50 years of Lunokhod-1 and Lunar Roving Vehicle (LRV-1): at the origins of mobile space technology

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Abstract

On November 17, 1970, the mobile robotic rover Lunokhod-1, consisting of a self-propelled chassis and a sealed container mounted on it, laid the first track on the lunar surface. The container was equipped with overhead and built-in service and scientific equipment, providing electricity, communication with the Earth, temperature control in the internal volume and carrying out scientific research along the route. On July 31, 1971, as Lunokhod-1 continued its exploration, it was joined at the other end of the Sea of Rains by a piloted lunar rover - Lunar Roving Vehicle of the Apollo 15 mission, crewed by Commander David R. Scott, who was the rover driver and by James B. Irwin who was the lunar module pilot.

For three Earth days, two mobile spacecraft, completely different in design and control methods, were simultaneously operating on the Moon, representing the scientific and technical potentials of two countries, but one humanity! They had common goals and results - they discovered new methods and demonstrated new possibilities to explore and develop the Moon, not just at separate spots, but over large territories.

The team of authors, which includes engineers, scientists and drivers of Lunokhod-1 and Lunokhod-1, presents in the article episodes from the history of the creation, design, testing and operation of both lunar rovers. The authors are convinced that the new lunar rovers, which will become the main engineering components of the 21st century lunar bases, should be universal in control methods and combine the best qualities demonstrated by mobile space robots and manned space rovers of the past.

Keywords remotely controlled moon rover, piloted moon rover, self-propelled chassis, mobility subsystem, wheel, traversability

Acronyms/Abbreviations

Lunar Roving Vehicle (LRV)
Special Design Bureau No.1 (Osoboe Konstruktorske Byuro: OKB-1), Rocket and Space Corporation "Energia" named S.P. Korolev (RKK Energia)
R&D institute VNII-100 (VNII-100)
JSC R&D institute VNIItransmash (VNIItransmash)
Marshal Space Flight Center (MSFC)
General Motors (GM)
Defense Research Laboratory (DRL)

1. Introduction

During 50 years that have passed since the start of mobile space machinery on the lunar surface, hundreds of books, articles, papers and reports on the outstanding events of those legendary years have been written in Russian and English. The overwhelming majorities of publications consider either automatic lunar rovers and their research, or piloted lunar rovers and the results of their research. The authors aim to give a comparative analysis of the structural and design features of the first lunar rovers and the results of their work from modern standpoint, when the political component is no longer relevant. At the same time, primary sources written in hot pursuit of grandiose events, as well as publications and personal impressions of the participants in the events were of great importance for the authors [1,2,3,4,5,6,7,8,9]

The difference in design and technical characteristics of these rovers is determined by the way they are controlled. Lunokhod-1 was driven mainly thanks to information received from the onboard cameras of the machine vision system. This system included 2 pairs of panoramic TV cameras located on the port and starboard sides and two navigation cameras that duplicate each other, installed on the front. Each pair had vertical and horizontal cameras and was used
for scientific and navigation purposes. The front navigation cameras of the so-called low frame-rate television transmitted during communication sessions to the ground control station the images of the lunar surface with frequency of about 3 frames per minute. Continuous sequence of these images of low quality, as well as, obtained only at a stop, higher quality surface panoramas allowed the driver, who was at the ground control station, to orientate in the terrain. Given the quality of low frame-rate television, it was not easy at that time, this can be judged from Fig. 1, where Luna-17 is in the frame from distance of 8-9 meters. (Fig. 1).

The driver transmitted by radio to the on-board chassis automation unit one of 8 available commands for straight forward and backward locomotion, maneuvering and stop. In the event of emergency situations, the "Stop" command was immediately generated and directly executed by the on-board chassis automation unit. The chassis automation unit detected the following emergency situations: dangerous angles of roll and trim of the suspended rover part; extremely high current of traction motors, for example, when overcoming steep slopes.

Unlike all previous stationary lunar stations, Lunokhod-1 conducted research on a route of about 10 km. The explored area was approximately 80,000 m². In 1973, Lunokhod-2 conducted research on a route of about 40 km.

Driving a Lunar Roving Vehicle (LRV) in terms of terrain view was not much different from driving a car in unfamiliar and unprepared terrain. But this area was too unfamiliar! In addition, instead of the usual steering wheel, the astronaut had a different control body.

The frame also housed a power source, communication, navigation and other service equipment, as well as attached and built-in scientific equipment, including a front surveillance TV camera and a movie camera, a drill with its own power source, a self-recording penetrometer, a set of devices for placement on the surface, a laser reflector, box for collected samples of lunar soil and other tools. Astronauts had constant communication with the Earth. On the first day, the astronauts made a ten-kilometer trip to conduct the research. In total, the crews of the Apollo 15, 16 and 17 expeditions have traversed more than 90 km on the Moon.

This advantage of new lunar expeditions, carrying out research on large areas, over the stationary ones, was due to the use of mobile machines. The main attention in this paper is paid to the systems and subsystems of automatic lunar laboratories and piloted vehicles that provide mobility.

2. The history of the lunar rovers is a continuation of the flight of the First Sputnic of the Earth

In the 20th century, the idea of movement on the surface of the moon was very popular in industrialized countries, primarily among science fiction writers and scientists. Not only famous scientists and popularizers of space K.E. Tsiolkovsky, Arthur Clarke, Hermann Oberth, but also journalists, engineers, lecturers of institutes and school teachers of physics and astronomy. In the memory of our generation, the surprise and fascination of people with progress in science and technology has caused a response from the organizers of various shows, attractions, quizzes, exhibitions in parks, stadiums and other public areas. But at the engineering level, the comprehension of the tasks of lunar
expeditions, the creation of real lunar rovers began among specialists associated with rocket science, after the flight of the first artificial Earth satellite.

