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TRANSLATIONS ON USSR SCIENCE AND TECHNOLOGY
PHYSICAL SCIENCES AND TECHNOLOGY
(FOUO 31/79)

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PUBLICATIONS

GEOPHYSICS, ASTRONOMY AND SPACE

MAIN PROBLEMS OF SPACE WALKING BY MAN

Moscow NA ORBITE VNE KORABLYA in Russian 1977 signed to press 12 Sep 77 pp 5-44

[Section 1 from the book "Na orbite vne korablya" by Yu. N. Glazkov, L. S. Khachatur'yants and Ye. V. Khrunov, Izdatel'stvo Znaniye, 100,000 copies, 176 pages]

[Text] The experience of manned space flights in the USSR and the United States convincingly demonstrates that man on board a manned spacecraft (PKK) or a manned orbital station (POS) is one of the main elements which ensure effective completion of the flight program. The required hardware, high professional training and extensive capabilities in control of the spacecraft systems permit the cosmonaut to actively affect the course of the flight.

For example, during the flight of the Mercury MA-9 PKK, a failure occurred in the automatic device which determines the sequence of instructions during reentry. The ground services and the astronaut managed to effect reentry by using manual control. This is not a singular case. Failures in the onboard equipment of other PKK have also occurred. Due to the active operations of the crew, the flights of the Voskhod-2, Gemini-8 and Apollo-13 PKK were completed successfully.

A space walk by man was necessary in some flights for successful completion of the planned program. For example, the spacecraft had to be unpressurized and work had to be carried out in pressure suits to correct malfunctions in the docking mechanism of the Apollo transport spacecraft during the first expedition of the Skylab POS. The repair operations were carried out and docking was successful. An emergency situation of the Skylab POS after orbital injection was also eliminated due to the operations of the crews in open space.

Thus, the flights of Soviet cosmonauts and American astronauts showed that man can perform maintenance, assembly, repair and transport of cargo beyond pressurized compartments directly in outer space. Therefore, the problem of future research in space is closely related to operations beyond the pressurized compartments of PKK and POS. Specifically, operations outside the spacecraft will comprise a significant fraction of the total work of cosmonauts during flights of the multiuse transport spacecraft (MTKK). The number and duration of space walks, pressure suit requirements and requirements on the life support and other systems were determined according to the MTKK program.

Approximately 1,073 space flights are planned during the period 1979-1990. These include:

space stations of the Spacelab type	56
large space observatories	36
modular stations	46
automatic satellites and stations of NASA*	147
miscellaneous satellites (television, communications and so on)	224
satellites of other agencies	305
assembly in orbit	259

Completion of this program can be provided by 597 flights of MTKK with different payload. The following main tasks of human activity in open space are planned during this:

1. Operation of large space telescopes (replacement of mirror modules, removal of contamination from the instruments, moving solar panels and so on).

2. Maintenance of space laboratories to study the earth's natural resources (assembly of parabolic antennas 9 m in diameter, installation of film cassettes and so on).

3. Putting the onboard systems into working condition (connecting electrical and hydraulic plugs and main lines, transport and attaching of solar panels and antennas, removing protective devices used during orbital injection and so on).

4. Inspection, debugging and repair of the external devices of orbital objects (hatches, mechanisms for opening optical sensors).

5. Scientific research and so on.

Thus, the problems have been postulated. It is no less important to determine the necessary number of space walks and their frequency. For example, maintenance of the Spacelab units may require 118 space walks to complete the tasks enumerated above under Nos. 2, 3 and 5. But 788 space walks are required to carry out all the tasks of maintaining space objects in orbit. The distribution of the number of walks outside the spacecraft, which are planned beforehand for a single flight, is shown in Figure 1. Figure 2 demonstrates the duration of one space walk, calculated for completion of operations by a single person.

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*NASA -- National Aeronautics and Space Administration (United States).

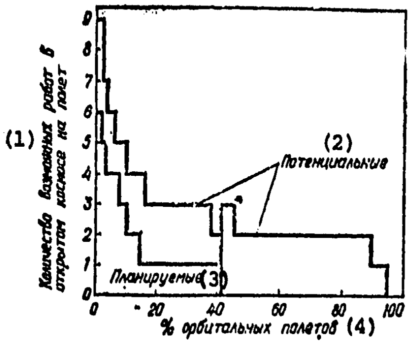

Figure 1. Distribution of Number of Planned and Potentially Possible Space Walks Per Flight

KEY:

1. Number of possible operations in open space per flight
2. Potential
3. Planned
4. Percent of orbital flights

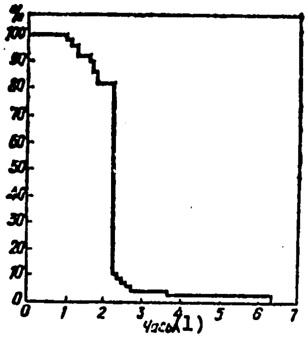

Figure 2. Duration of Operations in Open Space, Calculated for Completion of Operations by a Single Cosmonaut

KEY: 1. Hours

Which hardware can support planned and unforeseen operations? If was decided to conduct the space walk by the airlock method, using the airlock chamber (ShK). The length of the airlock chamber was selected at 3 m and the length of the tether was selected on the order of 21 m. This length permits one to complete 95 percent of all types of operations. The results of investigations and tests and, specifically, study of the proposed travel routes of the cosmonauts convinced us that it is feasible to recruit two crew members for operations outside the PKK. The total number of cosmonauts: 20 (commander and pilot) and 40 (payload specialists), was first determined to complete 788 space walks during 597 flights.

It was established during simulation of the cosmonaut's activity in open space that the upper part of the pressure suit is the most mobile (207,000 cycles during a simulated 12-year period). The pressure suit should have movable joints in the region of the shoulder, elbow, wrist, waist, knee, hips and ankles. This indicated analysis of the cosmonaut's body motions while performing maintenance on objects. Possible movements of the heat must also be provided. The mobility of the arms in the pressure suit and of the wrist in gloves has special significance.

Requirements on the life support system (SZhO), its type and composition were determined on the basis of simulation and the tasks of the space walk and requirements on the systems for supporting the cosmonaut's activity outside the manned spacecraft and manned orbital station were refined. The experience accumulated in the USSR and the United States in work by man in open space made it possible to determine the range of tasks entrusted to the cosmonaut outside the PKK and POS:

maintenance and repair of the PKK, POS and of automatic space objects;

installation-dismantling and assembly operations in orbit;

maintenance of scientific research apparatus;

rendering assistance to crews experiencing distress in orbit and also replacement of PKK and POS crews;

transport of various types of cargo;

experimental investigations in open space.

This list of tasks is naturally generalized and incomplete. The tasks will be corrected and expanded as investigations in space progress.

Brief Characteristics of Manned Space Objects Which Support Space Walks by Man

Manned spacecraft and manned orbital stations which support space walks by man are distinguished in design from manned objects which do not support human activity outside the craft. They primarily have additional equipment for depressurization and subsequent pressurization of the corresponding compartments, special pressure suit design, life support systems and so on.

A space walk was accomplished during the flights of the Voskhod-2, Soyuz-4 and Soyuz-5 PKK, a number of Gemini and Apollo PKK and the Skylab POS. Let us familiarize the reader with the brief characteristics of these and future manned objects, having especially determined the means for supporting space walks outside these objects.

Voskhod-2 was a manned spacecraft designed for orbital flight around the earth. Unlike the three-place Voskhod PKK, the Voskhod-2 spacecraft was made in a two-place variant. This increased the free space which facilitates movement of the cosmonauts in the cockpit during preparation for a space walk. A "soft" type airlock chamber, rotated into the working position in orbit, was designed for the space walk. The ShK was connected to the cosmonauts' cockpit by a pressurized hatch. The ShK was also equipped with a pressurized hatch on the side turned toward space. Thus, the Voskhod-2 had two pressurized spaces which were separated from each other and at the same time could connect one to the other.

This design made it possible to complete the space walk beyond the spacecraft without depressurizing the cosmonauts' cockpit. The hatches were controlled remotely from the console installed in the cosmonauts' cockpit or manually. Two movie cameras, a light system and a control console were placed inside the ShK and tanks with an air supply for repressurization of the ShK and with an emergency oxygen supply are placed outside it. The cosmonaut is supplied with oxygen from a self-contained backpack SZhO while working outside the PKK.

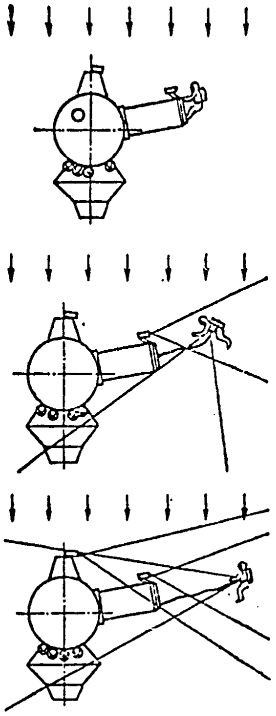

Figure 3. Drawings of A. A. Leonov During Preparation for a Space Walk

On 18 March 1965 cosmonaut A. A. Leonov of the USSR made the world's first space walk. The walk lasted for 23 minutes 41 seconds, of which 12 minutes 9 seconds were outside the PKK. The cosmonaut completed the planned program of investigations, having separated himself from the spacecraft to a tether length of 5.35 m. One can gain some idea of the experiment from Figure 3.

The Soyuz is a multiplace PKK designed for flights in geocentric orbit, maneuvering, approach and docking. The weight of the spacecraft is approximately 6.5 tons. Due to the modular design and the capacity for modernization, the Soyuz PKK is used for different purposes in space flights. Autonomous and group flights, an astronomical laboratory, a transport spacecraft for supplying the Salyut POS and modification for the joint flight in the Soyuz-Apollo international program -- this is an incomplete list of the tasks performed on the Soyuz PKK.

The spacecraft consists of an orbital module, a descent vehicle where a crew up to cosmonauts is located and an instrument-service module. The orbital module and descent vehicle are connected by a pressurized manhole, which permits the use of the orbital module as an ShK. In this case the orbital module is equipped with a depressurization and pressurization system and also a hatch for emerging into open space.

After development of the experimental orbital station consisting of docked Soyuz-4 and Soyuz-5 PKK in 1969, two cosmonauts transferred from one spacecraft to another across open space. The PKK were equipped with special devices for moving along their outside surface. The cosmonauts employed self-contained SZhO and pressure suits for operations outside the spacecraft. A diagram of the experimental POS is shown in Figure 4.

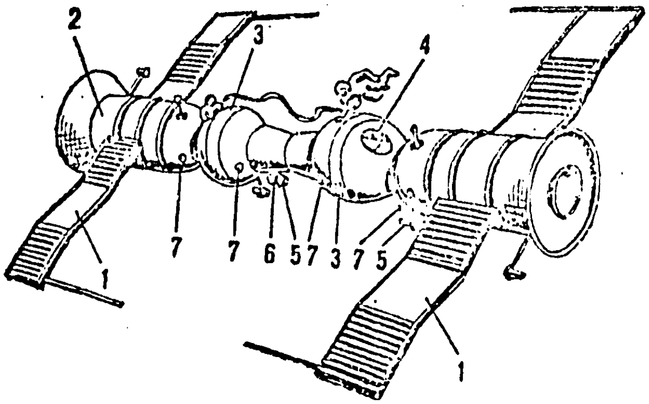

Figure 4. Diagram of Experimental Orbital Station Assembled From Soyuz-4 and Soyuz-5 Spacecraft: 1 -- solar panels; 2 -- instrument-service modules; 3 -- orbital modules; 4 -- exit hatch; 5 -- approach antennas; 6 -- docking assembly; 7 -- windows

The Gemini was a two-place PKK of the United States, designed for flights in geocentric orbit. The weight of the spacecraft is 3.13-3.80 tons. The spacecraft consists of the crew compartment, radar and orientation system modules and also an auxiliary module. An overall view of the Gemini PKK is shown in Figure 5. Unlike the variant using an ShK, the entire spacecraft was depressurized in the given case during the space walk.

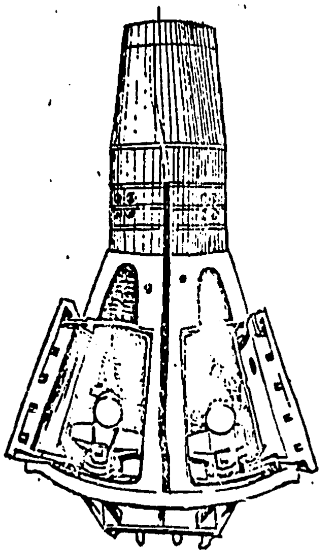

Figure 5. Gemini Manned Spacecraft

The Apollo is a three-place PKK of the United States, designed to deliver two astronauts to the lunar surface. The spacecraft is made in the form of a modular design consisting of a crew compartment, engine compartment and lunar lander (Figure 6). Depending on the flight goals, the spacecraft may consist of the crew compartment and engine compartment -- the main unit for flights in geocentric or selenocentric orbit. When an exit onto the lunar surface was planned, besides the main unit, the spacecraft contained a lunar lander which made a soft "landing" with two astronauts on board. The weight of the spacecraft, equipped for landing on the Moon, comprises 43-47 tons. The astronauts made a space walk in geocentric orbit, on the Moon-Earth route and also walked on the lunar surface. The space walk was accomplished through the hatches of the crew compartment and of the lunar lander and the walk on the lunar surface was made through the front hatch of the lunar lander. All the spacecraft compartments were depressurized in this case.

The Skylab is an experimental POS of the United States (Figure 7). Three expeditions of three astronauts in each were sequentially delivered by the Apollo transport spacecraft to the station. The weight of the station in orbit without the transport spacecraft is 77 tons. Skylab consists of

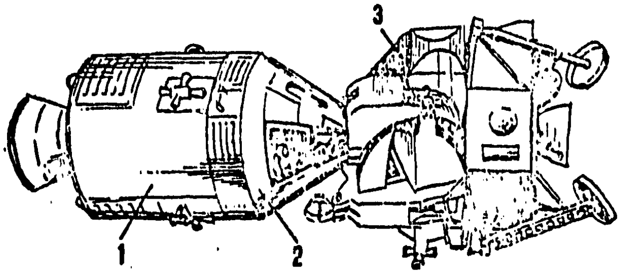

Figure 6. Apollo Manned Spacecraft in the Version for Landing on the Lunar Surface: 1 -- engine compartment; 2 -- crew compartment; 3 -- lunar lander

laboratory and housekeeping compartments, a waste discharge compartment, docking structure for docking of the transport spacecraft, a set of astronomical instruments and an airlock chamber. The ShK is hermetically separated from the remaining compartments of this station and permits two astronauts to make a space walk simultaneously. During the flight the astronauts made repeated walks outside the pressurized compartments of the station.

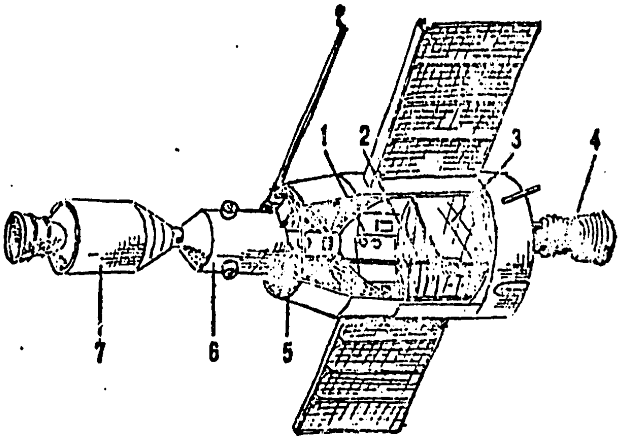

Figure 7. Skylab Manned Orbital Station: 1 -- laboratory compartment; 2 -- bulkhead; 3 -- housekeeping compartment; 4 -- station engine; 5 -- airlock chamber; 6 -- docking structure; 7 -- Apollo transport spacecraft

The MTKK (design) is a multiuse transport spacecraft of the United States. The proposed crew is three men and up to four specialists. A diagram of the MTKK at the moment of payload injection into orbit is shown in Figure 8. The MTKK includes first-stage booster units, second-stage fuel tank (jettisonable components) and the spacecraft itself with payload. The purpose of the spacecraft is to inject various payloads into orbit (automatic satellites, POS units and so on), maintenance and repair of unmanned space systems, rescue of PKK and POS crews who have experienced distress in orbit and so on. The maximum payload weight injected into orbit is 29.5 tons and that returned to earth is 11.3 tons. The tasks enumerated above require the active participation of astronauts outside the pressurized compartments.

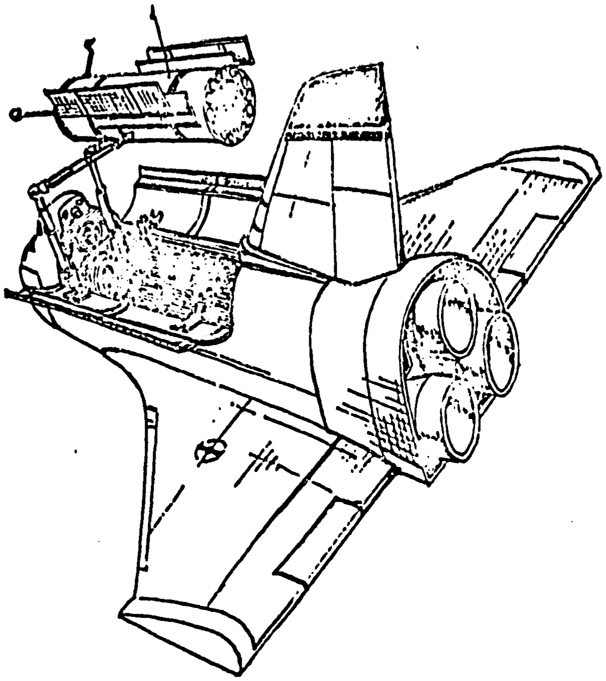

Figure 8. Multiuse Transport Spacecraft With Open Cargo Compartment at Moment of Payload Injection

Spacelab (design) (Figure 9) is a manned orbital unit with a crew of 2-4 persons, designed for multiple use. The unit is delivered into orbit and is returned to earth by an MTKK. The maximum weight of the unit is 11 tons. Its purpose is to carry out scientific-technical experiments in geocentric orbit without separation from the MTKK. The unit may contain pressurized and unpressurized compartments. It is planned to conduct routine and unplanned operations in open space. The design provides for an ShK with space exit hatch.

The long-term unit orbital station (design) is a manned orbital station with an operating period up to 10 years. The station is assembled in orbit from

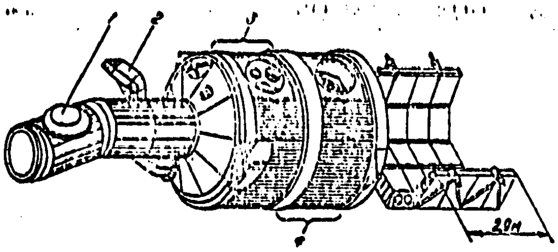

Figure 9. Spacelab Unit: 1 -- space exit hatch; 2 -- electrical and hydraulic communications lines of MTKK systems; 3-4 -- pressurized compartment

individual units delivered by the MTKK. The number of units may be different: from 3 to 6, and accordingly there may be 6-12 crew members. The stations are designed to carry out a complex of scientific investigations, to study the Earth's natural resources, for operation of satellite systems and so on. Obviously, some tasks and specifically operation of automatic space objects, will be related to space walks.

Thus, one may conclude that human activity outside a manned space object occupies one of the central positions in cosmonautics.

In the following sections we will discuss the practical operations of cosmonauts in open space according to the USSR and United States programs, methods of performing them and hardware.

Maintenance and Repair of PKK and POS

Unmanned space apparatus (KA) -- automatic artificial Earth satellites (ISZ) and stations (AS) -- consist of a set of assemblies and systems having specific designation and different degree of complexity. Man is located on board PKK or POS. Therefore, special requirements are placed on their onboard systems and, moreover, auxiliary systems are installed. Thus, a life support system which supplies the cosmonaut with oxygen, water and nourishment and which removes various types of harmful impurities (carbon dioxide, ammonia and so on) from the pressurized cockpit, is absolutely necessary. The requirements on the temperature-humidity conditions of the gaseous medium, vibrations, noise, g-forces and on the dependable functioning of onboard systems are increased.

PKK and POS are used for national economic and scientific research purposes. These are, for example, study of the Earth's natural resources, communications, television and astronomical, astrophysical and meteorological investigations. They are also used to develop the design of various systems modifications, some production operations and production processes directly under space flight conditions.

Let us present an approximate list of the onboard systems of PKK and POS:

the structure and its components;

power supply systems;

orientation and stabilization system;

servo member system (engines, control gyroscopes, flywheels and so on);

radio control and trajectory measurement system;

navigation and control system;

scientific research apparatus (payload);

life support system;

temperature regulating system;

reentry and landing support system;

emergency rescue system;

radio communications system;

approach and docking support system and so on.

The combination of these systems may vary as a function of the flight goals. This is primarily related to payload. For example, the multipurpose Soyuz PKK may be assembled in different versions as a function of designation. The self-contained manned astronomical observatory (Soyuz-13) was equipped with astronomical instruments of the Orion-2 system, but there was no approach and docking system on it. The spacecraft was equipped with a welding apparatus operating under space vacuum conditions in the experiment with space welding. The experiment with docking two spacecraft and transfer of two cosmonauts from one spacecraft to another (Soyuz-4 and Soyuz-5) required that an approach and docking system, depressurization and pressurization systems, pressure suits and other equipment be supplied. The Soyuz manned spacecraft can be used as a transport spacecraft to deliver crew and cargo to orbital stations and to return the crew and necessary research materials to Earth (Soyuz-11, Soyuz-14, Soyuz-17, Soyuz-18, Soyuz-21 and so on). In this case the spacecraft is equipped with an approach and docking system, system for transfer to the orbital station and so on and a place is provided for storing the cargo delivered to Earth.

The operating efficiency of onboard systems and their dependability are determined by an optimum combination of human activity and operation of automatic systems and by optimum distribution of functions between the automatic systems and the cosmonaut. We feel that it is erroneous to postulate the question itself of which is better: an automaton or man. Man has a number of indisputable advantages over an automaton, but at the same time an automatic system has a number of qualities which are more valuable compared to man. For example, automatic systems retain their efficiency during accelerations several orders higher than does man.

Automatons can operate at ambient air temperatures on the order of 1000°C, whereas overheating of the human organism makes him completely inefficient. The tolerances to ambient air pressure are incomparably more rigid for man than for technical systems. The radiation resistance of electronic systems is tens of times higher than the permissible radiation doses for man. However, man with his experience, intuition and skill to combine unrelated events into a unified logical system at first glance and with the skill to separate more significant information for a given moment and with many other qualities is an irreplaceable link in space research. It is obvious that the main engineering-psychological task of designing space objects consists in developing a complex "man-automaton" system in which the deficiencies of one link are compensated by the advantages of the other.

The scales of investigations in space will increase and capital investments in space programs will also increase. Thus, the expenditures for the Mercury Program comprised 0.275 billion dollars, those for the Gemini Program comprised 1.290 billion dollars and those for the Apollo Program comprised on the order of 25 billion dollars. It is natural that these capital investments require an increase of economic effectiveness of the implemented space programs. And this in turn is most closely related to the operating dependability of the onboard equipment and with maintenance of it directly during flight.

The problem of maintenance is rather complex and is determined primarily by the fact that the dependability of onboard equipment of space objects depends on many flight factors, the level of development of science and technology, production and so on. The conditions of space and of the space medium themselves (deep vacuum, cosmic radiation and meteorite hazard) reduce the dependability of space object systems. These factors especially affect the assemblies and systems located on the outside surfaces of space objects and outside pressurized compartments.

This naturally requires periodic inspection, preventive maintenance, replacement and repair of systems directly in open space. For example, the prolonged effect of cosmic radiation may lead to deterioration in the properties of organic materials. Solar panels used as power supply sources lose their efficiency due to the effects of solar radiation. As a result the energy required for the onboard equipment is reduced. A deep vacuum is harmful to materials, including "volatile" elements, which considerably alters their operating characteristics.

The length of a flight is one of the main factors affecting the dependability of onboard systems of space objects. The longer the spaceflight, the more difficult it is to ensure the efficiency of the onboard equipment at a given level of dependability. And after all crew safety depends on the operating dependability of the systems and assemblies of the manned spacecraft or station.

The length of manned flights is ever increasing: 424 hours for Soyuz-9, 1,512 hours for the autonomous flight of the Soyuz-18 and the flight with the Salyut-4 orbital scientific station and from 143 to 298 hours for lunar expeditions. The length of three crews remaining onboard the Skylab manned orbital station comprised 28 days, 59 days and 84 days, respectively. The length of the flight of the first expedition on the Salyut-4 POS comprised 30 days and that of the second comprised 63 days. Thus, development of orbital near-Earth, near-lunar and lunar stations of long duration and organization of expeditions to the planets require dependable functioning of the onboard systems for many months and even years.

One can vividly demonstrate the dependence of the probability of successful manned flight on its duration at the modern level of production technology:

flight to Mars (length of flight approximately 2 years) -- 0.006;

flight to Venus -- 0.03;

lunar landing by the Apollo program (length of flight 200 hours) -- 0.95;

flight of the Mercury spacecraft -- 0.95.

Ensuring the probability of a successful flight of 0.95 may be taken as the required dependability for manned flight.

The dependability of a space rocket complex can be determined by the expression:

$$P = P_1 P_2 P_3 P_4, \tag{1}$$

where P_1 is the dependability of the complex during launch; P_2 is the dependability of the complex during orbital injection; P_3 is the dependability of the complex during orbital flight; and P_4 is the dependability of the complex during reentry and landing.

If the value of P is close to 100 percent (for example, 95 percent), one may be confident of a successful space flight. In the remaining $(1 - P) = R$ cases, it is obvious that additional measures are required to ensure dependable operation of the onboard equipment. If the degree of dependability of auxiliary equipment is taken as P_{dop}, then one can determine the probability of a successful flight:

$$P^{*} = 1 - R \cdot R_{\text{доп}},$$

where

$$R_{\text{доп}} = 1 - P_{\text{доп}}. \qquad (2)$$

What additional measures may increase the level of operating dependability of onboard equipment and consequently of crew safety and the efficiency of the entire space flight? One of the possible methods of solving this problem is maintenance (TO) of the onboard equipment of the PKK and POS during space flight.

Maintenance of the onboard systems can be divided into automatic, remote and crew servicing.

Automatic TO assumes automatic identification of failure and switching to reserve systems or units.

Remote TO may be organized by using an unmanned satellite equipped with manipulators, television camera and other equipment. The operator can control the satellite from Earth, from the PKK or the POS. Crew maintenance assumes, for example, diagnosis, repair and postrepair checks with direct participation of the cosmonaut.

Each of these types of TO has its own positive and negative aspects. Automatic TO, the most prevalent today, is related to an increase in the weight and overall dimensions of space objects. Remote TO has its own limitations -- the use of manipulators, delay of control signals and so on. Moreover, each of the types of TO may be suitable or unsuitable depending on the phase of space flight.

For example, the most preferrable for the orbital injection phase is automatic TO, which is related to transience of processes and characteristics of crew disposition: the cosmonauts are located in the reentry vehicle and are strapped to their seats and the flight proceeds under acceleration conditions. TO by the crew is reduced in this case to switching to reserve units upon failure of automatic equipment.

