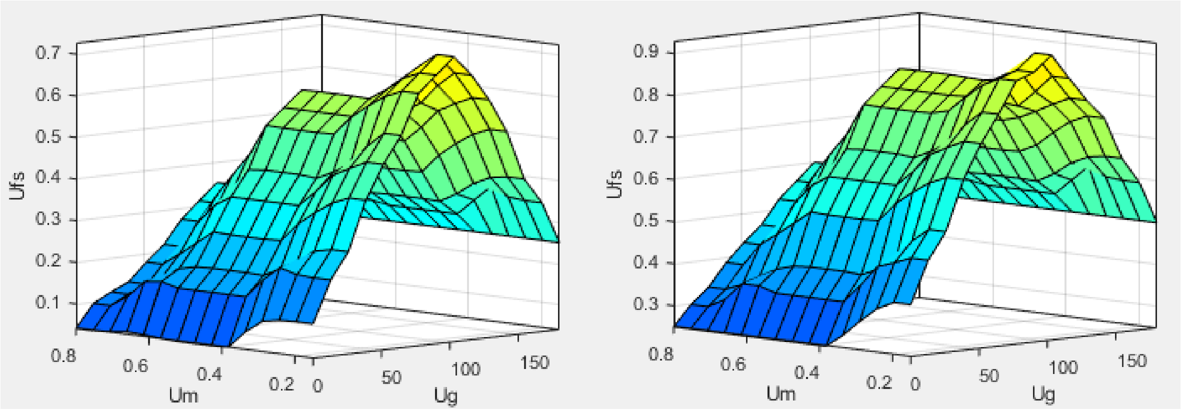
Plot points: 101

Opened system FSCAF, 54 rules

Figure 7: Visualization of the calculation of the necessary adhesion force value using the developed fuzzy subsystem

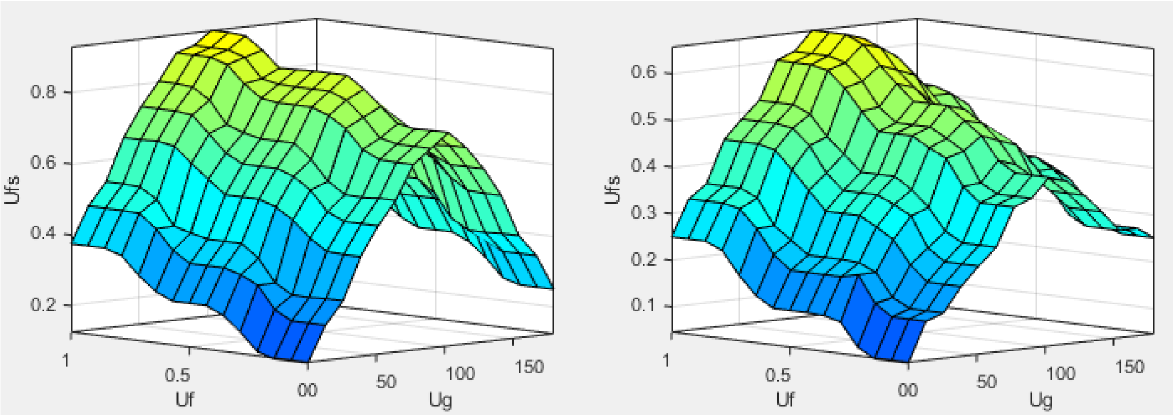
In this case, the calculation of the adhesion force value is performed for the following values of the input variables: $u_\gamma = 90$; $u_\mu = 0.326$; $u_F = 0.271$. In turn, at these values of the inputs, the current value of the adhesion force signal u_{FS} is 0.661.

The characteristic surfaces of the developed fuzzy subsystem for calculation of the necessary adhesion force value are presented in Fig. 8-10. In particular, the dependences $u_{FS} = f(u_\gamma, u_\mu)$ at $u_F = 0.1$ and at $u_F = 0.9$ are shown in Fig, 8, *a* and *b*, respectively.