2.1. Pages of the history of the creation of lunar rovers in the USSR

The idea of a lunar rover, taking into account the real achievements of rocket technology, was born in the USSR in the same place where the idea of the first Sputnik was born - in Special Design Bureau No.1 (OKB-1), Podlipki town, near Moscow - at an enterprise that is now called the Rocket and Space Corporation "Energia" named S.P. Korolev (RKK Energia) [10]. According to the recollections of the veterans of this enterprise, the Chief Designer of OKB-1 S.P. Korolev instructed young engineers to think about the possible overall and mass characteristics of the lunar rover even before 1957.

In September 1959, the Luna-2 station, created at OKB-1, for the first time, after several unsuccessful launches of the Vostok-L launch vehicle, reached the lunar surface. In the same year S.P. Korolev came with a proposal to create a self-propelled lunar vehicle to the head of the tank design bureau of the Kirov plant in Leningrad - the chief designer of heavy Soviet tanks Zh.Ya. Kotin.

In 1961, Korolev (Fig. 3) tried to involve the Scientific Automobile and Tractor Institute in Moscow in this task. But in both cases, the cooperation did not work out. The leaders of the scientific and technical teams understood that the problem could not be solved quickly and easily, and, apparently, they were afraid of damaging the main topics of their enterprises.

In July 1963, a leading engineer of OKB-1 V.P. Zaitsev arrived on a business trip to a nearby suburb of Leningrad, Gorelovo, where a tank R&D institute VNII-100 (VNII-100), now JSC R&D VNIItransmash (VNIItransmash), was located since 1949. He handed over to the director of the institute a proposal of his leader - to study the possibility of creating a lunar self-propelled apparatus and develop its project. Director of VNII-100 V.S. Starovoitov took on a possible risk and appointed A.L. Kemurdjian (Fig. 4), who has already shown his capabilities to start research and development from scratch.

On May 30, 1964, Sunday, S.P. Korolev with a group of leading OKB-1 employees flew by his plane to Leningrad to get acquainted with VNII-100 and the results of the research performed. The main report was made by A.L. Kemurdjian. He spoke about the performed design studies for the wheeled and tracked versions. He noted some contradictions between VNII-100 and the design department of OKB-1, which put forward excessively high requirements for the characteristics of the lunar apparatus. In particular, the terms of reference specified speed of up to 20 km/h, the required cruising range was 100 km.

According to the recollections of I.I. Rosenzweig [11], Korolev agreed with the need to correct the terms of reference. He said that the main thing in the first flight is reliability. Records should not be planned, there are still a lot of important circumstances of locomotion and driving control on the Moon are not clear. It is necessary for the first rover to travel at least 10 km at low speed.

It is surprising that this forecast for the future Lunokhod-1 turned out to be accurate!

On the whole, the visit was successful. "Sergei Pavlovich made a decision - to make a lunar rover and entrust this work to VNII-100" [12]. On the same day, he decided the issue of transferring the newly built building to VNII-100 for a closed test-range with various soil channels, from which the life of all running models began (Fig. 5).

In the summer of 1964, a small team of Kemurdjian, which engaged leading specialists from other departments of VNII-100 to the work, sent to OKB-1 the first report "Determination of the possibility and choice of direction in the creation of a self-propelled chassis of the L2 apparatus." In addition to the concepts of the wheeled and tracked self-propelled chassis, a working hypothesis of a physical model of the lunar soil was presented in the report. It was developed in March
1964 at a large meeting of astronomers, scientists who studied the Moon by radio-physical methods, and OKB-1 and VNII-100 specialists in Kharkov [10].

![Fig. 5. Linear, circular and ring soil channels of a closed test-range for testing the wheels and models](image)

The lunar regolith in the model was described as "Silicate rock in a foamy - porous or fragmented state ...". It was pointed out that the mechanical properties of the proposed model "correspond to volcanic tuff, slag ...". The strength of the surface layer was estimated in the range of 20–100 kPa.

Although this model was never formalized as the official point of view of the Academy of Sciences of the USSR, in fact it was used already in the development of the lunar station Luna-9, which made the first soft landing on the moon on February 3, 1966. Korolev did not live to see this event in a matter of few days. He died on the surgery table on January 16, 1966.

In the meantime, after Korolev's visit, the specialists of the institute who had previously worked in the project on a temporary basis were assigned to the Kemurdjian’s department. There was an active recruitment of young specialists from the leading universities of Leningrad and Moscow, who had a penchant for research work. The structure of the department was reorganized, which now fully corresponded to the tasks of creating a lunar rover. The first wheeled and tracked models were created, as well as a special model for studying the remote control methods. (Fig. 6). The interaction of wheels with simulants of lunar soil was investigated in a flying laboratory under lunar gravity.

By the end of 1965, VNII-100 was fully ready for detailed design, but it turned out that the draft of the terms of reference for flight models of self-propelled chassis must be coordinated with new customer. A series of unsuccessful launches of lunar stations of the Luna series for the purpose of a soft landing, the lagging behind the schedule of development of the lunar complex H1-L3, which was created for manned lunar expeditions, forced S.P. Korolev to agree with the proposal to reduce the amount of work done by OKB-1 by transferring the topic "Exploration of the Moon and Planets of the Solar System by Automatic Spacecraft". S.P. Korolev himself chose a successor, whom he knew well from the post-war period of the beginning of work on the creation of the rocket industry in the USSR. It was G.N. Babakin, head of OKB-301, which was part of the S.A. Lavochkin plant (now Lavochkin Association, Khimki town, near Moscow). He became the Chief Designer of the lunar rovers and of all lunar and interplanetary automatic stations [13, 14].