Remote and crew TO is feasible during orbital flight and during the stay on the surface (for example, on the Moon or Mars). The possibility of unforeseen failures, difficult access to repair points and many other factors, we feel, make crew TO more preferrable. Crew maintenance assumes the participation of man in identification of the failure, determining the degree of importance and program of repair, selecting the hardware required for repair and conducting the repair and postrepair checks themselves.

The dependability of a typical life support system with different variants of maintenance is shown in Figure 10.

Operations inside pressurized compartments have their own features related specifically to weightlessness. However, the operating conditions in

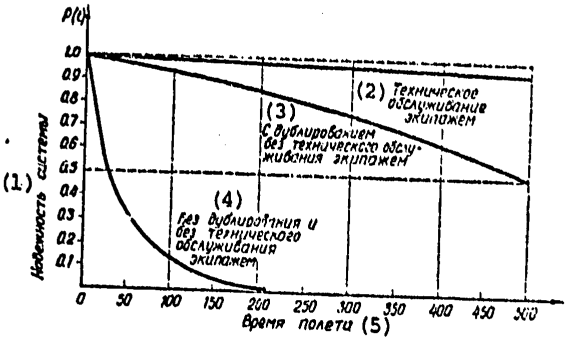

Figure 10. Dependability of SZhO With Different Variants of Maintenance

KEY:

1. System dependability
2. Crew maintenance
3. With duplication without crew maintenance
4. Without duplication and without crew maintenance
5. Time of flight

pressurized compartments can be approximated to ground conditions to some degree. Universal attaching devices, equipping the operator's positions, spare parts and tools, design of onboard equipment convenient for performing repair-maintenance operations and so on have been created for this.

Another matter of working outside the spacecraft or station. The specifics of the medium, the need for donning a pressure suit and in some cases a weightless state all create some characteristic features and limitations during maintenance and requires solution of a number of problems.

As we have already said, man will perform a complex of engineering-technical tasks and specifically of repair-preventive maintenance operations with the onboard equipment and maintenance of it outside the spacecraft or station.

A significant part of the apparatus-assembly composition of the onboard systems of PKK and POS is related to one or another degree to open space, i.e., to the space outside the pressurized compartments of the space object. For example, the temperature control system is based on dissipation of heat by a heat carriers in radiative heat exchangers located on the outside surface of the spacecraft. The solar panels (SB) of the power supply system, for example, on the Soyuz PKK and on the Salyut and Skylab POS are also located on the outside surfaces. The main SB of the Skylab station have dimensions of 30 m on the station unit. Both SB consist of three sections mounted on cantilevers. The cantilevers with panels are folded and are attached to the station hull by explosive bolts until orbital injection. After orbital injection, the panels are unfolded into the working position. In unfolded form, each panel has dimensions of 7 x 9 m and the total area of the SB is 110 m^2.

The radio communications system also has a set of various antennas installed into the working position after orbital injection of the object. This is related, for example, to the pencil-beam antenna of the Apollo spacecraft, which occupies the working position after separation of the spacecraft from the third stage of the Saturn-5 carrier rocket. The solar panels and radio antennas of the approach and docking system of the Soyuz PKK are also unfolded after orbital injection.

The orientation and stabilization system communicates with the surrounding space by various types of sensors used in controlling the spatial position of the spacecraft. This is related, specifically, to optical sensors: the optical sighting device of the Soyuz PKK, the optical periscope used by the astronaut during control of the Mercury PKK, astronavigation instruments of the Apollo PKK and so on.

The engine units to provide forward motion and rotary motion around the center of mass and also tanks with spare fuel, oxidizer and compressed gases are located on the outside of the spacecraft in open space. It is natural that situations may occur during the space flight which require the cosmonaut's participation in maintenance of the systems, i.e., a space walk.

Now familiarize yourself with Table 1. The distribution of operations in open space during maintenance of individual systems of PKK or POS is given in it.

Table 1

System	Requirements on prevalent type of TO	Operations conducted outside the PKK, percent
Approach and docking	Replacement of components	50
Engines	Elimination of leaks and replacement of components	80
Electronics	Replacement of components	10
Structure	Repair of detected damage and elimination of leaks	75
Power supply sources	Replacement of components	10
SZhO	Elimination of leaks and contaminants and replacement of components	5

These are theoretical investigations and conclusions. But they have been confirmed by the practice of space flights. Analysis of failures during the flights of the Mercury, Gemini and Apollo PKK and of the Skylab POS permits one to determine the most typical malfunctions which may potentially cause or have caused the necessity of working in open space:

separation of the meteorite-heat shield; installation of the heat shield cover in orbit (Skylab);

forced unfolding of the solar panel directly in orbit (Skylab);

weakening of the attachment of individual structural assemblies and parts (Mercury and Apollo);

failure of shroud ejection mechanisms (Gemini);

clouding of the windows and the objectives of optical instruments (Apollo and Skylab);

engine failures (Gemini and Apollo);

leakages of gases and liquids (Apollo and Skylab);

failures in the docking system (Apollo).

The attachment of the heat shield to the satellite hull weakened during the flight of the Mercury-6 spacecraft. To refine the nature of the malfunction, a space walk could have been required but this was not planned for the Mercury program. The flight managers and the crew of the Gemini-9 spacecraft were forced to abandon docking since the main shroud designed for docking did not separate from the apparatus. The crew proposed a space walk to cut the electric wires holding the main shroud. However, the flight managers rejected these operations. The windows became very clouded during the flight of the Gemini spacecraft. This interfered with observation and photography from the spacecraft. The clouding was removed by an astronaut who emerged from the spacecraft.

The optical instruments and windows also became clouded during the flight of the Apollo spacecraft. During the flight of the Apollo-17 spacecraft, astronaut Evans made a space walk. Inspecting the housing of the engine compartment, he detected delamination of the upper coating burned by a stream of hot gases flowing from the engines.

Human capabilities in performing repair operations and maintenance in open space were manifested more clearly during the flight of the Skylab orbital station. Analyzing the crew activity of the Skylab station, one can compile a cyclogram of maintenance and repair operations in open space:

preparation to emerge beyond the pressurized compartments;

space walk;

moving to the location of preventive maintenance or repair;

inspection of the assemblies and systems and checking them;

performing the required operations;

checking operations after completing the work;

moving to the airlock chamber;

entry into the pressurized compartments of the spacecraft or station.

This diagram is considerably simplified. Each specific case may have its own characteristic features which considerably change the sequence of events. For example, one may be required to ascertain installation-disassembly operations, transport of spare components and so on with respect to the maintenance object. When moving along the outside surface of the spacecraft, station or other space object, the cosmonaut may perform such an important operation as inspection of the outside surface. This is necessary when gas leaks from the pressurized compartments or leaks of liquids occur, for example, from the circuit of the heat control system.

Thus, inspection and repair are important constituent parts of maintenance and specifically of maintenance related to operations outside the spacecraft. Inspections, replacement or repair of solar panels, ejection or unfolding and docking mechanisms, removal of contaminants from optical surfaces, correction of spacecraft assembly and subassembly failures, repair of antennas and drives, determination of leakage points and inspection of the external surface are far from all the maintenance tasks solved outside the spacecraft in open space.

Maintenance and Repair of Automatic Space Objects

Along with investigations in space using manned space objects, unmanned space objects are employed just as extensively and many more unmanned objects than manned objects are launched.

Automatic devices in space perform the role of scout, from the tracks of which man can operate. Thus it was with investigation of circumterrestrial space and thus it was with organization of expeditions to the Moon. Actually, the flight of Earth's first space ambassador, citizen of the Soviet Union Yu. A. Gagarin, followed after launching of the first artificial Earth satellite, biological satellites and after careful preparation and testing.

Automatic devices also laid the road of man to the Moon. The Luna and Zond automatic stations provided study of circumlunar space and of the lunar surface, a soft landing on the lunar surface, complex investigations from selenocentric orbit and collecting samples of lunar soil with return to Earth. The flights of the American automatic apparatus for study of the Moon were Ranger, Lunar Orbiter and Surveyor. And finally, landing of astronauts on the lunar surface occurred after manned circumnavigation of the Moon. Venera, Mars, Pioneer and Mariner automatic interplanetary stations are now periodically launched toward the planets of the solar system. Automatic devices will also be used in the future as the first investigators, especially in unstudied or little studied environments and environments unsuitable for human viability.

ISZ and KA are now used extensively for scientific research, to check new technical solutions (modernization of control systems, testing of new engines and so on), to study the Earth's natural resources and so on.

ISZ and KA may be classified by designation in the following manner:

research satellites;

communications satellites;

meteorological satellites;

geodetic satellites;

satellites to investigate the Earth's natural resources;

satellites to test onboard and ground equipment;

biological satellites;

KA for investigations of the Moon and planets.

ISZ and KA carry on board apparatus designed for extensive and multifaceted investigations and observations. This is frequently unique, complex and very expensive apparatus. Besides the payload (the apparatus of purposeful designation), ISZ have the same systems as any controlled space object, i.e., orientation and stabilization system, servo member system (engines, control gyroscopes, flywheels, gravity stabilization components and so on), electric power supply systems, temperature control systems, radio engineering system and many others. But the systems required to support man on board are absent in them.

It is natural that various malfunctions may occur both in service systems and in research apparatus. There were cases in the practice of space research when the most insignificant failures on board the ISZ or KA either made them generally unsuitable for operation or sharply reduced the efficiency of their practical use. This is related primarily to components which begin to function after orbital injection: the solar panels, antennas, components of the orientation and stabilization gravity system and so on.

An emergency condition of ISZ systems may require replacement and this is related to a nonroutine launch with additional expenses. If it becomes possible to conduct repair operations in orbit, these expenses will be reduced and repair in orbit itself may be economically effective.

Systems are created from automatic satellites in orbit which provide communications, navigation and meteorological service. For example, the Transit system of five satellites assists ships of the commercial fleet and oceanographic vessels to determine their coordinates. Among the total number of satellites of this class, part were injected into orbit to replace those that failed. Navigation and geodetic satellites and those for development of onboard equipment utilize the gravity orientation and stabilization system. The American ATS satellite, designed to test onboard and ground equipment of future meteorological, communications and navigation satellite systems and for scientific research, is equipped with a similar system. These orientation and stabilization systems do not require continuous fuel expenditure (compressed gases and liquid fuel) stored on board the satellite. There are four hollow rods in the system formed after orbital injection of the satellite by "pulling" a tension tape lubricated from a drum through a filler. The rods seemingly form a cross. The angular distance between rods and their length are regulated. Two similar rods serve to damp librations. These systems have a considerable number of movable mechanical subassemblies. Failures in them may lead to a reduction of efficiency or may lead generally to failure of the satellite due to loss of orientation.

A characteristic feature of interplanetary spacecraft, like some ISZ operating in high orbits (approximately 11,000 km), is a second start after injection into the intermediate geocentric orbit. The onboard equipment is checked and prepared for the second start during flight in the initial geocentric orbit for transfer to the specific trajectory. It is during this period, the period when the apparatus is in the intermediate geocentric orbit, that human interference is possible. Man can check and repair failed onboard equipment. Thus, for example, American specialists were forced to cancel operation of a number of ISZ (ATS-IV INTELSAT-2,-3 and so on) due to injection into an uncalculated trajectory. If a manned spacecraft (for example of the MTKK type) had been in orbit around the Earth, the cosmonauts could have transferred the satellite into the calculated orbit.

There were cases in the practice of space flights when the propulsion unit of the satellite itself was used to inject the ISZ into the calculated orbit due to operational failures of the carrier rocket power plant. This was reflected in the further flight program since it reduced the onboard fuel and oxidant reserves. Moreover, leakage and total depletion of the fuel reserves may occur while retaining the efficiency of other onboard systems. Even in these cases ISZ and other unmanned space objects could be refueled directly during space flight.

The designs of future automatic space objects already provide during the development stage their maintenance by man directly in orbit.

Thus, for example, it is planned to inject the LST satellite (observatory for astronomical observations weighing 11 tons and 3.6 m in diameter) into an orbit 610 km high by using the MTKK. The satellite will be returned to Earth for preventive maintenance after 2.5 years of operation also by using the MTKK. Longer operation without repair is unprofitable and reduction of the operating period requires additional flights of the MTKK which is related to high expenditures. Therefore, maintenance of the satellite by cosmonauts transported to it by the MTKK is provided during the operating period. Three types of maintenance are planned:

1. Delivery of the satellite into the MTKK payload compartment. The solar panels, antennas and other components of the satellite structure unfolded in orbit must be folded.

2. Grasping the satellite with the MTKK manipulator and attaching it at some distance from the spacecraft.

3. Arranging the satellite on the MTKK work table.

All three types of maintenance require the active efforts of man in open space.

According to the first design, the satellite hull should be pressurized with an artificial atmosphere so that the cosmonauts can work without pressure suits when performing maintenance operations. The second design (it is regarded as more preferable) envisions the manufacture of a satellite with an unpressurized hull; the cosmonauts will work in pressure suits when maintaining it.

The active interference of man may also be required during failure of satellite-to-earth data systems on the ISZ. The cosmonaut may then disassemble the information carrier from the ISZ and return it to Earth. A similar experiment was conducted during the flight of the Gemini-10 PKK when an astronaut, making a space walk, transferred to the unmanned object and dismantled a device with scientific information. In this case the Gemini-10 PKK was at a distance of several meters from the object.

Maintenance of automatic objects and systems in orbit poses new problems and primarily problems of detecting the object in orbit, approach or docking with it, transferring the cosmonaut to the object for maintenance, transporting the equipment required for work and, finally, conducting checks, preventive maintenance or repair operations. The problem of vital activity under weightlessness conditions occupies a significant place in this multifaceted activity of man in open space.

Thus, one can conclude that maintenance of automatic ISZ, space apparatus and satellite systems requires the active efforts of man in orbit. Preventive maintenance, gathering useful information, inspection and estimation of operational suitability, unplanned repair, transfer to working orbits, transport, refueling and so on may primarily be related to these operations.

Installation-Dismantling and Assembly Operations in Orbit

If one traces the course of development of space research, one can clearly see the trend toward an increase in the weight and overall dimensions of space apparatus.

This is quite explainable since the payload volume and weight and consequently the weight and overall dimensions of the spacecraft and carrier rocket structure increase with expansion of research.

The tasks of the future require orbital assembly of even heavier space objects and even larger structures. These objects may primarily include interplanetary spacecraft, block orbital stations of long duration, refueling stations, large (more than 30 m in diameter) radio and optical telescopes and large-area solar panels. For example, one of the future NASA programs is a spacecraft variant assembled in orbit from separate units. Unit injection into orbit and subsequent supply of the spacecraft will be provided by the MTKK. Development of an orbital station of long duration also provides assembly of it in orbit from individual units delivered by the MTKK to the installation orbit (1-2 units of the station per flight).

Naturally, installation-dismantling and assembly operations are required when performing a wide range of tasks in open space:

maintenance and repair of manned and automatic space objects;

assembly of small and large space objects;

technical supply of manned stations;

crew rescue;

servicing scientific apparatus and experimental investigations.

Actually, dismantling operations of failed units and subassemblies with subsequent installation of them may be required.

For example, antenna diameter in the future may reach 30-45 m. Such an antenna would have to be assembled in orbit in open space. In this case the most optimum is apparently a modular design of the system. Individual modules will be assembled into one unit and this means that operations in transporting the units to the assembly point, joining them and adjustment will have to be carried out. For example, a 45-meter antenna can be assembled from 240 panels. The technology of installation on this scale is unusual since the "escalator" principle is employed. This principle includes the fact that the cosmonaut "stands" on a platform (Figure 11) and begins assembly with a round section, moving along a rail installation as need requires. Having finished one row in this manner, he transfers to the second and so on. Simulation of this type of assembly operations in a hydraulic environment showed that the cosmonaut is capable of effectively completing the required installation. During tests, an operator in a pressure suit should raise the panel, incline it at an angle of 90°, rotate it by angle of 90° and secure it at the corresponding position on the round panel. Some results of tests are presented in Table 2.

Table 2

(1) Размер панели, м	(2) Среднее время, затрачиваемое на монтаж, мин
1,5 × 1,5	0,54
1,2 × 2,4	0,65
2,25 × 3	0,80

KEY:

1. Panel dimensions, m
2. Average time expended on installation, min

These data are very valuable when calculating the total time to assemble this antenna. Utilizing time expenditures, one can compile the total cyclogram of the cosmonaut's work during assembly.

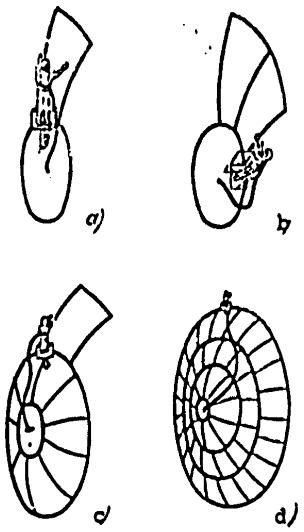

Figure 11. Sequence of Antenna Assembly: a -- beginning of assembly; b -- assembly of first row; c -- assembly of second row; d -- end of assembly

The tests clearly showed that a pressure suit, life support system, installation for moving the cosmonaut, systems for tethering the cosmonaut and required equipment, developed method and technique of assembly are required when performing these operations.

One of the most important assembly operations in space is transport of individual modules to the assembly point. When performing this operation, the cosmonaut must move in supported (with contact of some surface) and unsupported space. Individual units for moving the cosmonaut are required for working in unsupported space.

Maintenance of Scientific Research Apparatus

Multilateral investigations during space flight require various types of scientific research equipment on board the space object. This equipment is placed both inside the pressurized compartments of PKK, POS and automatic ISZ and on their outside surfaces.

The apparatus placed in open space may include instruments for studying meteor erosion and contamination of surfaces, to investigate cosmic rays and stellar radiation and instruments to take spectrographs of the Earth's surface. Moreover, the effect of flight conditions on various structural materials was investigated during some space flights. The scientific-technical apparatus is placed in open space if it cannot be located in pressurized compartments or, for example, if the instrument must be separated from the space object hull to eliminate the space object's effect on the results of investigations.

Analysis of experiments planned during space flights shows that part of them requires active efforts of man in open space. To determine his functions beyond the spacecraft, 1,212 scientific-technical experiments planned by NASA for the period 1968-1980 for PKK making flights in geocentric orbits, were analyzed. The list of studied experiments included:

astronomical;

biological;

investigations in the study of the Earth's natural resources and of space physics;

meteorological investigations;

investigations of communications equipment;

experiments related to tests of new space technology and the use of orbital systems;

investigations in the field of space medicine.

Of the 1,212 experiments, approximately 500 were analyzed to determine the functions of man inside the PKK and during space walks. The following cosmonaut functions were determined:

installation and unfolding of scientific equipment;

testing and checking scientific equipment;

levelling and calibration;

controlling the operation of apparatus;

moving loads and containers with the results of scientific observations;

removal and replacement of units;

repair.

Moreover, 56 percent of the total number of operations require work in open space. Specifically, these are operations related to astronomical investigations and to study of the Earth's natural resources. Medical and biological investigations require only 5 and 22 percent, respectively, of operations in open space.

Scientific-technical experiments related to operations in open space are presented in Table 3.

Only work with the X-ray focusing telescope may require several operations in open space:

1. Correction of malfunctions after unfolding the structural components in space and so on.

2. Adjustment by using laser systems.

3. Connecting the monitoring apparatus, the data orientation system, solar panels and other operations.

Table 3

Area of investigations	Experiments
Astronomical	One-meter telescopes; set for study of the sun (90-centimeter solar telescope); X-ray focusing telescope; 10-kilometer interferometer
Biological	Capture of microorganic cultures in circumterrestrial orbit; effect of space conditions on bacteria spores; effect of space conditions on primates; multipurpose biological installations
Communications and navigation	Assembly of 30-45-meter antennas and large energy units
Physical	Investigations of the physics of space and of the luminescence of sunrises and sunsets
Development of production operations in orbit	Assembly of large structures; assembly of orbital stations around the earth

Experiments with a set of scientific apparatus for studying the Sun and other celestial bodies were conducted extensively during the Skylab program. The complex was controlled from the inner pressurized compartments of the orbital station. Maintenance of the complex required the astronaut's working in open space -- extracting cassettes with the results of photosurveys, transport of them to the inner compartments of the station and installation of new film cassettes. The astronauts were supposed to perform the following operations:

preparatory operations, depressurization of the airlock chamber, opening the hatch and taking a space walk;

moving to the work site by means of hand holds;

preparation of the work site;

dismantling of cassettes;

moving to the airlock chamber;

entering the airlock chamber, closing the hatch and pressurizing the chamber;

transfer to the station compartments.

Three main work sites: "central," "peripheral" and that near the ShK, are provided at the site of the planned operations. Two astronauts should take a space walk to replace cassettes. They exit through the ShK hatch in turn (oxygen is supplied through the tether from the orbital station's SZhO). One astronaut remains near the ShK hatch while the other moves along the station structure. He moves by using hand holds located on the outer skin of the station. There are securing devices for the feet at the work sites so that the astronaut, having freed his hands, can extract the cassettes. The astronaut should rotate the set of astronomical instruments at the "central" work site to replace the next cassette. Four cassettes are replaced here. The astronaut "climbs" to the work area along a ladder to replace two cassettes at the "peripheral" work site. The cassettes with the exposed film are transported by the second astronaut by means of special manipulators for servicing the work sites. Cassettes with unexposed film are also transferred. Two astronauts must complete 150 operations during 2 hours (by calculation) to replace six cassettes. The third crew member is located inside the POS near the console during these operations to monitor the operation of the onboard systems and to provide insurance to the astronauts working in space.

The standby variant of transporting the cassettes provided for using a loop-shaped rope retracted by hand.

The final step is to deliver the film with the results of scientific observations to Earth by means of the transport supply spacecraft.

An experiment for trapping meteor particles and microorganisms was planned and partially conducted in the Gemini program. The scientific equipment (a holder with various types of traps and also with biological specimens for investigation of the affect of space flight conditions on them) was installed on the unmanned Agena object in the region of the docking assembly.

The scheme for performing the experiment provided that the astronaut takes a space walk after the manned Gemini satellite docks with the unmanned Agena object and opens the doors of the holder, folded during the orbital injection leg. In one of the subsequent flights, another astronaut dismantles the holder after docking during extravehicular operations and delivers it to the spacecraft and then to Earth. An experiment with this technique, but without docking, was performed during the flight of the Gemini-10 PKK.

Thus, one may conclude that man's working in open space occupies one of the central positions both in completed and in future scientific investigations using manned and unmanned equipment.

Assisting PKK Crew During Space Flight; Replacement of Crews

The statistics of manned flights shows that, despite the increase of the dependability of onboard equipment, there is the probability of malfunctions occurring which threatened the life of the cosmonaut. We have already mentioned failures during the manned flights of the Gemini-8 and Apollo-13 spacecraft. Malfunctions complicated the process of docking the main unit of the spacecraft to the lunar module during some flights of the Apollo PKK of various types. A leak of fuel components occurred in the engine unit of the Apollo transport spacecraft during the flight of the Skylab orbital station. The malfunction was so serious in nature that a decision was made to prepare a modified rescue spacecraft for launch to evacuate the crew from the station. And this decision was cancelled only after careful checks on the Earth and working out the methods of reentry on simulators.

These examples show that operations of assisting PKK crews in orbit are not imaginary, but quite real. Such typical malfunctions as failure of the propulsion units, orientation and stabilization systems, depressurization of pressurized compartments, failure of the life support and temperature control system of the PKK and other malfunctions in transport supply spacecraft docked to orbital stations may require urgent measures to evacuate the crew from the object and subsequent return to Earth.

There are now several concepts which provide rescue of cosmonauts in flight:

1. The presence of individual rescue devices on board.

2. The presence of a special rescue spacecraft in orbit near the orbit of the PKK or POS.

3. Launch of a rescue spacecraft from Earth if an unplanned situation occurs on the PKK or POS.

In the first case the rescue equipment is placed on board the manned orbital object. The design of this apparatus is shown in Figure 12. The technology of its practical use includes the following. If an unplanned situation occurs in orbit, the cosmonaut in a pressure suit with SZhO should be located inside the apparatus, should prepare it for return to Earth, should leave the emergency object, should orient it, switch on the retrorocket engine to provide reentry and should land with a parachute. Rescue using these types of apparatus requires that the cosmonaut fulfill operations in open space.

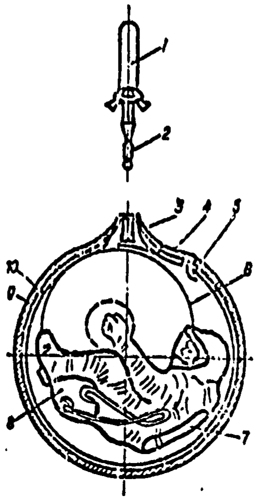

Figure 12. Individual Rescue Apparatus: 1 -- solid-fuel retrorocket; 2 -- tail section of engine; 3 -- engine orientation lever; 4 -- window; 5 -- quick fastener; 6 -- inner shell; 7 -- parachute; 8 -- compressed oxygen tank; 9 -- ablation coating; 10 -- inner coating

Equipment of the second type includes a rescue spacecraft designed to assist the crew during flight to the Moon. The technology of using the rescue spacecraft is explained in Figure 13. The use of this design saves considerable time from the moment the unplanned situation occurs until the crew is evacuated from the spacecraft. Evacuation can be accomplished through the inner pressurized passages formed after the spacecraft dock or across open space if docking is impossible (failure of the docking subassembly, uncompensated rotation and so on).

An example of a third rescue variant is the program for evacuating the crew from the Skylab station. In the event of an unplanned situation, return to Earth is accomplished in the Apollo transport spacecraft docked to the station. If the transport spacecraft cannot be used (malfunctions occur in the systems of the transport spacecraft itself), a rescue spacecraft should be launched from Earth. The rescue spacecraft may dock to the side (second) docking assembly of the mooring structure. It is typical that the rescue spacecraft is a modification of the Apollo transport spacecraft. Only 24 hours are required to reequip it to a rescue variant.

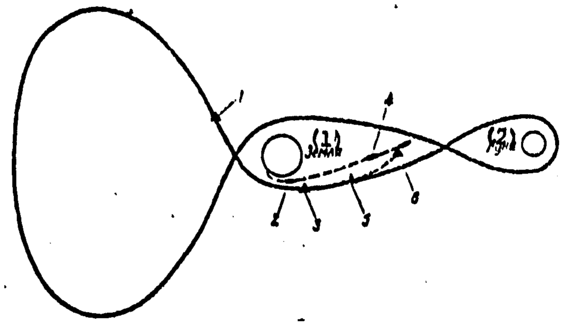

Figure 13. Diagram of Using Rescue Spacecraft: 1 -- rescue spacecraft in parking orbit; 2 -- launch of lunar spacecraft; 3 -- rescue spacecraft at moment of lunar spacecraft launch; 4 -- lunar spacecraft at moment emergency occurs; 5 -- rescue spacecraft at moment of emergency on lunar spacecraft; 6 -- encounter of rescue spacecraft and emergency lunar spacecraft

KEY:

1. Earth
2. Moon

There is a design of a rescue spacecraft based on the Gemini PKK, which is named Big Gemini. The modified spacecraft is designed to rescue three astronauts.

One of the tasks of the MTKK is to rescue the personnel of manned orbital objects. The maneuvering capability of the MTKK with variation of the angle of inclination of orbit and brief periods of preparation for the next launch (approximately 14 days from the moment of return to Earth) considerably increase the possibilities of crew rescue. Specifically, the time the crew is in orbit after an unplanned situation occurs is reduced.

