Запропоновано використання під час гуманітарного розмінування мобільних робототехнічних комплексів, що обладнані маніпуляторами на основі механізмів із паралельними кінематичними структурами. Розглянуті особливості конструкції та характеристик маніпуляторів. Установлені особливості оснащення маніпуляторів, які використовуються для безпосереднього маніпулювання об'єктами. Визначені геометричні та силові параметри різьбового з'єднання підривача з корпусом міни. Обґрунтована схема дії зусиль у різьбовому з'єднанні. Встановлені особливості виникнення силових реакцій різі при гравітаційному навантаженні підривача та при затягуванні різі. Проведено експериментальне визначення зусиль, які виникають при відгвинчуванні підривача протитанкової міни за допомогою маніпулятора. При вимірах використано спеціальне оснащення у вигляді набору спеціальних схватів. У результаті вимірів встановлені зусилля затягування різі та моментних навантажень, необхідних для відгвинчування підривача. Здійснено обґрунтування раціональних кінематичних і динамічних алгоритмів роботи маніпулятора в процесі відгвинчування підривача. Для цього здійснено виміри переміщень підривача при дії несиметричних силових та моментних навантажень. Проведені виміри параметрів циклічних навантажень необхідних для розфіксації різьбового з'єднання підривача і міни. Запропоновано спеціальний алгоритм динамічних навантажень підривача, який забезпечує раціональні умови його відгвинчування. Наведені результати експериментальних досліджень щодо дистанційного знешкодження вибухонебезпечних предметів та невибухнувших боєприпасів на прикладі протитанкової міни. Показано доцільність запропонованої технології гуманітарного розмінування територій, забруднених вибухонебезпечними предметами

Ключові слова: мобільний робототехнічний комплекс, маніпулятор, протитанкова міна, вибухонебезпечні предмети, дистанційне знешкодження

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SUBSTANTIATING THE REQUIREMENTS TO FUNCTIONAL INDICATORS FOR THE MANIPULATORS OF MOBILE ROBOTIC DEMINING COMPLEXES

V. Strutynsky
Doctor of Technical Sciences, Professor
Department of Design Tools and Machines
National Technical University of Ukraine
«Igor Sikorsky Kyiv Polytechnic Institute»
Peremohy ave., 37, Kyiv, Ukraine, 03056

V. Kotsiuruba
Doctor of Technical Sciences, Professor
Department of Operative and Combat Support
Institute of Operational Security and Logistics
National Defence University of Ukraine named after Ivan Cherniakhovskyi
Povitroflots'kyi ave., 28, Kyiv, Ukraine, 03049

A. Dovhopoliy
Doctor of Technical Sciences, Professor, Chief Researcher*

O. Husliakov
PhD, Head of Research Laboratory
Research Laboratory*

R. Budianu
PhD, Senior Researcher, Leading Research Fellow
Department of Development of
General-Purpose Weapons and Military Equipment*

O. Kolos
Deputy Head of the Research Department
Research Department for the Development of Engineering Weapons and
Radiation, Chemical and Biological Protection of the Special Forces Weapons
Development and Military Equipment Development
Central Scientific Research Institute of
Armament and Military Equipment of Armed Forces of Ukraine
Povitroflots'kyi ave., 28, Kyiv, Ukraine, 03049

I. Hrechka
PhD, Associate Professor
Department of Theory and Computer-Aided Design of
Mechanisms and Machines
National Technical University «Kharkiv Polytechnic Institute»
Kyrpychova str., 2, Kharkiv, Ukraine, 61002
E-mail: girinap7@gmail.com

*Central Scientific Research Institute of Armament and
Military Equipment of Armed Forces of Ukraine
Povitroflots'kyi ave., 28, Kyiv, Ukraine, 03049

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1. Introduction

Armed confrontations imply that significant territories are contaminated with explosive objects (EOs), resulting in losses of both civilians and military personnel. To reduce losses and labor costs, as well as improve the safety of humanitarian demining operations, appropriate technologies for the remote demining and disposal of EOs are required.

The world experience shows that the most effective means for executing humanitarian demining operations has been the use of mobile robotic complexes (MRCs) equipped with a chassis hosting a manipulator. To expand the functionality of special-purpose MRCs, different types of manipulators are applied, in particular, based on mechanisms with parallel kinematic structures. Advances in this field are relevant as such manipulators are characterized by high load-bearing capacity, low material consumption, high accuracy, as well as by small dimensions and weight. Their use makes it possible to dispose of massive ammunition provided the application of compact MRCs. These types of manipulators are new and insufficiently studied technical devices, which is why their use for MRCs requires defining their characteristic properties that can be used for demining when dealing with EOs in the form of mines. It is also necessary to define the parameters of mines and special features in demining them. Research should involve experimental samples of manipulators and the mockups of anti-tank mines (ATMs). This is a necessary condition for justifying the expedience of executing demining operations using specialized MRC that are equipped with manipulators based on mechanisms with parallel kinematic structures.

