DEVELOPMENT OF THE CONCEPT OF INTELLIGENT MOBILE PLATFORMS FOR THE INTERNATIONAL SCIENTIFIC LUNAR STATION

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The article analyzes and develops domestic engineering developments of concepts of lunar bases and vehicles for their construction and operation. The concept of intelligent mobile platforms (IMP) is proposed, which are unified self-propelled chassis with automatic docking and coupling devices (ADCS) and local navigation subsystems. Various attachments are installed on the self-propelled chassis, which determine the purpose and technological characteristics of the vehicle. Such vehicles can be used as independent lunar rovers with hybrid control, and as links of a multifunctional lunar train designed for special operations, including long-distance expeditions of hundreds of kilometers. Based on the Lunar Reconnaissance Orbiter Camera images published by NASA, a possible route of the expedition from the International Lunar Science Station (ILSS) site near Malapert Massif to the back side of the Moon has been laid out, taking into account the level of illumination and elevation angles of the terrain along the entire route. The purpose of the expedition is to conduct scientific research along the path of travel, delivery of equipment and deployment of an automatic branch of the LLRS - lunar observatory on the back side of the Moon in the shadow of the Earth's radio noise. On the basis of computational and theoretical studies and design and layout developments, an advance design was made, including the technical appearance of the IMU and its main tactical and technical characteristics.

Keywords: lunar station module, intelligent mobile platform, lunar train, lunar exploration

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INTRODUCTION

On June 16, 2021 in St. Petersburg during the Global Space Exploration Conference (GLEX-2021), leaders of Roscosmos and the National Space Administration of China presented the roadmap for the joint project of the International Scientific Lunar Station (ISLS). On June 12, 2024, the President of the Russian Federation signed Federal Law No. 128-FZ "On Ratification of the Agreement between the Government of the Russian Federation and the Government of the People's Republic of China on Cooperation in the Field of Building an INLS".

The purpose of the article is to develop and analyze design concepts of intelligent mobile platforms (IMP) - unified mobile components of new generation lunar robots with hybrid control, oriented to support the work on the creation and operation of ISLVs. The Soviet Lunokhod-1 and -2 and the U.S. Lunar Roving Vehicle (LRV) are prototypes of IMPs in terms of self-propelled chassis. But the LRVs equipped with various attachments and built-in equipment, in the authors' view, should have an expanded composition and functions. After all, they are supposed to be used not only to create autonomous robots and manned vehicles for transportation of cosmonauts, payloads, scientific research and (or) technological operations, but also multilink mobile robotic complexes (MRTC) - lunar trains of the XXI century.

Autonomous and manned lunar rovers, delivered to the Moon fully assembled and ready for independent movement already on the landing platform of the spacecraft (SC), are necessary at the earliest stages of designing and constructing a TPLF. Without them, in particular, it is impossible to carry out a qualified survey of promising areas of the Moon for selecting the location of the TPLS construction and for refining the construction documentation. At the next stages of the construction of the ISLV, they will be used to prepare construction sites, build roads, transport cargo between the lunar spaceport and the construction sites of the various station structures, and to participate directly in the installation of these structures. As construction of the INLV progresses, lunar rovers will be increasingly used to support scientific research, water and mineral exploration in the vicinity of the station.

However, a number of tasks of construction and effective operation of the TPLM with the help of single lunar rovers are impossible. In particular, preliminary design developments suggest that transportation and installation of large modules of the ISLV with a mass of about 20 tons will require at least two-linked lunar rovers. Subsequent exploration of vast territories of the Moon, support of technologies for the development of lunar resources, conducting research during long and distant (hundreds of kilometers) expeditions are practically impossible without multilink MRTCs. In fact, these complexes will have to create for the crews all the conditions for life, labor and recreation that will be created on the MLRS, but with a lower level of comfort.

CURRENT DOMESTIC CONCEPTS OF THE LUNAR BASE AND ITS MOBILE COMPONENTS

In general outline, the concept and design appearance of the long-term lunar base (LTB), on behalf of the head and chief designer of the Experimental Design Bureau-1 (OKB-1) S.P. Korolev, for the first time in the USSR were worked out on the engineering level
under the leadership of V.P. Barmin back in the 1960s (Merzhanov, 2018) in the State Union Design Bureau of Special Machine Building (GSKB Spetsmash), which was later renamed the Design Bureau of General Machine Building (KB OM) and is now called the Center for Ground-Based Space Infrastructure Facilities Operation (TsENKI).

In our opinion, the ideas of building a lunar base as a set of cylindrical hermetic modules connected with each other by hermetic passages and installed on the pre-aligned lunar regolith are still relevant. After all, both then and now the dimensions of space cargoes are determined by the geometry of the rocket head fairing. The authors of the project envisioned using regolith only for low cylinder capping in order to fix the modules on the construction site. The project envisioned at least two airlocks for entry to the station and exit to the lunar surface.

In terms of mobile robotics, in our opinion, the concept of lunar trains, similar to the sledge-tractor trains that were successfully used for the construction of Soviet scientific stations in the harsh conditions of Antarctica, proposed in the DLB project, is still relevant. According to the developers' ideas, the lunar trains should have included at least four links: a tractor, a living car, a power plant and a drilling station.

However, modern technologies and experience of operation on the Moon of the Soviet all-wheeled four-wheel drive Lunokhod-1 and -2 make it possible to create a lunar train, all links of which, performing different functions, will be really equal in their traction and dynamic characteristics. It will be not just a step forward in terms of such operational and tactical characteristics of the lunar train as cross-country ability, reliability, resource, functional capabilities. Creation, after three flights to the Moon, even the simplest three-link lunar train, including a manned lunar rover with a sealed cabin and airlock, a robotic lunar rover with an onboard power plant, including solar and isotope energy sources, as well as another robot with a stock of life support components, allows us to solve the strategic problem of organizing an emergency mobile double of the stationary MLRS.

The authors believe that in subsequent design and layout developments can be guided by the proposed in the last century overall dimensions of cylindrical shells of TPLM modules: length ≈ 8 m, diameter ≈ 4 m, mass of about 18 tons. But the idea of delivery to the Moon compressed into an accordion shell modules with subsequent deployment of their full length in the lunar vacuum due to the internal pressure of gases in modern astronautics has not been developed. This method of deployment obliges to install all service and scientific equipment directly on the Moon. But the practice of creating the first Soviet orbital station MIR, the International Space Station (ISS), and the Chinese station Tiangong, as technological analogs of lunar stations, has shown that the assembly and testing of ISS modules on Earth, even in specially equipped workshops, takes years. Planning a full cycle of such works directly on the site of modules operation is unpromising. Only various docking operations, autonomous and complex tests of new equipment as part of an orbital or lunar station are inevitable here.

In 1974, the Central Design Bureau of Experimental Mechanical Engineering (CDBEM) - (this was the name of OKB-1 since March 1966, now the Rocket and Space Corporation (RSC) Energia), developed Technical Proposals for a lunar expeditionary complex, which was named Zvezda (Semenov et al., 1996)

By this time, the USSR and the USA were summarizing the results of the completed pioneering lunar studies. A huge amount of new information about the surface of the Moon, about the peculiarities of interaction with it of self-propelled chassis of remotely operated lunar rovers (Anisimov et al., 1971; Kemurjian et al., 1976; Ivanov et al., 1978; Avotin et al., 1979; Kemurjian et al., 1982; Gromov et al, 1986) and manned lunar rover - Lunar Roving Vehicle (LRV) (Costes et al., 1972; Young, 2007), obtained by contact methods, in one way or another reflected and still reflects on all subsequent domestic and foreign design developments of the lunar base.

In particular, the mentioned Soviet design study of 1974 preserved the idea of a tractor, which is called "Heavy Lunokhod" in the documents of TsKBEM. The design appearance of this lunokhod: rigid wheels, wheel formula 8× 8, lever suspension of wheels with elastic elements in the form of torsions, on-board turning method - all this was in line with the design solutions of the self-propelled chassis of Lunokhod-1. Main parameters: crew of two cosmonauts, total mass of 8.2 tons, including the mass of the power plant with rated power of 8 kW - 2.25 tons, average speed of 5 km/h, duration of one expedition up to 12 Earth days, volume of the pressurized compartment 25 m^3: dimensions of the pressurized cabin: length 8 m, width 4.5 m. The concept of lunar trains was not developed, but also not refuted.

VNII-100 (now JSC "All-Russian Research Institute of Transport Machine Building" (VNIITransmash)), where, under the leadership of A.L. Kemurdzhian, the self-propelled chassis (SP) of Lunokhod-1 was created, in the 1970s was a co-executor of the design studies of OM Design Bureau on the lunar base in terms of mobile equipment. P.S. Sologub, the closest associate of A.L. Kemurdzhian, was the head of VNII-100, and E.V. Avotin, a member of his department, was the supervisor of the contract between the enterprises.

However, the full-size operating mockup of a two-section manned lunar rover (Fig. 1), which actually became the first realization in metal of the DLB authors' ideas on the lunar train, was created at VNII-100 with the participation of the authors of this article in the late 1970s within the framework of the formally not yet closed Soviet lunar program "E-8" (Marov, Hantress, 2013). The front section of the mockup was designed to accommodate the seats of two cosmonauts, components of the navigation, power supply, and motion control systems. The second section could accommodate attachments for scientific research and transportation of payloads - lunar soil, drilling mechanisms, etc. The sections of the self-propelled chassis mockup were fully unified.

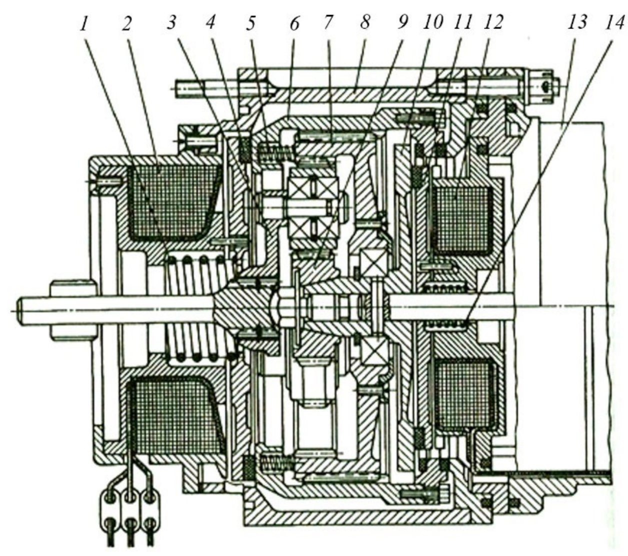
In contrast to the SS of the Soviet lunokhods, three new technical solutions were implemented in this mockup: a coupling device that preserves three angular degrees of freedom of the sections when moving on difficult terrain (Gorbunov et al, 1985); a two-stage automatic gearbox with electromagnetic control as part of the traction drive of the motor-wheels (Korepanov et al., 1972); and metal wheels with a diameter of 0.8 m with a profiled elastic tire made of steel wire mesh (Mitin et al., 1981). The maximum speed of the model on unprepared terrain with elevation angles of no more than 5°-7° was 4.8 km/h (Gromov et al., 1986).