All the documentation for the automatic stations and the corresponding production backlog of OKB-1 were transferred to Khimki. Some specialists who were involved in the lunar and planetary programs, including Korolev's close associates - S.S. Kryukov and O. G. Ivanovsky. This attitude of Korolev, the personal qualities of G.N. Babakin (Fig. 7) simplified and accelerated the transfer of the business and the organization of new cooperation.

![Fig. 6. The first operating model of VNII-100 for testing the mobility and remote control](image)

The two enterprises carried out together the launch of station Luna-8, the landing failure of which occurred already at the final stages of landing. And the next launch was already supervised by Babakin, and this flight has ended the series of failures that had exhausted everyone. The Luna-9 station made a soft landing for the first time on February 2, 1966. B.Ye. Chertok stated in his book [15] these events and the level of nervous tension of the key participants.

The first contract between VNII-100 and new Customer was signed in November 1965. In the new cooperation, the work "began and developed with all the completeness necessary for the implementation of the grandiose plan" [10]. During 1966 and 1967, it was possible to conduct joint space experiments on the lunar orbital stations Luna-11, Luna-12 and Luna14, which made it possible to determine the choice of structural and lubricant materials for heavily loaded gear and friction pairs of traction drives of the self-propelled
chassis. The frictional characteristics of friction pairs when working in open space and the methodology for conducting such tests in ground laboratories were detailed.

Collaborative projects, experiments and discussions have been extremely rewarding. Increasing space qualifications while communicating with high-level professionals in real business evolved very quickly [16].

![Fig. 7. G.N. Babakin (1914-1971) - chief designer of the lunokhods and lunar and interplanetary stations](image)

Onboard the Luna-13 station, the next joint experiment was also successful to assess the bearing capacity of the lunar soil and its density in natural bedding using two instruments - a soil meter (a penetrometer) and a radiation density meter. They were placed on the ground using two spring-driven manipulators (Fig. 8). Then the indenter of the penetrometer was inserted into the regolith while operating a miniature jet engine, the nozzle of which was directed vertically upward. The result of measuring the strength of the upper regolith layer is 44 kPa. This figure was consistent with the characteristics of the accepted physical model of the lunar regolith. All this strengthened the developers' confidence in the correctness of technical solutions and test methods. The designers of both enterprises agreed on the optimal options for the mechanical and electrical coupling of the self-propelled chassis with the container, which allowed the parties to approve the terms of reference for the development and manufacture of the flight models.

![Fig. 8. Luna-13: evaluation of the strength of the regolith using a penetrometer (right)](image)

Thanks to well-elaborated system of development, manufacturing, autonomous and complex tests, a high level of dedication and increased professionalism, the flights models of self-propelled chassis for several flights, as well as a spare kit, stand and equipment for incoming control of self-propelled chassis were delivered to Khimki in the summer of 1968. They did not manage to complete only the running tests of the flight models. They were completed in the summer of 1969. In Kamchatka, in the area of fresh volcanic formations, tests were successfully completed to confirm the travers ability, lifetime and other characteristics of the self-propelled chassis. And in the Crimea, near the Center for Deep Space Communication, where a special test site was established, a joint team of Lunokhod developers, together with its control crews, completed the training of remote driving skills.

By this time in the space division of VNII-100 three departments were organized, including a production site, certified, among other things, for the installation of a chassis automation unit and a test equipment development bureau. The total number of employees was 190. The average age of self-propelled chassis developers was 26 years. In a relatively short time, during the most intense stage of manufacturing and delivery of flight models, up to 500 people took part in the work.

2.2. Lunar Roving Vehicle in the USA history pages

An extensive analysis of the projects of lunar rovers in the United States, in the period before the Soviet satellite flight on October 4, 1957, was made in [17]. It is interesting to note that the future head of the American lunar program, Wernher von Braun, also participated in this unannounced competition of amateur projects in 1953. He proposed at that time the concept of a lunar rover with a caterpillar drive. From the illustrations for the book by Anthony Yang [18], it can be seen that, already being the director of the Marshal Space Flight Center (MSFC), Wernher von Braun took part not only in the discussion of projects, but also personally got acquainted with the design of the current models of the future lunar rover in the driver's seat. And in the photo (Fig. 9) he is closely acquainted with the TV camera, which was planned to be installed on board the LRV.

![Fig. 9. Wernher von Braun points out the zoom lens of the TV camera to be used on the LRV](image)
The cited sources indicate that the topic of movement on the lunar surface began to be studied professionally in 1959 as part of the "Project Horison", which was devoted to the problem of creating a lunar base. The project was carried out by the specialists from the US Ballistic Missile Agency. Many of them then went on to work in the newly created MSFC in 1960, and here they continued to study the Mobility system (MS). It seems that in this initial period of study, just as in the USSR, specialists were worried about the main question - the method of transportation. There is no point in mention the possibility of flying devices on the Moon. They were rejected in both countries for a variety of serious reasons. As well as the others, more complex in comparison with the wheel and track ways of locomotion - walking, jumping, crawling and etc.

Since the USA immediately set the goal for the presence of people on the Moon, there was a lot of controversy over the question of what should be the workplace of astronauts on a piloted lunar rover? There were two main options here: a pressurized cabin, in which astronauts can stay for a long time, or an open jeep, the travel time in which was limited by the characteristics of the life support subsystem built into the spacesuit. This, of course, increased the number of possible options. In the USSR, it did not come to the design phase of a piloted lunar rover.

On April 12, 1961, the first flight of Yuri Gagarin into the space took place. It was a strong impetus for all of humanity. On April 26 (local time) same year, President John F. Kennedy made a famous speech in the Senate, in which the visit to the Moon by humans and their return to Earth in the current decade was proclaimed a national task.