2. Literature review and problem statement

The recent available studies and publications report research into MRC for carrying out special activities. The scientific literature provides investigations of the MRC kinematic characteristics, specifically those that examined the operational space of manipulators. A large body of research have addressed the static characteristics of MRCs; however, insufficient attention has been paid to studying their dynamic operational processes. Thus, paper [1] described the design features of MRCs and their basic components; however, the authors ignored the accuracy of activities executed when using robotic complexes. Study [2] noted that the design features of the chassis greatly affect the functionality of MRCs; however, it is more expedient to supplement the theoretical research into this issue with experiments. Work [3] reports results from studying MRCs equipped with lever-type manipulators with consistently connected links. Despite a rather detailed study of lever-type manipulators, the authors did not address the issue of using such a manipulator when dealing with EOs of the ATM type. Paper [4] emphasizes features related to designing manipulators; the cited study, however, investigated manipulators of the open type only.

Work [5] reports research into MRCs based on mechanisms with additional kinematic connections. Study [6] aimed to define patterns in the geometry of mechanisms, in particular the geometrical precision issues [7]. Paper [8] addresses studying the kinematics of MRCs. Typically, these studies relate only to a certain type of MRCs. More complex tasks are solved by the authors of publications dealing with the dynamics of MRC. Article [9] reports effective methods for studying dynamics. The dynamic MRC models are proposed in paper [10]. High-frequency dynamic processes in manipulators were investigated in [11]. Paper [12] paid special attention to issues on ensuring the dynamic accuracy of MRCs. Those publications that address studying the dynamics do not take into consideration a change in the inertial parameters of manipulators during operation, which is especially characteristic of the mechanisms with a parallel structure. That is why these issues require further research.

Among the publications that report research into the features of manipulators based on parallel mechanisms, one should highlight paper [13]. However, it should be noted that the examined manipulators are typically constructed based on the scheme of a tripod or hexapod mechanism [14]. One peculiarity indicated is the difference in the execution of the direct and inverse kinematics problems in these mechanisms [15]. Authors of [16] confirmed the importance of considering the deformativeness of the bearing system of manipulators in determining their functional properties. However, they did not pay attention to issues related to defining the operational space of manipulators and taking into consideration the type of element base when determining their static characteristics.

The scientific literature typically defines the MRC manipulators characteristics without considering special features of EOs, specifically ATM. Paper [17] that addresses military MRCs investigated manipulated objects. Certain algorithms of MRC operation that enable working with EOs are provided. Study [19] takes into consideration special features in arranging the manipulator on a mobile base. Authors of [20] pointed to the need to use mechatronic control systems in robots that perform special operations [20].

Our analysis of recent available studies and publications has revealed an unaddressed issue implying the justification of expediency of executing operations to dispose of EOs using MRCs. As regards MRCs equipped with manipulators built on the basis of mechanisms with parallel kinematic structures, it is necessary to justify the requirements to them.

3. The aim and objectives of the study

The aim of this study is to substantiate the feasibility of constructing manipulators based on mechanisms with parallel kinematic structures intended for carrying out operations on humanitarian demining of territories.

The results to be obtained would make it possible to substantiate technical requirements to manipulators as part of MRCs, to experimentally confirm the efficiency of manipulators based on mechanisms with parallel kinematic structures.

To accomplish the aim, the following tasks have been set:

– to prove that the MRC manipulators built on the basis of mechanisms with parallel kinematic structures possess rational force characteristics and could be recommended for carrying out EO demining operations;

– to devise a demining technology and algorithms for operating the manipulators based on mechanisms with parallel kinematic structures in order to execute operations on humanitarian demining of territories;

– to define the geometric and force parameters for connecting an ATM fuse;

– to determine experimentally the efforts that emerge at unscrewing an ATM fuse using the manipulator with parallel kinematic structures and to construct a special algorithm to rationalize the ATM disposal process by the manipulator.

4. Establishing the features of mobile robot manipulators; considering their features while performing demining operations

The MRC manipulators that are used in carrying out demining operations should have a high cargo-bearing capacity at minimum weight, demonstrate low energy and material consumption, as well as allow flexible control algorithms. These requirements are met by manipulators based on mechanisms with parallel kinematic structures, which represent spatial rod structures with links of variable length or with movable hinge joints.

Within the framework of current research, a series of MRCs with manipulators based on mechanisms with parallel kinematic structures have been designed. The rational one is the MRC based on a hexapod mechanism (Fig. 1).