Fig. 1. Running mockup of the two-section self-propelled landing gear of the manned lunar rover
(from the author's archive).

Application of the gearbox, the scheme of which is shown in Fig. 2, made it possible to regulate not only the speed of movement, but also the torque on the wheels and, consequently, the traction force in the contact of the wheels with the ground. The schematic of the wheel of this layout is shown in Fig. 3. The combination of a rigid rim with sufficiently high ground serrations and a profiled metal mesh tire mounted on this rigid rim made it possible to extend the range of speed control. On steep ascents, for example, when leaving the craters, the gearbox operates in the first gear, providing a nominal speed of about 1 km/h with maximum torque. At the same time, the mesh tires of the aft wheels, the most loaded wheels, in the process of their elastic deformation under a heavy load, allow the ground hooks to come into operation, which are capable of realizing maximum traction forces.

On a relatively flat surface with elevation angles up to 5°-7° , such as between craters, where the lunar regolith has a higher bearing capacity, mesh tires work effectively, providing sufficient contact patches with the surface when driving and increasing the smoothness of movement at maximum speed.

The technical solutions used in this layout are partially still valid and are the scientific and technical reserve of the A.L. Kemurdzhian school, a prototype for the design of a new generation SS. Only the coupling device, the design of which does not provide the possibility of automatic docking of sections, needs to be radically redesigned. At that time such a task had not been set yet. So the design of reliable automatic docking and coupling units (ADCU) with minimal weight is a completely new, the most difficult design task in the creation of CPM. The great Soviet experience of creating docking devices for spacecraft (Syromyatnikov, 1984) can be applied here only partially, due to the large differences in the laws of motion in outer space and on the surface of celestial bodies.



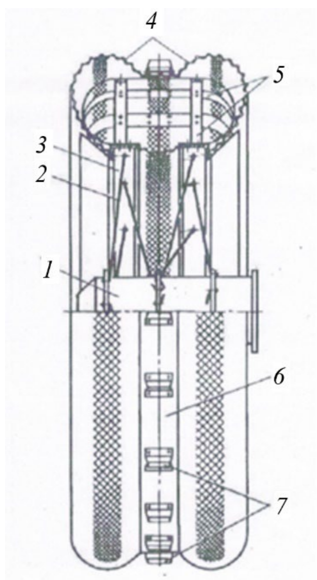


Figure 2. Two-stage automatic gearbox. *1* - gearbox spring, *2* - 1st gear electromagnet, *3* - driver, *4* - 1st gear brake disk, *5* - 2nd gear spring, *6* - drum, *7* - epicycle, *8* - housing, *9* - sun gear, *10* - disk on the motor shaft, *11* - wheel brake disk, *12* - wheel brake *electromagnet*, *13* - motor, *14* - wheel brake spring.	**Fig. 3.** Scheme of a wheel with elastic profiled metal mesh tire of two-section layout: *1* - hub, *2* - spokes, *3 - right* wheel rim hoop, *4* - elastic metal mesh tire, *5* - elastic metal plates, *6* - bandage, *7* - ground hooks.

Some aspects of the IMP concept were reported by the authors at international specialized conferences (Malenkov, 2017; 2023; Malenkov, 2019; 2022).

DISCUSSING THE CHALLENGES OF MOBILE ROBOTICS IN PROMISING AREAS OF MNLS CONSTRUCTION

General approaches to the topic

Regardless of the specific circumstances and time of implementation, all scenarios for the creation and operation of the MNLS will inevitably include the stage of preliminary survey of the spacecraft landing site (lunar spaceport), the site of construction of other MNLS structures, the stage of preparation of these sites and the route connecting this spaceport with the construction site, the stages of delivery to the Moon of the overall modules of the station, its construction and deployment of scientific equipment, as well as the stages of preparation and implementation of long-term lunar expeditions for practical use. Optimal variants of designing new mobile lunar equipment should, if possible, take into account the needs and peculiarities of all these stages.

In case of well-organized preliminary study of the selected area with the help of the lunar orbiter hardware, one or two lunar rovers based on unified IMU may be enough to perform the survey stage. A tandem of manned and autonomous-autonomous lunar rovers seems to be optimal. Onboard penetrometers of the robot and its navigational instruments specify the bearing capacity of the ground and terrain parameters along the entire spaceport-station route. With the help of the manned lunar rover, astronauts within a lunar day can make a spot check of the robot's research results and focus on selecting the locations of the TPLS structures.

In terms of general approaches to design, the prototype of the lunar robot may well be Lunokhod-1, and the prototype of the manned lunar rover - Lunar Roving Vehicle (LRV). The presence of two lunar rovers with instruments and equipment for engineering survey, on the basis of a single CPM will allow parallel testing and testing in full-scale conditions the design of the self-propelled chassis, as well as the design and software of the LARV.

Preliminary calculations show that the landing of spacecraft with lunar base modules with a mass not exceeding 18 tons should be performed on a preliminarily horizontally leveled pad with hardened lunar regolith. This increases the level of reliability and safety against overturning, as well as facilitates the working conditions of the canting and unloading devices for these modules.

The size of the pad depends on the accuracy of the landing of the lunar spacecraft. For example, on January 19, 2024, Japan's Smart Lander for Investigating Moon (SLIM) made a very precise but not quite successful landing on the slope of a small crater. According to media reports, the lander landed on its side only 55 meters away from the target point.

Achieving high accuracy and safety of landing is one of the main objectives of Russian and Chinese satellites, which will subsequently deliver to the Moon modules manufactured on Earth and ready for installation.

After successful landing of the spacecraft at the spaceport site, it is possible to unload the overall modules of the station from the spacecraft landing platform onto a special lunar transportation vehicle, which is, according to preliminary estimates, a coupling of two CPMs with a common cargo platform. Then these modules are transported along the prepared route to the construction site and assembled - connected modules in accordance with the specified configuration of the station.

Laying of special tracks is necessary for reliable and safe transportation of heavy TPLM modules from the unloading site at the spaceport to the installation site with minimum possible energy consumption. The road works of the CPM with special attachments on such a route may include the following works:

- leveling the surface by filling pits, cracks and small craters and cutting bumps and localized hills;

- Strengthening of the soil on the route to a bearing capacity that reduces the coefficient of resistance to wheeled BMI movement;

- routing of the route corners taking into account the limitations caused by the design of vehicles (VVs) that will be used for transportation of TPLS modules.

The current level of knowledge about the lunar soil as a supporting surface for the motion of the vehicle allows us to ensure the possibility of solving the above problems. The authors have also developed original methods and devices for unloading large-size modules of large mass ISLVs. However, these issues are beyond the scope of this article.

Currently, the southern polar regions of the Moon are of the greatest interest for the creation of lunar stations. In these regions, more prolonged solar illumination is provided, but since the Sun is low enough, the surface temperatures do not depend so much on the time of the lunar day as, for example, in the equatorial region. In the polar region of the visible part of the Moon direct radio communication with the Earth is possible, which is important for the creation of a permanent information channel Earth-MNLS. But the most important factor of the polar regions of the Moon is the presence of water ice reserves in the regolith, in deep craters, in the zones of constant shadow. Water is necessary for life support of the MNLS crew and can also serve as a source of rocket fuel components.

Malapert Mountain Massif (Basilevsky, 2019), located near the south pole of the Moon, is chosen as the scenario for the IMP application in this study. Its coordinates are approximately 86° south latitude and 0° east longitude. The top of the mountain rises 5 km from the base and has constant visibility from Earth, which means that direct radio communication is possible. The solar irradiance at the summit is between 87 and 91% during lunar days, which makes it possible to maximize the time of solar energy production. It may be noted that this area is also among the 13 preferred locations for a lunar base, selected by NASA on the recommendations of scientists and specialists.

Fig. 4 (left) shows a photograph of the Moon's south pole. The direction to Earth is perpendicular to the top of the photograph. South of Mount Malapert are the 51-km-long Haworth Crater and 52-km-long Shoemaker Crater, the bottoms of which are in permanent shadow, and neutron spectrometric orbital measurements indicate significant water ice in the regolith.

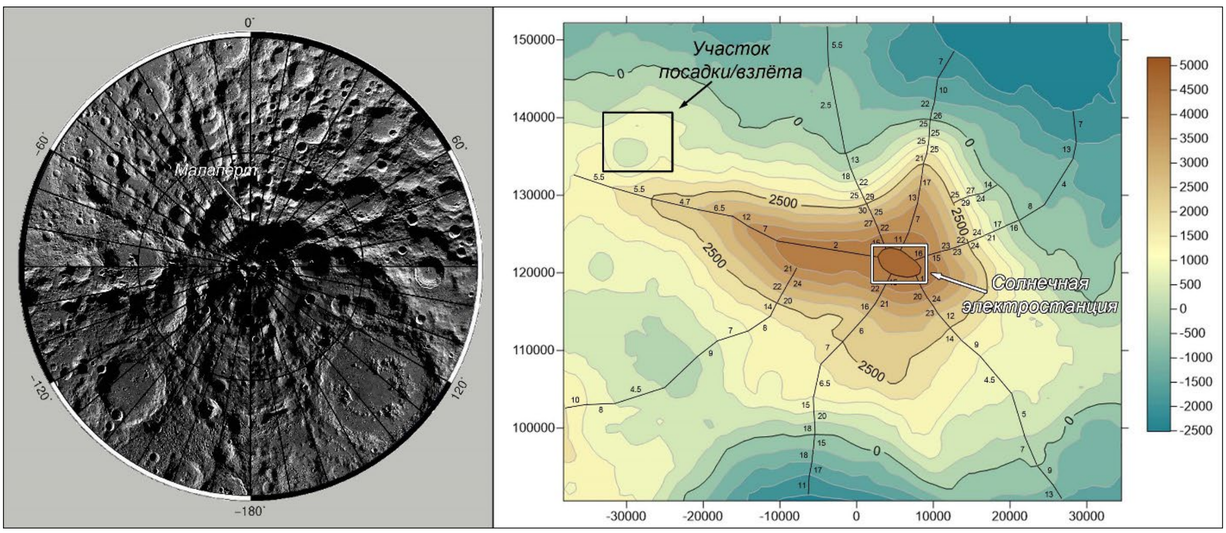


Figure 4. Photo of the South Pole of the Moon from the Lunar Reconnaissance Orbiter Camera and a map of Malapert Mons with presumed areas of location of the MNLS lunar spaceport at the foot (landing/ takeoff site) and elements of the lunar base at the top (solar power plant). The numbers on the vertical and horizontal axes on the map are distances in meters. The numbers between the horizontals on the map are the average angles of inclination of the surface in degrees. (The map in the figure on the right and the values of distances and angles of inclination of the surface on it are based from the LDEM80S20M digital surface model compiled from data from the Lunar Orbiter laser Altimeter (LOLA).