Transfer to the rescue spacecraft, accomplished without mutual docking of the objects, envisions such an important operation as moving in unsupported space. But it may happen that the crew members are injured. In this situation the transfer operation is replaced by one of transport of the wounded cosmonaut. Individual equipment is used for moving and transport. This equipment will be necessary in the event of unplanned situations of a technical nature or due to loss of the efficiency of cosmonauts (unconscious state, disorientation and so on) located in open space.

As one can see, space walking is of important significance when performing rescue operations in orbit.

Cargo Transport

Thus, the cosmonauts perform the most diverse tasks in open space. These are both maintenance of manned and unmanned space objects and installation-dismantling and assembly operations, rendering assistance in orbit and servicing the scientific apparatus. Performing these tasks is related not only to the movement of man but also to transport of various types of equipment. For example, scientific investigations in the field of astronomy, biology, the physics of the cosmos, navigation and communications, maintenance of orbital stations and assembly of large structures number 53 operations with cargo transport to a distance up to 18 m and 39 operations with cargo transports with mass up to 40 kg.

The experiment in trapping meteor particles in orbit and also in studying the effect of space conditions on microorganisms, conducted in the Gemini program, required transport of scientific equipment with mass of approximately 3.2 kg. Astronomical operations in the Skylab program were also related to transport operations in open space, during which the astronauts transferred approximately 700 kg of cargo.

Replaceable equipment, film cassettes, traps, holders, movie cameras, failed units, tools, installation parts and so on -- this is far from a complete list of the transported equipment. All this equipment has different weight and overall dimension characteristics and, consequently, different devices for transport, and in most cases requires special means of securing.

Cargo transport is frequently most closely related to the movement of man. Depending on the conditions and the specific task, movement of man may occur upon contact with the surface of the space object or in unsupported space. The first experiment of movement in unsupported space was achieved during the space walk of the Soviet cosmonaut A. A. Leonov. Moving along the surface of the PKK by using hand holds was accomplished during the flight of the Soyuz-4 and Soyuz-5 PKK during transfer of two cosmonauts from one spacecraft to another.

Cargo transport can be accomplished by three methods:

directly by the cosmonaut himself during movement in contact with the surface of the space object;

by means of various types of devices and manipulators;

by using jet devices for moving in unsupported space.

The first method is simple, but inconvenient since the cosmonaut's hands are occupied with moving and the transported cargo must be attached to the pressure suit.

Transport by using a manipulator was used during transfer of film cassettes from the set of astronomical instruments to the Skylab station. Three manipulators with mass of 13 kg each were located near the ShK hatch and provided mechanical contact with the work sites. The distance of transport was approximately 9 m. The effect of forming a rod with unreeling a pre-stressed metal tape is used in the design and principle of transport. Two tapes, being unreeled from a drum, are wound into tubes upon emerging from the cassette, and one tube is inside the other. The length of the rod is approximately 8.2 m and the process of extension and retrieval lasts for approximately 1 minute. The transported cargo is attached to the end of the rod tapes.

Cargo transport using jet devices considerably expands the range of cargo movement and the maneuverability of delivering it. These devices will be used more in assembly of large structures in orbit. Assembly of modular objects or of constituent structures can be accomplished by injection of separate unit into orbit with subsequent joining of them into a unified structure. It is known that orbital injection using carrier rockets is accomplished with given accuracy. Thus, the units injected into orbit will be located in a specific zone. Assembly of the final structure obviously requires detection of the units in this area, approach to them and transport of them to the assembly site. This is a complex engineering-technical task.

There were cases of losses of different equipment during operations in open space and with the open hatches of PKK. For example, the astronauts lost their movie camera during the flight of Gemini-10. The lost apparatus may contain valuable scientific observations (cassettes, movie and still cameras and so on). Transport operations using jet devices are also required to retrieve it.

There is a large number of practically unnecessary objects in orbit, in addition to useful space systems. These are, for example, fragments of the collapsed stages of carrier rockets and satellites. Equipment which has become unnecessary after conducting of one or another operations has been dumped into space. For example, approximately 32 kg of various objects were dumped beyond the spacecraft during the flight of the Gemini-12 PKK. Being located in sufficiently high orbits, they have a long lifetime. The threat of collision with them in orbit will increase as the number of these types of objects increases. Therefore, one should expect that the problem of "cleaning up" space occupies a specific place in cosmonautics and this task is also closely linked to operations in cargo transport. It is quite obvious that force and specifically, the tractor force of the rocket engine should be applied to a body of one or another mass to move it in unsupported space. In this case the orientation and stabilization of the transported cargo must be provided from the viewpoint of safety, installation requirements and so on.

Rather high requirements on the accuracy of orientation, stabilization and the relative speeds of mooring will also be placed during organization of loading-unloading operations in the "transport supply spacecraft-orbital station" system across open space.

Thus, organization of transport operations in open space is one of the most important aspects of the cosmonaut's activity in orbit.

Experimental Investigations in Outer Space

Space walks by man are necessary to conduct an entire complex of experimental investigations. Some of them may be enumerated:

testing pressure suits of different modifications;

testing various types of tools for working outside the spacecraft;

testing the repairability of various systems, their design version which facilitates the task of maintenance and evaluating the equipment of "work platforms" for conducting repair and maintenance operations;

investigations and analyses of various types of installations and devices for moving the cosmonaut (jet devices, tethers, hand holds, attaching devices and so on).

For example, methods of maneuvering in unsupported space and approach with a spacecraft using a tether, methods of moving along the outside surface of the spacecraft using hand holds and attaching devices and procedures for various methods of movement were evaluated during the flight of the Voskhod-2, Soyuz-4 and Soyuz-5 PKK. Pressure suits for working in open space and life support systems were tested. Prior to landing on the Moon, a pressure suit of "lunar" modification was tested in open space during the flight of the Apollo-9 PKK. Tools for working in open space in standard and special version, equipment of the "work platform" for conducting repair operations and devices for moving the astronaut in unsupported space were tested in the Gemini program. The astronauts of the Skylab POS installed a container on its outside surface with various specimens of onboard equipment which could be disassembled and returned to Earth to study the prolonged effects of space flight conditions. Specimens of heat shield materials in open space, where they were delivered by astronauts, were tested during the flight of the station.

Such complex and grandiose operations have been proposed in the future in orbit that tests of various systems and units under conditions of real space flight will be simply necessary.

These types of experimental investigations include testing the welding unit under conditions of a space vacuum on board the Soyuz-6 PKK.

An example of experimental investigations in open space is also the experiment on board the Skylab orbital station to evaluate various types of units for moving in unsupported space.

6521
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GEOPHYSICS, ASTRONOMY AND SPACE

ONE PRINCIPLE FOR MEASURING ANGLES OF ATTACK AND SLIP DURING SPACECRAFT FLIGHT IN 'NEAR' SPACE AND THE ATMOSPHERE

Moscow DATCHIKI I VSPOMOGATEL'NYYE SISTEMY KOSMICHESKIKH APPARATOV. ROBOTY I MANIPULYATORY. TRUDY IFAK in Russian 1978 signed to press 8 Aug 78 pp 39-48

[Article by A. B. Krymov]

[Text] The considered principle of measurement is based on analysis of the dynamic pressure distribution along the meridional cross-sections of the spherical element, which is part of any spacecraft surface during atmospheric flight, and on analysis of the ion flux distribution fixed by ion traps whose axes of sensitivity are arranged in specific planes during space flight. Algorithms for processing the data of primary sensors, constructed by the unified principle both for atmospheric and for space flight, are proposed which permit determination of the angles of attack and slip over a wide range of variation.

Information about angles of attack α and slip β may be useful for purposes of manual or automatic control at all stages of flight of circumterrestrial spacecraft, especially multiple-use spacecraft.

This information is especially necessary at stages of orbital injection and return to earth (atmospheric stages of flight). Its presence permits solution of the problem of spacecraft stability and controllability and makes it possible to construct systems for control of angular motion which provide acceptable (close to constant) quality of transient processes, despite the very wide variation of the dynamic characteristics of spacecraft as the control object.

In view of the fact that the space segments of the trajectories of many types of circumterrestrial spacecraft are close to circular, information about angles α and β is equivalent in most cases to the information ordinarily used about pitch ϑ and slip ψ angles. For example, the latter occurs during manual control of the angular position of the longitudinal axis of the spacecraft over a wide range of possible bank angles γ. Whereas engines which create a moment around the "lateral" axis of the spacecraft to control angle ϑ at angles of γ close to zero and engines which create a moment around the "vertical" axis at angles of ψ, the engines exchange roles at angles of γ close to 90°.

This exchange considerably complicates both the cosmonaut's work during manual control and the structure of the corresponding automatic control systems. The indicated exchange of role of the engines does not occur when using angles α and β as the control coordinates.

Systems for measuring angles α and β for atmospheric flight, based on reproduction by using models of pressure distribution on any spherical surface, were considered in [1]. These models were equisectional potentiometers, while the values of angles α and β were determined by the voltage distribution on the potentiometers by electromechanical tracking systems.

Further investigations, some results of which are outlined below, indicated the possibility of using the ion flux distribution flowing around the spacecraft during circumterrestrial space flights to determine angles α and β and they also permitted development of algorithms for calculating angles α and β on the basis of analyzing their corresponding distributions. These algorithms are convenient for realization both by using specialized computers and by using BTsVM [High-speed digital computer].

The shape of the nose cone in the form of a spherical element is feasible in multiuse spacecraft and their prototypes to provide the best thermal conditions during atmospheric flight. In this regard, the pressure distribution on the indicated element may be used to determine angles α and β.

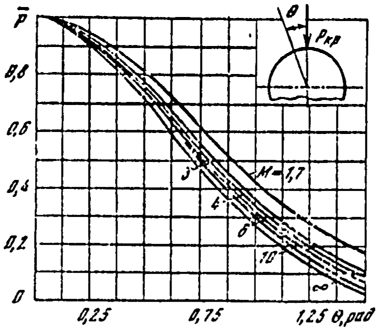

Figure 1. Relative Dynamic Pressure Distribution in Spherical Element Cross-Section Passing Through the Critical Point

As is known [2], the relative dynamic pressure distribution $\bar{p}(\theta)$ at high supersonic and hypersonic flight speeds represents an axisymmetrical surface with maximum at the critical point -- a point where the free-stream flow is normal to the surface of the spherical element. Relative dynamic pressure is understood as the ratio of the dynamic pressure component at the current point of the spherical surface located at angular distance θ from the critical point to the dynamic pressure component at the critical point.

Functions $\bar{P}(\theta)$ for different M numbers are shown in Figure 1.

Let us use the rectangular coordinate system OXYZ (Figure 2), whose origin coincides with the center of a sphere, and whose axes OX and OY are parallel to the longitudinal and vertical axes, respectively, of the spacecraft, as the reference system.

Let us additionally denote by θ_y and θ_z the angular distances from axis OX of the meridional projections of the flowing point of a spherical surface onto planes OXY and OXZ.

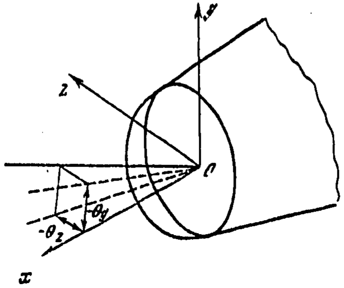

Figure 2. Adopted Coordinate System

If distribution $\bar{P}(\theta)$ at angles α and β equal to zero is taken as the base (the critical point coincides with the longitudinal axis of the spacecraft), the surface of $\bar{P}(\theta)$ will be shifted in coordinates θ_y and θ_z upon the appearance of α and β not equal to zero (Figure 3). In this case the angular positions θ_{ym} and θ_{zm} of the maximum relative dynamic pressure distribution curves for the cross-sectional lines of the spherical element by planes OXY and OXZ are related to α and β in the following manner:

$$\alpha = \theta_{ym}, \tag{1}$$

$$\beta = \arcsin \frac{\cos\theta_{ym} \sin\theta_{zm}}{\sqrt{1 - \sin^2\theta_{ym} \sin^2\theta_{zm}}}. \tag{2}$$

During atmospheric flight, usually β and accordingly $\theta_{zm} \leqslant 10°$ and instead of (2) one can use expressions

$$\beta = \theta_{zm} \cos\theta_{ym} \quad \text{or} \quad \beta \approx \theta_{zm}. \tag{3}$$

As is known, besides neutral gases, the atmosphere contains a significant quantity of ionized gases in the range of altitudes from 50-80 km to several thousand kilometers. The charged particle concentration at the same altitude depends on the geographic location, time of year and time of day, solar

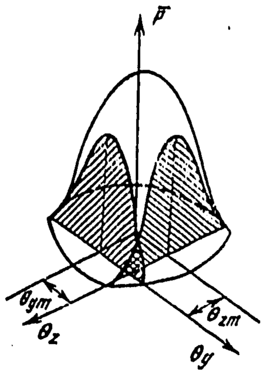

Figure 3. Spatial Relative Dynamic Pressure Distribution in Coordinates θ_y and θ_z

activity, the earth's magnetic state and a number of other factors and may vary hundreds and thousands of times. An example range of variation of positive ion concentration, obtained as a result of generalizing data of more than 20 investigations of different authors carried out during different years and by using various apparatus (H is altitude in km and N is the number of positive ions in cm^{-3}) is shown in Figure 4.

It should be noted that very significant variation of ion concentration (10-100 times) may occur during orbital flight within comparatively short time intervals (minutes and tens of seconds). Due to the smallness of spacecraft dimensions compared to the distance covered by them within an indicated time, let us further assume that the ion concentration varies synchronously over the entire spacecraft surface.

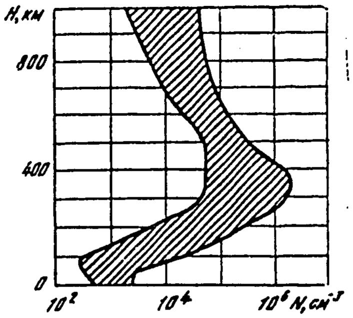

Figure 4. Dependence of Positive Ion Concentration on Altitude

Since the mean velocity of the thermal motion of molecules and also the velocities of the jet streams (ionospheric drifts) are significantly less than the spacecraft flight speed, the ionosphere may be assumed "fixed" and one can judge the angular position of the spacecraft toward the velocity vector by the direction of the free-stream ion flow with respect to the spacecraft-bound axes [3].

The dependence of the number of trapped particles on the angular position of the ion trap axis θ to the spacecraft velocity vector, the same as $\bar{P}(\theta)$, is an axisymmetrical surface with maximum at a point corresponding to $\theta = 0$.

If the current of a cylindrical ion trap (TsIL) is denoted by I(0) with the arrangement of its axis along the flow, and if the current during inclination of its axis by angle θ to the flow is denoted by $I(\theta)$, the relative current of the TsIL does not depend on ion concentration and is determined by the expression

$$\bar{I}(\theta) = \frac{I(\theta)}{I(0)} = \frac{2\cos\theta}{\pi}\left(\arccos\frac{c}{d} - \frac{c}{d}\sqrt{1-\frac{c^2}{d^2}}\right), \tag{4}$$

where d is the TsIL diameter and c is the shift of the flow passing through the input grid with respect to the cathode (Figure 5).

The value of c in the general case depends in a very complex manner on the design and potentials of the TsIL electrodes,* angle θ and also on the kinetic energy and charge of the ions.

In the case of the simplest two-electrode TsIL (the input grid of the cathode)

$$c = \frac{hT\sin 2\theta}{qU_k}\left(\sqrt{1+\frac{U_k q}{T\cos^2\theta}} - 1\right), \tag{5}$$

where h is the length of the TsIL (the distance between the input grid and cathode), $T = mV^2/2$ is the kinetic energy of the particle (it is equal to approximately 7.2 eV at flight speed of 7.2 $\text{km}\cdot\text{sec}^{-1}$), q is the particle charge and U_k is the cathode potential.

As will be shown below, traps with a static characteristic $\bar{I}(\theta)$ in the form of two linear segments are preferrable for purposes of measuring angles α and β. Therefore, the use of a two-electrode trap is not feasible since function $\bar{I}(\theta)$ is very curvilinear in this case.

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*The potential of the input grid, usually equal to that of the spacecraft surface, does not exceed 4-8 V and is essentially unreflected in the trajectories of O_2^+ ions, which comprise the main part of the positive plasma ions. This potential will subsequently not be taken into account.

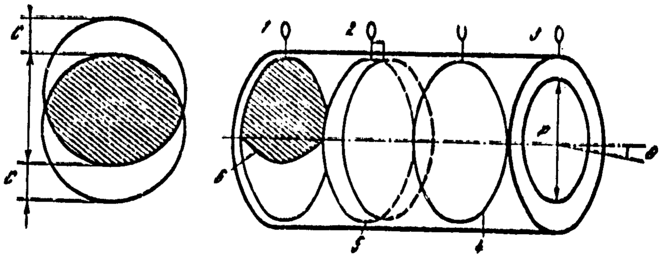

Figure 5. Diagram of Cylindrical Ion Trap: 1 -- cathode; 2 -- control grid; 3 -- input (aperture) grid; 4 -- reflecting grid; 5 -- equipotential gap; 6 -- overlap area

An acceptable form of the characteristic $\overline{I}(\theta)$ can be found for multielectrode TsIL with corresponding selection of their design parameters and grid potentials. The value of c is determined in this case by the expression

$$c = \frac{T\sin 2\theta}{q}\left[\frac{h_{n-1}}{U_{n-1}}\left(1+\frac{q\sum_{i=1}^{n-1}U_i}{T\cos^2\theta}\right)+\right.$$
$$\left.+\sum_{k=2}^{n-2}\left(\frac{h_{k-1}}{U_{k-1}}-\frac{h_k}{U_k}\right)\left(1+\frac{q\sum_{i=1}^{k-1}U_i}{T\cos^2\theta}\right)-\frac{h_1}{U_1}\right]+ \qquad (6)$$
$$+\sum_{l} h_i^0 \operatorname{tg}\left(1+\frac{q\sum_{i=1}^{l}U_i}{T\cos^2\theta}\right),$$

where n is the number of potential trap electrodes (the input grid is assumed to be zero), h_i is the distance between the grids of the i-th potential gap, h_i^0 is the distance between grids of the i-th equipotential gap (following the i-th potential), U_i is the potential increment in the i-th gap and l is the number of equipotential gaps (the equipotential grids do not follow each of the potential gaps).

The formula expresses the total ion deflection in the potential and equipotential gaps. The first potential gap and so on is located behind the input (zero) grid.

Function $\overline{I}(\theta)$ for a three-electrode trap (grid-grid-cathode) is presented as an example in Figure 6.

An increase in the number of electrodes permits control of the static characteristics of the TsIL over a wide range.

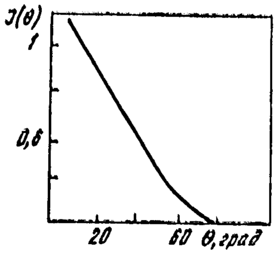

Figure 6. Dependence of Relative TsIL Current on Angular Position of Its Axis to Velocity Vector

Two rows of drain openings on the spherical element may be used to measure angles α and β during atmospheric flight (Figure 7). The openings arranged on the cross-sectional line of the element by plane OXY serve to determine the angle of attack, while those arranged along the cross-sectional line by the plane normal to plane OXY and passing through the center of the sphere at angle φ to axis OX are used to measure the slip angle. Angle φ is selected from the condition

$$\varphi = \frac{\alpha_{max} + \alpha_{min}}{2}, \tag{7}$$

where α_{max} and α_{min} are the maximum and minimum anticipated angles of attack.

In the general case there should be several planes of arrangement of the drain openings with large variations of angles α and β. However, taking into account the fact that usually angle $\beta < 10°$ and $|\varphi - \alpha| \leq 20\text{-}25°$ during atmospheric flight, the two planes indicated above are sufficient. In this case a slight mutual effect of angles α and β on the accuracy of their measurement and the corresponding pressure distributions in the cross-sections are provided.

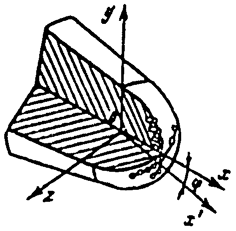

Figure 7. Diagram of Arrangement of Drain Openings

A block diagram of an analog-logic computer and angles $\alpha(\beta)$ is shown in Figure 8.

A number of values corresponding to the discrete values of the difference static characteristic $\bar{P}(\theta) - P(\theta + \Delta)$, Δ is the angular distance between the openings connected to one sensor, selected in the range of 60-75° according to [1], is taken from the differential pressure sensors connected by channels to the drain openings.

Characteristic $\bar{P}(\theta) - \bar{P}(\theta - \Delta)$ is shifted with variation of angle α in coordinates θ_y and therefore its zero corresponds to the angle of attack. It is obvious that the value of the angle of attack can be found as the sum of values of the intervals of sensor arrangement to the interval where the characteristic passes through zero and of the addition (Figure 9)

$$\delta = \frac{-U_{\Sigma i}\lambda}{U_{\Sigma i+1} - U_{\Sigma i}}, \tag{8}$$

where λ is the angular interval between the drain openings, $U_{\Sigma i+1}$ is the value of the sensor signal corresponding to the right boundary and $U_{\Sigma i}$ is that corresponding to the left boundary of the segment on which the characteristic passes through zero.

In this case

$$\alpha = m\lambda + \delta, \tag{9}$$

where m is the number of entire intervals to the segment where the characteristic passes through zero.

The logic part of the diagram, consisting of relay and logic elements, determines the interval on which the characteristic passes through zero and connects by means of keys the sensor signals corresponding to the working section to the computing circuit 8 and a signal is fed simultaneously from the voltage divider to the output adder Σ, corresponding to the whole number of intervals to the interval where the characteristic passes through zero.

The calculating algorithm $\alpha(\beta)$ is realized in the following manner with the presence of a BTsVM on board (Figure 10.

Signals from the sensors are converted to digital code in the analog-code converter (PAK) and are fed into the BTsVM, where the angle of attack (slip angle) is determined by the algorithm considered above.

During atmospheric flight, the dynamic pressure and during space flight the ion concentration vary over a wide range and synchronous automatic regulation of amplification is required to maintain acceptable accuracy characteristics of the sensors and of the entire system. This regulation is accomplished by

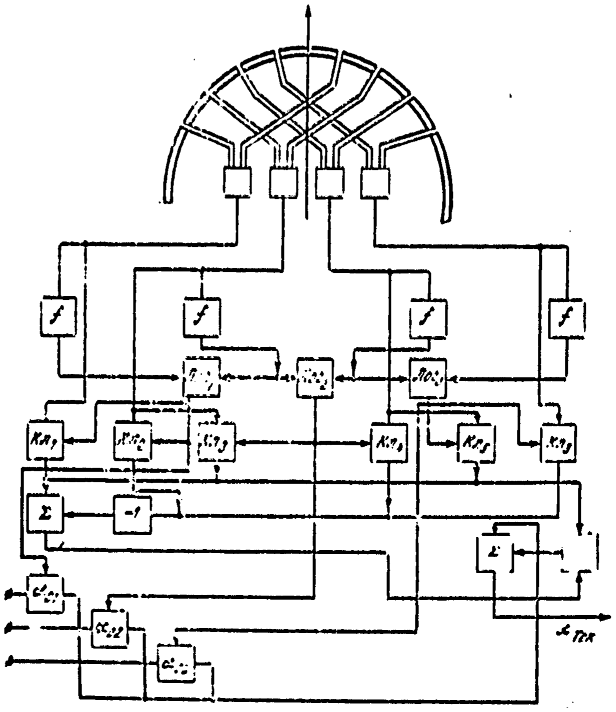

Figure 8. Block Diagram of Analog-Logic Computer of Angle $\alpha(\beta)$

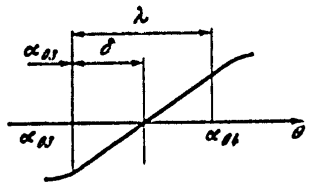

Figure 9. Determination of Addition δ

feedback along the angle of inclination of the working section of the difference characteristic

$$K=\frac{U_{\Sigma i}-U_{\Sigma i+1}}{\lambda}. \qquad (10)$$

The effect of the algorithm on the boundaries of the working range is also expanded where angles $\alpha(\beta)$ are determined by the signals of the extreme left and extreme right sensors by interpolation.

In the case when absolute pressure sensors are used, the circuit must be supplemented by adding elements which make it possible to obtain signals proportional to the difference pressure and the angles of attack (slip angles) are subsequently determined by the algorithm presented above.

Due to the validity of Newton's theory of flow during space flight (if the TsIL is not shaded), the relative ion distribution $\bar{I}(\theta)$ of the TsIL is determined, all things being equal, only by their angular position to the velocity vector. Therefore, during analysis it is convenient to assume that the TsIL are located on some sphere with axes of sensitivity directed toward its center.

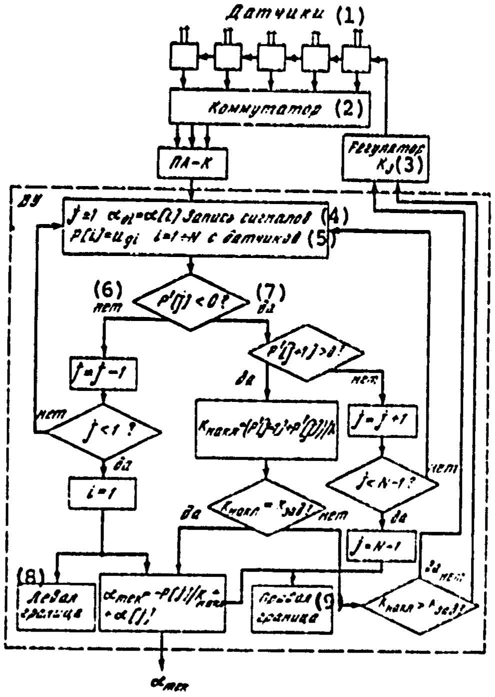

Figure 10. Algorithms for Determining α

KEY:

1. Sensors
2. Commutator
3. Regulator
4. Signal recording
5. From sensors
6. No
7. Yes
8. Left boundary
9. Right boundary

With an increase of the measured range of angles when the mutual effect of angles α and β on measurement accuracy is significant, the measuring meridian must be rotated immediately after variations of angles α (or β) to eliminate the indicated effect, which requires both an increase in the number of TsIL and in developing problems related to their arrangement and connection.

One can name a number of methods of arranging the TsIL on a spherical surface at angles of different grids: latitudinal-latitudinal, meridional-latitudinal, meridional-meridional, at the vertices of spherical triangles and so on, but they either have regions with nonuniform distribution of sensors or complicate the signal processing circuit.

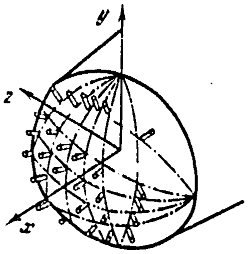

Figure 11. Diagram for Arranging TsIL

We feel that the best variant of arranging the TsIL is at the nodes of intersection of the meridional grids with the mutually perpendicular polar axes (Figure 11). However, the entire sphere is divided into six sections corresponding to the side of a spherical cube and the center of each side is used as the pole for the meridians of conjugate to eliminate the effect of the meridian convergence factor when the sensors are located near the poles (Figure 12).

The problem of the computer in this case is to find the corresponding measuring quadrant, to select the measuring meridians in the found quadrant and then to calculate angle α (β) by the signals of the measuring meridian sensors. The search for the quadrant (Figure 13) in which the maximum surface $I(\theta)$ is located can be carried out, for example, by reselecting the sum of signals of sensors located at the vertices of spherical quadrangles.