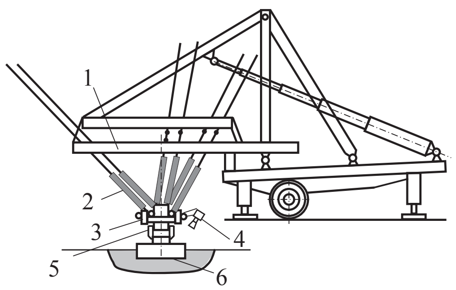


Fig. 1. Schematic of MRC with a manipulator based on a hexapod mechanism and its application in carrying out demining operations: 1 – base; 2 – variable length rods; 3 – moving platform; 4 – video camera; 5 – grip; 6 – ATM

A demining MRC includes base 1, which hosts six variable-length rods 2, which are connected to movable platform 3 that carries the necessary devices. Such devices are video camera 4 and specialized grip 5 that interacts with ATM 6.

The MRC manipulator has a rod system comprising six variable-length rods. The length of each rod is changed by autonomous drives that include electric motors, pass-through transmissions, and screw-nut transmissions.

Changing the length of the rods alters the spatial position of platform 5 of the manipulator. The platform hosts the grip for clamping an ATM fuse.

As a prototype, we have implemented the MRC that includes a manipulator based on the mechanism with parallel kinematic structures, the MRC frame, which is fixed with hinges on two beams attached to a vehicle.

The grip of manipulator 3 interacts with an ATM fuse. In this case, the grip is exposed to force factors in the form of principal vector $\vec{F}$ and the main momentum $\overline{M}$. The magnitudes and directions of these force factors depend on the specific conditions for a contact between the fuse and an ATM shell and may vary widely.

The force factors, variable in the magnitude and direction, acting on the grip are perceived by the manipulator rods. The presence of a hinge joint between the frame and the platform predetermines the emergence of axial loads only in the rods. The rods perceive both stretching and compressive loads. The structure of the rod system is implemented in such a way that all the forces $\vec{F}$ and momenta $\overline{M}$ that act on the grip are effectively perceived by efforts T_1,..., T_6 in rods (Fig. 2).

The presence of parallel kinematic structures includes the action of bending deformations in the bearing system of the manipulator, which differs from lever-type manipulators. Accordingly, the manipulator based on a mechanism with parallel kinematic structures would make it possible to change, in a wide range, the force factors $\vec{F}$ and $\overline{M}$, which are required for the demining process carried out by unscrewing the fuse from the ATM shell.

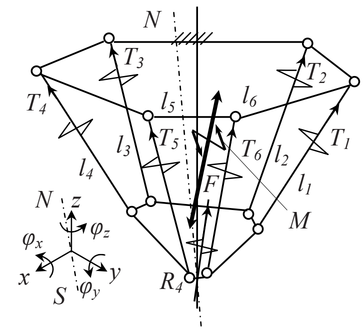


Fig. 2. Perception of external loads $\vec{F}$ and $\overline{M}$ by the rod system of the manipulator with the emergence of efforts T_1,..., T_6 in separate rods

5. Determining geometric and force parameters for the threaded connection between a fuse and the ATM shell

In the process of current research we have determined characteristics for the threaded connection between a fuse and the ATM shell. There is a threaded hole in the ATM shell, with a special thread into which the fuse is screwed; at one side, it has a flange with slots, at the other – the corresponding thread.

The thread has only a few working threads in the connection. Therefore, at tightening the connection there emerge complex spatial force and momentum loads. These loads depend on the position of the fuse and the hole, actual geometric dimensions of the thread, and a series of other factors. To explore them, we measured the connection geometry and determined the static forces and momenta arising in the connection under a stationary state and at slow displacement.

To determine the real geometry of the threaded connection, we performed special measurements of the geometry of thread in separate parts of the connection, namely: the threads of the fuse and the hole in the shell. The connection has the thread with a special profile. The measured basic dimensions of the fuse thread and the hole thread are shown in Fig. 3.

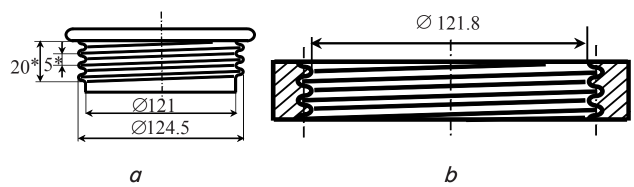


Fig. 3. Geometric dimensions of a special-profile fuse: *a* – sketch of threaded hole in the ATM shell that hosts a fuse; *b* – fuse

The surface of the fuse has three clearly defined turns of the thread, while the fourth (the thread cut-off) has an angular length of 90°. The hole of the ATM shell has about five turns of thread.