It was a huge moral support for the creators of technology for lunar expeditions. The head of the lunar program did not need to persuade the company to take on new topics. Top managers were ready to carry out initiative searches and studies, which most often ended with the production of operating models at their own expense and on a competitive basis.

To one degree or another, many specialists and scientists were involved in the search works. Among them were people who were devoted to the idea of creating an LRV regardless of the current conjuncture. So, for example, there was a cooperation of the manager of the lunar program of General Motors (GM) Samuel Romano, the head of the Defense Research Laboratory of GM (GM-DRL) Ferenc Pavlics and the scientist - head of the Mobility Research Laboratory Mechislav Bekker. Together with their teams, they have invented excellent technical solutions, developed methodologies and conducted convincing tests of a key system - the LRV mobility system (Fig. 10).

Fig. 10. S. Romano (standing), M.G. Bekker and F. Pavlics sit on the LRV model

Lockheed, Bendix, Boeing, General Motors, Brown Engineering, Grumman and Bell Aerospace System entered the struggle for the best technical solutions for the LRV design [19]. It was a marathon for several years with intermediate finishes and eliminations. So, at the beginning of 1964, based on the results of research, MSFC came to the conclusion that pressurized cabins were inappropriate for the next expedition. This increased the chances of open jeeps like the one made by GM-DRL (Fig. 11). The results of the creation of bulky lunar rovers with pressurized cabins have lost their relevance.

Fig. 11. A research model developed by GM-DRL in early 60es. The tests in large boulders

Then a decision came to use only one Saturn-5 rocket in each expedition. The very possibility of the participation of the mobile means of the mobile means
in the expedition was called into question. Jeep LRV in its working configuration had no place on the lunar module. But GM-DRL specialists have found a solution to this problem: there is enough time on Earth to compactly pack a three-piece chassis. And on the Moon, astronauts could restore the LRV to a working configuration using a dedicated deployment subsystem.

Meanwhile, the spacecrafts continued to fly to the Moon as part of the Ranger and Surveyor programs and to orbit around the Moon – that was the Lunar Orbiter program. The main task of the first program was to deliver the instrument container to the Moon in the hard landing mode. The execution of the first program cannot be considered satisfactory; the first three launches did not reach the goal at all. The last three launches, which ensured the fulfillment of the flight goal in 1964 and 1965, made it possible to obtain images of various areas of the lunar surface with a resolution of 0.5 m to 0.25 m (Ranger-9) before a hard landing.

In 1966 and 1967, the images of the surface were obtained from the Lunar Orbiter stations. The images, of course, expanded knowledge about the Moon, but for the competent design of the Mobility Subsystem, contact studies on the surface were needed. They were successfully carried out after successful soft landing on the Moon of the Surveyor-3 spacecraft on April 17, 1967. (Fig. 12).

Experiments with a scoop, which, using a manipulator, dug a trench in the lunar regolith, allowed researchers to estimate the bearing capacity of the lunar soil in the range of 21kPa - 54kPa. The estimate of the carrying capacity of 44 kPa, obtained earlier by the penetrometer of the Luna-13 station, was in this range!

It was not until 11 July 1969 that the final detailed requirements for the LRV were formulated under the guidance of MSFC program manager Saverio Morea (Fig. 13). Request for proposals was sent to 29 companies and corporations that have participated in one way or another in mobility research in the past 7 years.

As a result, the contract was signed in October 1969 with Boeing. A prerequisite of the contract was the involvement of GM-DRL as a subcontractor for the development and manufacture of the Mobility Subsystem. Despite great difficulties, including adjusting the working documentation, the Boeing-GM tandem delivered the first flight models for the Apollo 15 expedition in early March 1971. On July 26, 1971, the Apollo 15 crew took off to the Moon with LRV on board.

It is noted in [19] that the total number of GM-DRL employees involved in the creation of the Mobility Subsystem at that time was 400 people. Most likely, this figure includes not only direct developers - designers and testers, but also production services - managers, workers, technologists and others.

Concluding this section, we can admit that the total time of the design and search works including reflections and discussions, and hot time of the creation of the flight models of Lunokhod-1 and LRV-1 approximately coincide in both countries. In both cases, the professional study of the locomotion and transportation of scientific equipment and astronauts on the lunar surface began after the flight of Sputnik 1 - no later than 1959. Earlier production of flight models of Lunokhod-1 (1968), in comparison with LRV-1 (1971), is associated with the general plan of piloted expeditions of the Apollo program.

3. Mobile pioneers on the Moon
3.1. The reaction of people on Earth

The beginning of Lunokhod-1’s operation on the Moon on November 17, 1970 (Fig. 14) became an event of global significance. On November 18, 1970, all the central newspapers of the country on the first page published a message about the successful completion of the flight of the Luna-17 station and the beginning of the operation of Lunokhod-1 on the Moon. At that time, no one knew yet how a spacecraft was driven. The operation of the Lunokhod-1 exit from the Luna-17 station to the lunar surface and the first lunar track was laid by the crew commanded by Nikolai Eremenko. Driver Gabdulkhai Latypov was at the control panel of Lunokhod-1 [4].

Scientists and experts noted that this is a new direction in space exploration using mobile robots, they analyzed the technical characteristics and composition of scientific equipment. And among people that were far from space and science, the talks about the Lunokhod caused kind smiles. Everyone's reaction was warm. The children generally perceived the Lunokhod as a living creature. He fell asleep on a long moon night, and in the morning he was in a hurry to see the Sun. He opened up to the Sun like a flower. He obeyed the adults and could, on their instructions, visit the places which were dangerous for the humans.