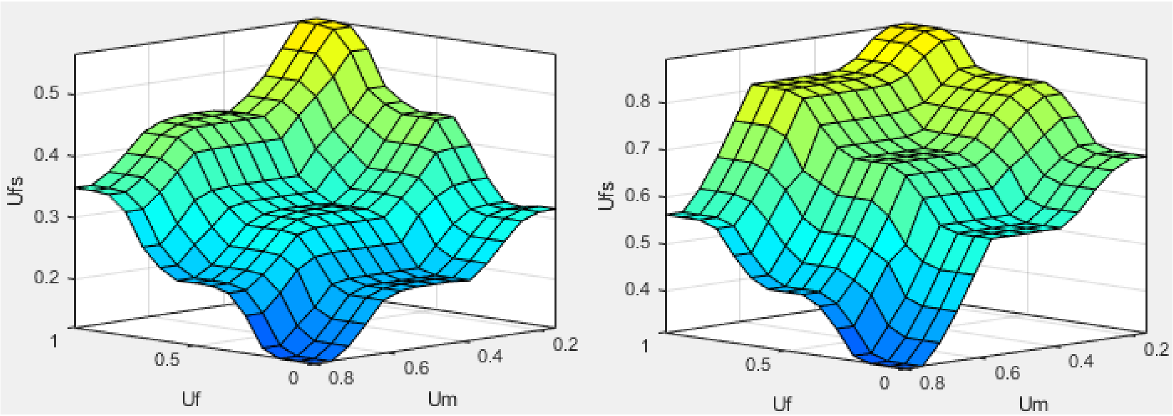
a *b*

Figure 8: Characteristic surfaces of the developed fuzzy subsystem $u_{FS} = f(u_\gamma, u_\mu)$ at: *a*) $u_F = 0.1$; *b*) $u_F = 0.9$



a *b*

Figure 9: Characteristic surfaces of the developed fuzzy subsystem $u_{FS} = f(u_\gamma, u_F)$ at: *a*) $u_\mu = 0.2$; *b*) $u_\mu = 0.7$



a *b*

Figure 10: Characteristic surfaces of the developed fuzzy subsystem $u_{FS} = f(u_\mu, u_F)$ at: *a*) $u_\gamma = 30$; *b*) $u_\gamma = 90$

Moreover, the dependences $u_{FS} = f(u_\gamma, u_F)$ at $u_\mu = 0.1$ and at $u_\mu = 0.9$ are given in Fig, 9, *a* and *b*, respectively. And, finally, the dependences $u_{FS} = f(u_\mu, u_F)$ at $u_\gamma = 30$ and at $u_\gamma = 90$ are shown in Fig, 10, *a* and *b*, respectively.

As can be seen from Fig. 7-10, the developed tactical-level fuzzy subsystem is quite efficient in determining the required value of the adhesion force in different operation modes based on the signals corresponding to the current value of the coefficient of friction u_μ, the current value of the traction force of the UMRP propulsion devices u_F and the current value of the angle of inclination of the working surface u_γ. This system can be successfully applied to determine the adhesion force for various types of the adhesion devices.

For stabilization and automatic control of the set value u_{FS} (calculated by the FSCAF) of the UMRP adhesion force under the action of various uncertain disturbances it is planned to design the executive-level intelligent subsystem based on neural network controller [45-47] in further studies.

5. Conclusions

In this work the development and research of the intelligent system for adhesion automatic control of the universal mobile robotic platform is carried out.

The proposed system has the two-level structure (with tactical and executive levels of automatic control) and is based on the principles of artificial intelligence that provide flexible automatic control of the adhesion force depending on the various modes of movement of the platform and the performance of various technological operations, as well as on many other factors. In particular, the tactical-level subsystem is designed on the basis of fuzzy logic and allows determining the necessary adhesion force of the UMRP to the working surface taking into account the current values of the angle of inclination of the surface, the coefficient of friction and the traction force of the propulsion devices. In turn, the designed fuzzy subsystem is implemented on the basis of Mamdani-type inference engine and has 54 production rules in the rule base compiled on the basis of expert knowledge. This gives the opportunity to ensure the most efficient use of the adhesion device with energy saving that provides reliable holding and movement of the platform on the working surface with different inclinations and characteristics in the process of performing various technological operations. The high efficiency of the developed fuzzy subsystem of the tactical level is confirmed by the simulation results obtained in the form of characteristic surfaces for various conditions. Moreover, the additional advantage of this system is that it can be successfully applied to determine the adhesion force for various types of the adhesion devices (propeller, vacuum, magnetic, electromagnetic, and others).

Further research should be carried out towards the development of the executive-level intelligent subsystem of the UMRP based on the neural network controller for providing high accuracy and speed of the adhesion force stabilization and automatic control when performing various technological operations.

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7. References

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