To establish the actual profile of the thread in the hole of ATM and the fuse, we conducted special measurements. These measurements use a contour imprint of the screw and nut thread obtained directly on the thread. We acquired the imprint of the profile of the fuse thread by deforming a plastic material (plastic) at the surface of the hole in the ATM shell and at the outer screw surface of the fuse.

Parts made of a plastic material (plastic) were pressed into the thread profile while their end surfaces were levelled. The result is the obtained imprints of the thread of the fuse and hole, whose surfaces define the actual profiles of the thread of the hole and the thread of the fuse.

The imprints on which the profile of the thread was formed were measured by scanning and corresponding magnification. The result is the determined actual geometrical size of the thread's profile and that of the hole in the ATM shell (Fig. 4).

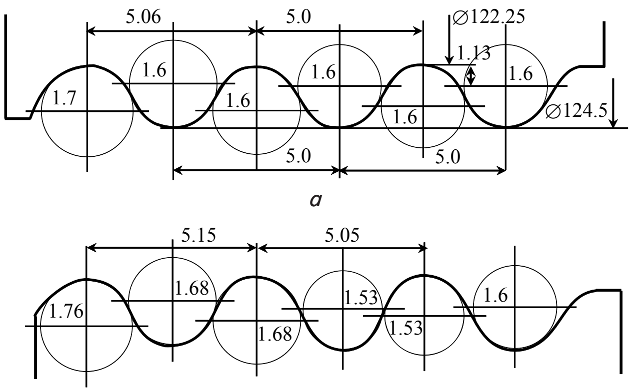


Fig. 4. Scanned actual profiles, their geometric dimensions and shape (mm): *a* — thread of fuse; *b* — thread of hole in the ATM shell

After scanning the ends of the imprints, we built curves (splines) based on them, which are the actual profiles of the thread.

The obtained shapes of the thread profiles are approximated by the circle arcs and straight lines (Fig. 5).

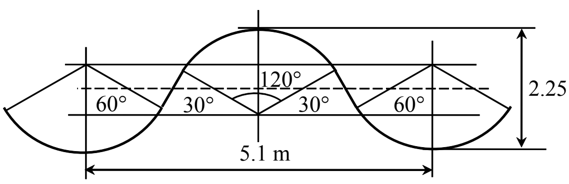


Fig. 5. Approximation of the thread profile by circle arcs and straight lines

The obtained geometric dimensions of the thread served as the basis for analyzing the geometric characteristics of the threaded connection and determining the ratio between the forces and momenta arising in the connection. In this case, we determined the static characteristics of the threaded connection and the ratio between the forces and momenta in the connection between the fuse and ATM.

The complexly-shaped threads of a large diameter do not have a clearly defined position of the screw relative to the threaded hole. This is due to a small number of thread's turns. Therefore, in the interaction between the fuse and hole there is a point contact between the surfaces of the fuse thread and the hole, which occurs in a curvilinear sloped plane. When the fuse is freely rotated in the threaded hole, it is exposed to a slight gravitational force of the order of 5–7 N. Under the influence of the gravitational force the fuse is lowered and the surface of its thread is in contact with the surface of the hole thread. The contact takes place at least in three regions K_1, K_2, K_3, arranged along a circle and that perceive the gravitational force (Fig. 6).

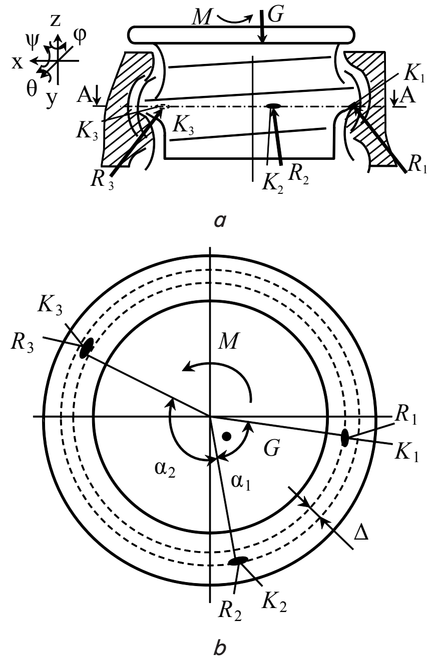


Fig. 6. Schematic of the emergence of force reactions of the thread that perceives mostly the gravitational loads on the fuse: *a* — side view; *b* — top view

Contact stresses in regions K_1, K_2, K_3 are insignificant. Therefore, to rotate the fuse, a slight torque would suffice. A given torque is defined by the friction coefficient of the threaded connection surfaces and could be approximately determined from dependence

$$M = G \cdot k, \tag{1}$$

where k is the friction coefficient; G is the gravitational force due to the mass of the fuse.