The topography of the Malapert Massif and its derivatives were studied using images from the Lunar Reconnaissance Orbiter Camera (LROC). According to the study, the Malapert Massif is a mountain, mostly with fairly steep slopes (up to 20°-30°), approximately 30-50 km long, extending in a northwesterly direction with a northerly extension. However, along the most gentle northwestern slope, the general elevation angle measured at a base of several kilometers does not exceed 12° for almost the entire length of the slope (Fig. 4 right). The surface slope angles at the base of the chassis of the vehicles used may be both greater and less than the values shown in Fig. 4, and their measurement is the subject of a special study. Digital surface models from LROC data provide the capability for such a study. Exceedance of the elevation angle of more than 12° is of local character and, therefore, can be eliminated with the help of road construction attachments of the IMP during route construction.

Therefore, when creating an ISLV, it is possible to consider the possibility of placing the spaceport (takeoff and landing site) on relatively level ground at the foot of the mountain, and the solar power plant - on the top of the mountain. The complex of its residential, scientific and other interconnected modules (base) can be placed between these two points, on a horizontally leveled area of a hollow slope. In this case, the best option for organizing transport communication between the cosmodrome and other structures of the lunar station is a route along the gentle slope of the mountain. The length of the route can be up to 40 km, but the length of the spaceport-base section, along which the most problematic modules with a mass of 18000 kg will be transported, can be significantly shorter.

The concept of using CPMs as part of lunar trains for long-duration expeditions

As the TPLS is constructed and the scientific and technological functions are expanded, including the establishment of high-speed links to Earth, a mobile communications network, facilities for the production of electrical and thermal energy, life support components, etc., it will be necessary to establish automatic monitoring stations for these facilities and the environment at some distance from the station. With time, remote stations for conducting separate studies, which can be called automatic branches of the ISLN operating in the visiting mode, will become possible and necessary.

Long, several lunar days, and long, several hundred kilometers, expeditions to create such branches with the performance of serious scientific and industrial tasks, such as those outlined in the article (Marov, Slyuta, 2021), are possible only as part of a lunar train. With the help of one lunar rover it is impossible to provide life support and safety of the crew, combining it with transportation of scientific equipment and geological samples, drilling wells, laying modern communications, performing scientific research, searching for minerals in the areas adjacent to the route, etc. One of the important tasks of such an expedition, in our opinion, could be the delivery of equipment and the creation of a lunar observatory on the back side of the Moon, in the shadow of the Earth's radio noise.

Practical discussion of the problems of such an expedition became possible after the Chinese Chang'e-4 spacecraft landed on the back side of the Moon for the first time in history, on January 3, 2019, and then the mobile laboratory Yutu-2 also began to explore the bottom of Von Karman crater for the first time in the world. Extensive scientific data were obtained on the terrain features and surface cover in the landing area (Ding et al., 2022). Reliable communication of the Chang'e-4 lunar station and the Yutu-2 mobile laboratory with Earth, up to now, is carried out by the Queqiao relay satellite, which is located on a halo-orbit centered on the Lagrangian point 2. The data transmission rate to Earth is 2 Mbit/s. The communication channels of Chang'e-4 station and Yutu-2 lunar rover to the relay satellite are at 256-280 kbps and 125 bps, respectively. (Zhang, 2019).

On March 22, 2024, China launched the second Queqiao-2 transponder into space, which is capable of providing better communication performance between objects on the back side of the Moon and Earth. Such lines could support the discussed expedition on the back side of the Moon. But the observatory needs permanent high-speed communication lines. Such fixed wire or relay communication lines could be laid during the expedition under discussion. They will connect the scientific equipment of the remote observatory with the MNLS for the subsequent transmission of a huge amount of information to Earth.

The information available in the world already now allows us to assess in a first approximation the possibility of realizing such an expedition in terms of, firstly, the passability of the vehicle, and secondly, the level of natural illumination of possible routes of movement in this polar region during the lunar day (Fig. 5). The main obstacle for both the autonomous lunar rover and, especially, for the lunar train are steep ascents. Based on the experience of Soviet and Chinese lunokhods, as well as LRV, critical for the loss of mobility on the lunar regolith can be the angle of ascent more than 25° . But for the lunar train motion variant, the maximum angle should be limited to 20° or even 15° . Today such arguments are not yet relevant, but it is important that in principle such restrictions are quite acceptable on the real topography of the area.

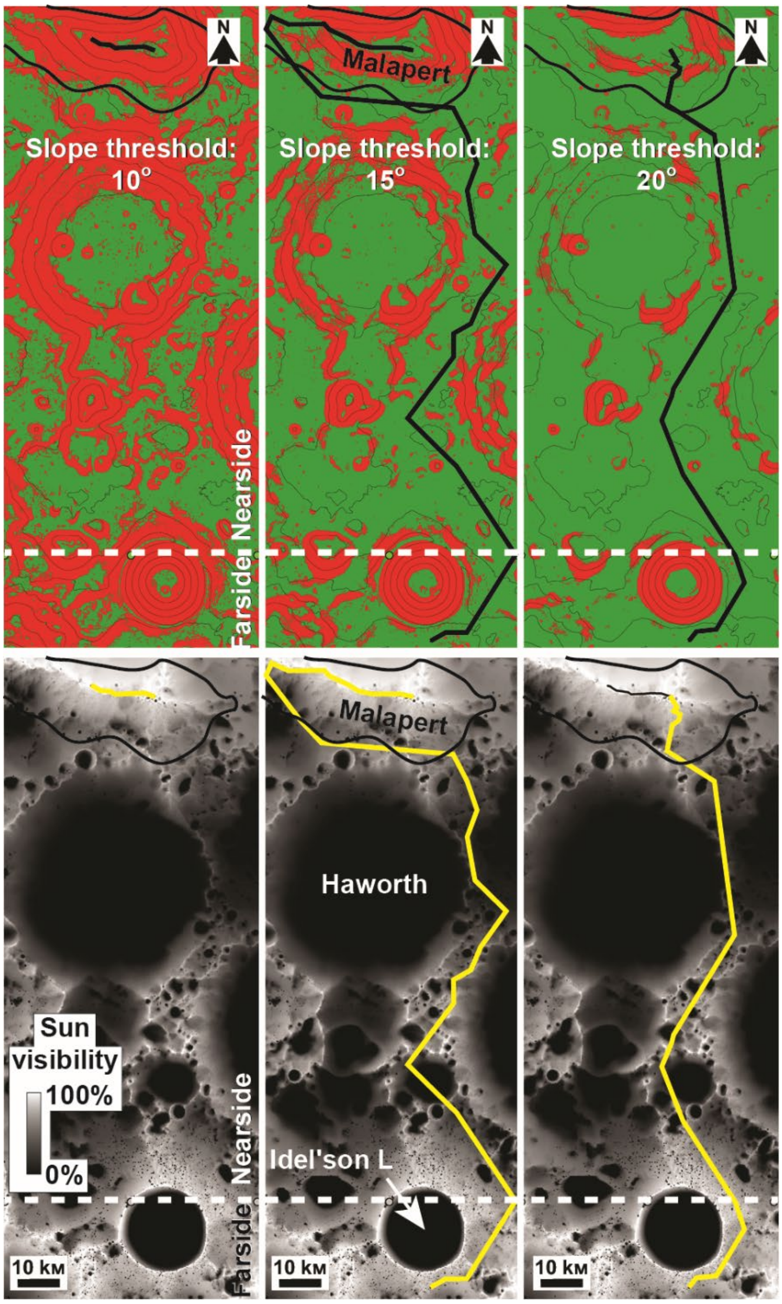


Figure 5. Distribution of slopes in the area of Mount Malapert and the south pole of the Moon (top); the areas where the surface slope is less than the specified limit of the lunar rover passability of 10, 15, and 20 deg. are marked in green. Solar illumination of the same area (bottom).

Black and yellow lines are recommended travel paths, taking into account the limitations of elevation angles and terrain illumination. Gradient and illumination maps are based on topographic data of LOLA altimeter (spatial resolution 60 m/px).

The upper part of Fig. 5 shows the topography of the areas along the possible routes of the above-mentioned expedition from MNLS to the back side of the Moon, where the green color shows the relief with ascents and descents up to 10° , 15° and 20° . The black broken line shows a possible travel route respecting the elevation angle restrictions. As can be seen, a large part of the terrain can be accessible for vehicles with at least 20° of terrain. Impassable areas at the 15° limit increase the length of the route, but do not exclude the possibility of expeditions to the South Pole, through which the light dashed line passes

In the lower part of Fig. 5, which shows the solar illumination of the same driving area during lunar days taking into account the real terrain, the driving routes are marked in yellow color. As can be seen from the figure, part of the route will inevitably have to be traveled in darkness, the train must necessarily have its own lighting and have the resources to withstand low temperatures not only at stops, but also in motion.

But for the most part the track is still not a nocturnal track. Now it is still difficult to compare dawns and sunsets on Earth, in which the atmosphere plays a huge role, and lunar twilight in the absence of atmosphere. All this is the subject of future research and calculations. For now we can only assume that in the border regions with insufficient natural light, the use of lighting devices will allow to realize not only controlled movement of the lunar train in the polar region, but also scientific research, as well as simple operations on the lunar surface along the entire selected route of movement during the lunar day.

So far, the location of the observatory on the back side of the Moon has not been chosen even at the scenario level. It is clear only that it is desirable to deploy it also near the South Pole. Unclear are the characteristics of communication of the lunar train with the MNLS and the Earth, for example, using a relay station like Queqiao relay satellite. These circumstances so far exclude the possibility of estimating the travel time to the location of the lunar observatory - an automatic branch of the ISLV.

With regard to the establishment of the observatory, the most time will be spent searching for a suitable area and preparing sites for two or three lunar train units. The attachments of one of these units will be the actual telescope with all on-board control and communication systems. The attachments of the other two links are likely to be power plants of various types with buffer batteries. These could be, for example, a solar power plant and a radioisotope thermal and electrical generator. So the unloading of the power plants will be the decoupling of these links at prepared sites and the subsequent reconfiguration of the lunar train in a new composition. Due to the mobility of the observatory, it is possible to choose the optimal location for the entire time of its operation.

What is the technical background for work on the Moon and in space today? Lunokhod-1 remained operational for 302 Earth days, 11 lunar days. During the lunar nights, the thermal control system of Soviet and Chinese robotic lunokhods worked and is still working on Yutu-2 in the mode of keeping the hardware operability inside a sealed compartment. The average speed of Lunokhod-1 was 0.14 km/h, and it traveled a path of about 10.5 km. Lunokhod-2 moved at an average speed of 0.34 km/h and traveled a distance of more than 37 km in 125 Earth days (Kemurjian, 1993). Yutu-2 has been operating on the return side for the fifth year.

The manned LRVs driven by the astronauts of the three Apollo missions (-15, -16, and -17) traveled a total of 90.34 km in just 9 Earth days. The total travel time for all three vehicles was 11 h 34 min (Young, 2007).

In terms of human time in space, in early 2024, Soviet cosmonaut Oleg Kononenko's stay in orbit exceeded 878 Earth days.