Fig. 14. Lunokhod-1 without screen-vacuum thermal insulation

Vladimir Vysotsky, the most sensitive tuning fork of social mood in the country, sang in one of his songs "our beloved moon tractor." It is said very warmly, but also very precisely - just look at the photo of its track on the surface of the Moon, it really resembles the tracks of a wheeled tractor on fresh arable land. Especially if you compare these wheel tracks with stiff rims and high lugs with the LRV-1 elastic mesh tire track (Fig. 15). And this has not happened by a chance, it was predetermined by design, because two rovers had different purposes and routes.

Fig. 15. The track of Lunokhod rigid wheel with lugs (left) and the track of LRV elastic tire with chevrons

LRV-1 (Fig.16) has joined Lunokhod-1 on July 31, 1971 on the opposite shore of the Sea of Rains. For three Earth days, two lunar rovers were simultaneously operating on the lunar surface! At that time, we did not think that this situation would be repeated again in the solar system soon. But now, when only 50 years have passed and three rovers are simultaneously operating on Mars!

Fig. 16. LRV has significantly increased the ability of astronauts to study the lunar surface. Crew Commander - First Lunar Driver David Scott

There are already 13 vehicles in the rover fleet. Today, the continuation of the development of new space technologies is the main result of the relatively short life of the roving pioneers. Undoubtedly, humanity will remember them and their creators, as it remembers now the first locomotive, automobile, airplane and rocket.
3.2. Scientific and technical results of the lunar rovers

Unlike the usual practice of restrained information about new space technology in the USSR, specialists and scientists were allowed to publish fairly detailed descriptions of the design of the Luna-17 station and Lunokhod-1 (Fig. 17). Already in 1971 in the publishing house "Science" under the editorship of the scientific director of the Soviet lunar program, academician A.P. Vinogradov, first volume of the monograph "Lunokhod-1 Mobile Laboratory on the Moon" [1] was published. The monograph has revealed the details of the design of the Luna-17 station, Lunokhod-1 as a whole, its self-propelled chassis and built-in and overhead rover container systems: thermal control, remote control system, and machine vision.

Fig. 17. General view and attachments Lunokhod-1. Modern 3d model front view (top), rear view (bottom).

The published results of space research covered only the first 3 months of the mobile laboratory operation. The results of scientific research along the entire route of Lunokhod-1 were summarized in second volume of the monograph [3]. In both publications the employees of several enterprises were asked to publish under pseudonyms. The pseudonyms of the developers of the self-propelled chassis, as well as the Chief Designer of the Luna-17 and Lunokhod-1 stations are disclosed in [9]. It is possible now to study LRV on the Internet (Fig. 18). There is a uniquely informative MSFC report [2], which is accessible to everyone. The name of the report rightfully contains the word “Bible”. Indeed, the authors N.C. Costes, J.E. Farmer and E. B. George have collected in the book the primary and considerably detailed information about the LRV, ground testing on various soils and the results obtained on the Moon. They managed to get acquainted with the research results during the Lunokhod-1 expedition; this report contains references to [20].

Fig. 18. General view and attachments LRV

It can be seen in Fig. 19 that the overall mass and geometric parameters of Lunokhod-1 and LRV are close.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Objects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lunokhod-1</td>
</tr>
<tr>
<td>Full mass, kg</td>
<td>756</td>
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<tr>
<td>Chassis mass, kg</td>
<td>105</td>
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<td>Wheel mass, kg</td>
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<tr>
<td>Track, m</td>
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<tr>
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<td>Clearance (on the Moon), m</td>
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<tr>
<td>The overcome angle of ascent on the regolith, degree</td>
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<tr>
<td>Type obstacles to overcome (protrusion height / shoulder depth / crack width), m</td>
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<tr>
<td>Turn radius: min / max, m</td>
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<tr>
<td>Static stability angle, degree: Longitudinal / transverse</td>
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</table>

* LRV operational – loaded; ** LRV deployed (empty operational)

Fig. 19. The parameters of the self-propelled chassis of Lunokhod-1 and Mobility Subsystem of LRV-1
The design of the rigid wheels of the Lunokhod lunar rovers is a creative success of designers, researchers and technologists (Fig. 20). The wheel formula 8x8 limited the diameter of the wheels, and the wheels of small diameter, in turn, limited the amount of elastic deflection of the tire. The choice of an onboard steering wheel (this is also for a tank and tractor type) requires a high axial stiffness of the propeller, which is unattainable for wheels with an elastic tire.

Fig. 20. Rigid wheel of Lunokhod lunar rovers

The key component of a wheel is its rigid rim. It has three profiled titanium welded hoops, covered on top with a braided wire mesh. The mesh is sewn with a wire to the outer hoops and pressed with rivets to the middle and outer hoops with two rows of oblique (not parallel to the wheel axis) titanium lugs installed with an offset along the installation angle, in a checkerboard pattern.

The hoops, connected by titanium lugs, form a load-bearing frame that determines the rigidity of the rim in the radial and axial directions. The mesh and high lugs determine the high traction and adhesion properties of the wheel.

The huge success of the LRV project is the elastic metal wheels. The wire-braided tire provides optimal ground contact and increased ride comfort. The wheel mates perfectly with both the suspension and the wheel turning mechanism (Fig. 21).

Fig. 21. LRV wheel with elastic tire and chevrons for tests in a dirt channel

Fig. 22 compares the results of the operation of Lunokhod-1 and LRV-1 on the Moon. It clearly shows in what situation particular rover had its own advantages. The main advantage of the piloted lunar rover is its high speed, close to the maximum permissible speed for this vehicle, when the wheels are detached from the ground. Moreover, the average speed of Lunokhod-1 has decreased in comparison with the planned speed due to the stops for careful assessments of the road situation by the driver. Here it is necessary to clarify that the first (low) speed of Lunokhod-1 was 0.8 km/h, the locomotion at second, higher speed (2 km/h) during this expedition was impossible due to a fault in the chassis automation unit. This, by the way, was the only and not the most dangerous failure of the self-propelled chassis components. Next Lunokhod-2 has been driven at both speeds - 0.8 km/h and 2 km/h.