The scheme of interaction between the surfaces of the fuse and the ATM hole significantly changes when tightening the thread. This occurs when the fuse end contacts the end surface of the hole. The contact region emerges at some domain M, which is in an unidentified part of the fuse end (Fig. 7).

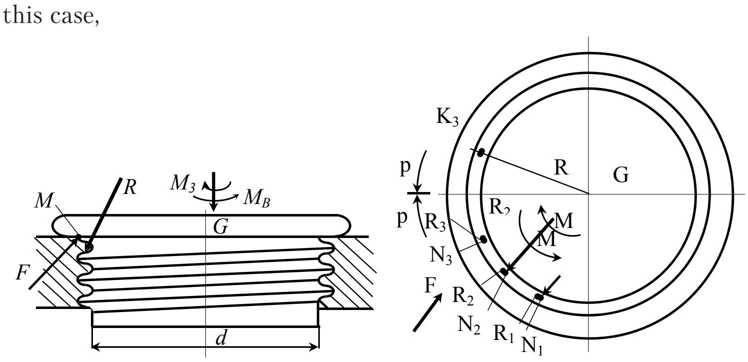


Fig. 7. Schematic of load action on the fuse when tightening the thread and contact zones of the fuse and the hole: *a* — side view; *b* — top view

In the contact zone, there emerges force F that acts on the fuse. A given force is much greater than the gravitational force G and acts in the local region of the fuse, causing its complex displacements. Displacing the fuse forms new contact points between the surfaces of the fuse and the hole. The number of contact points is uncertain and is 2 or more. Contact points N_1, N_2,..., N_4 are located close to region M, efforts R_1, R_2,..., R_4 emerge in them. The resultant of these efforts R, in a combination with gravitational force G, compensate for the action of effort F in the contact region.

The tightening momentum creates, due to the sloping plane, a significant contact load F. To simplify the estimation of magnitude of the contact load, we accept that the sloping plane equals a tilt of the thread (Fig. 8).

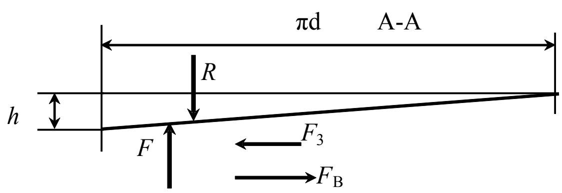


Fig. 8. Sweep of the screw thread line and the effort at screwing and unscrewing the ATM fuse

The inclination angle of a sloping plane is:

$$\beta = \mathrm{arctg} h/\pi d. \quad (2)$$

Relation between the tightening effort F_3 and contact load

$$F = F_3/\sin\beta. \quad (3)$$

Considering $\beta \approx 0$, we obtain

$$\mathrm{tg}\beta \approx \sin\beta \cong h/\pi d. \quad (4)$$

Accordingly, the contact effort is calculated from dependence

$$F = F_3 \times \pi d/h \approx 80\ F_3. \quad (5)$$

Thus, the slight force of fuse tightening F_3 provides for a significant contact effort F.

The considered dependences (2) to (5) do not take into consideration the forces of friction. However, the influence of the friction forces at tightening is insignificant.

The simplified scheme of tightening the thread does not exactly reflect the processes that occur at the same time. Given the complex profile of the fuse thread and error in the profile, a contact between the surface of the fuse and the hole is uneven.

When tightening, there is a distortion of the fuse, changing contact regions between the threads' surfaces. Contact regions N_1, N_2,..., N_4 are shifted towards the region of action of the contact load M.

New contact regions emerge, which are grouped in the region M of the effort action, tightening the thread. The contact regions change in the process of thread tightening; there is the tendency of concentrating the group of contact points. The resultant of reactions R_1,..., R_4 grows close to the contact load F whose magnitude increases. There are significant friction forces that increase over time due to contact deformities at points, adhesion, and other factors, in particular thermal deformations, vibration processes, relaxation of stresses in contact regions, and others.

All force factors that emerge at thread tightening depend on tightening momentum M_3. The momentum of thread unscrewing M_B differs from the tightening momentum and depends on many factors. The momentum of unscrewing is affected in particular by the design features of the manipulator and gripping mechanism. The momentum of thread unscrewing was determined experimentally when using a prototype of the manipulator, built on the basis of a mechanism with parallel kinematic connections.

6. Experimental determining of the efforts that emerge at unscrewing the ATM fuse using the manipulator

Our experimental research involved a prototype of MRC built on the basis of a mechanism with parallel kinematic connections designed at the National Technical University of Ukraine "Kyiv Polytechnic Institute named after Igor Sikorsky" (Ukraine). The MRC prototype has a manipulator that was built based on a hexapod mechanism with six variable-length rods, which enable the displacement of the grip for six coordinates. In the process of research, we used different grips with a varying number of fingers that differ in the structural execution (Fig. 9).