Selection of the measuring meridian within the found quadrant can be organized in two ways. The first method includes the fact that the measuring meridians for the slip angle are connected by the signals from the angle of attack computer. The second method includes the following. Since the signal level of the measuring meridian sensors passing near the critical point is greatest, then, having omitted the sensor signals through the diode matrix, we will have signals on its outputs corresponding to the desired meridian.

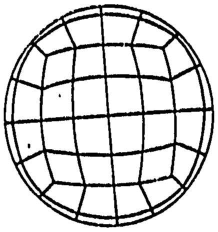

Figure 12. Twice-Meridional Grid on Spherical Cube

Angles α and β for the signals of the measuring meridian sensors can be found by the algorithm presented above for the case of using absolute pressure sensors.

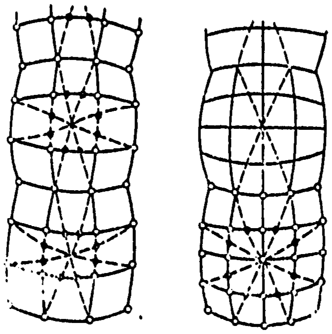

Figure 13. Determination of Optimum Number of TsIL

Since a minimum of 4-5 sensors is used in calculating the precise value of the angle of attack by the method indicated above, one or two of its working sections are located in an adjacent quadrangle (quadrant) upon shifting of the difference curve along the measuring meridian toward the boundary of the quadrangle, although the zero of the difference characteristic has still not passed the boundary of the measuring quadrant. Therefore, it is necessary that the measuring meridian continue beyond the limits of the quadrant. It is also necessary that the sensors on the measuring meridians be located at approximately equal angular distances. The latter leads to installation of additional sensors located other than at the nodes of twice-meridional grids (they are noted by crosses in Figure 13).

The desire to reduce the number of TsIL required for measurement leads to the necessity of expanding the working range of their static characteristics, which in turn causes a reduction in the accuracy of determining angles α and β.

As an example let us consider different variants of dividing the sides of a spherical cube for the case of circular measurement of angles α and β.

If the sides of the spherical cube are divided by measuring meridians into three, four and five parts (see Figure 13), respectively, 104 TsIL (56 main and 48 auxiliary) are required in the first case, 146 TsIL (98 main and 48 auxiliary) are required in the second case and 344 TsIL (152 main and 192 auxiliary) are required in the third case.

Since the static characteristics of $\overline{I}(\theta)$ near $\theta = 0$ are significantly nonlinear, the most linear parts shifted (by one-two intervals) from the origin must be taken as the working segments. Moreover, no fewer than three sensors must be located simultaneously on the linear segment. This is necessary so that the two other sensors connected to the computer correspond to the linear segment upon descent of one of the sensors onto the nonlinear segment. Thus, the working range of characteristic L_r consists of a linear segment measuring $L = 2\lambda$ on the left branch of characteristic $\overline{I}(\theta)$, the same segment on the right branch and a nonlinear segment having length $L_n = (1-2)\lambda$

$$L_r = (5-6)\lambda \tag{11}$$

For the considered variants of dividing the sides of a spherical cube when the angular distances between nodes (at which the TsIL is located) comprised 30, 22.5 and 18°, respectively, a TsIL is required with value of the working range of 90, 120, 67.5-90 and 54-72°, respectively.

If the measurement errors of the TsIL are taken as 1 percent, then as indicated by analysis, the mean errors of measuring angles $\alpha(\beta)$ caused by TsIL errors comprise 0.7, 0.55 and 0.45°, respectively, at the indicated values of the working ranges.

Thus, a sharp increase in the number of sensors in the third case yields a very insignificant advantage in accuracy and the second variant of division is apparently more preferrable.

The outlined principle of measuring angles α and β permits one to obtain information about the indicated angles at practically any stages of flight, both atmospheric and space, of circumterrestrial spacecraft. Moreover, only part of the general algorithm which permits circular orientation during space flight is used during atmospheric flight.

BIBLIOGRAPHY

1. Petrov, B. N. and A. B. Krymov, "Measuring the Angles of Attack and Slip Angles by Using Models of Pressure Distribution on a Frontal Spherical Surface," IZV. VUZOV, PRIBOROSTROYENIYE, Vol. 16, No. 12, 1973.

2. Belotserkovskiy, S. M. et al., "Supersonic Gas Flow Around Blunt Bodies (Theoretical and Experimental Investigation)," TRUDY VTS AN SSSR, Izd. VTs AN SSSR, 1963.

3. Swain, D. B. and W. H. Bennet, "Attitude Sensor for Vehicle Orientation in Space Flight," AIAA JOURNAL, Vol. 3, No. 3, February 1965.

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GEOPHYSICS, ASTRONOMY AND SPACE

A NEW METHOD OF SYNTHESIZING ARTIFICIAL MOTION AND ITS APPLICATION TO LOCOMOTING ROBOTS AND MANIPULATORS

Moscow DATCHIKI I VSPOMOGATEL'NYYE SISTEMY KOSMICHESKIKH APPARATOV. ROBOTY I MANIPULYATORY. TRUDY IFAK in Russian 1978 signed to press 8 Aug 78 pp 107-114

[Article by M. Vukobratovic, D. Hristic, D. Stokic and N. Glahazic, Yugoslavia]

[Text] The main difficulties which arise in solving problems of controlling complex dynamic systems are related to their high dimensionality. The traditional trend here is to linearize equations of dynamics with subsequent decomposition of them. In this case any differentiation of equations of dynamics usually leads to introduction of additional conditions and relationships, while variation of the operating mode of the system is accompanied by a decrease of solving accuracy.

When investigating most control systems, main attention is devoted to study of quite specific operating states or modes of both the system as a whole and of its individual parts. Based on the given states of individual subsystems of the investigated system as a whole, one can approach solution of the problem of reducing dimensionality in a new manner. In this case only part of the dynamics of the system not encompassed by the characteristics of the given state remains open to regulation. The required compensating effects on the given (known) characteristics are then organized by using the regulated part of the system.

Introducing the concept of nominal dynamic operating mode of the system forces one to consider the problem of the optimum solution (control) obtained for a complex multiconnected system. Thus, for example, redundancy of several mechanical systems is provided due to additional conditions of optimality, realization of which, however, is not always possible. In most cases the solution is found here in the range of "pure" control problems. A vivid example of realizing inconvenient conditions of optimization is various walking systems. A convenient mathematical model for these systems is differential equations of a complex pendulum system. In this case, specifically, the motions of the supports are assumed strictly monotonic.

Optimization of the motion of a walking system from the condition of some energy criterion (for example, a minimum moment of motion) presents a special problem of synthesizing control of motion of the indicated system. The attempt to realize a system of some kinematic program which seemingly realizes the special criterion of some global criterion of optimality as the law of control of motion is also quite appropriate. Hence, two stages can be determined in the procedure of synthesizing the control of motion of a walking system: selecting the control for the nominal dynamics of the system and correcting this control with regard to the effect of large disturbances. Both indicated levels can be determined in problems of controlling very diverse biological systems.

Among the variety of various types of motions made by living organisms, the walking method of locomotion is one of the most convenient for reproduction in artificial systems. The possible mathematical model of this motion is description of it by means of some conditions of stability of the dynamic system in the field of forces acting on it. Moreover, these conditions vary accordingly during motion. Analysis of the relationships between the force field and the conditions of stable motion determines their ambiguous nature. This is related to the fact that solution of the second-order differential equation which determines this relationship depends on two initial conditions (integration constants). Therefore, information about variation of integration constants must be used in the control law to organize stable motion of the walking system. This relationship has been named the second signal system.

Any variation of the initial conditions causes the required variations of the forces of the servo organs with subsequent correction of the law of control. The first level of the law of control (the level of nominal dynamics) provides stable repetition of phases of the selected type of motion in this case. The main difficulties of design are related here mainly to developing a high-speed small control digital computer. And since a real walking system (for example, a robot) is a nonlinear dynamic system of high dimensionality, the level of nominal dynamics in the law of control is most effectively represented by a set of algorithms which determine the different types of motion.

The second level of the law of control (adaptive) is called upon to work out the necessary correcting signals coming into the servo mechanisms upon variation of external conditions. Variation of the initial conditions for nominal modes leads to the appearance of additional relationships in the law of control which stabilize the "nominal" motions. Upon variation of the external conditions, similar to living organisms, any variation of accelerations, position or speed of motion of a walking system causes corresponding compensation signals in the control system. The latter in turn create the required controlling moments.

The general diagram of a system for controlling the motion of a robot is presented in Figure 1. Let us write the equation of motion of this system in the following vector form:

$$\dot{\xi} = f(\xi, t) + B(\xi, t)U, \tag{1}$$

where ξ is the n-dimensional vector of state, $f(\xi, t)$ is the vector-function of dimension n x 1, $B(\xi, t)$ is the matrix of constant numbers of dimension n x m and U is the m-dimensional vector of the input effects. In this case let us consider the general case of the control problem when the input and output signals of the system are not completely determined. Let us denote the known components of vectors U and ξ by $U_0(m_1 \times 1)$ and $\xi_0(n_1 \times 1)$, respectively, and let us denote the unknown components of these same vectors by $U_x(m_2 \times 1)$ and $\xi_x(m_2 \times 1)$, where $m_1 + m_2 = m$ and $n_1 + n_2 = n$.

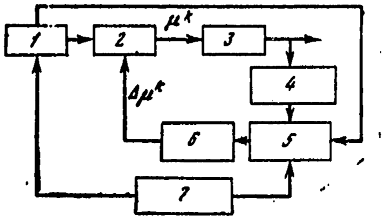

Figure 1. Stabilization System: 1 -- programming device; 2 -- servo devices; 3 -- robot; 4 -- sensors; 5 -- criterion of quality; 6 -- calculation of correcting moments; 7 -- new law of control

Let us then introduce the constant matrices P and R, related by the relations

$$[P_0 P_x]\begin{Bmatrix} U_0 \\ U_x \end{Bmatrix} = u, \quad \begin{Bmatrix} R_0 \\ R_x \end{Bmatrix}\xi = \begin{Bmatrix} \xi_0 \\ \xi_x \end{Bmatrix}, \tag{2}$$

$$\begin{bmatrix} R_0 \\ R_x \end{bmatrix}[B(\xi, t)]\,[P_0 \,\vdots\, P_x] = \left[\begin{array}{c:c} B_{00} & B_{0x} \\ \hdashline B_{x0} & B_{xx} \end{array}\right], \tag{3}$$

where matrices $B_{00,xx,0x,x0}$ have the following dimensions:

$$B_{00} - n_1 \times m_1; \quad B_{0x} - n_1 \times m_2, \quad B_{x0} - n_2 \times m_1; \quad B_{xx} - n_2 \times m_2.$$

Let us divide system (1) into two subsequent subsystems:

$$\{\dot{\xi}_0\} = \{f_0(\xi, t)\} + [B_{00}]\{U_0\} + [B_{0x}]\{U_x\}, \tag{4}$$

$$\{\dot{\xi}_x\} = \{f_x(\xi, t)\} + [B_{x0}]\{U_0\} + [B_{xx}]\{U_x\}, \tag{5}$$

where

$$\begin{bmatrix} R_0 \\ R_x \end{bmatrix} f(\xi, t) = \begin{Bmatrix} f_0(\xi, t) \\ f_x(\xi, t) \end{Bmatrix} \tag{6}$$

and $f_0(\dot{\xi}, t)$ is a vector-function of dimension $n_1 \times 1$ and $f_x(\xi, t)$ is a vector-function of dimension $n_2 \times 1$.

We note that solution (4) determines the significance of the unknown vector U_x for us

$$\{U_x\} = [B_{0x}]^T [B_{0x}]^{-1} [B_{0x}]^T (\{\dot{\xi}_0\} - \{f_0(\xi, t) - [B_{00}]\{U_0\}) \tag{7}$$

provided that matrix $[B_{0x}]^T[B_{0x}]$ is not identical. Substitution of (7) into (5) then leads us to the equation with respect to the unknown

$$\begin{aligned} \{\dot{\xi}_x\} = \{f_x(\xi, t)\} + [B_{x0}]\{U_0\} + [B_{xx}]([B_{0x}]^T [B_{0x}]^{-1} \times \\ \times [B_{0x}]^T (\{\dot{\xi}_0\} - \{f_0(\xi, t)\} - [B_{00}]\{U_0\}), \end{aligned} \tag{8}$$

and subsequent solution of algebraic subsystem (7) permits us to calculate the value of vector U_x. Thus, the system of equations (7)-(8) describes the procedure for synthesizing the nominal dynamics. The nominal trajector can be synthesized by using the procedure of synthesizing a linear optimla regulator [1]. It is obvious in this case that the synthesized linear regulator provides the required quality of stabilization processes in some vicinity of space with respect to this trajectory, which we denote by ξ^0. In similar fashion we determine the working zone for the nonlinear regulator (E^0), outside which the nonlinear characteristics already have a significant effect on the regulated process. Let us now turn to some region of the space of states

$$E^0 = E^0 \cap E^0,$$

for which

$$\| \xi(t) - \xi^0(t) \| > 0, \quad t \to \infty, \quad \xi(t_0) \notin E^0,$$

and some trajectory of reverse transfer of system ξ^A from a disturbed to a nominal state.

As already noted above, we shall consider a class of systems with limited number of operating modes (trajectories). To supplement this, one can indicate systems which accomplish direct compensation of large disturbances in some region of the space of states $\| \xi^A(t) - \xi^0(t) \| < \mathcal{E}$, which permits formulation of programmed trajectories from the conditions of stability for them. Consequently, if any disturbance acting on the system leads it to one of regions E^t, the problem of the regulator is reduced in this case to selecting the programmed trajectory which corresponds most to this region of disturbed state. In this case the volume of required calculations is very moderate [2, 3].

The criterion for selecting the programmed trajectory, which corresponds to state $\xi^{r}(t_0)$, is the minimum expression by number j

$$J = \frac{1}{2}\|\xi - \xi^j\|^2 = \frac{1}{2}\sum_{i=1}^{n} c_i(\xi_i - \xi_i^j)^2, \quad j = 0, \ldots, k. \tag{9}$$

If the set of programmed trajectories can be represented in the function of parametric vector $p(p_1, \ldots, p_r)^T$, where $r < n$, the selection process can be considerably facilitated by identification of the parameters of each trajectory. In other words, the problem reduces in this case to calculating the vector during minimization of our criterion:

$$\partial J/\partial p_j = 0, \quad j = 1, \ldots, r. \tag{10}$$

The calculated vector p^A also determines the new trajectory of ξ^A, corresponding to the state of the system $\xi(t_0)$. Since vector ξ contains n components and since it is a function of different parameters, also including the time here, difficulties arise in remembering all its possible values.

Summarizing the foregoing, let us note the main features of the outlined synthesis procedure. The state of the system should be described in the function of its number of parameters and time. The state of the system is checked by two circuits:

1) the circuit for controlling the nominal dynamics by using an optimum linear regulator for decomposition of the system into individual circuits regulated by means of simple feedbacks;

2) a circuit of large disturbances where some programmed trajectory most closely corresponding to the new state of the system is selected.

A number of examples of investigating complex systems is considered below.

Controlling the motion of a two-support robot. By its nature, the problem of synthesizing the law of motion of an artificial system is related to the range of problems of combined control since first, one must determine the controlling moments for each support. This follows from the fact that the dynamic responses of the supports may be regarded as the external effects on the mechanism. The resulting forces of responses of the support and of the locomotion surface are calculated at fixed points of the trajectory of motion. These points are characterized by a zero moment of resulting forces and also by altered form of the equations of dynamics. Thus, we can select the trajectories of motion of points with zero resulting moment, also characterized by zero moments with respect to the points of articulations of the movable elements of the robot structure (Figure 2). In this case the controlling moments M_0 are also zero moments, while the differential equations of dynamics assume the form

$$\{\dot{\xi}_x\} = \{f_x(\xi, t)\} + [B_{xx}]([B_{0x}]^T [B_{0x}]^{-1} [B_{0x}]^T (\{\xi_0\} - \{f_0(\xi, t)\})). \tag{11}$$

The space of unknown components of the equation of dynamics $\{\xi_x\}$ describes the compensating components required in this case to maintain a stable state and to accomplish equal motion or free movement of individual sections. Considering steady motion, we find that the parameters of state at the initial and final points of the step are unknown. These parameters can be calculated by using the following conditions: the value of the angular coordinates and their derivatives are equal at the initial and final points of the step, i.e.,

$$\xi(t) = \xi(0), \tag{12}$$

$$\xi(T) = \dot{\xi}(0), \tag{13}$$

where T is the period of the step. Thus, equations (11)-(13) permit one to calculate the compensating moments for the considered system.

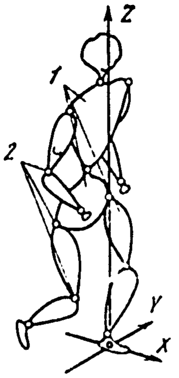

Figure 2. Points of Joining the Structural Elements With Zero Moment of Rotation: 1 -- structural elements; 2 -- joints

The second important problem of stabilizing the motion of a two-support anthropomorphic system is solved by using the adaptive level of the hierarchical structure of the law of control. The purpose of the stabilization mode is to return the disturbing parameters of the system to some nominal values. The specific characteristic of the problem of stabilizing the motion of a two-support robot is also the presence of additional degrees of freedom in the circuit of the control system, which are two angles of deviation of the supports in the longitudinal and transverse planes, respectively, with respect to the plane of motion. Additional global feedback, which encompasses the existing local feedbacks, is organized to control these coordinates in the system.

Since the most interesting in the stabilization problem is the case of large disturbing effects, let us dwell in somewhat more detail on it. When identifying the current state of work, the greatest difficulties are related to determining the parametric vector p^A, by means of which the nominal mode may be specifically described. For example, the uniform motion of a robot may be characterized sufficiently fully by variation of two of its parameters: s -- the relative length of the step and T -- the period of the walking motions. Let us consider the example of one simple type of motion with nominal trajectory ξ^0. Let us characterize the set of possible states by the equation

$$\xi_d(t) = s\xi_d(t/T), \tag{14}$$

where d is the index of the lower (support) part of the structure. By varying parameters s and T, we find a set of curves which characterize the state of the system as a function of these parameters. The following coupling equation between parameters s and T is valid for the remaining part of the structure:

$$\xi = \xi^0 + B_s(s - s_0) + B_T(T - T^0), \tag{15}$$

where coefficients B_s and B_T are calculated by the criterion of the minimum quadratic error. Substitution of (15) into (9) with subsequent fulfillment of conditions (10) leads to the following expressions:

$$a_{11}s + a_{12}T = b_1, \qquad a_{21}s + a_{22}T = b_2, \tag{16}$$

where $a_{11,12,21,22}$ are functions of coefficients B_s, B_T, b_1, b_2, i.e., functions of the parameters of state. Equations (16) permit us to determine point A close to the true position of the depicted point in the space of states of the system. The analytical procedure indicated above was checked by the digital modeling method with selection of the nominal state.

Let the motion of a robot be along trajectory No. 1 (Figure 3) and be subjected at interval $t/T = 0.7$ to the effect of a disturbing impulse calculated by means of a gyroscopic system. The new values of parameters s and T are then calculated by expression (16) with regard to the coordinates of the nominal state of the system. These parameters also determine the disturbed state of the system.

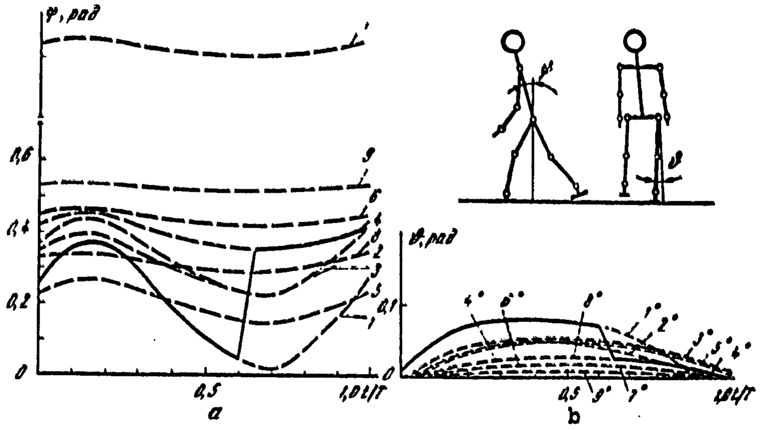

Figure 3. Ideal Trajectories of Motion of Elements of the Upper Part of the Structure (Dashed Lines); Transition to New Trajectories With Disturbances (Solid Line): a -- angles of deviation in transverse plane; b -- angles of deviation in longitudinal plane

The digital computer-calculated values of parameters s = 0.4 and T = 0.5 for the considered example, which determined the state of the system close to mode No. 4, are presented in Figure 3. This transition of the system from one state to another is noted by the solid line in this figure. The coordinate disturbances used in our example are more illustrative in nature since they leave the system in some region of its permissible states. It is obvious that in practice we may also encounter more severe situations when the system goes beyond the region of permissible states.

Control of anthropomorphic manipulators. In this case the nominal mode is that of reaching the goal and maintaining it, whereas the compensating motions are accomplished to solve special problems of manipulation. Hence, the problem of controlling anthropomorphic manipulators can be solved in two corresponding coordinate spaces, in the first of which the working zone is achieved and in the second of which problems of manipulations themselves are terminated. According to the foregoing, the following hierarchical levels can be determined in the control circuit of an anthropomorphic manipulator: the level of nominal dynamics with motions of the system of minimum complexity and the level of disturbed modes with motions of the compensating part of the system. A minimum structure with the required kinematic and compensating circuits can be determined in the kinematic circuit of the structure. The latter provides the degrees of freedom missing in the minimum structure in the system.

It is known that a structure with three degrees of freedom permits one to achieve an arbitrary point of space whose position in the Cartesian system can be characterized by three angles. The trajectory of motion of a manipulator in space may have an arbitrary form, essentially unrelated to its kinematic circuit. In the general case the position of the working point in space can be determined by using the following implicit form:

$$x = f_1(\Phi_1, \Phi_2, \Phi_3), \quad y = f_2(\Phi_1, \Phi_2, \Phi_3), \quad z = f_3(\Phi_1, \Phi_2, \Phi_3), \tag{17}$$

and the equation of motion of the extremity for small increments is written, respectively, in the form

$$\left(\frac{\partial f_i}{\partial \Phi_1}\right) \Delta \underset{\Phi=\Phi_0}{\Phi_1} + \left(\frac{\partial f_i}{\partial \Phi_2}\right) \Delta \underset{\Phi=\Phi_0}{\Phi_2} + \left(\frac{\partial f_i}{\partial \Phi_3}\right) \Delta \underset{\Phi=\Phi_0}{\Phi_3} = \Delta q\,(\Delta x, \Delta y, \Delta z)^T, \tag{18}$$

$$[A]\,(\Delta\Phi_1, \Delta\Phi_2, \Delta\Phi_3) = (\Delta x, \Delta y, \Delta z)^T, \quad a_{ij} = \frac{\partial f_i}{\partial \Phi_j}; \quad i, j = 1, 2, 3. \tag{19}$$

A rather wide class of problems of manipulation can be adequately described by using these equations for some baseline structure of a manipulator and the necessary controlling moments are calculated [4-7]. Since the baseline structure of the manipulator usually does not provide total solution of the posed problem, additional devices are used in the structure which permit one to achieve, for example, operation with a grasped object. The dynamics of these specific problems are taken into account in the general system of differential equations by means of conditions of form

$$f(\vec{F}_0, \vec{M}_0) = 0, \tag{20}$$

where $\vec{F}_0$ is the force of inertia of the object and $\vec{M}_0$ is the corresponding moment of inertia. It is obvious that the dynamic conditions of this type may be reduced to purely kinematic limitations. Without regard to slipping between the object and the grasping device, the expressions for determining the inertial forces and moments include a sufficiently large number of parameters

$$\begin{aligned} \vec{F}_0 &= \Phi_1(\tilde{\Phi}, \dot{\tilde{\Phi}}, \ddot{\tilde{\Phi}}, \Phi^*, \dot{\Phi}^*, R^E, \ddot{\Phi}^*), \\ \vec{M}_0 &= \Phi_2(\tilde{\Phi}, \dot{\tilde{\Phi}}, \ddot{\tilde{\Phi}}, \Phi^*, \dot{\Phi}^*, \ddot{\Phi}^*, \vec{M}^{RE}) \end{aligned} \tag{21}$$

where $\tilde{\Phi}$ are the generalized coordinates of a structure of minimum complexity, Φ^* are the generalized coordinates of peripheral devices and $\vec{R}^E$ and $\vec{M}^{RE}$ are the resulting external forces and moments. Continuous solution of equations (20) and (21) for measured values of $\vec{R}^E$ and $\vec{M}^{RE}$ permits one to calculate the required compensating forces and moments, i.e., to synthesize the adaptive level of control. In this case the indicated synthesis procedure is considerably simplified if the parameters of the right side of (21) are measurable and controllable. This goal is achieved, for example, by installation of the necessary sensors on the grasping device. The conditions of mutual compensation (equilibrium) of forces and moments acting on the object are the following algebraic equations:

$$\vec{F}_0+\vec{G}_0+\sum_l(-\vec{R}_l)+\sum_k\vec{R}_k^E=0,\qquad \vec{M}_0+\sum_l\vec{r}_{0l}\times(-\vec{R}_l)+\vec{M}^{RE}=0, \tag{22}$$

where $\vec{R}_l$ is the force recorded on the l-th sensor, $\vec{r}_{0l}$ is the gravity component directed toward this sensor, $\vec{G}_0$ is the gravity of the object and l is the number of sensors. It is then simple to calculate the values of $\vec{F}_0$ and $\vec{M}_0$ and also the corresponding increments $\Delta\vec{F}_0$ and $\Delta\vec{M}_0$ for the measured values of $\vec{R}_l$. They can be compensated by additional connections in the control circuit.

Let us consider the dynamics of the manipulator during "drinking" as an example of one manipulation problem. Providing motion of the glass parallel to the vertical axis, we thus achieve a zero moment of inertial forces. A number of simple constraints in this case ensures nonspilling of the liquid. For example, conditions (20) are written here in the form

$$\vec{M}=0,\ |\vec{F}_0|<|F|,\qquad \sum_l\vec{r}_{0l}\times(-\vec{R}_l^*)=0, \tag{23}$$

where $|F|$ is some maximum value of force. The second constraint concerns that of the rate of moving the glass. The third condition provides a zero value of the resulting angular velocity and acceleration of the glass, where $\vec{R}_l^*$ is the required reaction force during grasping of the glass. If condition (23) is unfulfilled, it is simple to calculate the necessary condition of compensation.

The considered problem was investigated experimentally by mathematical modeling methods. Specific difficulties in synthesizing the controlling moments are related here to the need to strictly maintain a vertical position of the glass during its equally accelerated and equally retarded motions. The minimum value of the controlling moment is limited by the value of the inertial force of the glass with the liquid. It is difficult to achieve a satisfactory solution of this special problem with a simple configuration of the manipulator.

Conclusions. A method of synthesizing the nominal dynamics of an object having excess degrees of freedom during partial uncertainty of it is outlined in the paper. The term "given dynamics" may be interpreted here as the conditions for simple efficiency of the system. A large number of interesting analogs to these conditions can be found in biology. Described in mathematical form as constraints, these conditions are essentially some criterion of optimizing the motion of the considered anthropomorphic manipulator. Thus, by studying the motion of a two-support robot, the condition of its stability can be written in the form of zero equality of the total moment at the points where the supports touch the surface of motion. Although the formulated problem as a whole is known in control technology (this is especially true of control of mobile objects), the distinguishing feature of the considered postulation is, we feel, the partial uncertainty of the nominal dynamics of the object and of the controlling moments. A significant feature of the considered postulation is also the need to identify the working mode in case of its large deviations from nominal values. To determine the range of deviations of parameters, continuous variation of the vector of states permits one to compare the real trajectory of the system with the closest nominal trajectory, whose parameters are placed into the memories of the control computer. We feel that the approach considered here to synthesis of control of a complex mechanical system using a digital computer is promising.