Fig. 22. Operational results of Lunokhod-1 and LRV-1 on the Moon

The difference in speed led to a significant difference in the distance traveled. But on the other hand, the device for assessing the traversability
(Russian abbreviation – PrOP) (Fig. 23), which automatically measured the bearing capacity and adhesion of the lunar regolith along the entire route, has made 537 measurements against 6 measurements that the LRV astronauts performed manually. Moreover, the robot made measurements at different geological and morphological areas of the terrain, including the bottom and steep walls of the craters. The ascent angles negotiated by Lunokhod-1 reached 25°. The protection alarm of the self-propelled chassis automation unit was repeatedly triggered because of the steep slopes.

Fig. 23. The device for assessing the travers ability in transport position. 1 –Upper head; 2 –Measuring wheel movement mechanism; 3 –Measuring (free rolling) wheel; 4 –Lower head; 5 –Cone and blade die; 6 –Upper wheel movement mechanism

The high cross-country ability of Lunokhod-1, movement on rough terrain, with increased slippage of the wheels, worsened its energy consumption indicators, according to which it obviously lost due to the difference in movement speed. As a result, the specific power consumption (reduced to a unit path) from the power supply source for Lunokhod-1 turned out to be almost 3 times higher than that for LRV-1. Of course, high-speed piloted and low-speed high-traffic lunar rovers will be required at the lunar bases. But, it is imperative to investigate the possibility of creating a hybrid lunar rover capable of operating in an optimal way depending on the circumstances.

3.3. Scientific instruments and equipment of lunar rovers

Transportation and maintenance of scientific instruments and equipment is one of the main tasks of the lunar rovers. For robotic lunar rovers, this is a scientific part of onboard equipment, the design and testing of which must comply with the general requirements for space technology. Portable scientific instruments and equipment have been developed for piloted LRVs, which stay on the lunar surface is limited.

3.3.1 Lunokhod-1: 17.11.1970 – 14.09.1971

The following onboard scientific equipment was installed on Lunokhod-1:

- Two navigation TV cameras:
  - Navigation and lunar science, mostly selection of objects for studying with TV panoramic cameras, X-ray fluorescence spectrometer RIFMA and Soil mechanics sensor PROP.
  - Four panoramic TV cameras (Fig. 24)

Lunar science: Study of topography, morphology and frequency distribution of small lunar craters and rock boulders, new morphological type of small craters formed by the low-velocity impacts was found [21, 22, 23, 24, 25].

Fig. 24. Расположение и углы зрения навигационных камер (5 и 6), панорамных камер вертикальной развертки левого (1) и правого (3) бортов и горизонтальной развертки левого (2) и правого (4) бортов. Фрагмент панорамы камеры вертикальной развертки, во время бортового поворота Лунохода-1 с радиусом равны нолью

- X-ray fluorescence spectrometer RIFMA
- Lunar science: Study of chemical composition of lunar soil along the route of Lunokhod-1. Measurements at several observation stations showed that composition of the lunar soil here is close to that of basalts [26].
- Soil mechanics sensor PROP
Driving conditions and lunar science: Analysis of the results of measurements of bearing capacity and shear strength in combination with measurements of the rover inclinations showed that values of the considered characteristics of lunar soil decrease with the surface slope increase [20].

- Laser retroreflector

Lunar science: Laser reflectors were also on Lunokhod-2 and were brought to the lunar surface by the missions of Apollo 11, 14 and 15. They reflected back the light signals sent from Earth’s observatories that allowed to measure the Moon-Earth distances with very high accuracy that, in turn, allowed to measure parameters of rotation of the Moon indicative for the presence/absence of liquid core in this body [27, 28, 29, 30].

- X-ray telescope PT-1

Extra lunar science: This device measured X-ray radiation and proton flux during the Lunokhod-1 movement and stations [32].

- Radiation detector PB-2H

Extra lunar science: This device measured intensities of solar and galactic cosmic rays, including angular distribution of solar protons [33].

3.3.2 Lunokhod-2: 15.01.1973 – 10.05.1973

The following onboard scientific equipment was installed on Lunokhod-1:

Three navigation TV cameras:

Navigation and lunar science, mostly selection of objects for studying with TV panoramic cameras, X-ray fluorescence spectrometer RIFMA, Magnetometer and Soil mechanics sensor PROP

- Four panoramic TV cameras

Lunar science: Study of topography, morphology and frequency distribution of small lunar craters and rock boulders, a case of landslide on the slope of small crater was found, a zone of negative balance with outcrops of bedrock was identified on the rim of Fossa Recta graben [34, 35].

- X-ray fluorescence spectrometer RIFMA

Lunar science: Study of chemical composition of lunar soil along the route of Lunokhod-2. Measurements at several observation stations showed that composition of the lunar soil here is changing due horizontal transportation of the surface materials by the impact cratering [36, 37, 38].

- Soil mechanics sensor PROP

Driving conditions and lunar science: Analysis of the results of measurements of bearing capacity and shear strength in combination with the by-eye measurements of the rover inclinations showed that values of the considered characteristics of lunar soil decrease with the surface slope increase [38, 39]

- Magnetometer

Lunar science: Measurements by this instrument during crossing eight craters with 50 to 400 m in diameter showed specific anomalies of local magnetic field probably resulted from piezoelectrical polarization of the target minerals by the crater-forming shock wave (Ivanov et al., 1976). Measurements at the unmovable observation stations combined with the results taken by magnetometer of Apollo-16 found that electrical conductivity beneath Mare Serenitatis is lower than beneath the surrounding highlands. This was interpreted as a result of the mare-forming basaltic volcanism which moved the heat-generating radioactive elements to the surface where the heat is easily being lost to the space [40].