Fig. 9. Installing a special grip on a movable platform of the manipulator

For experimental measurements. we have designed a series of structures for gripping devices. These devices have fingers of appropriate configuration (Fig. 10).

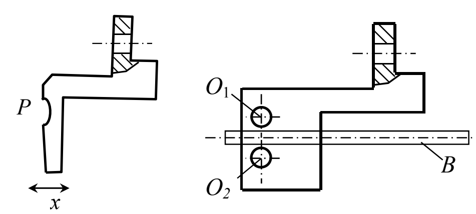


Fig. 10. Designed and fabricated fingers of a gripping device (grip) for unscrewing the ATM fuse: *a* – elastic finger; *b* – finger for conducting experimental measurements

The elastic finger (Fig. 10, *a*) has a thinning P, which provides for a certain freedom of movement along the x direction. A finger for experimental measurements was made according to scheme in Fig. 10, *b* with two holes O_1 and O_2.

By using these holes, the fingers of the grip hold lever B, intended for a momentum load on the manipulator grip.

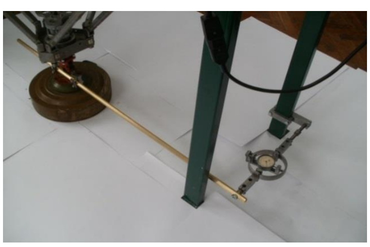
The fingers are installed in the gripping device of the MRC manipulator and serve to hold the ATM fuse, in particular at its rotation during tightening and loosening of the thread (Fig. 11).

Fig. 11. The gripping device used to experimentally determine the momenta of screwing and loosening the fuse

Experimental research has been undertaken to determine the nature of change in the efforts at screwing and unscrewing.

To this end, we used the equipment in the form of annular dynamometer and appropriate toolset. Loading the fuse was enabled in the tangential direction by a screw device (Fig. 12).

a

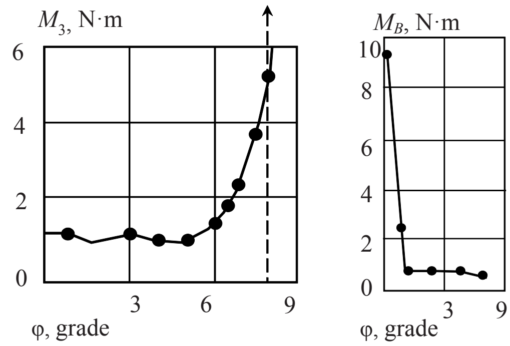


b

Fig. 12. Experimental set-up for determining the efforts of screwing and tightening the thread and loosening the fuse: *a* — front view; *b* — side view

The measurements of the momentum of screwing and unscrewing involved a cross-arm, fixed at the grip of the robot, and the dynamometer, fixed on the rack. In the process of conducting experimental measurements, the screw device shifted the end of the cross-arm thereby creating the momentum of not-loading the grip.

We carried out measurements of the momentum necessary to turn the fuse along the thread at screwing and unscrewing. The measurements were performed at the free fuse rotation. In addition, we measured efforts at screwing and tightening the thread. It was determined that the effort (momentum) of tightening the fuse sharply increases at the final moment of tightening (Fig. 13, *a*).



a *b*

Fig. 13. Experimental dependences of momenta on the fuse rotation angle: *a* — thread tightening; *b* — fuse unscrewing

It was established that the unscrewing effort (Fig. 13, *b*) exceeds the screwing effort by 1.8–2.5 times. This ratio increases with an increase in the dislocation – the time at which the threaded connection is in a tightened state. To reduce the effort of unscrewing, special measures have been suggested, which include a specialized design of the grip and, most importantly, special kinematic algorithms for manipulator operation. In order to reduce the effort of fuse unscrewing, a special design of the grip with elastic fingers has been proposed.

7. Substantiation of the kinematic and dynamic algorithms for manipulator operation

The main problem in removing the ATM fuse is to unscrew the tightened threaded connection. It follows from our research that there is the existence of significant efforts in the tightened thread. We have performed a study into the influence of separate displacements and corresponding loadings on a decrease in the momentum of unscrewing the threaded connection between the fuse and the ATM shell. The displacements and force factors were determined in the coordinate system associated with the ATM, which hosts the fuse with a tightened thread. In this case, the z axis is oriented along the axis of the fuse while the x and y axes are selected so that the x axis passes through the region of action from the contact load (shown by arrow at the surface of the fuse in Fig. 14).