Despite all the obvious differences in the working conditions of people on orbital stations and on the Moon, the qualitative complication of the tasks to be performed by the newly created mobile complexes on the Moon, compared to the tasks of the last century, it can still be stated that the estimates of the most complex lunar expedition from the MNLS to the back side of the Moon, are no longer groundless fantasies.

Rationale for the structure of intelligent mobile platforms and their mobility systems

In modern terminology, the lunar trains proposed by the pioneers of this topic are mobile robotic complexes (MRTC) with a variable structure. All structural links of such a complex should be self-propelled, capable of both autonomous movement and movement as part of the train over complex terrain, in manned and autonomous control modes. Using the terminology of the authors of the first developments, it can be said that the role of a tractor in the authors' concept is performed by each CMP included in the lunar train.

All systems inherent to modern lunokhods should not be included in the CPM. Specialization of the train units on the basis of unified CPMs is provided by attachments. For example, the attachment equipment of the first, command, link, along with the airlock, hermetic cabin with seats and other equipment necessary for driving and communication, will include a thermal control system that ensures temperature stability in this cabin and in separate compartments. There is no point in equipping the CPM with a lunar navigation system, and the communication system is probably needed in a limited capacity, for example, without communication with Earth, which will be provided by the attachments. The CPM power supply system, which is needed already at the development stages, will then become part of the attachment systems.

But the composition of the Lunokhod-1 SS inevitably goes beyond the structural framework of the Lunokhod-1 SS (Anisov et al., 1971) due to the fact that the development and acceptance tests of the ACCS should be carried out only as part of the onboard equipment of the SS and in the presence of one additional subsystem of local navigation. If we do not expand the classical composition of the SS, the new set can be called a traveling and docking system. Then, taking into account the above, the structural diagram of the IMP can be presented in the form of Fig. 6.

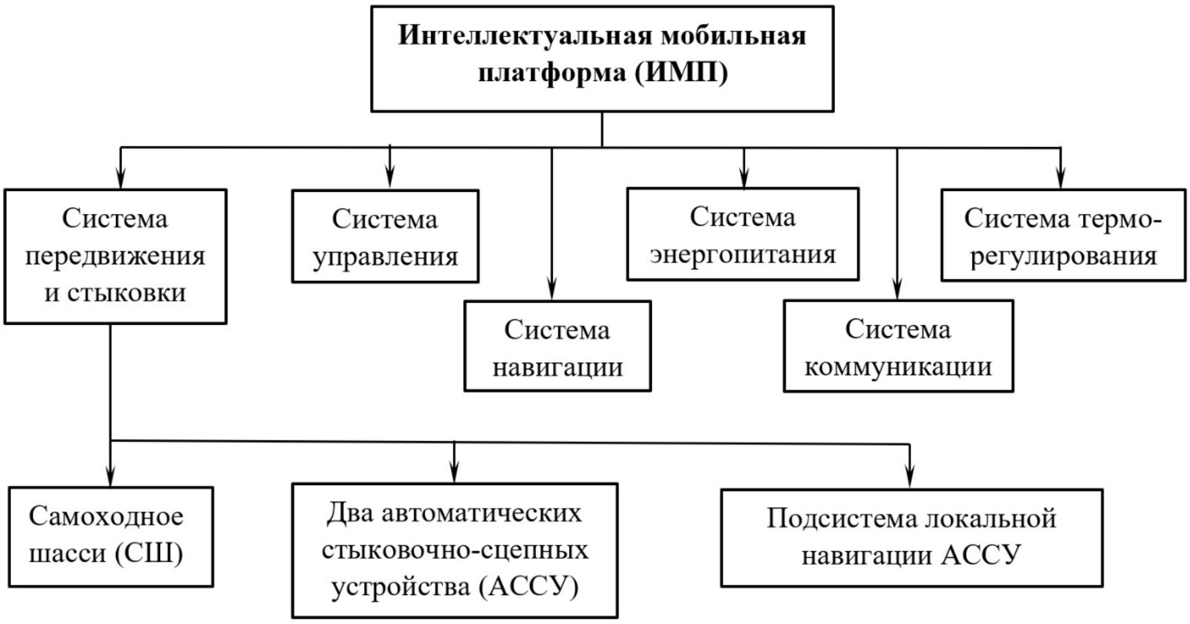


Figure 6. Structural diagram of the intelligent mobile platform.

Unlike the SS of robotic lunar rovers and Mars rovers, the CPM movement system should provide the possibility of hybrid control of movement of both autonomous lunar rovers and the entire lunar train: remote (from the lunar, and in emergency cases, ground control points), manned (with a pilot on board) and autonomous-automatic, with the operator setting only the finishing coordinates of movement. In this case, the management of the operations of docking of the CMP in the lunar train with a given order of the links and their undocking, for example, for the departure from the train of any link specified by the operator, as well as the subsequent restoration of the train in a new composition, in our opinion, should be provided exclusively by artificial intelligence onboard control systems of each pair of interacting platforms. The crew can intervene in these processes only in emergency situations, which will be related to extra-ship activities.

It is reasonable to use the most universal four-wheeled all-wheel drive SSH as the basic component of the travel and docking system. Provided that the center of mass of the lunar rover is symmetrically located relative to the wheelbase and track, four-wheeled SSHs provide equal traction and dynamic characteristics during forward and reverse travel, which is a significant advantage of the recommended scheme. For example, all-wheel drive six-wheeled Chinese and American lunar and Martian rovers with Rocker-Bogie type suspension have different traction-dynamic characteristics when changing the direction of motion, which significantly affects the parameters of support and profile passability, for example, the magnitude of the angle of climbing, as well as the resistance to longitudinal overturning (Malenkov, Volov, 2019)

As shown in the monograph (Avotin et al., 1979), six-wheeled SSs have a serious advantage over four-wheeled SSs only in on-board turning modes by means of different rotation speeds of wheels of opposite sides. This advantage is especially significant when turning in place, i.e., with a turning radius equal to zero when reversing the rotation of wheels of opposite sides. But in this case SS with non-rotating wheels are not considered. For sufficiently fine maneuvering in preparation for docking of the ACCS of two lunar train links, all wheels of the SS must be equipped with steering drives.

To ensure the alignment of the docking mechanisms of the two CMPs, each motor-wheel must also be equipped with an active suspension drive mechanism that allows the relative position of each wheel and the body to be adjusted vertically. Simultaneous operation of these drives of all four wheels allows to change the position of the longitudinal axis of the active ACCS in space, respectively the position of the longitudinal axis of the passive ACCS of the front standing link of the lunar train.

On the basis of four-wheeled chassis (Fig. 7) it is possible to obtain both eight-wheeled vehicles with rigid frame, and two-section SS with flexible linkage of links, and multi-wheeled moon train with the number of wheels multiple of 4.

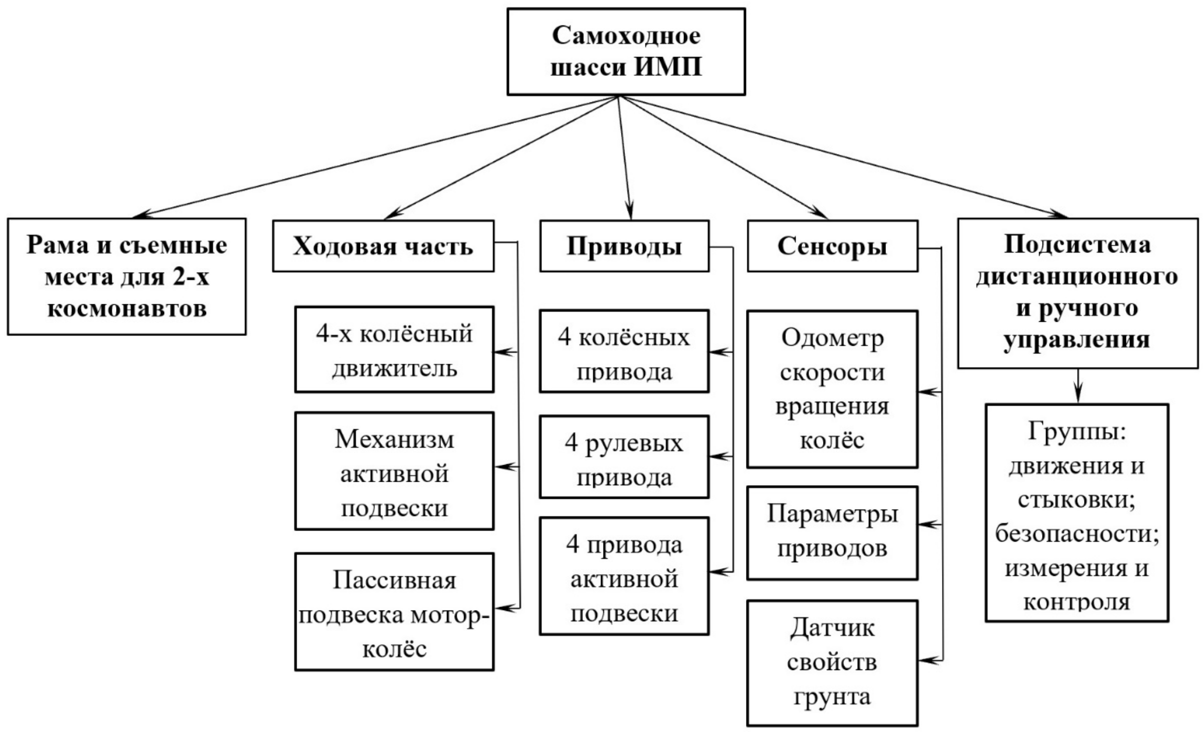


Fig. 7. Structural diagram of the self-propelled chassis of the IMP travel system.

The team headed by A.L. Kemurdzhian has a solid scientific and technical background in terms of vertical regulation of the wheels and body position. Back in 1983, a running model of an experimental self-propelled automatic chassis was created here, which provided both the movement in the wheel-stepping mode with intermittent gait by means of stepping mechanisms (MSH), and the wheel mode with regulation of the relative position of wheels and body vertically by means of the same MSH mechanisms (Fig. 8.) (Gromov et al., 1986). However, this regulation could be performed only during stopping.

Fig. 8. Fragment of tests of the experimental sample of self-propelled automatic landing gear at adjusting the relative position of wheels and body vertically in the area of recent eruptions of the Tolbachik volcano in Kamchatka.

In our century, the authors have developed technical solutions for the design of the chassis of modern SSHs, in which the transition from motor-wheels to propulsion modules (PMM) is realized. ODM, the scheme of which is shown in Fig. 9, combines in a single mechatronic design all the mentioned wheel drives: traction, steering and active suspension drive, with the possibility of switching to the wheel-stepping mode (Malenkov et al., 2017; Malenkov, Bogachev and others, 2019). At the same time, new technical solutions make it possible to adjust the clearance and control the active suspension while driving (Volov and others, 2017).