BIBLIOGRAPHY

1. Letov, A. M., "Analytical Controller Design," AUTOMATICS AND REMOTE CONTROL, Vol. 21, Nos. 4, 5 and 6, 1960; Vol. 22, No. 5.

2. Vukobratovic, M. and D. Stokic, "Dynamic Control of Unstable Locomotion Robots," MATHEMATICAL BIOSCIENCES, Vol. 24, 1975.

3. Vukobratovic, M. et al., "Algorithmic Control of Assistive Devices for Severely Handicapped Persons," Proceedings of the Fifth International Symposium on External Control of Human Extremities, Dubrovnik, 1975.

4. Vukobratovic, M. et al., "Development of Active Exoskeletons," MEDICAL AND BIOLOGICAL ENGINEERING, January, 1974.

5. Vukobratovic, M. et al., "Analysis of Energy Demand Distribution Within Anthropomorphic Systems," TRANS. OF THE ASME, JOURNAL OF DYNAMIC SYSTEMS, MEASUREMENT AND CONTROL, December, 1973.

6. Vukobratovic, M., D. Stokic and D. Hristic, "Dynamic Control of Anthropomorphic Manipulators," Proceedings of Fourth International Symposium on Industrial Robots, Tokyo, 1974.

7. Vukobratovic, M., D. Hristic and D. Stokic, "Algorithmic Control of Anthropomorphic Manipulators," Proceedings of Fifth International Symposium on Industrial Robots, Chicago, 1975.

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GEOPHYSICS, ASTRONOMY AND SPACE

SEMIAUTOMATIC MANIPULATOR CONTROL SYSTEMS AND COMPUTER INVESTIGATION OF THEIR DYNAMICS

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[Article by V. S. Kuleshov, A. G. Leskov, V. S. Medvedev and A. S. Yushchenko, USSR]

[Text] 1. Methods of semiautomatic control of manipulators. Selecting the method of manipulator control is determined by the class of working operations for performance of which it is designed. The most widely used for semiautomatic control systems is the high-speed method [1]. Control is accomplished by using special levers having 3-6 degrees of freedom [2]. The deviation of the lever determines the speed of rotation or the forward motion of grasping and the related object of manipulation. In combination type systems, the operator can assign the required orientation and position of the grasp in space and also some of the simplest operations from the computer control console.

The force-vector principle of control may be used in those cases when it is required to control the extent and direction of forces and moments applied to the object of manipulation [3, 4].

When performing operations which require precise positioning of the object of manipulation or of the working tool, the copying principle may be used in semiautomatic systems. However, the use of a computer significantly alters its realization. The kinematic diagram and geometric dimensions of the controlling member are now determined by the dimensions of the working zone and by ergonomic requirements; the kinematic diagram of the servo member may be different. Unlike copying type manual control systems [5], reproduction of the positions and orientation of grasp in semiautomatic systems does not require reproduction of the relative coordinates in slave member mobility. To emphasize this difference, let us call these systems semiautomatic position control systems. If there is a force reflecting channel, the computer permits highly accurate reproduction of the forces on the control member acting on the object of manipulation and relieves the operator of perceiving the forces causes by the mass of the manipulator.

Each of the enumerated methods of control is effective only when performing a specific class of operations. In this regard, different methods may be combined during development of semiautomatic manipulator control systems.

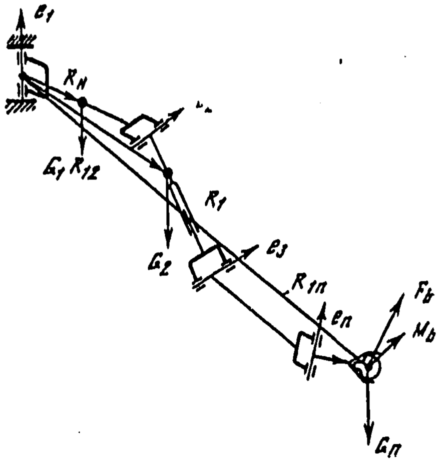

Figure 1

2. The dynamics of manipulator control systems. Let us consider the equations of manipulator dynamics and some algorithms of semiautomatic control using computers and let us compare them.

The slave member of the manipulator consists of sections connected in kinematic pairs which form an open kinematic chain (Figure 1). Let us denote the unit vectors of the rotational pair and sliding pair axes by e_i and h_i, the moment or force developed by the servo drive of the i-th pair as a function of the type of pair by Q_i and P_i, the weight by G_i, mass by m_i, the vector of the main moment of inertial forces of the i-th section during rotation around the center of mass by M_i and the vector of total acceleration of the center of mass of the i-th section by w_i. The vectors of the external force F_v and of the external moment M_v are applied to the center of mass of the last n-th section. Let us consider this section jointly with the object of manipulation.

The motion of the mechanism is described by the following equations of dynamics [6] in projections onto the rotational pair axes:

$$Q_{i_p}+\left[M_{\text{в}}+R_{i_p,n}\times F_{\text{в}}+\sum_{m=i_p}^{n}(M_m+R_{i_p,m}\times(G_m-m_m w_m))\right]e_{i_p}=0,$$
$$p=1,\ldots,l;$$

and in projections onto the sliding pair axes:

$$P_{j_r} + \left[F_B + \sum_{m=j_r}^{n} (G_m - m_m w_m)\right] h_{j_r} = 0, \quad r = 1, \ldots, k; \quad k + l = n.$$

Let us subsequently make use of the matrix notation of these equations

$$[QP] + [F_B - m_n w_n + G_n \mid M_B + M_n] A + [G - mw \mid M^0] B = 0, \tag{1}$$

where $[QP] = [Q_{i_1} \ldots Q_{i_l} P_{j_1} \ldots P_{j_k}]$ is the $[1 \times n]$ vector, $[F_V - m_n, w_n + G_n \mid M_V + M_n]$ is the $[1:6]$ vector and $[G_1 - m_1 w_1 \ldots G_{n-1} - m_{n-1} w_{n-1} \mid M_1 \ldots M_{n-1}]$ is the $[1 \times 6(n-1)]$ vector,

$$A = \begin{bmatrix} e_{i_1} \times R_{i_1,n} & e_{i_2} \times R_{i_2,n} \ldots e_{i_l} \times R_{i_l,n} & h_{j_1} & h_{j_2} \ldots h_{j_k} \\ e_{i_1} & e_{i_2} \quad \ldots \quad e_{i_l} & 0 & 0 \ldots 0 \end{bmatrix},$$

$$B = \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & 0 \end{bmatrix},$$

B_{11}, B_{12} and B_{21} are matrices consisting of the following columns:

$$B_{11} = \begin{bmatrix} 0 \\ \ldots \\ 0 \\ e_{i_p} \times R_{i_p, i_p} \\ e_{i_p} \times R_{i_p, i_p+1} \\ \ldots \\ e_{i_p} \times R_{i_p, n-1} \end{bmatrix}, \quad B_{21} = \begin{bmatrix} 0 \\ \ldots \\ 0 \\ e_{i_p} \\ e_{i_p} \\ \ldots \\ e_{i_p} \end{bmatrix}, \quad B_{12} = \begin{bmatrix} 0 \\ \ldots \\ 0 \\ h_{j_r} \\ h_{j_r} \\ \ldots \\ h_{j_r} \end{bmatrix}, \quad \begin{matrix} p = 1, \ldots, l', \\ r = 1, \ldots, k', \end{matrix}$$

$$l' = \begin{cases} l & \text{if} \quad i_l \leqslant n - 1, \\ l - 1 & \text{if} \quad i_l = n, \end{cases} \qquad k' = \begin{cases} k & \text{if} \quad j_k \leqslant n - 1, \\ k - 1 & \text{if} \quad j_k = n; \end{cases}$$

the number of zero components in each column of matrices B_{11} and B_{21} is equal to i_{p-1} and that in the columns of matrix B_{12} is equal to $(j_r - 1)$.

Equation (1) permits one to compare the different methods of control and to determine problems of further investigations.

Let us begin with consideration of control by the force vector. The human-operator develops force F and moment M on the control member, which represents a six-step lever as in high-speed control. During control, the operator observes the motion of grasping by using a visual information system (Figure 2). It is suggested that the control forces [QP] be determined by the formula

$$[QP] = [FM]A - GB, \tag{2}$$

where [FM] = $[k_1F_0k_2M_0]$; k_1 and k_2 are scale coefficients.

The second term on the right side of equality (2) can be introduced if the manipulator has no mechanical relief system.

By substituting the vector [QP] into the equation of dynamics, we find

$$[F + F_{\text{в}} - m_n w_n + G_n \,\vdots\, M + M_{\text{в}} + M_n]\, A = N. \tag{3}$$

The right side of this equation

$$N = [mw \,\vdots\, - M^0]\, B$$

determines the vector of the generalized force determined by the inertia of the manipulator. If, specifically, this term is close to zero, matrix A is nondegenerate and $[F_VM_V] = 0$, then the motion of the n-th section and the related object of manipulation will approach the motion of a free solid due to the effect of the controlling forces [FM] controlled by the operator

$$[F - m_n w_n + G_n \,\vdots\, M + M_n] = 0.$$

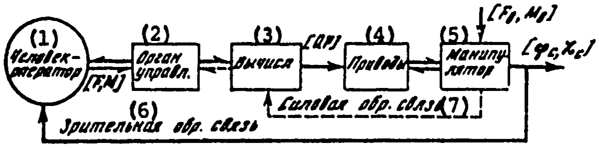

Figure 2

KEY:

1. Human operator
2. Control member
3. Computer
4. Drives
5. Manipulator
6. Visual feedback
7. Power feedback

In the remaining cases the motion of the n-th section will be deflected from that required due to the effect of inertial forces N and of kinematic couplings. By integrating equations (1) on a digital computer and by being given the generalized forces [FM] characteristic for typical working operations, one can determine the value of the corresponding forces N. The range of applicability of the control method by the force vector for a given manipulator can be determined with regard to the characteristics of the operator's indirect perception of the effect of these forces through the deviations of motion caused by them.

If the external forces $[F_V M_V]$ are unknown to the operator and also if there is a significant effect of inertial forces, it is feasible to have feedback which directly informs the human operator of the effect of the indicated forces.

During control by the velocity vector, the operator controls the speed of sliding motion and the angular rotational speed of grasping and the related object of manipulation in proportion to deviations of δx_r and $\delta\varphi_r$ which control the six-step lever. The velocity vector of relative motion in degrees of manipulator mobility

$$[\dot{\varphi}_{i0}\dot{x}_{j0}] = [\dot{\varphi}_{i_1 0} \ldots \dot{\varphi}_{i_l 0}\dot{x}_{j_1 0} \ldots \dot{x}_{j_k 0}]$$

is selected as equal to

$$[\dot{\varphi}_{i0}\dot{x}_{j0}]^T = A^{-1}\,[\overline{\delta x_0 \delta\varphi_0}]^T; \qquad [\overline{\delta x_0 \delta\varphi_0}] = [\delta x_p \delta\varphi_p]\,k,$$

k = diag$[k_i]$, k_i are proportionality constants.

Assuming approximately that the generalized forces developed by the drive are proportional to the error between the given and current values of speeds with respect to motion, we find the following law of control:

$$[QP]^T = \widetilde{k}A^{-1}\,[\delta\dot{x}\delta\dot{\varphi}]^T - [GB]^T, \tag{4}$$

where $[\delta\dot{x}\,\delta\dot{\varphi}] = [\delta\dot{x}_0 - \dot{x}\,\delta\dot{\varphi}_0 - \dot{\varphi}] = [\dot{x}_0 - \dot{x}\,\dot{\varphi}_0 - \dot{\varphi}]$ is the error between the given $[\dot{x}_0\dot{\varphi}_y]$ and current $[\dot{x}\dot{\varphi}]$ values of the grasping speeds of the manipulator and $\widetilde{k} = \mathrm{diag}[\widetilde{k}_i]$ is the matrix of the proportionality constants.

The equation of dynamics has the following form:

$$[\delta\dot{x}\delta\dot{\varphi}]\,(A^T)^{-1}\,\widetilde{k} + [F_в - m_n w_n + G_n \,\vdots\, M_в + M_n]\,A = N. \tag{5}$$

During control in the copying mode by using the computer, the control diagram is similar to that in Figure 3; feedback is accomplished in this case by position rather than by speed. With the previous assumptions, the controlling forces of the servo drives and the equation of dynamics have the following form:

$$[QP]^T = \widetilde{k}_1 A^{-1} A_3\,[\delta\varphi_{i3}\delta x_{j3}]^T - [GB]^T, \tag{6}$$

$$[\delta\varphi_{i3}\delta x_{j3}]\,A_3^T\,(A^T)^{-1}\,\widetilde{k}_1 + [F_в - m_n w_n + G_n \,\vdots\, M_в + M_n]\,A = N, \tag{7}$$

where matrix A_z corresponds to the controlling member and $[\delta\varphi_{iz}\, \delta x_{jz}]$ is the error vector between the given and current values of its relative coordinates. Force feedback (the dashed line in Figure 3) may also be accomplished in this system. Assuming the possibility of measuring the generalized forces R in each of the degrees of manipulator mobility, one can calculate the forces R_0 developed in the degrees of controlling member mobility by the formula

$$R_0 = (R - GB)\,A^{-1}A_{\text{в}} = (-[F_{\text{в}} - m_n w_n + G_n \mid M_{\text{в}} + M_n]\,A + N)\,A^{-1}A_{\text{в}} =$$
$$= -[F_{\text{в}} - m_n w_n + G_n \mid M_{\text{в}} + M_n]\,A_{\text{в}} + NA^{-1}A_{\text{в}}.$$

The human operator will perceive the following generalized force on the lever of the control member

$$[F_{\text{в}} - m_n w_n + G_n \mid M_{\text{в}} + M_n] + NA^{-1}.$$

The problem of analyzing the effect of the last term, determined by the manipulator inertia, as in the first case, requires special investigation.

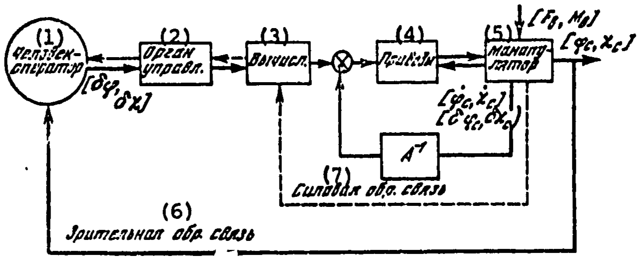

Figure 3

KEY:

1. Human operator	5. Manipulator
2. Control member	6. Visual feedback
3. Computer	7. Power feedback
4. Drives	

By comparing the considered control diagrams, we note that the method of manipulator control by the force vector has the simplest algorithm which does not require manipulation of matrix A. Unlike the other methods, it permits the operator to control the force and consequently the acceleration of motion of the object of manipulation, which is important when performing work with increased requirements on the dynamics of the process. Since the main feedback in the control system by the force vector is realized through the human operator, the main problem is to investigate this system as a biological engineering system.

The main distinction of the speed and position methods of control includes the presence of feedbacks in the technical part of the system, which is a multicoupling automatic control system. Problems of investigating the stability of the technical part of the system, the possibility of autooscillations occurring and taking into account the dynamics of drives in each of the degrees of mobility and of their mutual effect arise in this regard. Subsequent sections of the paper are devoted to investigation of these problems.

3. Linearized differential equations of manipulators. The equation of disturbed motion of the slave member of a manipulator with n degrees of mobility has the form [7, 8]

$$H(p)\,q(t) = M_0(t),\ H(p) = ap^2 + bp + c, \tag{8}$$

where H(p) is the operating matrix which characterizes the dynamic properties of the slave member as the control object, a, b and c are matrices, q(t) is the vector of the generalized coordinates of the slave member and $M_0(t)$ is the vector of moments developed by the drives of the degrees of mobility. Together with the equations of the drive complex

$$\begin{aligned} &N_{\text{м}}(p)x_1(t) = M_{\text{м}}(p)(u(t) - q(t)),\\ &N_{\text{c}}(p)x_2(t) = M_{\text{c}}(p)q(t),\ M_0(t) = x_1(t) - x_2(t) \end{aligned} \tag{9}$$

equations (8) describe the mathematical model of the manipulator dynamics (p is the operator of differentiation).

Here $N_m(p)$, $N_s(p)$, $M_m(p)$ and $M_s(p)$ are matrices whose elements have polynomials from p, u(t) is the control signal vector and $x_1(t)$ and $x_2(t)$ are the moving moment and moment of resistance developed by the drives.

Let us solve equations (8) and (9) with respect to the vectors of the slave member and control signal coordinates, having represented them in the form of the input-output relations

$$\begin{aligned} &q(t) = X^{-1}(p)W_{\text{м}}(p)u(t) = W(p)u(t),\\ &X(p) = H(p) + W_{\text{c}}(p) + W_{\text{м}}(p),\\ &W_{\text{м}}(p) = N_{\text{м}}^{-1}(p)M_{\text{м}}(p), \quad W_{\text{c}}(p) = N_{\text{c}}^{-1}(p)M_{\text{c}}(p), \end{aligned} \tag{10}$$

where W(p) is the transfer matrix of the manipulator control system complex. The diagonal elements of this matrix reflect the properties of separate systems and the elements not belonging to the main diagonal reflect the cross-influence of external effects.

A block diagram of the system corresponding to equations (10) is presented in Figure 4.

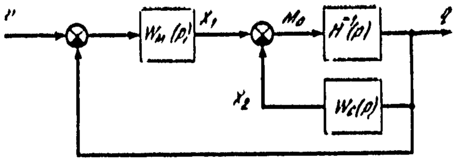

Figure 4

Study of the dynamic properties of manipulator control systems by their mathematical models is also a problem of investigating the manipulator as a multidimensional automatic control system.

4. Analysis of the stability of manipulator control systems. Let us compile the operating matrix of system (10) and let us calculate its characteristic determinant. We find

$$\mathcal{H}(p) = \begin{bmatrix} H(p) & E & -E \\ -M_c(p) & N_c(p) & 0 \\ M_M(p) & 0 & N_M(p) \end{bmatrix}, \tag{11}$$
$$\Delta(p) = \det \mathcal{H}(p) = \det N_M(p) \det N_c(p) \det [H_0(p) + W_c(p) + W_M(p)].$$

Let us assume that no transformations of any kind occurred which lead to a reduction of the order of the equations during calculation of matrices $N_m(p)$, $N_s(p)$, $M_m(p)$ and $M_m(p)$, which comprise the transfer matrices of the drive complex and also matrices W(p). Therefore, system (10) describes the relations between all the variable states and all the components of the input actions.

Let us make use of the Nyquist criterion to investigate the stability of this system. System (10) does not vary if the product $H_0(p)q(t)$ is added to the left side of the first equation in it and is subtracted. We have

$$\begin{gathered} H_0(p)q(t) = M_0(t), \quad M_0(t) = x_1(t) - x_2(t) - x_3(t), \\ N_M(p)x_1(t) = M_M(p)[u(t) - q(t)], \quad N_c(p)x_2(t) = M_c(p)q(t), \\ x_3(t) = [H(p) - H_0(p)]q(t), \\ H_0(p) = \operatorname{diag}[H_{01}(p) H_{02}(p) \ldots H_{0n}(p)], \\ H_{0i}(p) = a_{ii}p^2 + c_{ii}, \quad i = 1, 2, \ldots, n. \end{gathered} \tag{12}$$

The characteristic determinant of this system coincides with determinant (11). Let us calculate the characteristic determinant of an open system by assuming the value of $x_3(t) = 0$ in the second equation of system (12). Having performed the transformations of the operating matrix of the derived system similar to that presented above, we will have

$$\Delta_0(p) = \det N_M(p) \det N_c(p) \det [H_0(p) + W_c(p) + W_M(p)]. \tag{13}$$

The relationship between the values of $\Delta(p)$ and $\Delta_0(p)$ is established by the relation

$$\Delta(p) = \Delta_0(p) \det [E + R(p)], \tag{14}$$

where $R(p) = [H_0(p) + W_s(p) + W_m(p)]^{-1}[H(p) - H_0(p)]$. The determinant of matrix $E + R(p)$ is reduced to the form

$$\det [E + R(p)] = 1 + K(p),$$

where K(p) is the sum of all the main l-order minors $(1 \leq l \leq n)$ of the determinant of transfer matrix R(p) and $K(p) = L(p)/\Delta_0(p)$; L(p) is some polynomial of p.

Let us assume that system (12) is asymptotically stable in the closed state with respect to the mutual effect channels. This assumption conforms to that of the asymptotic stability of the complex of manipulator systems taken separately, i.e., systems determined without regard to interference.

For stability of manipulator control systems, it is then necessary and sufficient that the hodograph of function $K(j\omega)$ not encompass point $(-1, j0)$ upon variation of frequency ω from 0 to ∞. This algorithm for analyzing stability can be accomplished on a digital computer.

In the low-frequency range for elements of transfer matrix $W(j\omega)$, the following relations are valid

$$W_{ik}(j\omega) \approx \begin{cases} C_{ik}/C_{ii} & \text{at} \quad i \neq k, \\ W_{\text{м}i}(j\omega)/C_{ii} & \text{at} \quad i = k. \end{cases} \tag{15}$$

For the high-frequency range, we have

$$W_{ii}(j\omega) \approx -\frac{\det a_{ii}}{\det a} W_{\text{м}i}(j\omega). \tag{16}$$

It follows from expressions (14), (15) and (16) that $|K(j\omega)| \approx 0$ in the low-frequency range and the approximate equality

$$K(j\omega) \approx \det a \Big/ \prod_{i=1}^{n} a_{ii} - 1.$$

is valid in the high-frequency range.

Therefore, when approximating the construction of the hodograph $K(j\omega)$, it is sufficient to limit oneself to the low-frequency range (Figure 5).

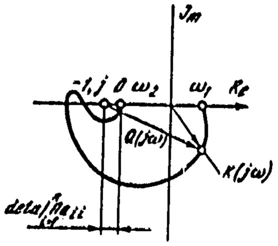

Figure 5

Since the significance of the fraction $\det a \Big/ \prod\limits_{i=1}^{n} a_{ii}$ may be considerably less than unity, consideration of the hodograph in the high-frequency range is not convenient. Therefore, the hodograph of function $Q(j\omega) = 1 + K(j\omega)$, which may also serve as an indicator of the control system interaction, may be constructed instead of hodograph $K(j\omega)$.

5. Analysis of the dynamic properties of manipulator control systems based on frequency methods. The frequency characteristics of separate systems correspond to diagonal, while those of cross couplings correspond to nondiagonal elements of the matrix

$$W(j\omega) = X^{-1}(j\omega) W_{\text{и}}(j\omega). \tag{17}$$

Let us represent each of the matrices in the form of the sum of two matrices -- with real and imaginary elements. The significance of the matrix elements at different fixed values of frequency is determined by addition, multiplication and conversion of matrices with complex elements.

To determine the degree of distortion of the frequency characteristics of a system taken separately as a function of the values of the parameters of other systems of the complex, it is suggested that the following estimates be used

$$\delta_i(\omega) = 1 - |\Delta_i(j\omega)|, \quad \Delta_i(j\omega) = \hat{X}_{ii}(j\omega) X_{ii}(j\omega), \tag{18}$$

where $\hat{X}_{ik}(j\omega)$ are elements of matrix $X^{-1}(j\omega)$. In this case the frequency characteristic of the i-th separate system $W_{ii}(j\omega)$ may be expressed by the frequency characteristic of the corresponding system $\widetilde{W}_i(j\omega)$ taken separately in the following manner:

$$W_{ii}(j\omega) = \Delta_i(j\omega) \widetilde{W}_i(j\omega). \tag{19}$$

The validity of the following equality follows from the properties of the product of the direct and inverse matrices

$$W_{ii}(j\omega)\hat{W}_{ii}(j\omega) = 1 - \sum_{\substack{k=1\\ k\neq i}}^{n} W_{ik}(j\omega)\hat{W}_{ki}(j\omega), \tag{20}$$

where $\hat{w}_{ki}(j\omega)$ are elements of the k-th column of matrix $W^{-1}(j\omega)$.

Comparing relation (20) with expression (19), we have

$$W_{ii}(j\omega)\hat{W}_{ii}(j\omega) = \hat{X}_{ii}(j\omega)X_{ii}(j\omega) = \Delta_i(j\omega),$$

hence follows the relation

$$|\Delta_i(j\omega)| = \left|1 - \sum_{\substack{k=1\\ k\neq i}}^{n} W_{ik}(j\omega)\hat{W}_{ki}(j\omega)\right|. \tag{21}$$

The following inequality is then valid

$$\delta_i(\omega) = 1 - |\Delta_i(j\omega)| \leqslant \sum_{\substack{k=1\\ k\neq i}}^{n} |W_{ik}(j\omega)\hat{W}_{ki}(j\omega)|$$

and one can write

$$\delta_i(\omega) \leqslant \sum_{\substack{k=1\\ k\neq i}}^{n} |W_{ik}(j\omega)\hat{W}_{ki}(j\omega)|. \tag{22}$$

Let us denote

$$|W_{ik}(j\omega)\hat{W}_{ki}(j\omega)| = \bar{\delta}_{ik}(\omega).$$

According to inequality (22), we find

$$\delta_i(\omega) \leqslant \sum_{\substack{k=1\\ k\neq i}}^{n} \bar{\delta}_{ik}(\omega). \tag{23}$$

It follows from expression (23) that the extent of distorting the frequency characteristic of the i-th system taken separately is greater, the larger the modulus of each of the terms on the right side of inequality (23), and the k-th system for which $\bar{\delta}_{ik}(\omega) > \bar{\delta}_{il}(\omega)$, i, k, l = 1, ...n, i ≠ k, k ≠ l and l ≠ i, will have the strongest effect on the dynamics of the i-th system. The "contribution" of the k-th following system to distortion of the dynamic properties of the i-th system, which occurs due to interference of the control systems through the slave member, can be judged by the value of $\bar{\delta}_{ik}(\omega)$.

Realizing the proposed algorithms on a digital computer, one can accomplish multilateral investigation of the dynamic properties of manipulator control systems by performing actions with complex matrices.

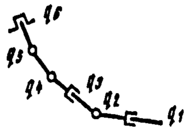

Figure 6

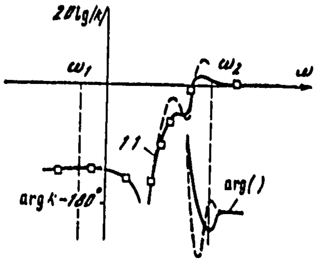

Figure 7

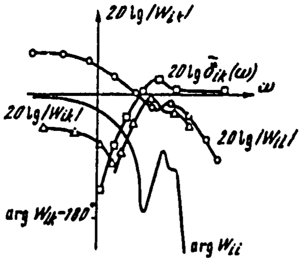

Figure 8

These algorithms are the basis of the developed library of standard computer programs which permit calculation and subtraction of the frequency characteristics of the channels of a multicoupled manipulator control system on the graph plotter of a digital computer and which permits analysis of its dynamic properties.

Example. The effectiveness of the proposed algorithms is illustrated in the example of investigating the dynamic properties of a six-section manipulator. The kinematic diagram of the slave member of this manipulator is presented in Figure 6.