Fig. 14. Installing indicators on the ATM mockup for measuring the fuse transverse-angular displacements

Special experimental investigations were carried out to determine the angular position of the arrow passing through the contact load area relative to the ATM shell. To this end, the fuse, installed in the ATM, was loaded along the perimeter with vertical loads; we measured the deformation of the flange of the fuse. Indicators were mounted at different points relative to the contact region. Vertical displacements of the perimeter of the flange of the fuse relative to the ATM shell were measured at four points. The points for measuring deformations of the fuse flange and loading, which serve to select the base system of coordinates and the diagrams of the flange displacements along the circle arc, were measured at different loads.

Based on our experimental research, it has been proposed, in order to facilitate the fuse unscrewing, to implement its periodic momentum loads using the manipulator drives. According to the proposed procedure for experimental study, we dynamically loaded the fuse by implementing insignificant rotational displacements of the grip of pulse character, registering the effort for unscrewing the fuse.

It follows from the results reported in chapter 5 that a tightened contact between the fuse end and a turn of the thread occurs only in a separate region along the perimeter of the connection (shown by arrow *S*). Therefore, the connection stiffness is much greater only in a separate region *M* (Fig. 15).

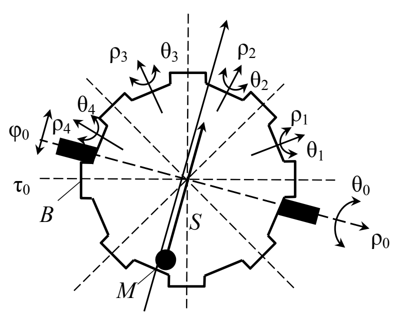


Fig. 15. Schematic of the grip position relative to the slotted flange when unscrewing the thread

In the direction that is diametrically opposite to region *M* (shown by arrow *S*), the connection stiffness is minimal. Therefore, to reduce the static friction effort, it has been proposed to perform the oscillatory motion of the grip through transverse-angular displacements θ_0 relative to the ρ_0 axis, which is approximately perpendicular to the direction of the maximum change in the stiffness corresponding to the direction along arrow *S*. Following five cycles of the transverse-angular displacements, one carries out a sharp swivel movement of the grip relative to the *z* axis in direction τ at turning angle φ_0. The grip's fingers move along direction τ_0; the finger hits the ledge of the slotted flange B of the fuse. The loading cycles are then repeated.

We performed experimental measurements of the required number of load cycles required to unfix the threaded connection between the fuse and the ATM. It was established that 3–5 cycles of dynamic loading make it possible to ensure a shift of the fuse at the tightened threaded connection (Table 1).

It follows from analysis of Table 1 that the transverse-angular cyclic loading of the threaded connection significantly reduces the strength of friction force at rest and makes it possible to implement the breakdown of the thread and achieve initial rotation of the screw.

Table 1

The number of loading cycles required to unfix the threaded connection under dynamic transverse-angular loading of the fuse

No. of measurement	Number of loading cycles									
	1		2		3		4		5	
	θ_0	τ_0	θ_1	τ_1	θ_2	τ_2	θ_3	τ_3	θ_4	τ_4
1	5	1	5	1	5	1	5	1	5	1*
2	7	1	7	1	7	1*	–	–	–	–
3	5	1	5	1	5	1	5	1*	–	–
4	7	1	7	1	7	1*	–	–	–	–
5	5	1	5	1	5	1*	–	–	–	–

*Note: sign * marks the momentum when the threaded connection is unfixed*

In case such a loading is not carried out, but the impact transverse-angular loading is instead performed relative to the *z* axis along direction τ, it is then necessary, in order to unscrew the fuse thread, to execute 20–30 and more impact loading cycles. In most cases, such a load is impractical and could lead to the destruction of the protrusions of the slotted flange or to the fuse getting stuck in the ATM.

Under actual conditions, the direction of the fuse warping relative to the threaded hole of an ATM is unknown. Therefore, the algorithm for dynamic displacement of the grip has been suggested, which provides the possibility of loosening the tightened threaded connection of the fuse installed in the ATM shell.

The grip is located and oriented along some direction on the slits of the fuse. A given direction is shown by axis I–I; it is random (Fig. 16).