- UV/Visible Astrophotometer

Lunar science: The instrument measured the radiation of visible and UV light in the lunar sky. It was found that the radiation increased when the zenith angle of the Sun approaches to 90°. This was interpreted as evidence for presence above the lunar surface of levitated dust [41, 42].

- Laser corner reflector

4.3 Portable devices and equipment LRV-1 (31.07 – 02.08) 1971

The composition of the portable equipment, as well as the composition of the scientific instruments of the Soviet lunar rovers, was not constant for all expeditions. In particular, the following equipment was and was used by astronauts on board the LRV-1 during research during their trips: Lunar Surface Drill with a built-in battery, a set of drill rods and a pedal to facilitate work on the ground; Lunar Self-Recording Penetrometer (LSRP) (Fig. 24); and a Laser Ranging Retro Reflector that simply lay flat on the ground (Fig. 25).

![Fig.24. Lunar Surface Drill (left) and Lunar Self-Recording Penetrometer (LSRP)](image-url)
The penetrometer was introduced manually by the astronaut, and the decoding of data on the nature of the change in soil resistance was carried out already on Earth [43, 44]. The maximum force was 215 N, the maximum immersion depth was 0.76 m.

In addition, the equipment of astronauts during their "Extravehicular Activities" (EVA) included "Lunar Surface Sample Collection Equipment", located on spacesuits for extravehicular mobility of astronauts. The astronauts also used the “Lunar Geological Hand Tools" attached to the LRV stern. All this helped to collect the most interesting samples of lunar soil at various points along the route of their movement. They traveled 27.9 km and brought 77.6 kg to Earth. In total, in the last three expeditions, 291 kg were collected. The first three expeditions of the Apollo program returned a total of 97.6 kg to Earth. Laboratories have unlimited opportunities for the most complex studies of lunar soil.

4. Discussion: what from past experience continues to be relevant for new rovers?

Apparently, we need to start by defining what a planetary rover (Russian - planetokhod) is, taking into account the experience of the lunar rovers and the unique experience of the long-term operation of American mars rovers.

In our understanding, a planetary rover is a spacecraft made in the form of a mobile all-terrain vehicle, which is designed to support the work and transport of astronauts, scientific instruments, equipment and materials on the unprepared surface of celestial bodies.

High cross-country ability and travers ability is especially important for robotic rovers. First, they are scouts and rescuers and therefore must navigate difficult terrain and loose sands. Secondly, a remote driver or the robot's own intelligence, with autonomous control, can make a mistake and send it to dangerous areas. For a piloted driver, increased cross-country ability will also not be superfluous, however, here the driver is still able to choose the safest route.

This is the main contradiction for a designer, he creates a car in clean workshops and white gloves, taking into account the strict restrictions on weight, dimensions and energy consumption usual for spacecraft. And then, somewhere on Mars, this graceful licked structure will bury itself along the bottom in abnormally loose sand or tear the wheels into trash on sharp stones. The talent of the developers is to find the optimal combination, in one way or another, satisfying all the conflicting requirements.

Design in this case requires a systematic approach, and a feature of the Mobility system (in Europe, including Russia, they often say Locomotion System) is a comprehensive consideration of surface properties, that is, design in the "Terrain - machine" system.

4.1. General approaches to the creation of the self-propelled chassis of the Lunokhod and the LRV mobility subsystem

The structure of Lunokhod-1 and its main system - self-propelled chassis - is shown in (Fig. 26). The structure of the LRV and its mobility subsystem are shown in Fig. 27. (Term “System” in Russia and “Subsystem” in USA are equivalent in meaning in this article).

As can be seen from Fig. 26 and 27, robotic and piloted lunar rovers share some common systems. But there are also differences due to different driving methods. The absence of a driver on board Lunokhod-1, in dangerous situations, should to some extent be compensated for by onboard automation. Therefore, a self-propelled chassis, in addition to a mobility subsystem, includes a chassis automation unit, programmable devices and sensors, some of which are involved in an autonomous control loop. This increases the safety of remote driving and reduces the psychological stress on the driver.

The chassis automation unit converts the commands received on board from the ground control panel and issues them to the executive bodies. It generates its own commands based on information from traffic safety sensors - roll and trim sensors and traction motors current sensors; programs and implements the program of operation of the device for assessing the cross-country ability and the ninth, free-rolling odometer wheel. Its functions also include converting signals from all sensors for transmission to Earth.

The chassis automation unit is located inside a sealed container (the equivalent name is the instrument compartment), where normal climatic conditions are provided by the original thermal control system developed by the specialists of the head enterprise Lavochkin Association. The gyroscopic roll and trim sensor, built into the automation unit, turns out to be
close to the center of mass of the sprung part of Lunokhod-1 (Fig. 28). Continuous processing of odometer information about the actual distance traveled and about the speed of rotation of the Lunokhod-1 wheels makes it possible to estimate the value of the wheel slip (slip) coefficient and, if necessary, to change the course in a timely manner.

Each component of a self-propelled chassis, of course, can have an independent meaning. For example, the device for assessing the traversability also performs scientific research on the physical and mechanical properties of soil in natural bedding. But, as one of the components of the system, it, first of all, met its requirements in terms of its interface characteristics. It withstood autonomous tests on various models of the lunar soil under the influence of various factors of outer space. But a positive conclusion about installation on board, the device received during complex tests as part of a self-propelled chassis.

The design of the Lunokhod and LRV is completely independent from each other. But it turned out that the leaders of engineering and scientific teams both in the USSR and in the USA adhered to the same systemic principles of creating new space technology. With regard to all-terrain transport vehicles, these principles were set forth in the works of M.G. Becker. In 1973, his fundamental work was published in Moscow in Russian.