Function $k(j\omega)$, calculated on the digital computer for several positions of the kinematic chain, is presented in Figure 7. It is obvious that the hodograph of function $K(j\omega)$ for the considered manipulator does not encompass the point (-1, j0). Therefore, the manipulator control systems are also stable with regard to interference.

It is more feasible to calculate function $Q(j\omega) = 1 + K(j\omega)$ with respect to manipulator control systems. Since $Q(j\omega)$ directly links the value of the frequency characteristics of complexes of separate systems and those taken separately, i.e.,

$$\Delta(j\omega) = Q(j\omega)\,\Delta_0(j\omega),$$

then consideration of function $Q(j\omega)$ permits one to also judge the effect of system interaction on the properties of a complex of systems taken separately, besides determining the fact of the stability of separate systems (according to the arrangement of curve $Q(j\omega)$ with respect to point (0, j0)).

The results of calculating the frequency characteristics of separate manipulator control systems and also of functions $\delta_{ik}(\omega)$ are presented in Figure 8. It is obvious from the figure that the interaction of control systems leads to significant variations in the properties of separate control systems and to the appearance of the cross effect of external actions. In this case functions $\delta_{ik}(\omega)$ determine the "contribution" of k-th control systems to distortion of the dynamic properties of the separate i-th system.

The proposed algorithms may be the basis for universal investigation of the dynamic properties of tracking manipulator control systems.

BIBLIOGRAPHY

1. Whitney, D. E., "Resolved Rate Control of Manipulators and Human Prostheses," IEEE TRANS. ON MAN-MACHINE SYSTEMS, June 1969.

2. Saenger, E. L. and C. D. Pegden, "Terminal Pointer Hand Controller and Other Recent Teleoperator Controller Concepts," Proceedings of the First National Conference on Remotely Manned Systems, California Institute of Technology, 1973.

3. Nevins, I. L. and D. E. Whitney, "The Force Vector Assembler Concept," ICISM-JFTOM Symposium on Theory and Practice of Manipulators, Udina, Italy, September 1973.

4. Maslova, N. K. and A. S. Yushchenko, "Some Algorithms for Manipulator Control Using Digital Computers," IZV. VUZOV, MASHINOSTROYENIYE, No. 2, 1975.

5. Kuleshov, V. S. and N. A. Lakota, "Dinamika sistem upravleniya manipulyatorami" [The Dynamics of Manipulator Control Systems], Moscow, Energiya, 1975.

6. Stepanenko, Yu. A., "Algorithms for Analysis of the Dynamics of Three-Dimensional Mechanisms With Open Kinematic Chain," in "Mekhanika mashin" [The Mechanics of Mashines], No. 44, Moscow, Nauka, 1974.

7. Popov, Ye. P., A. F. Vereshchagin, A. M. Ivkin, A. G. Leskov and V. S. Medvedev, "Construction of Robot Control Systems Using Dynamic Models of Manipulating Devices," Report at the Sixth International Symposium of IFAK "Control in Space," Yerevan, Izd. Arm. NIINTI, 1974 (Rotaprint).

8. Leskov, A. G. and V. S. Medvedev, "Analysis of the Dynamics and Synthesis of Motion Control Systems of the Slave Members of Manipulators," IZV. AN SSSR, TEKHNICHESKAYA KIBERNETIKA, No. 6, 1974.

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GEOPHYSICS, ASTRONOMY AND SPACE

ALGORITHMS FOR COMBINATION AND SUPERVISORY CONTROL OF MANIPULATOR-ROBOTS

Moscow DATCHIKI I VSPOMOGATEL'NYYE SISTEMY KOSMICHESKIKH APPARATOV. ROBOTY I MANIPULYATORY. TRUDY IFAK in Russian 1978 signed to press 8 Aug 78 pp 124-127

[Article by Ye. P. Popov, A. F. Vereshchagin, V. L. Generozov, S. L. Zenkevich and V. B. Kucherov, USSR]

[Text] The most modern manipulator-robots of today combine human intellectual capabilities and the capabilities of high-speed computer equipment in the control system. Man can solve a wide range of target designation problems both at the level of controlling the speed, trajectory or position of the manipulator and at the level of forming subtargets of the computer in the combination and supervisory control modes [1], which transforms these subtargets by means of control algorithms into direct instructions to the slave drives of the robot.

Let us consider the functions of control algorithms when the human operator is introduced into the process of automatic control of the actions of a manipulator-robot at a high level of the hierarchical control system by assigning the required technological operation to the robot in generalized form.

The control hierarchy. The problem of controlling the slave member of the manipulator-robot from a digital computer when performing a given operation in the automatic mode can be divided into three main steps determined by three hierarchically related levels of the control system.

Generalized information which determines the content of the operation and also the location of the required objects and tools is fed to the higher-level input, called the strategic level [2]. This level, usually relying on heuristic procedures, separates the operation into a sequence of elementary grasping motions which change position and orientation. In this case the given operation is converted by the higher-level algorithm into a sequence of macroinstructions, for example, of the following type:

$$\theta(s_1, p_1); \quad \theta(s_2, p_2); \quad \ldots; \quad \theta(s_n, p_n),$$

where s is the parameters of the final state of grasping and p is the parameters which determine the mode of transition to state s (for example, motion in a straight line with retention of orientation, provision of given force by grasping and so on).

The problem of the next level, called the tactical level, is conversion of the macroinstructions of elementary grasping motions to laws of matched variation of generalized coordinates of the slave member in which grasping changes according to the given mode of motion from the current position to the given final position.

If motion during each stage of mobility is provided by a self-contained drive, the output of the tactical level of control is the input control signals of these drives -- the desired laws of motion in the movable joints of the mechanism.

The last, slave level of control is formed by the combination of the tracking drives. The input of this level is the desired laws of motion in the movable joints with regard to the permissible speeds and accelerations of the drives and other restrictions.

These laws may be calculated by two methods at the tactical level.

The control signals of the drive in the entire range of control which realizes the macroinstruction are determined in time and calculated for any macroinstruction of type $\theta(s, p)$ in the first method. Moreover, the length of execution is a function of the permissible speeds and accelerations of drive tracking [4]. The digital computer then generates these signals, usually represented in the form of spline-functions at the drive input for execution.

The second method assumes sequential correction of the grasping position by calculation and realization of the sequence of small increments of the generalized coordinates of the slave member [3]. Linearization with subsequent solution of linear equations and inequalities is used extensively when calculating small increments of generalized coordinates.

The tactical level of control should have the capability of using both the first and second method of control. The first method is convenient when performing complex operations which permit preliminary planning. The second method is especially convenient when performing one-time small movements, but also permits one to perform complex grasping motions.

Elementary problems of planning trajectories in those cases when performance of one or another motion is standardized or when the higher level of control does not place any restrictions on the method of transferring grasping to given positions are also solved at the tactical level.

Thus, the digital computer solves three main problems at the tactical level: planning of elementary grasping motions, separation of goal-oriented grasping motion to matched motions of self-contained drives and, finally, formation of drive control signals with regard to the technical capabilities. One of the forms of realizing this control ideology is described in [4].

The inverse operator problem. The result of a digital computer operating at the stage of planning the elementary motion may be a sequence of vectors

$$s^1, s^2, \ldots, s^m,$$

which determine the position and orientation of grasping at sequential points of the required trajectory. If each drive controls variation of one generalized coordinate of the slave member, it is primarily of interest to describe the trajectory of motion in terms of generalized coordinates. A system of nonlinear equations determined by the design and current configuration of the slave member must be solved for this purpose for each node of the trajectory

$$s^i = f(q^i), \quad i = 1, 2, \ldots, m, \tag{1}$$

where $q^i = (q^i_1, q^i_2, \ldots, q^i_n)$ is the vector of generalized coordinates.

The effectiveness of control depends primarily on how quickly and clearly this inverse problem is solved on the digital computer.

The matrix of generalized coordinates is found as a result of solving a sequence of inverse problems

$$(q^i_j), \quad i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots, n,$$

corresponding to the required grasping trajectory.

The problem of constructing these continuous control signals, which take into account the technical capabilities of the drives, and of the following sequence of moments of time now occurs

$$t_1 < t_2 < \ldots < t_{m-1} < t_m,$$

to which the following conditions are fulfilled

$$q_j(t_i) = q^i_j$$

and the control time t_m is minimum.

In control by the second method -- the method of small sequential changes of the position of the slave member, the inverse problem reduces to the need to solve linearized equations

$$\Delta s^i = s^{i+1} - s^i \cong J(q^i)\,\Delta q^i, \qquad (2)$$

where J is a Jacobian matrix for the right sides of equations (1) to determine variation of Δq by the given increment Δs of the vector of state of grasping.

If n = 6 and the kinematic diagram of the mechanism is selected in a suitable manner, the inverse problem can be solved precisely both in the nonlinear and in the linear variant. However, the absence of a solution at some points of the trajectory, degenerate situations, ambiguity and restrictions on the generalized coordinates force one to seek special methods of realizing the planned trajectories. The problem becomes considerably more complex at $n > 6$, since in this case additional problems related to the need to overcome the excess degrees of mobility occur. For example, what minimum group of drives realizes the given motion by the number of drives? If the drives are distinguished by priority, which drives and to what extent should they participate in motion?

One can answer these questions if the sequence of linearized problems (2) is solved during the control process by the linear programming method [3].

Linear programming of motion. Let us represent the desired values in the form of the difference of two new nonnegative variables:

$$\Delta q_j = x_j^+ - x_j^-, \quad x_j^+ \geqslant 0, \quad x_j^- \geqslant 0.$$

Let us find the nonnegative vector x of dimension 2n + 1, which minimizes the linear function

$$x_{n+1} + \sum_{i=1}^{n} \gamma_i (x_i^+ - x_i^-), \quad \gamma_i \geqslant 0$$

with linear restrictions

$$-x_{n+1} \leqslant \sum_{j=1}^{n} J_{ij}(x_j^+ - x_j^-) - \Delta s_i \leqslant x_{n+1}, \quad i = 1, 2, \ldots, 6$$
$$G_k^- - q_k \leqslant x_k^+ - x_k^- \leqslant G_k^+ - q_k, \quad x_k^+ \geqslant 0, \quad x_k^- \geqslant 0, \quad x_{n+1} \geqslant 0,$$

where J_{ij} is elements of matrix J and (G_k^-, G_k^+) is the lower and upper bounds of values of the k-th generalized coordinate.

Let us note the characteristics of the given linear model. If max $\gamma_i \ll 1$, we are practically talking about Chebyshev approximation of grasping motion to the instruction vector of increments Δq. Moreover, positive penalties γ_i eliminate those idle motions of drives which do not lead to grasping motion in combination and if $\gamma_i > \gamma_j$, preference will be given to a drive with the number j with equal contribution to the resulting grasping motions. Finally, doubling the number of variables does not lead here to ambiguity if the simplex method is used to solve the problem, since the following will occur if it is used

$$x_i^+ x_i^- = 0.$$

Control using a linear model consists of the following steps:

1. Measuring the values of the generalized coordinates.

2. Determining the instruction vector of variation of the grasping position Δ s if the goal of control has not yet been achieved.

3. Formation of the linear programming problem and solution of it.

4. Working out the calculated increments of generalized coordinates by the drives.

5. Return to the first step.

The human operator in the considered hierarchical control system may participate in control not only at the highest level. For example, the operator may directly control the grasping position (vector s) or its increment (Δ s) by means of a special lever. In this case the digital computer solves only problems of matched variation of generalized coordinates and formation of input drive signals.

However, realization of the total hierarchical robot and manipulator control structure requires a computer complex consisting of two digital computers: a large digital computer which permits programming of complex problems in high-level languages and a mini-computer which receives output information of higher levels and which generates control signals for the slave drives.

The proposed control structure permits one to develop control systems differing in the designation and design of robots and manipulators. The considered algorithms for combination and supervisory control are realized by simple hardware and can be used to perform various operations by robots of any types.

BIBLIOGRAPHY

1. Popov, Ye. P., "Combination and Supervisory Control of Manipulator-Robots," Proceedings of the Sixth All-Union Conference on Problems of Control, Vol. 2, 1974.

2. Ignat'yev, M. B., F. M. Kulakov and A. M. Pokrovskiy, "Algoritmy upravleniya robotami-manipulyatorami" [Algorithms for Manipulator-Robot Control], Moscow, Mashinostroyeniye, 1972.

3. Vereshchagin, A. F., V. S. Generozov and V. B. Kucherov, "Algorithms for Control of Manipulators by the Velocity Vector," IZV. AN SSSR, TEKHNICHESKAYA KIBERNETIKA, No. 3, 1975.

4. Paul, R., "Modeling, Trajectory Calculation and Servoing of a Computer-Controlled Arm," STANFORD ARTIFICIAL INTELLIGENCE PROJECT, 1972.

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GEOPHYSICS, ASTRONOMY AND SPACE

THE PROBLEM OF PERCEPTION AND SYNTHESIS OF A MODEL OF THE EXTERNAL ENVIRONMENT BY A SELF-CONTAINED PLANETARY ROVER

Moscow DATCHIKI I VSPOMOGATEL'NYYE SISTEMY KOSMICHESKIKH APPARATOV. ROBOTY I MANIPULYATORY. TRUDY IFAK in Russian 1978 signed to press 8 Aug 78 pp 132-140

[Article by L. N. Lupichev, G. A. Buyvolov and T. M. Vorob'yeva, USSR]

[Text] On the stereo television method of terrain perception. Self-contained planetary rovers which perceive information about the real external environment and which utilize this information for "intelligent" behavior, will in the future be the main ambassadors to the remote planets. In this regard visual perception of the surrounding terrain by a planetary rover is one of the primary problems, solution of which is required for development of these planetary rovers.

In our postulation, visual perception is regarded as a problem of restoring the terrain from which a stereo pair of images was obtained. In this case the known elements are the arrangement of the optical axes and the focal distance of the stereo cameras.

In solving the problem, it is permissible that diffuse light reflection occurs and also that the image brightness of the terrain objects not depend on the distance from the object to the camera. The function of stereographic photograph brightness is determined as a real function of two variables which has sufficiently "good" properties such as continuity and integrability.

Solution of the problem consists in the following. The brightness functions $u_1(x_1, y_1)$ and $u_2(x_2, y_2)$ of the left and right stereo image, respectively, are equalized. The coordinates of the image points x_1, y_1 and x_2, y_2 are expressed by means of direct photogrammetric transformations by coordinates of the corresponding x, z, y on the terrain (Figure 1).

Then

$$u_1 [x_1 (x, y, z), \quad y_1 (x, y, z)] - u_2 [x_2 (x, y, z), \quad y_2 (x, y, z)] = 0. \tag{1}$$

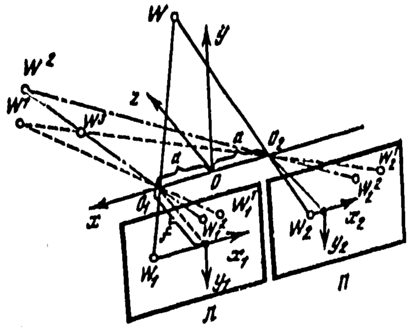


Figure 1. Stereo Pair Coordinate System With Zero Convergence Angle: w -- point of perceived surface; w_1 and w_2 -- image of point in left (L) and in right (P) remote cameras, respectively; o_1 and o_2 -- objectives of left and right remote cameras

The solution of equation (1) is not the only one. Finding the true solution is based on the use of the smoothing functional. This capability ensues from the theorem proved below, which states that for the case when the surface is described by a continuous function, any false solution is described by a function with a finite number of breaks.

Theorem. Let the brightness function u(w) of points $w \in G$, where G is a set of points of the perceived surface, have at least one extreme value $u^{e1}(w^1)$ or several extreme values

$$u^{e1}(w^1),\ u^{e2}(w^2),\ \ldots,\ u^{ei}(w^i),\ \ldots$$

such that among them there is no single pair of extreme values equal in brightness, i.e.,

$$u^{ei}(w) \neq u^{ej}(w),$$

where $i, j = 1, \ldots, n;\ i \neq j$.

Let there be some set $G^k \subset G_{12}$ and $G_{12} \supset f_{12}(G)$, where G_{12} is a set of all pairs of points of equal brightness of the left and right images and $f_{12}(G)$ is the mapping of G onto G_{12}, then

$$G \subset f_{12}^{-1}(G_{12}).$$

If

$$f_{12}^{-1}(G_{12}) \setminus G = G_n \neq \phi,$$

i.e., the set of false solutions G_1 does not have an empty interior and $G^k \cap G_1 \neq \phi$, i.e., G^k contains at least one false point. The set G^k is then not a set of the values of the continuous function $y_1 = y_1(x, z)$, where y_1 is a false solution.

Proof. Let us consider two points of equal brightness w^1 and w^2 of the true surface with coordinates x^1, z^1, y^1 and x^2, z^2, y^2, respectively. Let us assume that a false solution is found by the image of point w^1 on the right screen w_2^1 and by the image of point w^2 on the left screen w_1^2 in the form of a false point with coordinates x^3, z^3, y_1^3 (y_1^3 is a false height). Let us assume that w^1 is a local maximum (minimum) brightness function $u(x, z)$. Then, according to the conditions of the theorem, w^2 is not a point of an extreme value of brightness. Let us impart as many small increments δx^2 and δz^2 as desired to coordinates x^2, z^2 such that

$$u(x^2 + \delta x^2, z^2 + \delta z^2) > (<)\, u(x^2, z^2).$$

But it is impossible to find a point which satisfies the condition

$$u(x^1 + \delta x^1, z^1 + \delta z^1) > (<)\, u(x^1, z^1).$$

by determining the extreme value in the vicinity of point w^1 with coordinates $x^1 + \delta x^1$, $z^1 + \delta z^1$. Therefore, function $y_1(x, z)$ at point x^3, z^3, y^3 undergoes a break due to the continuity of the photogrammetric transformation. The theorem is proved.

The smoothing functional for the lines of intersection of the surface by plane xz (we note that the other surface cross-sections can be found by rotating the camera around the x-axis) has the form

$$M^{\beta}[x, z(x)] = \int_A^B \left\{ v^2[x, z(x)] + \beta \left(\frac{dz(x)}{dx} \right)^2 \right\} dx, \qquad (2)$$

where $z(x)$ is the distance to the line of intersection of the surface by plane xz; β is a parameter,

$$v[x, z(x)] = u_1[x_1(x, z(x))] - u_2[x_2(x, z(x))].$$

In the case of a zero angle of convergence, the direct photogrammetric transformations have the form

$$x_1 = \frac{f}{z}(x - a) \qquad x_2 = \frac{f}{z}(x + a), \qquad y_1 = y_2 = \frac{f}{z}\, y,$$

where f, a is the focal distance of the stereo camera and the base, respectively, and

$$v[x, z(x)] = u_1[f(x-a)/z] - u_2[f(x+a)/z].$$

The second term of (2) provides selection of the "smoothest" function or a function which minimizes the norm of the derivative

$$\beta\int_A^B \left(\frac{dz(x)}{dx}\right)^2 dx.$$

The true solution z(x) is found from the Euler equation for the Lagrangian smoothing functional (2)

$$\beta\frac{d^2z}{dx^2} + \varphi(x, z) = 0, \qquad (3)$$

where

$$\varphi(x, z) = \frac{f}{z^2}\{u_1[f(x-a)/z] - u_2[f(x+a)/z]\} \times$$
$$\times \{[\partial u_2(x_2)/\partial x_2](x+a) + [\partial u_1(x_1)/\partial x_1](x-a)\} = 0.$$

In this case the values of coordinates at the reference points of terrain are taken as the initial conditions x_0, z_0, z'_0. The reference points are determined by means of the "mask" method. The "mask" method is based on the idea of using information about the surroundings of the point to establish a pair of points of brightness functions of the left and right photographs corresponding to the same point of terrain. Due to the fact that comparison of each point of one image with each point of another image results in an impermissibly large volume of calculations (N^2 comparison operations if N is the number of image points), it is suggested that some typical, confidently identifiable surroundings of points -- "masks" -- be used. The "masks" may be rectilinear, concave or convex sections of the contour arranged in different directions (Figure 2). The main feature of stable "masks" is the connectedness of the "black" and "white" zones and the simplicity of the interface (Figure 2, a-d). "Masks" which do not satisfy this feature (Figure 2, e and f) do not provide clear fixation of the corresponding points (Figure 3). By comparing the "mask" with all points of the right and with all points of the left image, one can find a pair of points having similar "masks" and, consequently, similar surroundings to each other. To do this, a total of 2N comparison operations is required.

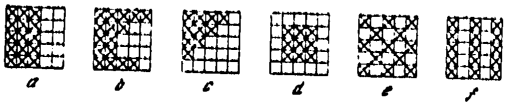


Figure 2. "Masks" for Establishing Corresponding Points: a-d -- stable; e and f -- unstable

It is suggested that the degree of conformity of the "mask" with the section of image be judged by the distance between the "mask" and the section of the image in space R^n, whose coordinates are the brightnesses of the individual elements of the "mask" and of the corresponding section of image.

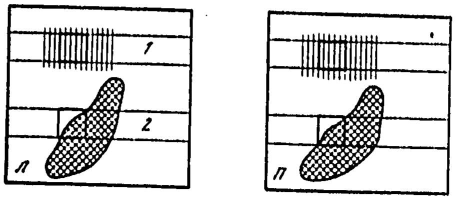


Figure 3. Example of Undecipherable Fixation of Corresponding Points Due to Instability of "Mask" (1) and Fixation of Stable "Mask" (2)

Example. The problem of restoring the terrain by a stereo pair of images is solved. Brightness functions $u_1(x_1)$ and $u_2(x_2)$ are presented in Figure 4. Equation (3) is solved, like the Cauchy problem, by the numerical method. In this case the initial conditions are determined by the "mask" method and the brightness functions $u_1(x_1)$ and $u_2(x_2)$ are represented in the form of discrete values with sufficiently large number of levels of discreteness. The developed calculating algorithm is applied to a specific section of terrain. The solution found in the form of the layout is shown in Figure 5. Here the real contour of the object on the terrain is depicted by the solid line and the solution of equation (3) is shown by the points.

The outlined procedure for restoring terrain by its stereo image without additional measurements of distance to individual objects of terrain, which utilizes ideas of the smoothing functional and the "mask" method, and specific calculation provide the basis to assume that an autonomous working program for visual perception of the surrounding situation by a self-contained planetary rover, realized with the permissible volume of calculations, can be developed on their basis.

Another simpler method, which however requires additional equipment, is that of perception of terrain by scanning with a laser beam.

Synthesizing a model of relief from rangefinder data. A laser scanning range finder permits one to obtain input information about relief directly in the

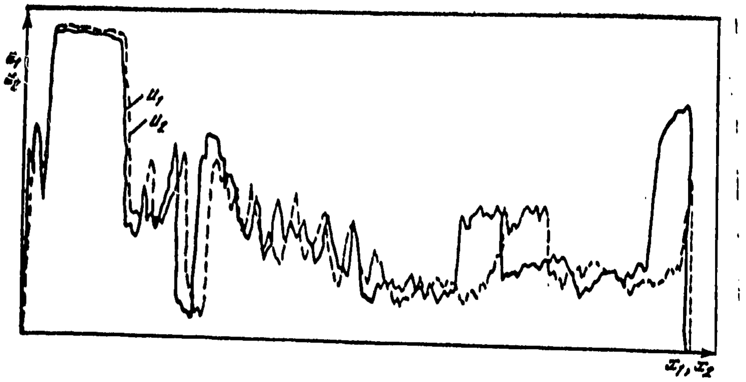


Figure 4. Brightness Functions of Stereo Pair of Terrain

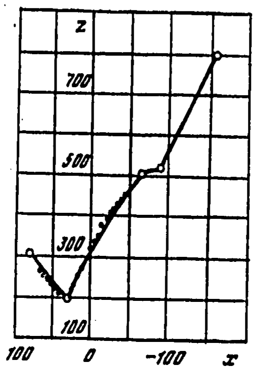


Figure 5. Fragment of Layout of Restored Section of Terrain

form of coordinates of a finite number of points of its surface. Restrictions on the height of location of the rangefinder under conditions of severely broken terrain leads to extremely nonuniform distribution of these points in the area of the photographed zone and significant surface regions may generally be inaccessible to observation since they are shielded by other sections of the same surface. This circumstance makes it very complicated and in some cases makes it impossible to investigate terrain in remote zones. However, the fact of the occurrence of screened zones contains specific and very significant information about the presence of one or another features of relief. Based on the "language" approach, it is possible to establish the corresponding semantic relationships and subsequently to operate with them when plotting a model of the relief and when determining forbidden zones. In combination with the gradient method, which takes into account the quantitative relationships between elements, introduction of semantic relationships permits one to represent the description of the model in more compressed form and to determine all the features of relief on it. Since restrictions in the storage capacity usually do not permit storage of the entire file of photographed points of the relief, compression and encoding of information should be conducted in real time parallel with its arrival. This is achieved by using the formation of two intermediate extreme matrices of dimension n x m: matrices $\{Y_{ij\ max}\}$ and $\{Y_{ij\ min}\}$, where $i = 1, \ldots, n$ and $j = 1, \ldots, m$. The cells of the extreme matrices are filled as coordinates x, y, z of relief points come in from the surveying system. The number of the line i and column j of the matrix where the number y should be directed is determined by coordinates x and z, but coordinates y_{ij} are recorded in the corresponding cell only after comparison with the contents of this cell. With this method, the number of storage cells is completely determined by selecting the dimension of the matrix and is independent of the number and distribution laws in the area of the photographed relief points, in other words, compression of any information flow to a previously given volume is guaranteed.

Besides information compression, the algorithm provides separation of screened zones since the corresponding cells remain unfilled. The process of synthesizing a relief model terminates with formation of a matrix of mean heights $\{Y_{ijsr}\}$, where $y_{ijsr} = 0.5\ (y_{ijsr\ max} + y_{ijsr\ min})$ and of a logic matrix $\{L_{ij}\}_0$ of zero step from the extreme matrices, to which information about the presence of screened zones and information about the presence of dangerous drops of heights inside the square $\Delta x_i \times \Delta z_j$, i.e., the information which would be unavoidably lost with averaging of heights by area, is rerecorded. The process of forming matrix $\{L_{ij}\}$ and of the language used in it will be considered below.

The relief model synthesized by the proposed method is sufficiently simple and compact, takes into account the characteristics of obtaining information about relief by the oblique-angled scanning method and specifics of operation of onboard digital computers, does not require large storage capacities and permits a search for dangerous zones and laying out trajectories without constructing any additional networks and reference graphs, reducing these operations to sequential transformation of matrix $\{L_{ij}\}_0$.

Determining forbidden zones. Let us relate the sections of surface not achievable to the apparatus and sections, entry into of which may lead to tipping over, to zones forbidden to traffic. The synthesized relief model and the presence of a resolver of data about the apparatus itself in the memory permit one to consider the problem of determining forbidden zone as comparison of the model of the apparatus capabilities with that of objectively existing external conditions.

The considered method of determining forbidden zone permits one to solve this problem by sequential transformation of the relief model. The concept of the shift operator $S_{i \pm k, j \pm 1}$, which permits comparison of the contents of the i and j cell with the contents of the i ± k and j ± 1 cell of the same matrix, is introduced for this purpose. Operator S can be given in matrix form and the shift operation is then carried out by multiplication of the matrices or it can be realized in the form of a comparison program. Let us call the operators which compare adjacent cells first-step operators. There will obviously be eight of these operators.