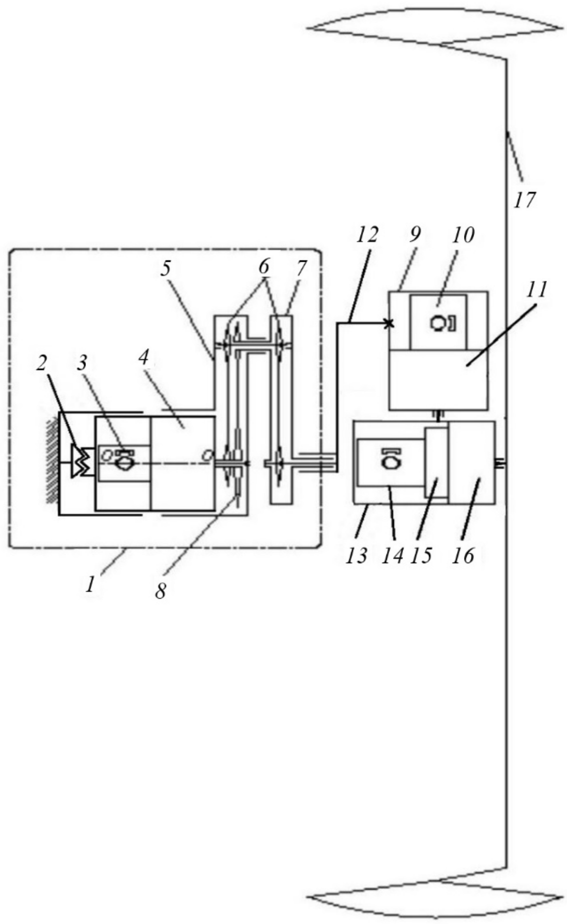


Figure 9. Kinematic diagram of the ODM of the IMP self-propelled chassis:
1 - drive of active suspension on the basis of two-lever MSH of circular type (the drive is conventionally shown turned by 90° relative to the axis 0-0); *2* - mechanical clutch for switching the modes of active suspension and wheel stepping; *3* - electric motor; *4* - reducer; *5* - first lever; *6* - reactive chain transmission ($i=1$); *7* - second lever; *8* - chain summing transmission (($i=2$); *9* - steering mechanism; *10, 11* - electric motor and reducer of steering mechanism; *12* - rigid mechanical connection of output shaft of active suspension drive with steering mechanism; *13* - traction drive of motor-wheel; *14, 15, 16* - electric motor, two-speed gearbox and reducer of traction drive; *17* - wheel.

The wheel formula of the SS and, consequently, of the CMP and of the entire lunar train link as a whole can be written as 4× 4 × 4 × 4, where the first digit indicates the number of wheels, the second digit indicates the number of drive wheels, the third digit indicates the number of wheels with steering mechanisms, the fourth digit indicates the number of wheels with active suspension drives, the design of which, if necessary, provides the possibility of switching to the wheel-stepping mode.

The modular approach meets the idea of unification due to the possibility of thorough experimental life testing of the entire chassis and drives of the SS with simulation of all operating conditions during testing of one module. This drastically reduces the requirements for dimensions and other characteristics of test equipment - thermovacuum chambers, various kinds of loaders, shock and vibration stands, etc. At the same time, the maximum density of ODM design layout and ease of ODM interface with the supporting frame are achieved.

A simplified layout of the CPM travel system is shown in Figure 10. Since the AHSS must provide freedom of rotation of each CPM relative to three axes, they can be conventionally shown as ball joints.

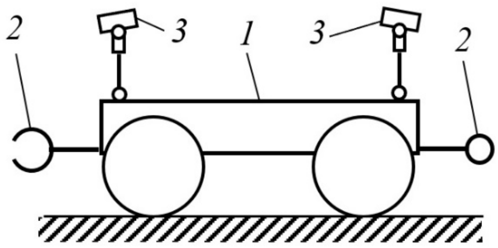


Figure 10. Simplified layout diagram of the intelligent mobile platform:
1 - self-propelled chassis; *2* - active (left) and passive (right) automatic coupling and coupling devices (ACCD); *3* - cameras for local navigation when performing docking and undocking operations of the lunar train links in the sequence specified by the operator.

The train composition will be determined by the transportation and technological tasks of station construction, and in long-distance, long expeditions also by scientific tasks, as well as by the tasks of prospecting and mining of minerals, etc. As a minimum, except for the first, command, and the next, residential, links, the MRTC in long expeditions should obviously include links providing backup power supply for all links (mobile power station); backup storage (and possibly synthesis) of astronauts' life-support products; cargo link for transportation of construction materials, equipment and soil samples, link for transportation of pipes, deployment and soil drilling, etc. A simplified layout diagram of the train of three CPMs is shown in Fig. 11.

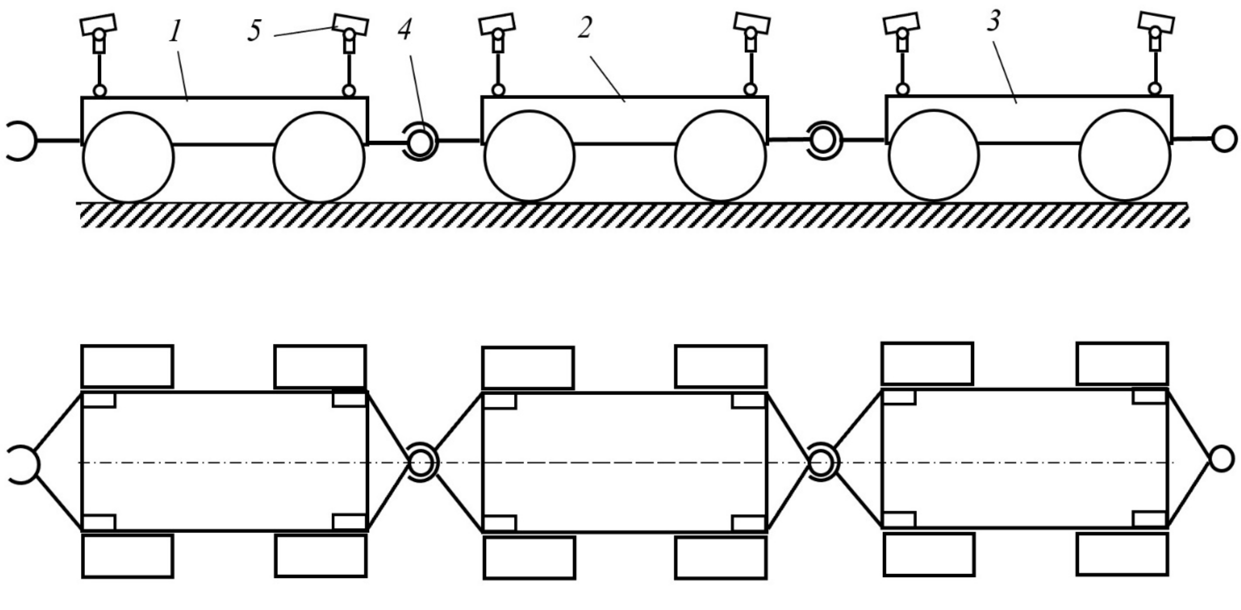


Fig. 11. Simplified layout of a three-link MRTC (attachments are not shown conventionally) based on three CPMs: *1, 2, 3* - self-propelled chassis; *4* - ACSU with three degrees of freedom; *5* - cameras of the local navigation system.

The train may also include a mobile unit in the form of a fast-moving, non-hermetic all-terrain vehicle of the Lunar Roving Vehicle type, designed for terrain reconnaissance, rig support and maintenance, as well as for operational use in emergency situations. The rover can be transported on an adapted cargo vehicle, which must be equipped with ramps for entry/exit of the rover and elements of its fastening on the cargo platform.

Estimation of the main parameters of the self-propelled chassis IMP

As shown above, the self-propelled chassis is the main subsystem of the CPM mobility system, designed for the attachment and transportation of all service equipment installed on this chassis, as well as special attachments.

Estimation of geometric parameters of the driving wheels of the self-propelled chassis. For the design evaluation of the parameters of the driving wheels of the self-propelled chassis we take the mass of the machine, which can serve as a command link with a sealed cabin, 3 tons. Let's determine the dimensions of the wheels, based on the load-bearing capacity of the ground and ensuring the necessary coefficient of rolling resistance of the wheel. The calculation scheme is shown in Fig. 12.

Based on the operating experience of Soviet lunokhods, we take the coefficient of rolling resistance on lunar regolith $f = 0.2$ and consider in the first approximation movement on a flat horizontal surface. To estimate the amount of wheel pressure on the ground, we proceed from the average value of ground strength of 14.3 kPa obtained from the analysis of the Soviet lunokhod tracks (-1 and -2) (Bazilevsky et al., 2021).

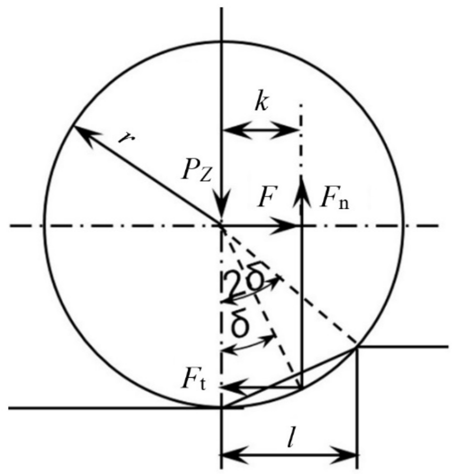


Fig. 12: Calculation diagram of forces during uniform rolling of the wheel on the lunar regolith:

P_Z - downforce; F_n - normal ground reaction; F_t - horizontal ground reaction; *F* - horizontal traction force applied to the wheel axis; *k* - shoulder of vertical ground reaction ($k= f{\cdot}r$, where *r* - wheel radius); *l* - longitudinal dimension of ground deformation area

According to the calculation scheme of Fig. 12, the vertical reaction of the ground is equal to $F_n= P(Z)$. The specific pressure on the ground is $q= P(Z)/s$,

where *s* is the projection area of the wheel rim surface interacting with the ground on the horizontal plane.

$$s= l{\cdot}b, \tag{1}$$

where *b* is the width of the wheel, *l* is the longitudinal dimension of the pad *s*.

$$l= r{\cdot}\sin(2\delta), \tag{2}$$

where $\delta = \arcsin(k/r)$ or $\delta = \arcsin(f)$.

Then.

$$s= b{\cdot}r{\cdot}\sin(2{\cdot}\arcsin(f)). \tag{3}$$

Thus,

$q = P_{(Z)}/(b \cdot r \cdot \sin(2 \cdot \arcsin(f)))$. (4)

Hence, the radius of the wheel is equal to:

$r = P_{(Z)}/(q \cdot b \cdot \sin(2\arcsin(f)))$. (5)

Given a machine mass of 3 t, we find the vertical wheel force acting on the ground for a four-wheeled chassis at lunar gravity (free fall acceleration g_M=1.62 m/s$^{2)}$.

$P_Z = 3000 \cdot 1.62/4 = 1208$N.

We take the width of the wheel in relation to its radius in proportion to the geometry of the wheels of Soviet lunokhods: $b = 0.8r$.