It is possible to single out other common approaches in the creation of Soviet lunar rovers and American LRVs, which the developers adhered to.

- The choice of a metal wheel prime mover with a treadmill in the form of a wire mesh.
- The choice of an electromechanical all-wheel drive transmission with integrated traction drives based on DC brush motors with independent excitation. Input drive shaft brake.
- The choice of independent, articulated – lever type (parallelogram), elastic (in the form of torsion bars) suspensions of the wheels.
- The choice of physical models of lunar soil in the form of natural quartz sand and crushed materials with particles of various sizes.
- Development of the wheel design during testing in linear and circular soil channels, including simulation of the lunar gravity.
- Sufficient power reserve of traction motors.
- The choice of the kinematic scheme of the traction wheel drives, allowing to break the connection between the traction motor and the wheel (transformation of the driving wheel into a driven one)
- Electromechanical component redundancy.
- Final tests and driving practice on special and natural ranges.
Concluding the review, it can also be noted that throughout the history of the creation of robotic and manned lunar rovers, from idea to flight models, research and searches took place in a competitive environment, based on consideration of at least two options. In the United States, this was actually government policy implemented by MSFC. Therefore, the competitive environment here was made up of the teams of various companies. In the USSR, the creation of a competitive environment is a merit of the leaders of the creation of the lunar rover G.N. Babakin and his self-propelled chassis A.L. Kemurdjiana. They managed to organize the work in such a way that every serious technical decision was made only after a thorough discussion of possible options. This approach, ultimately, led to the professional growth of young engineers and scientists, to the formation of real schools for the creation of mobile space technology for the Moon and other carried bodies. In particular, after Lunokhod-1, a walking device was created for studying the mechanical properties of Mars soil - PrOP-M, which was delivered to the surface of Mars by the Mars-2 station in 1971; a mobile device for exploring the surface of the Mars satellite - Phobos (PrOP-F) with a hopping propulsion device, which was sent to its destination on board the Phobos-2 interplanetary automatic station. Unfortunately, these mobile devices did not have a chance to test their driving performance. but a completely new experience was obtained.

This experience allowed VNITRANSMASH in 1986 to develop, manufacture and deliver to Chernobyl two remote-controlled robots with bulldozer dumps in just two months, which proved to be good for clearing and decontaminating the roofs of the 3rd power unit of the Chernobyl nuclear power plant. These robots at the station were called "Lunokhod".

It should be noted that when creating lunar rovers and performing new tasks, a wide scientific and technical cooperation was developed, covering the most advanced enterprises in their research. This became possible only thanks to the powerful state support for the development of space technology.

4.2. Differences in technical solutions for the design of the Mobility Subsystem of Lunokhod and LRV

Technical solutions should be considered for specific units and assemblies. The difference in their technical appearance and characteristics can be formulated as follows.

- **Wheels:**
  a) Lunokhod-1 - a rigid rim (≈ 300 N/mm) - titanium hoops are connected to the hub with spokes, and between each other by titanium grousers and wire mesh, no steering drives;
  b) LRV - elastic wire mesh tire (3.7 N/mm) with plate chevrons, wheel steering drives of the front and rear axles

- **Traction drives:**
  a) Lunokhod-1 - two-speed motor, planetary gear;
  b) LRV - motor with speed control, harmonic gear.

- **Suspension of the wheels:**
  a) Lunokhod-1 - the parallelogram levers swing in the longitudinal plane, triple titanium rod torsion bar;
  b) LRV - the parallelogram levers swing in lateral plane, two separate steel torsion bars.

- **Carrying structure:**
  a) Lunokhod - no frame, the bottom of the container plays the role of a frame;
  b) LRV - three-section deployable frame.

The modern practice of creating rovers shows that certain design principles and some specific technical solutions of the first rovers have already become classics in this area of space technology. For example, the choice of an electromechanical all-wheel drive transmission with traction drives built into the wheels...
based on DC motors with independent excitation and wave or planetary gears; a choice of metal wheels with rigid rims and high lugs, with a treadmill made in the form of a braided wire mesh. Methods and equipment for testing with simulated environments on the Moon or Mars and a real reference surface have become commonplace.

What else will remain relevant - this will be determined by new developers of new planetary rovers. The authors wish them success in their interesting and important work!

5. Conclusion

Despite the fact that the Lunokhod and LRV have been created independently of each other, the systematic approach to the development and even some technical solutions were common for both lunar rovers. This is the evidence of uniform understanding by the project team leaders the essence of new tasks and optimal choice of the solution ways. The great work of the rover teams is worthy of respect and admiration!

The Lunokhods and LRVs have clearly demonstrated their usefulness and effectiveness for the exploration of celestial bodies. Since late 90s, more robotic planet rovers have already been developed. Piloted LRVs will certainly have the followers too. The need for both, as well as for the rovers with dual control, will certainly increase on the route from exploration to development of the Moon and Mars.

New planetary rovers are being created based on modern technologies. Especially impressive is the rapid increase of the system operational lifetime, the volume and quality of the scientific information received. At the same time, the already proven structural and functional schemes and design approaches of the past do not lose their relevance. Practice shows that particular technical solutions for the subsystems of planetary rovers of both types are not outdated either.

Against the background of continuous development of information technologies, no innovations have yet been seen in terms of improving the driving performance and expanding the locomotion functionality of self-propelled chassis and rover mobility systems. Analysis of modern rover operations shows that there are considerable reserves for increasing scientific efficiency of planet exploration missions.

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List of References


[26] Zvereva A.M., Severny A.B., Terez E.I. Measurements of the brightness of the lunar sky on


1971.