If one assumes that $k = 0$ and $l = 0$, we find the zero-step operator S_0 which, unlike the remaining operators, compares the contents of the cells with identical coordinates of different matrices. Operator S_0 is used in formation of matrix $\{L_{ij}\}_0$ from matrices $\{Y_{ij}\}_{max}$ and $\{Y_{ij\ min}\}$. The technical characteristics of the apparatus are modeled by a function of the estimate of passability $Q = f(\alpha_1, \ldots, \alpha_n)$, which takes into account the range of operator S_1, the geometric dimensions of the apparatus, its kinematic and dynamic characteristics, the capability of overcoming elements of relief of various type and so on. If the characteristics of the apparatus are known, then $Q = f(\alpha_1, \ldots, \alpha_n)$ may be represented in the form $Q = f(\alpha)$, where α is the range of operator S. The range of variation of α is limited by the geometric dimensions of the apparatus in the layout. The function of the estimate of passability represented in Figure 6 permits translation of the quantitative relations determined by the effect of operators $S_{i\pm k,\,j\pm l}$ on matrix $\{Y_{ij}\}$ to semantic relationships which are recorded in matrix $\{L_{ij}\}$.

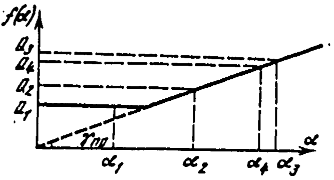


Figure 6. Function of Passability

The following glossary is used to describe the results of comparing the relief model with the capabilities of the apparatus in matrix $\{L_{ij}\}$: passable cell -- code "0," screened cell -- code "1" and forbidden cell -- code "2." Expansion of the glossary by taking into account the directions, for example, of the "cell covered in direction 5," divisions of zones with incomplete information into screened zones and zones located outside the visual field, taking into account the nature and stage of determining the coefficient -- "prohibition by height of obstacles," "prohibition by slope steepness," "prohibition of zero step" and so on, is possible. All transformations of matrix $\{L_{ij}\}$ are made with regard to the semantics of the content of its cells. This is achieved by establishing the hierarchy of codes. Thus, for example, when determining forbidden zones in a three-code system, the prohibition code has the highest priority, the screening code has the second priority and the passability code has the third priority. In the case of synthesizing a model of the external medium by survey data from two different points, the code hierarchy will be different, specifically, the passability code will be higher than the screen code. Different codes of the same rank are simply added.

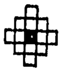
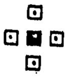
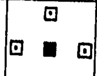
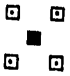
Шаг(1)	0	1	1'	2	2'	3	4
Матрица(2)	$\{y_{ij}{}^{\max}_{\min}\}$	$\{y_{ij\,\text{ср}}\}$	$\{L_{ij}\}_1$	$\{y_{ij\,\text{ср}}\}$	$\{L_{ij}\}_2$	$\{y_{ij\,\text{ср}}\}$	$\{y_{ij\,\text{ср}}\}$
Оператор(3)	■						
Оценка(5)	a_0	a_1	–	a_2	–	a_3	a_4
Результат(6)	$\{L_{ij}\}_0$	$\{L_{ij}\}_1$	$\{L_{ij}\}_{1'}$	$\{L_{ij}\}_2$	$\{L_{ij}\}_{2'}$	$\{L_{ij}\}_3$	$\{L_{ij}\}_4$

Figure 7. Structure of Algorithm

KEY:

1. Step
2. Matrix
3. Operator
4. Estimate
5. Result

To form forbidden zones around small-scale local obstacles determined only by short-range operators, the induction operation accomplished by the action of operators S_1-S_{12} directly on matrix $\{L_{ij}\}$ is introduced. The total structure of the algorithm is presented in Figure 7.

The considered algorithm permits one to determine dangerous zones for any relief and is universal in this respect. The boundaries of the forbidden zones are moved away from the obstacles by a distance which provides safety of the apparatus, regardless of the class of the obstacle and of at which step these obstacles were determined. The algorithm also takes into account the geometric dimensions of the apparatus, which subsequently permits consideration of the apparatus as a geometric point when laying out trajectories.

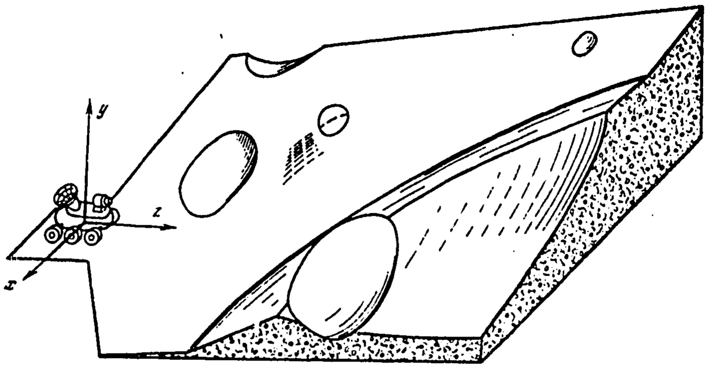


Figure 8. Fragment of Relief

The algorithm is easy to realize in machine languages of different level. The results of applying it to the fragment of relief depicted in Figure 8 are presented in Figure 9. Processing was carried out by the ICL 4-70 machine by a program written in FORTRAN language.

In cases where there is a priori information about the nature of the terrain, the algorithm can be truncated. Operation on even surfaces with separately arranged local obstacles can be accomplished successfully by using short-range operators and induction of prohibitions; in "dune" type terrain, one may be limited by use of only long-range third- and fourth-step operators; if there are no obstacles, processing can be stopped immediately after the zero step and so on.

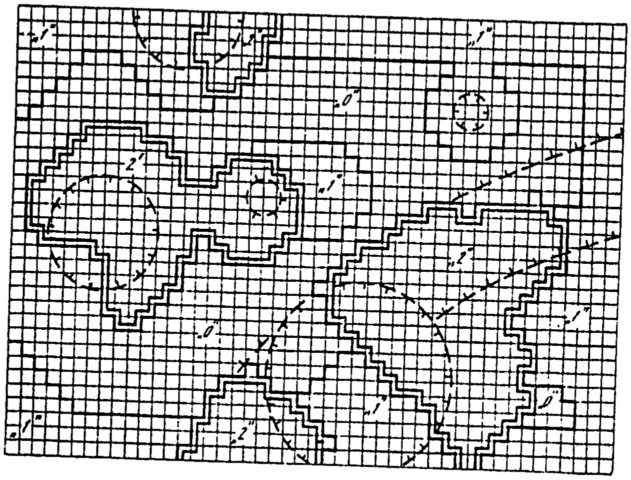


Figure 9. Results of Processing on Digital Computer

The structure of the algorithm also provides the possibility of self-teaching and adaptation of the robot. During prolonged functioning, the apparatus may move considerable distances and may find itself in sections made up of various types of rock with different supporting capacity. This circumstance requires operational reformation of the function of the estimate of passability, for example, by data of instruments of the scientific complex about the measured soil characteristics. Moreover, the characteristics of the apparatus itself may also change due to failure of individual subassemblies or reduction of its energy supply. It is hardly possible to take into account beforehand all variations of the external medium which may occur on a remote and insufficiently studied planet; therefore, problems of organizing the process of self-teaching and adaptation of the apparatus acquire special significance. The considered algorithm permits the apparatus to utilize its own experience rather simply and efficiently. Thus, for example, if conditions have principally changed, the apparatus will find itself in critical situations about which the sensors of the angles of inclination, tactile sensors, the motor overload protective system and so on will signal. If a time reduction of the threshold (horizontal section) of function Q corresponds to each case of response of the tactile sensor and reduction of angle γ of function Q corresponds to cases of an increase of the skidding coefficient or angles of inclination of the apparatus above permissible levels, in the final analysis the robot itself will determine the required measure of safety and will adapt to external conditions, including adaptation to variation of the soil characteristics in the previously unprovided range.

BIBLIOGRAPHY

1. Douglas, A. and O'Handly, "Scene Analysis in Support of a Mars Rover," COMPUTER GRAPHICS AND IMAGE PROCESSING, No. 2, 1973.

2. Mutch, T. A. and W. R. Patterson, "Examining the Martian Surface With the Viking Lander Camera," Proceedings of the American Society of Photogrammetry, 39th Annual Meeting, March 11-16, 1973, Washington.

3. Tikhonov, A. N., "Solving Incorrectly Postulated Problems and Methods of Regularization," DAN, Vol. 155, No. 3, 1963.

4. Koslov, B. L., L. N. Lupichev, E. N. Orel, J. K. Hodarev and I. V. Shamanov, "On a Method of Construction of Roving Vehicle Control System," Proceedings of the 21st Congress of the IAF, Constance, 5 October 1970.

5. "Kosmicheskaya ikonika" [Space Ikonics], edited by B. N. Radionov, Moscow, Nauka, 1973.

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GEOPHYSICS, ASTRONOMY AND SPACE

INVESTIGATING THE ALGORITHMS FOR CONTROLLING THE MOTION OF A SELF-CONTAINED PLANETARY ROVER BY THE MATHEMATICAL MODELING METHOD

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[Article by V. F. Vasil'yev, P. M. Gurvich, L. N. Lupichev and I. V. Shamanov, USSR]

[Text] Developing a system for controlling a self-contained planetary rover, moving by instructions from earth without direct participation of man in control, is related to solution of a number of problems [1]. The purpose of the motion of this apparatus may be to achieve some terminal zone or to cover a given route. It is assumed that the apparatus is equipped with a scanning system, computer, moving member control devices, navigation means, course, bank, trim, covered-path sensors and so on.

The onboard scanning systems permit reception of information only about a comparatively small, local section of the surface. A safe local trajectory of motion of the planetary rover should be determined from the results of its processing on the apparatus. The total (global) trajectory consists of the aggregate of local sections.

A system of interrelated algorithms should be developed for onboard solution of problems of processing information about the surface, determining a safe trajectory and controlling the motion of the planetary rover along this trajectory. Analysis of the efficiency and effectiveness of these algorithms during their joint operation can be carried out by using computer mathematical modeling of the controlled motion of the planetary rover along the surface. To do this, a mathematical model of a sufficiently large section of surface should first be constructed in the computer and the initial location of the apparatus and the direction of motion or the coordinates of the target should also be given.

Complex modeling of controlled motion includes the following steps:

-- determining the position of the axes of the apparatus (angles of bank and trim);

-- obtaining information about the section of surface (local zone) in front of the apparatus;

-- determining the passability in the local zone;

-- determining the trajectory of motion of the apparatus within the local zone;

-- modeling the motion of the apparatus along the trajectory.

As a result of sequential fulfillment of these steps, the apparatus "covers" some local section of the trajectory, after which all the steps are repeated, the apparatus "covers" the next local section and so on. Motion along a global trajectory is simulated in this manner.

Based on the outlined principles, a complex mathematical model, the block diagram of which is presented in Figure 1, was constructed.

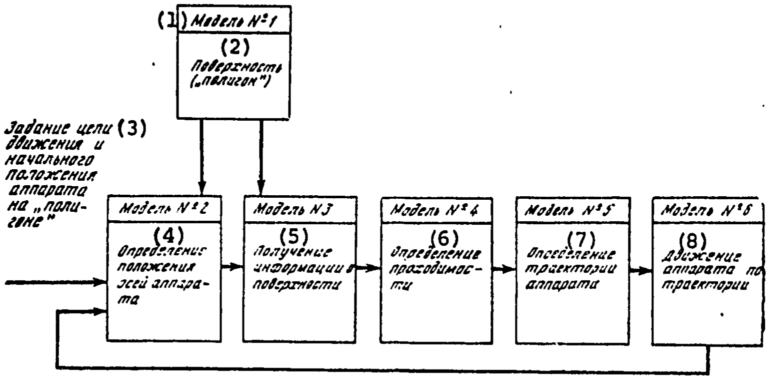

Figure 1

KEY:

1. Model No.
2. Surface ("test area")
3. Assignment of target, movement and initial position of apparatus on "test area"
4. Determining the position of apparatus axes
5. Obtaining information about the surface
6. Determining passability
7. Determining the apparatus trajectory
8. Motion of apparatus along trajectory

In model No. 1 the surface is shaped in the form of a "test area" with dimensions of 200 x 47 m. Different laws of variation of the total inclination of terrain and the distribution of obstacles on it (given in the form of "stones" and "craters") were used to obtain the various types of surfaces. The distribution density of obstacles is usually assumed to be quite high to check the investigated algorithms under complex conditions. Graphs of the distribution density of obstacles on the lunar surface [3] and on a test area (for one of its variants) are presented as an example in Figure 2. The surface was stored in the computer memory in the form of heights given with respect to the base horizontal plane and in nodes of some regular grid covering the test area. The boundary nodes of the grid form the conditional "fence" (so that the model of the apparatus remain inside the test area under all conditions).

Subsequently, the motion of the apparatus is meant as the motion of one of its points -- the arbitrary geometric center of the reference surface of the apparatus, while the trajectory of motion is understood as projection of the spatial trajectory of this point onto the base plane. It is obvious that in real situations, a specific position of the apparatus on a given surface clearly corresponds to the position of any point on this flat trajectory.

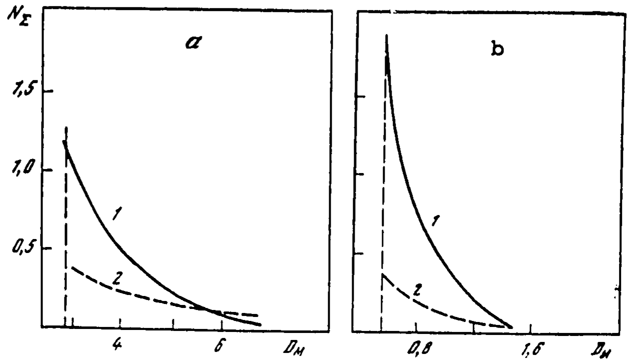

Figure 2. Graphs of Distribution Density of Obstacles on the Lunar Surface and on the Test Area: a -- "craters"; b -- "stones"; 1 -- surface of test area; 2 -- lunar surface; N_Σ -- number of obstacles per 100 m^2 with diameter greater than D

In model No. 2, the angles of bank and trim, i.e., the spatial position of the axes, were determined according to the position of the apparatus (given on the horizontal plane in the form of a point on the trajectory). "Setting" the apparatus on the surface of the test area was simulated for this purpose.

Simulating the surface scanning (model No. 3) included determination of the spatial coordinates of the points of intersection of the arbitrary "beams" of the scanning system with the model of the test area surface. Thus, only the geometric diagram rather than the physical process of scanning the surface was simulated. This approach is explained by the fact that on the one hand, it is sufficient in most cases for complex modeling to limit oneself to the geometric diagram of scanning without going into its physical details and on the other hand, it is very difficult to reflect with sufficient accuracy the complex physical processes occurring during surface scanning by using a mathematical model.

Different variants of the scanning diagram were used during modeling. The nominal local zone (i.e., the zone formed during scanning of a horizontal surface) was usually a sector (Figure 3). The scanning height (from 1.5 to 2.5 m), the azimuth angle of scanning (from 60 to 120°), the scanning range (from 8 to 13 m) and so on varied.

Information about the spatial coordinates of the measured points were used to analyze the passability of the zone in model No. 4. The safety of motion through some point of the surface was determined by such criteria as the value of the angle of deviation of the vertical axis of the apparatus from the local vertical, the presence of stones, scarps and cracks of impermissible dimensions and so on. The algorithms of model No. 4 are based on the principle of separating the local zone into three types of regions: authorized (safe) for traffic, forbidden to traffic and regions with incomplete information [1]. This separation was accomplished by analyzing the mutual arrangement of the measured points and by determining the sections on which the apparatus was in an impermissible position and also sections, the number of measured points on which is insufficient to analyze their passability.

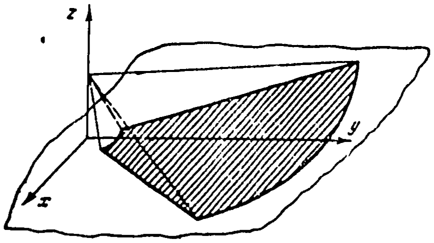

Figure 3

Another method of determining passability is based on mathematical modeling of the apparatus position on the surface. In this case it is possible, without separating the entire zone into three types of regions, to determine the safety of the trajectory by checking the apparatus position on the surface at a number of sequential points of the trajectory by the adopted criteria of permissibility.

The local trajectory (model No. 5) was selected in the following manner. Either a finite set of independent local trajectories or the characteristics of some class of trajectories distinguished by one or several parameters was stored in the computer memory. The trajectory from a given set or class was selected according to the adopted criteria of optimality. The safety of the selected trajectory and fulfillment of some boundary conditions which provide joining of two adjacent local trajectories were then checked. If the boundary conditions and the safety conditions were fulfilled, the trajectory for further

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motion was regarded as found, otherwise another trajectory was selected and so on.

One of the classes of trajectories investigated during complex modeling is presented in Figure 4. By changing the value of parameters a, R, b and φ, the meaning of which is obvious from the figure, one can obtain very diverse sets of trajectories which cover the local zone in a "fan." A sufficiently effective criterion of optimality for this class of trajectories is the criterion of the minimum angle of error between the direction of global motion and the direction of the trajectory at point B.

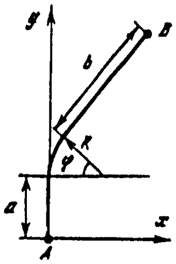

Figure 4

Different types of lateral maneuvering, backing up with subsequent travel to the side and so on were investigated on a model for situations in which the local zone was completely impassable.

In some cases the location of obstacles on the terrain may lead to "cycling" of the global trajectory. This phenomenon can be eliminated if the direction of global motion is controlled during bypassing of these obstacles. One of the very simple methods of controlling global motion is that in which intermediate targets are formed during motion and the direction of global motion is changed.

According to this method, an algorithm for global control is proposed which occupies a higher level of hierarchy with respect to algorithms for determining local trajectory.

The basis for constructing this algorithm is the dependence of the angle of direction toward intermediate targets on the angle of deviation of the current course of motion from the direction toward the initial target. The proposed algorithm, contained in model No. 5, does not permit the planetary rover to deviate far from the boundary of the obstacle and, thus preventing "cycling," provides bypassing of the obstacle.

The "motion" of the apparatus along the selected trajectory occurred in the last step (model No. 6). The motion controlled only by a time program or motion controlled by a program using feedback for elimination of deviations can be simulated here as a function of equipping the apparatus with covered path counting devices, its technical capabilities and methods of control.

A section of test area measuring 50 x 47 m, on which one of the trajectories of motion of a planetary rover constructed by the complex modeling method is shown as an example, is presented in Figure 5. In this variant the azimuth angle of scanning was equal to 90°, while the nominal scanning range was 12.5 m. Motion was organized by the start-stop principle, i.e., with stops of the apparatus to scan the surface and to select a trajectory for further motion. Local trajectories are related to the class presented in Figure 4. It was assumed during modeling that motion occurs without deviations from the selected trajectory. Investigations conducted by using a hybrid computer showed that motion along a given trajectory can be performed with sufficiently high accuracy with comparatively simple law of control of the members of motion of the apparatus [2].

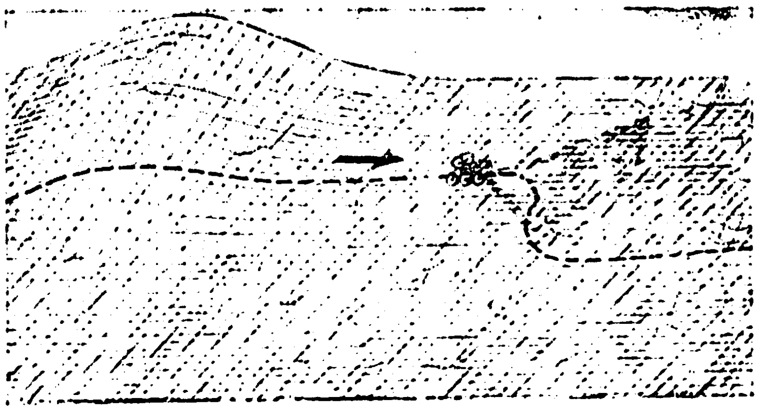

Figure 5

Some results of modeling. Different variants of algorithms contained in the model were investigated when working with a complex model.

The dependence of changes of configuration and area of the local zone on inclinations of the apparatus and on the surface relief was analyzed when simulating the receipt of information on the surface. These fluctuations may be significant in many situations. Maintaining an adequate scanning zone in front of the apparatus was possible by introducing control of the scanning system during its functioning or by introducing algorithms for selecting measured points of the surface in the model. A number of variants of this control was investigated which is based on variation of the scanning laws, inclination or rise of the transceiving part of the scanning system with respect to the body of the apparatus and so on.

A method of determining passability, based on separation of a local zone into three types of regions, was very efficient for purposes of selecting trajectories, although in the case of simple situations it is excessively cumbersome compared to direct modeling of the apparatus position on the checked trajectory.

Modeling showed that the class of local trajectories considered above and the proposed criterion of optimality usually permit motion along a very efficient global trajectory.

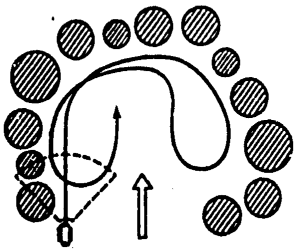

Figure 6

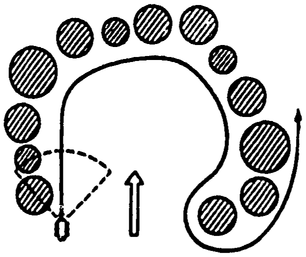

Figure 7

An increase of the azimuth angle of the scanning system is of great significance for increasing the maneuverability of the apparatus during motion along a surface with complex relief. It is feasible to have this angle not less than 90-120°. An increase of the scanning range, although desirable, is impossible in many situations since passability further than 10-12 m from the apparatus cannot be reliably estimated due to the scanning height.

Modeling showed that the use of algorithms which employ replacement of the direction of global motion is feasible when bypassing extended obstacles. The trajectories of motion of an apparatus for two cases: without and with the use of the proposed algorithm, are presented as an example in Figures 6 and 7.

BIBLIOGRAPHY

1. Petrov, B. N., L. N. Lupichev, V. I. Agafonov et al., "The Problem of Controlling Self-Contained Mobile Planetary Complexes," Proceedings of the Sixth International Symposium of IFAK, Tsakhkadzor, 1974, Moscow, Nauka, 1976.

2. Grayver, M. Yu., E. S. Skvortsov, A. A. Faynleyb et al., "Investigating a System for Control of a Self-Propelled Apparatus by Using a Hybrid Computer System," in "Primeneniye gibridnoy vychislitel'noy sistemy GVS-100 dlya resheniya zadach upravleniya" [Using the GVS-100 Hybrid Computer System to Solve Control Problems], Moscow, Institut problem upravleniya, 1975.

3. "Peredvizhnaya laboratoriya na Lune 'Lunokhod-1'" [The "Lunokhod-1" Mobile Laboratory on the Moon], Moscow, Nauka, 1971.

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GEOPHYSICS, ASTRONOMY AND SPACE

AUTOMATIC CONTROL OF A MOVING PLANETARY ROVER COMPLEX

Moscow DATCHIKI I VSPOMOGATEL'NYYE SISTEMY KOSMICHESKIKH APPARATOV. ROBOTY I MANIPULYATORY. TRUDY IFAK in Russian 1978 signed to press 8 Aug 78 pp 154-162

[Article by J. Benes and P. Kolar, Czechoslovakia]

[Text] Postulation of the problem. Automatic control of a self-controlled group (complex) of self-moving planetary rovers operating jointly to reach a given section of the surface of a planet is considered [1, 2]. The planetary rovers contained in the complex are connected to each other by thin metal wires whose length may vary. By using these wires, the planetary rovers can create forces acting on each other and they also serve as communications lines. The selected area can be assigned by means of topographic coordinates of the investigated planet or by the position of the field extremum of some physical value. Obstacles in the form of randomly variable three-dimensional structure of the relief and sections of soil which make it difficult for the planetary rover to adhere to the soil, i.e., shifting sands, stones and so on, may occur in the path toward the target. Three types of obstacles are considered. In overcoming an obstacle of type A, the planetary rover may tip over, but it can be overcome by means of the other planetary rovers by creating active tractive forces through the wires. An obstacle of type B cannot be surmounted by a planetary rover, but the metal wires connecting the planetary rovers can pass over it. Thus, these types of barriers includes holes and cracks in rock, from which the planetary rover is unable to extricate itself without the assistance of the other planetary rovers. An obstacle of type C is characterized by the fact that both the planetary rover and the connecting metal wires cannot pass through it.

Description of the moving complex. Complexes consisting of 9, 16 or 25 planetary rovers are typical. The complex is delivered to the planet in a container which opens up after landing. The complex is then rolled out onto the surface of the planet and the center of the lower left planetary rover is taken as the origin of the Cartesian system. The complex, i.e., all its planetary rovers, contain information about the target which must be reached and also about known or hypothetical operating conditions. The complex then represents a self-controlled system. The connecting links (metal wires) with four values of their length: 0, 1, 2 and 3, were considered in modeling.

Description of the planetary rover. The planetary rover, which is a component of the complex, consists of two main parts: a frame and a rotating part, as shown in Figure 1. The frame is a gimbal suspension for the rotating part.

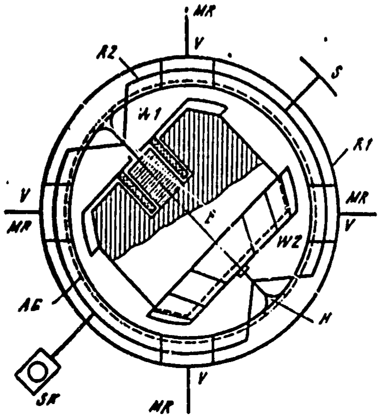

Figure 1. Operating Principle of Planetary Rover (Bottom View)

The rotating part consists of a ring with a recess for a yoke R2, main body B attached to it and two umbrella-shaped flywheels W1 and W2. The payload (scientific instruments and power supply) are located in the main body. It also contains cavities in which the electric motors of flywheels W1 and W2 are located. The "rotor" of each motor is attached to a fixed axis, while the "stator" rotates. Thus, the "rotor" and "stator" in these motors have opposite functions. The "rotor" axis is attached to the ring with the recess R2, to which it is attached. The inner races of the "stator" ball bearings are also attached to this axis. Two important devices: the main sensor S and spike SK with spring and ball located below ring R1, are placed on the ring with the recess.

The ring with the recess R2 can be rotated with respect to ring R1. One of the design solutions which provide this may be sliding of the front part of projection H along annular groove AG in ring R1. Instead of a sliding head, one can use two adjacent ball bearings. A pair of forces resulting from rotation of flywheels W1 and W2 in opposite directions is used to rotate ring R2. The electric motors can set the flywheels in motion: a) in opposite directions of rotation and b) in the same directions of rotation to provide forward motion of the planetary rover. The motor is reversed for regime a) and is switched off for regime b) during normal operation. We note that an alternative solution may be suggested for providing rotation of ring R2, namely, to make an auxiliary electric motor which would raise the telescoping feet for this purpose. In this case the feet themselves would descend due to the effect of gravity in mode a).

The frame is a ring R1. Four electric winches V with electromagnetic braking device for the metal wires MR are located on this ring. A computer which controls forward motion, power cables and payload, which must be located on the rotating part, are placed on the ring.