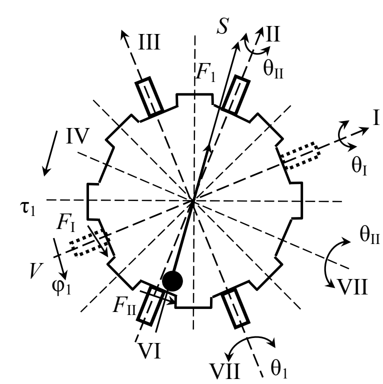


Fig. 16. Schematic of the grip location relative to slits when implementing the dynamic algorithm for unscrewing the fuse

The grip's fingers capture the slits at position I–I and clamp them in the diametrical direction. In this case, the robot control system carries out a cyclic transverse-angular loading of the fuse through its cyclic rotation at angle θ_1 in the positive and negative directions relative to the perpendicular axis I–I. The implementation of the fuse transverse-angular loading is followed by a sharp turning of the grip relative to the fuse axis at angle φ_I. At the end of the turn, the impact loading on the protrusions of the fuse slits is ensured by forces F_I.

After that, the grip opens and, using the robot control systems, rotates relative to the *z* axis at an angle equal to the step of the slits, and sets at position II–II. After clamping the slits by the grip, a cyclic transverse-angular loading on the grip is ensured by turning it at angle θ_{II} relative to the axis perpendicular to axis II–II. Upon competing 5 cycles of transverse-angular loading, the grip abruptly rotates relative to the *z* axis thereby creating a dynamic impact load on slits by forces F_{II}.

If the thread is unscrewed, the process of cyclic loading is terminated. If the thread is not unscrewed, the grip leaves position II–II and moves to position III–III. In this, and in future positions (IV–IV...VIII–VIII), a cyclic transverse-angular loading of the fuse is executed with a subsequent momentum pulse loading to unscrew the fuse.

In total, the grip displaces in eight positions. In case the fuse is not unscrewed during it, then the robot control system is used to increase the amplitude of transverse-angular displacements and the intensity of pulse momentum loading of the fuse. The process is repeated until the unscrewing of the fuse.

Following the onset of unscrewing, the grip moving algorithm changes. The grip displaces to a certain position, clamps the fuse on slits and rotates it at an angle equal to one or two steps of the slits. This process continues until the fuse is removed completely.

8. Discussion of results of studying manipulators for mobile robotic demining complexes

The results of our research helped establish that the issue of humanitarian demining is difficult enough. The type of EO and external conditions under which demining is performed is of great importance. Accordingly, the type of EO imposes certain requirements on the robotic complex and the manipulator used in demining.

The current work reports our research on determining actual geometric parameters of a threaded connection between a fuse and an antitank mine shell (Fig. 4). Based on the results obtained, we determined the force parameters for a threaded connection (Fig. 7). Specifically, it was found that the fuse unscrewing effort significantly exceeds the effort of screwing.

Refining the theoretical study using the results from experimental measurements allowed us to substantiate requirements to MRC manipulators, which could be used in demining.

The application of manipulators based on mechanisms with parallel kinematic structures is advisable to demine EOs of considerable weight.

The result of our research is the constructed algorithm of manipulator operation provided an EO has a fuse installed in the threaded hole. In this case, there exist the force parameters required to remove the fuse.

Thus, it has been established that application of parallel-structure mechanisms when executing demining operations makes it possible to ensure the rational perception of forces and momenta that are necessary for a guaranteed removal of an anti-tank mine fuse, as well as other EOs.

Based on current research, we have established and comprehensively substantiated a possibility of demining using mobile robotic demining complexes equipped with manipulators based on mechanisms with parallel kinematic structures.

9. Conclusions

1. It has been proven that the manipulators of mobile robotic complexes, built on the basis of mechanisms with parallel kinematic structures, provide the most rational perception of forces and momenta that are required to remove an anti-tank mine fuse in the process of disposal of it. Therefore, the manipulators of this type are recommended for use at MRCs intended for humanitarian demining and performing operations for disposal of explosive objects.

2. It has been established that the threaded connection between the fuse and the shell of an anti-tank mine is in a complex strained-deformed state with the emergence of a series of points along the thread contour, which are located asymmetrically relative to the axis of the fuse. That leads to an increase in the effort of unscrewing the fuse, which is 1.8...2.5 time greater than the effort of screwing. To improve efficiency of the fuse unscrewing process, it is recommended that the fuse should be periodically clamped by the manipulator's grip. In this case, a transverse-angular momentum loading of the fuse is created relative to the axis of the perpendicular plane of the grip's fingers location with a subsequent impact loading of the fuse by a momentum of forces, oriented along the axis of the fuse. Periodic clamping must be repeated when the grip rotates around the axis of the fuse at an angle corresponding to the angular step of the fuse slits until the moment the fuse thread is released. After the shift, the fuse is unscrewed and removed.

3. The results of our study helped establish the design features for manipulators in the above-specified structure; define the efforts that arise when unscrewing a mine fuse; construct a special algorithm for rationalizing the demining process using a manipulator. That has made is possible to substantiate technical requirements to specialized demining equipment that involves promising mobile robotic demining complexes.

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