Substituting this condition into formula (5), we obtain an expression for the wheel radius:

$$r = \sqrt{\frac{P_Z}{0.8q\sin(2\arcsin(f))}}.$$

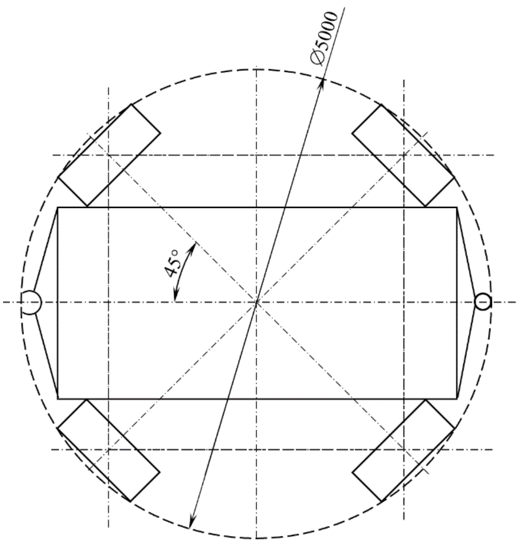
(6)

From here we find the radius of the wheel:

$$r = \sqrt{\frac{1208}{0.8 \cdot 14300 \times \sin(2\arcsin(0.2))}} = 0.52 \text{ м}.$$

Thus, to ensure the supportability of the self-propelled chassis in accordance with the initial data, the wheel radius must be at least 0.52 m.

Self-propelled chassis layout. Delivery of all CPMs to the Moon should be carried out in complete assembly with their attachments, ready for automatic deployment and subsequent movement. We take the inner diameter of the rocket fairing to be 5 m. Thus, the CPM, taking into account the possibilities of converting the self-propelled chassis, should be placed inside a circle with a diameter of 5.0 m, corresponding to the inner diameter of the missile fairing (Fig. 13). Figure 14 shows the operating position of the landing gear



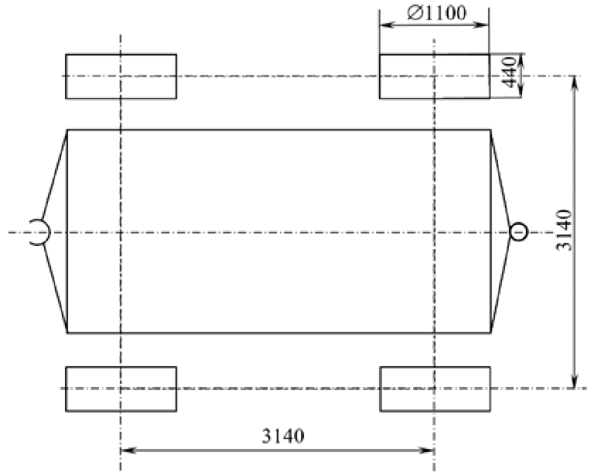


Figure 13: Chassis layout diagram in converted position.

Fig. 14. Composition diagram of the IMP self-propelled chassis in operating position.

IMP for expeditions and lunar trains. As noted, the scenario for this study involves terrain travel in the vicinity of the lunar base and the entire Malapert Massif, as well as long-distance routes to the Moon's south pole.

Let us consider the ascent motion of a four-wheeled CPM having a mass together with payload of 3 t. The payload in this case can be an equipped cabin and cosmonauts up to two people, tools and equipment: drilling, energy, cargo for the expedition life support, etc. To increase the contact patch and corresponding reduction of specific loads acting on the lunar regolith, as well as to increase passability, it is advisable to use wheels with the maximum possible diameter.

Fig. 13 shows that the diameter of the wheel should not exceed 1.1 m, the width is assumed to be 0.4 m according to the proportions of the wheels of Soviet lunokhods. To partially compensate the dynamics from the interaction of the wheel with the ground, the wheel should be metal-elastic. As an analog of such a wheel can serve, for example, the wheel (Fig. 3) of the mockup of a two-section planetary rover shown in Fig. 1.

To ensure smooth running and increase comfort of the manned lunokhod, the chassis is equipped with an independent torsion suspension with rocking arms of the guiding mechanism in the longitudinal plane, similar to the suspensions of Lunokhod-1 and Lunokhod-2, which showed high cross-country ability when overcoming escarpments and counterscarpments.

The passive elastic suspension is supplemented by an active wheel suspension, based on double wishbone mechanisms of the circular type with a lever arm of 100 mm, which allows to increase the suspension travel up to 400 mm, for example, to change the ground clearance, to overcome obstacles with the wheels of a height greater than the travel of the elastic suspension, to maintain the horizontal position of the body when driving on an uneven profile and on a slope, to ensure the alignment of the ACCS in height when docking two CPMs. The kinematic diagram of such a suspension is shown in Fig. 9.

Taking into account the great variety of conditions of movement on the surface of the Moon, in order to expand the speed and power ranges of regulation of the motor-wheel traction drive, a two-stage gearbox built into the drive is used, which provides a speed of movement in the first gear of 1 km/h and in the second gear of 5 km/h. The two-stage gearbox can be considered as an analog (Fig. 2).

The ratio of the SS mass to the total mass of the vehicle is one of the important parameters for modeling the running tests characterizing the interaction of the propulsion system with the ground. The ratio of the acceleration of gravity on the Moon to the Earth acceleration of gravity is equal to 1/6, so it is advisable that the ratio of the mass of the SS to the total mass of the machine does not exceed this value, since during various running tests of the self-propelled chassis, including open ranges it is possible to test running models without using complex devices and systems to simulate reduced gravity. During sea trials in this case the mass of the running mockup simulates the weight of the whole vehicle on the Moon. The simulation of the position of the machine's center of gravity is performed by an additional load of relatively small mass, which is installed at a certain height on the running mockup.

This principle of self-propelled chassis design was used in the development of Soviet lunokhods. The lunokhods' SSH consisted of motor-wheel units, the chassis automation unit, and the cable network. The SSH had no frame, and the motor-wheel blocks were attached directly by brackets to the instrument container of the lunokhods. The mass ratio of the SS to the total mass is 1/7 for Lunokhod-1 and 1/8 for Lunokhod-2. For the walking models a special frame was additionally used, to which motor-wheel blocks were attached and power supplies were installed. The weight of the walking models was approximately 1/6 of the weight of Lunokhod-1 and Lunokhod-2, thus the weight of the walking models in terrestrial conditions simulated the weight of Lunokhod-1 and Lunokhod-2 on the Moon.

The CPM includes a self-propelled chassis with a frame and power supplies, so it is quite rational to consider the CPM in full configuration for use as a walking model. For this purpose, the mass of the CPM should be equal to 1/6 of the total moving mass of the CPM with cargo and in this case 3000/6=500 kg. This will allow testing of running models of the CPM in full configuration, which is especially important for running tests, to verify the operation and algorithms of the control system, vision and ACCS. The traction drives of motor-wheels and active suspension drives by loading modes, taking into account the low speeds of movement, will operate conditionally in the lunar gravity field.

In the design analysis of traction drives of motor-wheel drives, the machine is considered for a long time overcoming a rise on cohesive soil in first gear, for example, when leaving craters. It is considered that the bearing surface under the wheels of both sides has the same characteristics, and the movement occurs in the direction of the angle of the greatest rise. Due to the low speed of the planet rover, the character of motion in the wheeled mode can be considered quasi-static.

The calculation diagram for traction calculation of uniform rectilinear uphill movement is shown in Fig. 15.

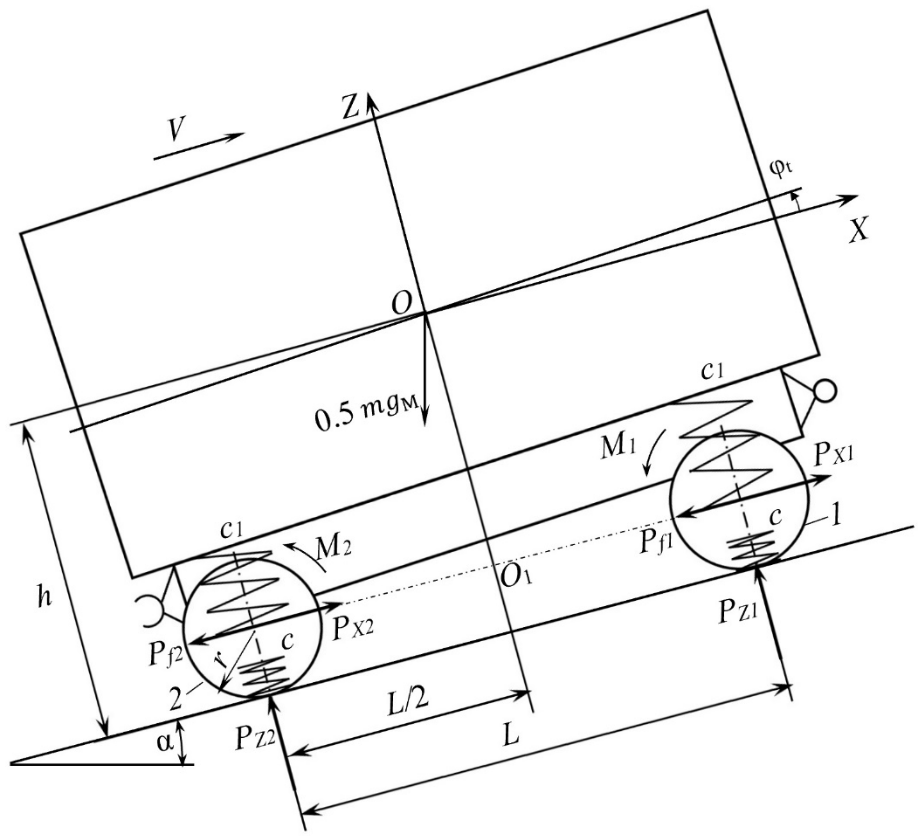


Figure 15. Calculation diagram of a four-wheeled CPM with a load when moving uphill: V - speed of the machine; P_{Xi} - traction force of the wheel; P_{Zi} - normal reaction of the wheel; P_{fi} - rolling resistance force of the wheel; M_i - reaction torque of the traction drive; O - center of mass of the machine; L - wheelbase; h - height of the center of mass of the machine; r - radius of the wheel; α - angle of ascent; c_1 - stiffness of suspension; c - radial stiffness of wheels; m - total mass of IMP with load; g_{M} - acceleration of gravity force on the Moon; *1* - front wheel, *2* - rear wheel; φ_t - angle of body rotation due to elasticity of suspension and wheels under the action of moment of forces.

The forces acting in contact between the wheels and the ground are applied to the wheel axle. Reactive torque, equal in magnitude to the torque on the output shaft of the wheel drive, is applied to the drive housing and acts on the suspension through it. Under the action of the reactive torque of the traction drives and the torque from the longitudinal component of the machine's gravity, the elastic suspensions of the wheels will have different deformation. The rear wheels will have greater deformation, the front wheels less deformation.

The chassis is absolutely symmetrical with respect to the vertical longitudinal plane passing through its center. Therefore, we can consider only half of the machine in the calculation.

In this case, the scheme is statically determinable and the problem is solved by formulating the static equilibrium equations.

To determine the torques on the wheels in uniform motion, consider the equilibrium conditions of all acting forces in projections on the *XOZ* coordinate axes and all moments. Let us write the corresponding statics equations as the sum of forces on the Z axis and the sum of moments with respect to the point O_1:

$$\sum Z_i = 0, \sum M_{01} = 0 \quad . \tag{7}$$

Based on the conditions (7), we obtain the following expressions:

$$P_{Z1} + P_{Z2} - \frac{mg_{\mathrm{M}}}{2}\cos\alpha = 0, \tag{8}$$

$$P_{Z2}\frac{L}{2} - M_2 - M_1 - P_{Z1}\frac{L}{2} - \frac{1}{2}mg_{\mathrm{M}}\sin\alpha(h - r) = 0. \tag{9}$$

Taking into account that the reactive torque on the wheel is equal to

$$M_i = P_{(X)i} \cdot r \,, \tag{10}$$

and the tractive force of the wheel is

$$P_{Xi} = P_{Zi}(\mathrm{tg}\alpha + f), \tag{11}$$

by the joint solution of (8) and (9), we obtain the corresponding expressions for determining the normal reactions on the wheels:

$$P_{Z1} = \frac{mg_{\mathrm{M}}}{4L}(L\cos\alpha - 2h\sin\alpha - 2fr\cos\alpha), \quad (12)$$

$$P_{Z2} = \frac{mg_{\mathrm{M}}}{4L}(L\cos\alpha + 2h\sin\alpha + 2fr\cos\alpha). \quad (13)$$

The initial data for the calculation are presented in Table 1.

Table 1: Input data for traction calculation

Parameter name, dimension	magnitude
Gross weight, *m*, kg	3000
Free-fall acceleration on the Moon, g_{M}, m/s^2	1.62
Height of center of mass, *h*, m	1.2
Wheelbase, *L*, m	3.14
Wheel radius, *r*, m	0.55
Coefficient of resistance to movement, *f*	0.2
Travel speed, *V*, m/s	0.28

The distribution plots of normal wheel reactions are shown in Fig. 16

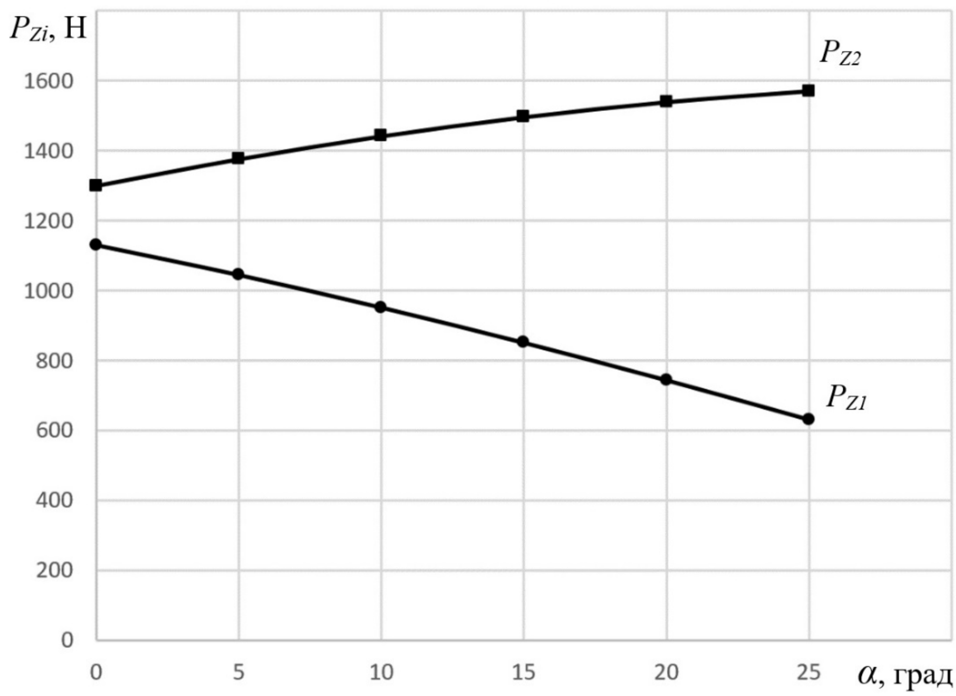


Figure 16. Distribution of normal reactions on the wheels of a four-wheel chassis as a function of the angle of lift.

Find the power requirement for the traction drive of the most loaded feed wheel by the formula

$N = P_{Z2}(tg\alpha + f)V/ .\eta$ (14)

At $V=0.28$ m/s, η =0.6 we obtain

N=1539(tg 20° +0.2)0.28/0.6=402 W.

Thus, the required power of the traction drives of the motor-wheels is assumed to be 400 W. Calculations also show that in second gear, at a speed of up to 5 km/h, with full payload, this engine power provides movement on horizontal surfaces and small gradients, up to 5° . First gear should be used for overcoming prolonged ascents.

Estimation of the power consumption of the IMP and battery parameters. The maps shown in Fig. 4 maps allow us to make a first estimate of the expedition time, for example, for a safe route with elevation angles not exceeding 15° . The length of the trace, constrained from the MNLS in the Malapert Massif area to the dashed intersection line passing through the South Pole, is more than 300 km. The design speed of the lunar train may be 1 km/h in low gear for travel on difficult terrain with elevation angles up to 20° and speeds up to 5 km/h for travel with elevation angles less than 5 .°

Let's assume that the average speed of movement is 2.5 km/h. Let's describe the time of movement of the crew of four cosmonauts using the time grid of Earth days. Let's assume that the actual movement is no more than 8 hours per Earth day. The rest of the time is taken up by stops for refining the route, analyzing the state of equipment, communications, etc., processing of scientific materials, personal time and sleep. Then, for a day the train will pass 20 kilometers, and the total time of the expedition movement in one direction will be 15 Earth days. Another 15 Earth days may be required for work of cosmonauts in spacesuits on the surface of the Moon along the travel route. According to the terminology established in Soviet cosmonautics, this is extravehicular activity (EVA). During EVA with the use of autonomous CPM can be performed: scientific research and mineral exploration in the areas adjacent to the trajectory; work on laying high-speed communication lines between the observatory and the ISLV; work on providing mobile communication with the ISLV, as well as between the expedition members along the entire trajectory.

Thus, the total one-way expedition time, including stopovers at research sites, would be about one lunar day or about an Earth month.

With the rated power of the motor-wheel traction drive of 400 W, the rated driving power for the four-wheel chassis is 1600 W. Based on this value, let's estimate the capacity of the battery that will ensure the movement of the BMI as part of the train in the scenario of a long expedition.

To drive in nominal mode for 8 h, the IMP needs 1.6× 8=12.8 kWh of energy. This value can be taken as the capacity of the battery. One more battery of the same capacity can be taken for crew life support and control system operation. If we focus on the energy capacity of modern lithium-ion batteries, which is up to 250 W×h/kg (Kulova, 2019), the mass of one battery would be 51 kg. Two batteries would account for approximately one-fifth of the mass of the CPM. To charge the batteries during parking, a power plant of at least 1.6 kW would be required. Assuming solar panels as the power plant, with a solar intensity of 1000 W/m^2 and a solar panel efficiency of 20%, a solar panel area of 8 m^2 would be required to generate 1.6 kW of power. A solar panel of this size fits within the dimensions of the CPM and, for example, can be placed in a folded position on the roof of the command unit cabin.

Composition and modes of operation of the support-motor module of the self-propelled chassis IMP. It is proposed to use active suspension based on a double-lever mechanism of the circular type (Fig. 9).

According to Fig. 9, the ODM includes a steering mechanism *9,* a wheel traction drive *13* and a double wishbone actuator *1*, which performs the function of active suspension. In Fig. 9, the actuator *1* is shown conventionally rotated relative to the axis O-O at 90° . In the active suspension operation mode, the levers *5* and *7 of* the drive *1* in the nominal position, when the free axes of these levers coincide, are located parallel to the support surface and perpendicular to the rotation axis of the slewing mechanism.

Given the rather large size of the wheel, the wheel traction drive, steering mechanism and active suspension mechanism are located in the inner volume of the wheel. At the same time, the active suspension drive itself is quite compact, providing significant travel in the active mode, since the total suspension travel is equal to four times the arm length of the double wishbone mechanism.

During operation of the active suspension drive, linear movement of the free axes of the arms *5* and *7 of* the drive *1* perpendicular to the supporting surface is performed with simultaneous operation of the traction drives *13* of the motor-wheels, providing movement of the CPM in the wheeled mode.

The free axis of the first lever *5* always coincides with the actuator *1*, the free axis of the second lever *7* always coincides with the axis of the rigid mechanical connection with the non-rotating body *9* of the steering mechanism (wheel turning mechanism). In the rated position of actuator *1,* the free axes of the levers coincide

An important design feature of the active suspension actuator is to ensure that the position of the steering mechanism actuator *9* is always oriented in such a way that the kingpin axis always passes through the wheel contact patch with the driving surface. This orientation is provided by the reactive chain gear *6* incorporated in the lever mechanism. The input sprocket of the chain transmission is connected to the drive housing *1*, which is connected to the chassis frame by a coupling *2*, and the output sprocket - through a rigid mechanical link *12 -* to the non-rotating housing *9* of the steering mechanism

The transmission ratio of the chain transmission is equal to one, so that when the levers rotate, the wheel module with the slewing drive performs only a plane-parallel motion normal to the travel surface with respect to the machine body

Such kinematic connection also provides transmission of the reactive torque of the traction drive *13* directly to the chassis frame, as a result, the suspension drive is not additionally loaded by the reactive torque from the wheel drive, which simplifies its control algorithms and reduces energy consumption. The torsion element of the passive elastic suspension is also unloaded from the action of the reactive torque of the traction drive due to the four-link parallelogram scheme of the balancer.

In addition, the actuator of the double wishbone mechanism during the operation of the active suspension is fully counterbalanced by the longitudinal component of the weight of the machine when driving uphill or downhill. These forces are closed in the lever mechanism of the drive and the engine load is only losses in the transmission mechanism from the action of these closed forces. Given the high efficiency of chain drives, these losses are negligible.

The scheme of operation of the two-lever mechanism of the circular type as part of the active suspension drive ODM is shown in Fig. 17. When operating the suspension drive (Fig. 17a), power is supplied to the brake electromagnet *3*, which is turned off and releases the shaft of the electric motor *2*. Rotation from the electric motor *2* is transmitted through the gearbox *4* to the first lever *5*. Since the sprocket *8* chain transmission is fixed in the housing *1*, the lever *7* due to the chain transmission ratio of the summing gearbox *8* with a ratio $u = 2$ will rotate in the opposite direction relative to the lever *5* with twice the relative speed, which provides linear movement of the axis of the output shaft of the two lever mechanism.

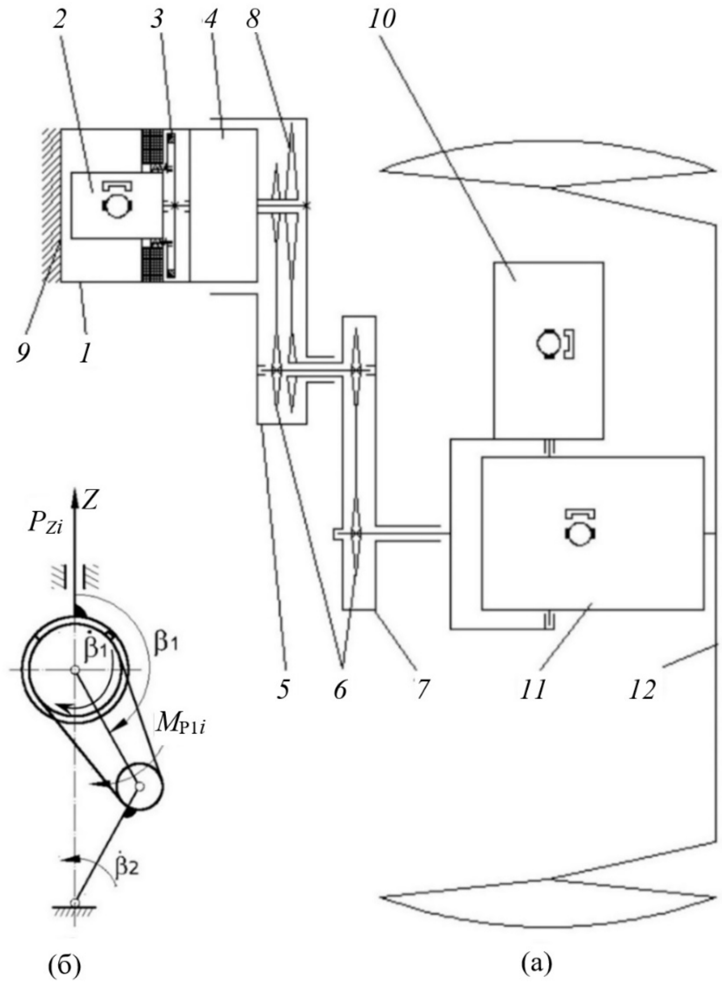


Fig. 17: Kinematic diagram of the active suspension drive (a) of the ODM and its two-lever circular-type mechanism (b):
1 - drive body; *2* - electric motor; *3* - electromagnetic brake; *4* - reducer; *5* - first lever; *6* - reactive chain transmission (*u=1*); *7* - second lever; *8* - chain transmission of summing reducer (u=2);β_1 - angle of rotation of the first lever; *9* - suspension or chassis frame; *10* - steering drive; *11* - traction drive; *12* - wheel;$\dot{\beta}_1, \dot{\beta}_2$ - angular velocity of levers; $M_{P(1)(i)}$ - moment of rotation on the first lever; $P_{(Z)(i)}$ - vertical force at work of the two-lever mechanism.

Since the first and second levers are kinematically connected, the displacement of the output shaft axis of the second lever according to Fig. 17b is determined by the formula

$$z = 2 \cdot l \cdot \cos\beta_1, \tag{15}$$

where$z-$ is the linear coordinate of the free axis of the second lever relative to the axis of the first lever; l is the length of the lever; β_1 is the angle of rotation of the first lever.

Thus, it is possible to measure the vertical travel of the suspension and the vertical coordinate of the wheel axis relative to the chassis frame in order to automatically control the suspension when the chassis moves on difficult terrain.

Results of design and layout developments and design-theoretical substantiation of the concept of intelligent mobile platforms. The conducted research confirmed the possibility of designing unified self-propelled chassis and IMPs based on these chassis for use both as part of autonomous lunar rovers of various purposes and as part of lunar train links. The design parameters of the unified self-propelled chassis, including their payload capacity, are given in Table 2.

Table 2. Estimated parameters of the CPM self-propelled chassis at the stage of concept selection

Parameter name, designation, unit of measurement	CPM for the autonomous lunar rover and for the lunar train link
Purpose of the CPM	Provide mobility of specialized attachments, transportation of astronauts and cargo, support for scientific research and technological operations
Wheel arrangement	4 × 4 × 4 × 4
Wheelbase, m	3.14
Track, m	3.14
Wheels diameter (by ground hooks), *d*, m	1.1
Wheel width, *b*, m	0.44

Wheel type	With metal-elastic profile tire organized on a rigid rim with ground studs
Combined active-passive suspension type	Active (actuated) lever suspension of circular type, capable of reconfiguration for realization of wheel stepping mode. Passive suspension - lever parallelogram with longitudinal sway of arms and elastic elements in the form of torsions
Lever arm leverage of suspension travel adjustment mechanism in vertical direction, m	0.1
Active suspension travel:	
Nominal ground clearance, m	0.45
Maximum ground clearance, m	0.65
Minimum ground clearance, m	0.25
Passive suspension travel, m	0.4
Speed, km/h: 1st gear 2nd gear	 1.0 5.0
Weight of self-propelled chassis IMP, kg	500
Payload, kg	2500

Max. lift angle with full load in first gear, deg	20
Required power of the traction motor of the motor-wheel, W	400
Angle of rotation of steering drive SS IMP, deg	45

About general view of the self-propelled chassis IMP, revealing with some simplifications the concept of its design, is shown in Fig. 18.

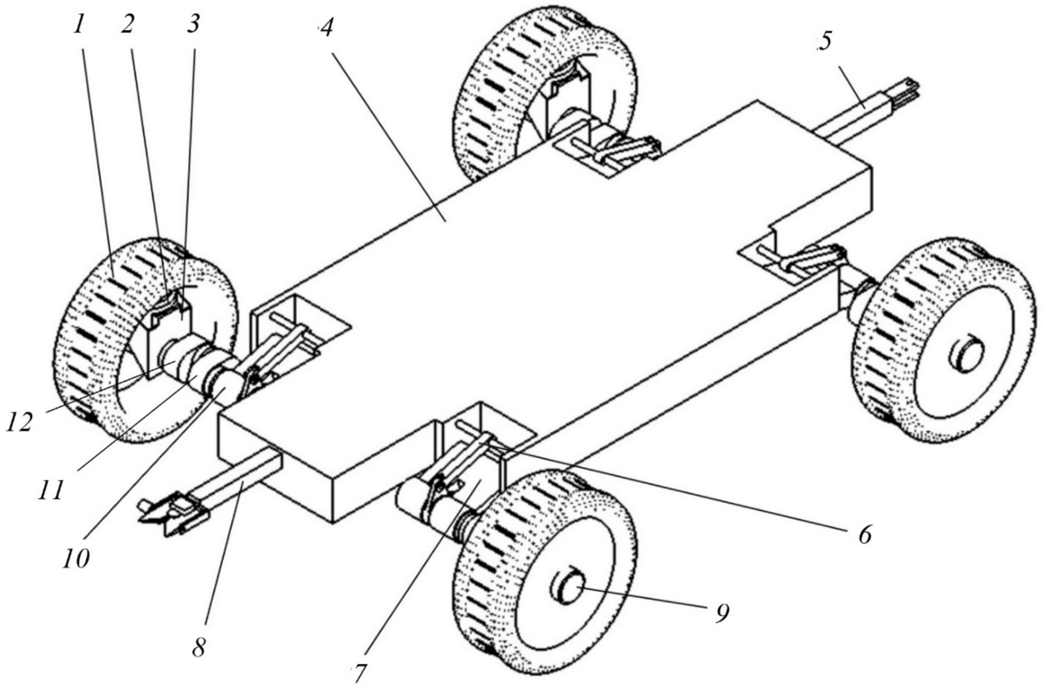


Figure 18: Concept of the CPM. General view and composition of the traveling and docking system (attached components of control, communication, local navigation systems, as well as cable networks are not shown conventionally): *1, 9* - motor-wheel with built-in traction drive; *2* - steering mechanism with drive; *3* - bracket of rigid mechanical connection of active suspension drive with steering mechanism; *4* - frame of self-propelled chassis with built-in power supply

system and electronic units of control, local navigation and communication systems; *5, 8* - passive and active ACCS mechanisms; 6, 7 - reactive lever and balancer of passive suspension with elastic element in the form of torsion; *10* - active suspension drive; *11, 12* - levers of active suspension mechanism.

Undoubtedly, the design parameters and the design appearance of the IMP will be refined during the development process. However, the developed concept already now allows us to assess the possibility of performing the most important technological operations at the stage of building the ISLV (unloading, transportation and assembly of station modules) and at the stage of operating the ISLV (long expeditions, including to the back side of the Moon). The development of the ACSU and the structural design of the IMU as a whole, creation of 3D models and computer simulation of various scenarios of the IMU application during the creation and operation of the ISLV is also in progress.

CONCLUSION

At present, there is experience in delivery and operation of lunar rovers on the visible and back sides of the Moon, as well as experience in operation of orbital space stations. This allows us to move from descriptive to engineering methods of developing the concept of the design appearance of a unified intelligent mobile platform (IMP), on the basis of which, using special attachments, it is possible to create both autonomous lunar rovers and lunar trains for various purposes: laying roads and other communications; unloading, transportation and installation of ISLV modules; long-distance expeditions, for example, in order to organize automatic branches of the ISLV to expand the frontline of scientific research, search and extraction of minerals

The proposed methodological approaches and the design, layout, and computational-theoretical studies performed on their basis allowed us to justify the engineering concept of a CPM with an empty mass of 500 kg, which can accommodate various attachments with a total mass of no more than 2500 kg. Such CPMs, with a total mass of 3000 kg, are intended both for autonomous use and for performing various transportation and technological operations and scientific research as part of lunar trains.

The advantages of the concept of unified multifunctional CPMs are the following capabilities:

- reduction in the cost of manufacturing and conveyor assembly of CPMs at a high level of development of designs not only during testing, but also during operation on the Moon under gradually increasing resource and complicating conditions;

- realization, after installation of specialized attachments, not only of transport, but also of road, construction, assembly, geological exploration and mining technologies, as well as of complex scientific research practically on the whole territory of the Moon, including eternally dark craters and the back side of the Moon;
- creating favorable conditions for the timely development of various attachments for autonomous lunar rovers and lunar trains, oriented to the use of the IMP payload;
- increasing the cross-country ability of autonomous lunar rovers on loose soils and difficult terrain during autonomous operation due to the use of active suspensions and wheel-walking mode of motion;
- ensuring patent purity and technological independence of lunar mobile robotics based on domestic prototypes and new domestic patentable solutions;
- maximizing the use of scientific and technical background and experience in designing self-propelled landing gear of planetoids, accumulated in the past and new centuries by engineers and scientists of the school of the chief designer of the self-propelled landing gear of Lunokhod-1 A.L. Kemurdzhian.

To summarize, we can speak about the concept of permanent mobility of all independent components of the ISLV, including doublers of its manned modules, to improve the safety of the station crews and to ensure the possibility of its reconfiguration and disposal of unnecessary equipment as the technologies of lunar exploration inevitably improve.

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