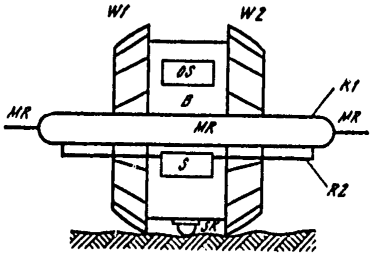

Figure 2. Working Principle of Planetary Rover (Front View)

The sensors of the planetary rover. All planetary rovers of the complex are equipped with the same sensors. Some of them can be disconnected since the use of the sensors is mutually interchangeable, which is provided for the case of damage of some planetary rovers or parts of them. The main sensor S (Figure 2) can switch on: 1) the sensor of obstacles of type A, which determines the characteristics of friction, rolling and sliding of soil; 2) the sensor of obstacles of type B; and 3) the sensor of obstacles of type C. The latter two sensors can be combined with an optical sensor OS installed on the main body B.

Each planetary rover is equipped with sensors which determine the forces of tension of the metal wires. Sensors which measure the scalar values of the scalar field, for example, temperature, may be installed as additional sensors and they are switched on only on the planetary rovers located in the corners of the complex since it is advantageous to have more remote distances during these measurements.

The operating principles and properties of the complex. The organization of the complex is based on the following principles.

1. All the planetary rovers of the complex are identical. Their difference consists only in the functions which the peripheral and inner planetary rovers perform, namely, which of their sensors are switched on to analyze the surrounding medium (to determine obstacles and the physical characteristics of the medium).

2. Non-hierarchical organization belongs at the basis of planetary rover control. There is a common decentralized time block which synchronizes the actions of the planetary rovers. Each planetary rover operates so as to reach the target together with its neighbors. This is achieved by using information about the location and state of adjacent planetary rovers and about the surrounding situation, which is used to coordinate the actions of individual planetary rovers.

The proposed solution of the problem permits one to increase the probability of reaching the target by using several jointly operating planetary rovers, which provide mutual assistance when obstacles occur in front of some of them, and to increase the functional dependability under unfavorable conditions if even some planetary rovers cease operation.

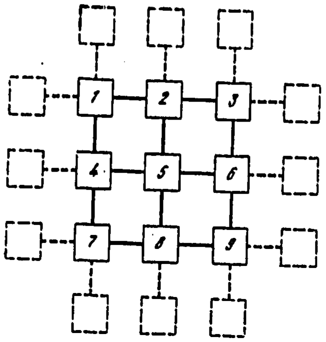

Figure 3. Model of Moving Complex

Investigations in bionics touching on: a) some remarkable properties of colonies of organisms (especially of subphylum Mastigophora of phylum Protozoa) and b) some remarkable properties of spiders (order Araneina) which utilize spider webs for different purposes, sometimes as an information carrier. The planetary rovers of the complex are connected in exactly the same way by thin metal wires in the center of which are conductors. The wires create tension which is measured by sensing elements and also serve as means of communications. There is also partial analogy between the complex and a joint group of plants creeping up rises.

Theoretical method of the investigation. Some planetary rovers of the just described self-contained self-controlled moving complex, operating according to a given algorithm, can be described in the form of finite automatons. From this viewpoint the complex is a finite array of internally connected, identical machines with finite states, each of which can change its own state within discrete time intervals as a function of the states of some of the other machines in the array, and the array is subject to specific effects of the surrounding medium. The appropriate mathematical model of these types of objects can be represented in the form of cellular or tetragonal-honeycomb automatons, in the theory of which well-known concepts of the index of neighborhood, local transition, transition function and configuration are used. Utilizing this theory as the reference point, we can obtain a model of a moving complex in the form of a finite array, as shown in Figure 3, which we will regard as part of an infinite array of a special cellular automaton. The automatons corresponding to individual planetary rovers are denoted by the numbers in the figure.

When the motion of the complex along the surface of the planet was simulated, we were not interested in the time evolution of the state of individual planetary rovers of the complex, but studied the arrangement of the complex on an unchanging surface. Therefore, we created a mathematical structure similar to a cellular automaton and called this the demonstration space.

1. Let us assume that an infinite plane is divided into equal squares with unit area. The center of one square is selected as the origin of the Cartesian system with axes parallel to the edges of the network of squares. The position of the center of each square is determined in this coordinate system by a pair of whole numbers. Let us assume that $D = \{(i, j): i, j$ are whole numbers$\}$. The elements of set D determine the position of individual squares of the array. The squares of the array represent the surface of the planet in the given scale.

2. We placed one identical copy of the automaton with a transition diagram indicated in Figure 4 in each square of the array, where $\bar{s} \in \{s_k^{(1)}: k = 4, \ldots, n$ and $1 = 0, \ldots, 4\}$. It is obvious that the set

$$S = \{s_0, s_1, s_2, s_3\} \cup \{s_k^{(l)}: k = 4, \ldots, n; \quad l = 0, \ldots, 4\}$$

is the set of states of automaton G.

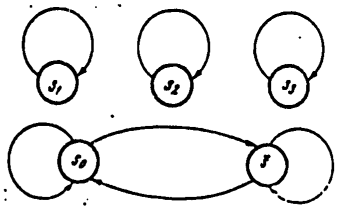

Figure 4. Diagram of Transitions of Automaton

When G_x, i.e., automaton x in square $x \in D$ is in one of states s_1, s_2, s_3 or s_0, this means that there are obstacles A, B and C in the corresponding region of the planetary surface or there are no obstacles, or the planetary rovers of the complex are not located there. If G_x is in state s_k^1, this means that the planetary rover of the complex with number k is located in the corresponding square of the planetary surface (see Figure 3) and is moving in direction 1. (If 1 = 0, 1, 2, 3, 4, the planetary rover is immobile, is moving upward, is moving downward, is moving to the right or is moving to the left, respectively.)

3. Let c be an arbitrary mapping from D to S, $c: D \rightarrow S$, and let A(D, S) be a set of all these mappings. We will refer to mappings c the same as for the configurations and set A(D, S) will be called the space of configurations. Let us briefly call image x, which is element D in configuration c, denoted as c(x), as the contents of x.

4. Let $N_c: D \rightarrow D^9$ be the function of the neighborhood of configuration c, given in the form

$$N_{c(x)}(x) = x + a_1, \ldots, x + a_5, x + a_6(c(x)), \ldots, x + a_9(c(x)),$$

where $x \in D$, $a_1 = (0, 0)$, $a_2 = (-1, 0)$, $a_3 = (1, 0)$, $a_4 = (0, -1)$, $a_5 = (0, 1)$, $a_i(c(x)) = y_i - x$, $y_i \in D$, $i = 6, 7, 8, 9$.

We note that for each value of $x \in D$ the neighborhood consists of two parts: a) a fixed part $x + a$, $i = 1, \ldots, 5$ and b) a variable part $x + a_i(c(x))$, $i = 6, 7, 8, 9$, which depends on contents x and may vary with variation of configuration c. The variable part of the neighborhood is considered only in cases when

$$c(x) \in \{s_k^{(l)}: k = 4, \ldots, n; l = 0, \ldots, 4\}.$$

Then y_i in expression $a_i(c(x)) = y_i - x$ is the coordinate of the position vector of the adjacent planetary rover of the moving complex in set D. If c(x) corresponds to a peripheral planetary rover which has a number of neighbors less than four in the complex (all the planetary rovers, with the exception of No. 5, will be peripheral in Figure 3), we then substitute $a_i(c(x)) = y_i - x$ for y_i, equal to any value $z \in D$, into the remaining expressions.

According to the same principle, we substitute any value of D in cases when

$$c(x) \notin \{s_k^{(l)}: k = 4, \ldots, n; l = 0, \ldots, 4\}$$

for y_i in all the variable part of the neighborhood.

Let us assume that N is a class of functions of neighborhood for all configurations c

$$N \in \{N_c: c \in A(D, S)\}.$$

Let us call class N the space of neighborhoods.

5. We shall assume that mapping

$$c(N_c): D^9 \to S^9,$$

determined in the form

$$c(N_{c(x)}(x)) = (c(x + a_1), \ldots, c(x + a_5), \\ c(x + a_6(c(x))), \ldots, c(x + a_9(c(x))).$$

is a configuration of neighborhood $x \in D$ to configuration c.

6. Let $\sigma : S^9 \to S$ be the mapping which satisfies the conditions

$$\sigma(c(N_{c(x)}(x))) = \sigma(c(x+a_1), \ldots, c(x+a_8)) \text{ для } c(x) = s_0,$$
$$\sigma(c(N_{c(x)}(x))) = \sigma(c(x+a_1)) = c(x) \text{ для } c(x) = s_k,\ k = 1, 2, 3.$$

Let us call mapping σ a local transformation.

Definition. The demonstration space is a space determined by four parameters (D, S, N, σ), where D is a set of ordered pairs of whole numbers, S is a set of states of the automaton indicated in Figure 4, N is the space of neighborhoods and σ is the local transformation.

$$\begin{tikzcd}
D \arrow[r, "c_0"] & A(D,S) \arrow[r, "N"] \arrow[drr, "\tau"'] & D^9 \arrow[r, "c"] & A^9(D,S) \arrow[d, "\sigma"] \\
 & & & A(D,S)
\end{tikzcd}$$

Figure 5. Operating Diagram

As can be seen from the definition, the specific nature of the demonstration space is determined by the characteristics of the cellular automaton indicated in Figure 4 and is mainly the innovation of introducing object N (the space of neighborhoods). The neighborhood of each automaton does not depend on the location occupied by the cell in the classical cellular automaton and remains fixed both in configuration and during the course of evolution of the cellular automaton. On the other hand, the neighborhood of each element is a function of the configuration of a given moment in the demonstration space and, therefore, varies with each step of discrete time.

It was assumed in old concepts of cellular automatons that a complex has fixed connecting links between elements; on the contrary, the demonstration space describes a complex with time-variable links between elements. The links vary at each step of discrete time, i.e., N is then a set of all possible links between elements of set D of the demonstration space.

The operating diagram. The operating diagram of transition from configuration c_t to configuration c_{t+1} is shown in Figure 5. The initial configuration of the demonstration space and thus the projection of the obstacles of the real surface of the planet in the corresponding elements of set D are given by mapping c (see the setting of the automaton to the corresponding isolated states in Figure 4). The cells of the automaton of that part of set D which corresponds to the initial position of the moving complex on the surface of the planet are simultaneously set to the corresponding states. The corresponding neighborhood and the configuration of neighborhood are determined during evolution of the demonstration space, which follows the given configuration c_t. It is obvious that mapping c(N) is actually a ninefold shift of configurations. The local transformation σ is given by the set of algorithms of behavior of individual planetary rovers. Let us indicate the conditions to which the transformations in the automaton should be subordinated: a) targets of all types should remain at the same location in all configurations and b) if the cell is empty, it gathers information only from the four adjacent neighbors. This situation can be changed only if the planetary rover is located at any of these neighbors and moves in the direction toward this cell.

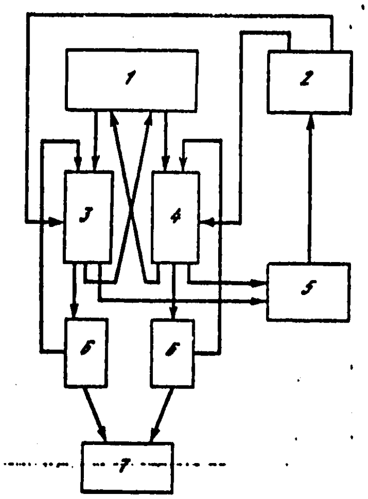

Figure 6. Diagram of Algorithm: 1 -- determination of direction from gradient; 2 -- random search of direction; 3 -- investigation of surrounding medium (x, -x); 4 -- investigation of surrounding medium (y, -y); 5 -- position of complex "running aground"; 6 -- length of connecting links; 7 -- new position of element

If the cell is in a state which indicates the presence of the same planetary rover in a given section of space, the algorithm of variation of state (i.e., transformation σ) is used, a block diagram of which is shown in Figure 6. The algorithm of the random search for direction, which will provide extrication of the complex from the "trap" of obstacles if possible "running aground" occurs, is also contained in this transformation. In this case the neighborhood is determined so that a given cell gathers information, on the one hand, from four adjacent neighbor cells and, on the other hand, from cells whose state is simulated by the presence of adjacent planetary rovers of the moving complex. The initial configuration with zero number and three subsequent configurations with numbers 30, 100 and 150 of demonstration space with 120 x 60 = 7,200 cells during one experiment conducted on a digital computer are shown sequentially in Figures 7, 8, 9 and 10. The darkened rectangles in the figures fully represent the planetary rovers of the complex and obstacles of type A are denoted by "-," those of type B are denoted by "+" and those of type C are denoted by "*." The target is the extreme value of the scalar field described by the equation

$$f(x, y) = \frac{1}{1 + (x - 95)^2 + (y - 46)^2} .$$

Its position in the selected coordinate system is thus determined by vector (95, 46).

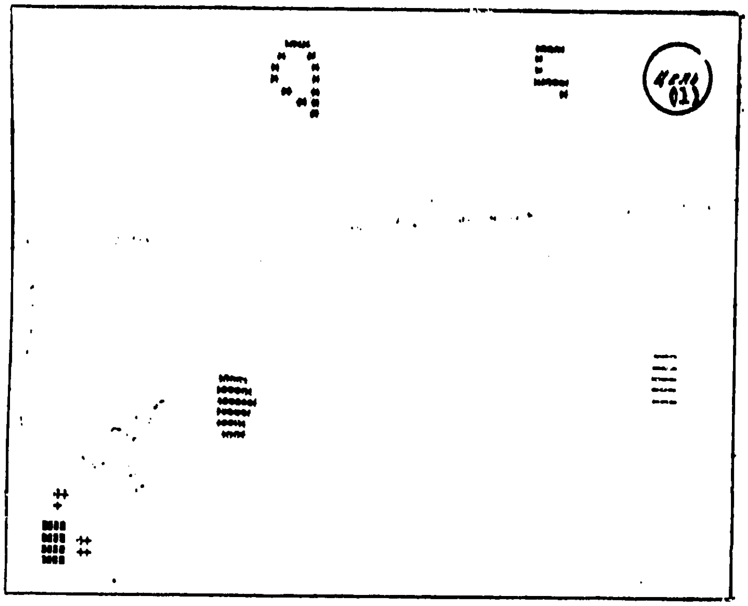

Figure 7. Configuration No. 0

KEY: 1. Target

Conclusions. The results obtained in experiments on a digital computer showed good efficiency of the developed algorithms of artificial thinking. The efficiency of the self-contained moving complex's reaching the target in a random situation must be evaluated by three interrelated criteria: the probability of reaching the target P_g, the time required to reach the target T_g and the cost of reaching the target. The mean value of the cost is determined approximately by

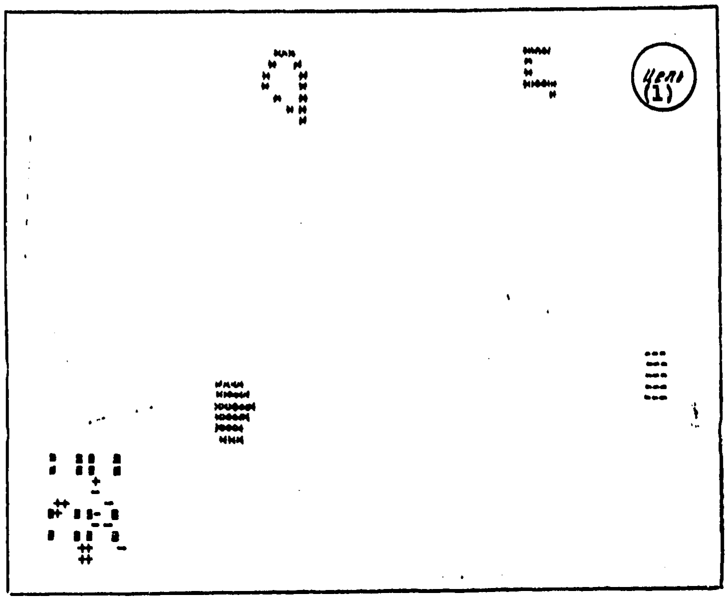

Figure 8. Configuration No. 30

KEY: 1. Target

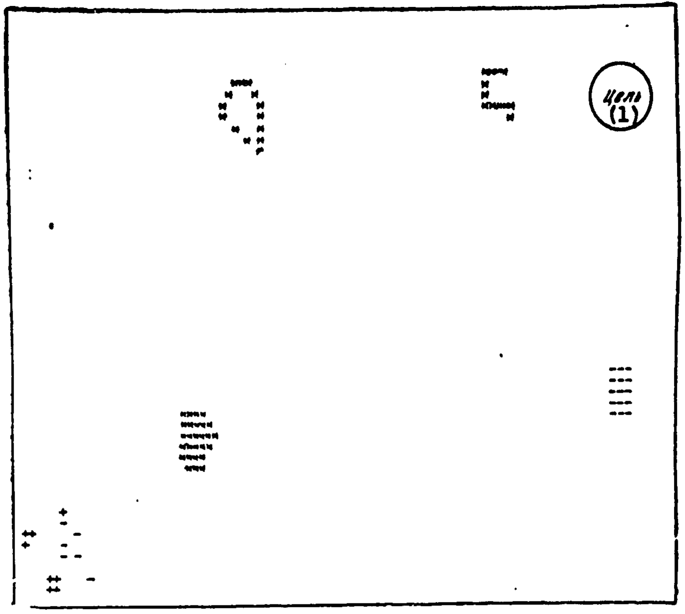

Figure 9. Configuration No. 100

KEY: 1. Target

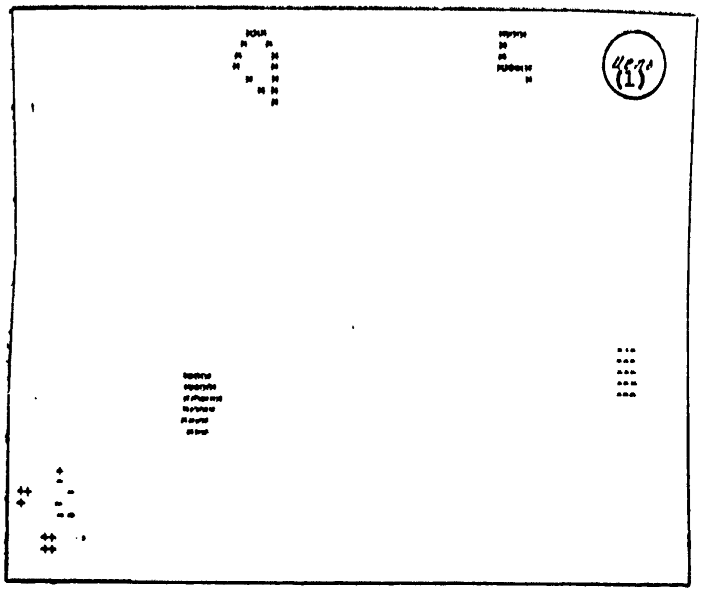

Figure 10. Configuration No. 150

KEY: 1. Target

where $\bar{L}$ is the mean length of the trajectory, $\bar{A}$ is the mean number of changes of orientation of planetary rovers of the complex by angle $\pi/2$ and q_e and q_0 are the corresponding values of costs for L and A separately.

Only the method of stochastic experiments, by modeling the behavior of the complex on a computer, can be used in practice to estimate functions $P_d = f_1(T_d, Q_d)$, $T_d = f_2(P_d, Q_d)$ and $Q_d = f_3(P_d, T_d)$ in the presence of randomly arranged obstacles. The most recently published photographs of the surface of Venus at the point of landing of the "Venera-9" station, which can be used as the basis for similar experiments after photogrammetric restoration of the situation, may be cited as an example of a field of randomly arranged obstacles.

Digital computer experiments permit one to analyze another criterion of efficiency, namely the ratio $\nu = P_d/P^{(J)}$, where $P^{(J)}$ is the probability of reaching the goal by an individual planetary rover and P_d is the probability of reaching the goal by the complex.

The complex described here can be used not only to investigate the surfaces of remote planets, but also for scientific investigations in dangerous zones and under water. In the latter case it is even easier to change the position of the elements of the complex. An algorithm of the behavior of the elements of the complex as a purposeful joint group may even be formulated with slight modification if metal wires are not used to create tension and if other means of communications are used. A wide range of problems in which the location of the target varies in time (i.e., the position of the target varies according to the increase of incoming information about the surface of the planet) or in which the parameter of the scalar field, i.e., temperature, varies in time, may also be investigated. These are cases of the problem of pursuit, for solution of which the principles of organizing a self-contained moving complex described above are possible.

BIBLIOGRAPHY

1. Katys, G. P., V. M. Il'inskiy, I. K. Mel'nichenko and S. Ye. Zdor, "Some Problems of Construction and Control of Automatic Devices for Investigation of Planetary Surfaces," in "Upravleniye v kosmose" [Control in Space], Vol. 2, Moscow, Nauka, 1972.

2. Benes, J., "Hyberneticke systemy s automatickou organizaci" [Cybernetic Systems With Automatic Organization], Prague, Academia, 1966.

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PUBLICATIONS

COMPUTER STRUCTURES AND SOFTWARE

Moscow STRUKTURY EVM I IKH MATEMATICHESKOY OBESPECHENIYE (Computer Structures and Their Software) in Russian 1978 pp 2-7, 154-171

[Annotation, table of contents, foreward and chapter 3 from book by L. N. Korolev, Glavnaya redaktsiya fiziko-matematicheskoy literatury izdatel'stva Nauka, second edition, revised and expanded, approved by the USSR Ministry of Higher and Middle Special Education as a textbook for students of higher educational institutions in Applied Mathematics specialties, 352 pages]

[Text] The book contains a review of domestic and foreign general-purpose computers. It includes the structural features of some of the most interesting computers, their software and the influence of programming concepts on computer structures.

The book is intended for students in the second and third courses specializing in the field of systems programming and computer software. It may be useful to auditors at faculties for increasing qualifications. The book should be considered an introduction to the study of computer structures and should give a general idea of those directions being taken by computer development.

The second edition has been revised and expanded. The first edition was published in 1975.

CONTENTS

Part One Domestic Computer Hardware

Part Two Foreign Computer Hardware

FOREWARD

The basis of the book is the contents of a course of lectures on computer structures given over a period of several years in the school for mathematics and cybernetics of the Moscow State University for students in the second and third courses and for auditors of the faculty for increasing qualifications affiliated with this school.

The idea of creating such a course belongs to academician A. N. Tikhonov who in his time suggested to the author the scope of information which should be included in this course. This course of lectures was entitled "The Structure of Contemporary Computers".

In working on the book the author tried to include information about the most characteristic contemporary domestic and foreign computers. The development of computer hardware is taking place so rapidly that many computers which were considered modern in structure and technical implementation four or five years ago can no longer be considered so today.

Information on the structures of computers already removed from production now is also contained in the book. This material is also useful since it shows the evolution in the structural organization of computers, the ideas held previously in the field of computer technology and the influence of software on the development of computer structures. Less attention is given in the book to the subject of software since in spite of their intimate connection with questions of structure they require a separate more detailed examination.

The computers considered in the book are intended primarily for scientific and technical calculations. An attempt to cover all aspects of computer hardware development in one book would make it too large in scope and less accessible to a broad group of readers.

Academician Sergey Alekseyevich Lebedev is the founder of computer hardware development in our country. The author had the fortune to work for many years under the guidance of this remarkable man who developed the BESM computer series. With his name is associated an entire epoch of computer hardware development in our country. S. A. Lebedev was one of the first to comprehend the enormous significance which computer technology would have in all areas of scientific and industrial activity for society.

The intensive process of developing ever newer computers is taking place in all countries.

A large amount of attention was given to the subject of developing computer hardware and software in the resolutions of the 24th and 25th CPSU Congresses and so their important role in the process of the scientific and technical revolution is emphasized. The dissemination of knowledge in the computer technology field is urgent and vital since ever larger numbers of people are connected in one way or another with computers. The author hopes that the book he is offering will be useful in this way.

The second edition of the book differs in that material on new computers is introduced, more attention is given to the YeS computer series and some of the figures and parameters have more defined more accurately.

The author was assisted in working on the lecture course and the book by many coworkers of Moscow State University and the Institute of Precision Mechanics and Computer Engineering of the USSR Academy of Sciences to whom the author extends his gratitude.

Chapter 3. Soviet Fourth Generation Computers

1. Premises in Developing Computers of the New Generation

Almost 30 years of computer hardware development, its introduction into many areas of science, industry and control and development of the theory and practice of programming are yielding rich material for scientific analysis, generalizations and, fundamental for further development of this area of knowledge, elaboration and production.

As usually happens in any area of science and engineering under development, each forward advance opens up new prospects and is inclined to present a whole new set of problems and tasks needing to be solved on which further progress depends.

In this section we will attempt to cover in more detail some problems of this kind with one very simple goal: to answer the question why a sufficiently well-developed and well-tested third generation computer structure does not satisfy the requirements of future development.

Efficiency in Using Computer Systems

Computer systems hardware and their software area, I am sorry to say, the most expensive products of modern industry. And this is still true in spite of the fact that hardware costs are being reduced constantly.

Analysis of the capacity of computers operating in the package processing mode indicates that in a number of cases these expensive systems are not utilized efficiently enough. This is not simply a reference to the large ratio of downtime to operating time of computers which sometimes reaches 50 percent. If computing time is analyzed carefully, it seems that more than half of this time is spent in debugging programs in much of the equipment. The portion of time spent on computing debugged programs, i.e. obtaining results useful to society, amounts to a rather small part of the overall machine time.

A very appreciable part of the overall computer operating time is consumed by the process of translating, gathering and editing communications, steps necessary for preparing problems to be computed.

If one thinks of the remote time of using first generation computers and the first steps in programming when the role of translator, program assembler and communications editor was played by a programmer-expert who coded the program in digital machine code, then it can be said that now the overhead for each operation from the use of an executed instruction has grown by a factor of two to three.

The use of high-level languages, of all of the powerful, modern hardware for automating programming including translators, loaders, macrogenerators, libraries, debuggers and so on is reducing costs considerably and cutting down on the labor of a large army of programmers and computer users. According to many evaluations, computer use for elaborating and preparing problems for computing results in a 10- to 15-fold reduction in expenditures of intellectual labor of specialists, in time at any rate. For this reason, the overhead mentioned is actually very useful work which yields a direct economic return.

Nevertheless, the problem of changing the ratio of time spent by the computer on problem preparation and on obtaining useful results to the benefit of the latter remains urgent.

The problem of using the hardware efficiently can be viewed from some other points of view directly concerned with the subject of the structural organization of computers.

An extensive instruction set is characteristic of general-purpose third generation computers. The arithmetic-logic unit is able to execute operations on numbers in various forms of notation, on byte strings and on logical data. In the translation process, a small subset of the entire instruction list is used primarily. For the most part these are instructions associated with translating texts. The capabilities of the ALU in executing arithmetic operations with floating point with double precision are not used at this time.

On the other hand, instructions for processing textual data are not employed in the process of executing problem computation. This means that, in fact, at different processing stages either those or other computer capabilities are not in use. If only one processor is operating in the computer system, its operating units which implement the instruction system capabilities are used less than 30 percent in practice. Imagine that there are two processors in the computer system, one of which is well suited for translation and the other best suited for executing arithmetic operations. If it is supposed that they may operate in parallel, it can be expected that the ratio of active use of the hardware will increase noticeably. In one or the other processor the internal idle time of the logic units will be reduced during some period.

But in this case a new problem arises, the problem of balancing such a system. If the processor-translator is prepared to compute problems very rapidly and the processor-counter computes them slowly, then invariably the time will come when the processor-translator has to stand idle and wait. A similar picture is observed in using the most expensive part of the computer, the main memory. If we observe the dynamics of access to the OZU [main memory] during computing, we can see that some of the memory fields are standing idle for a considerable time and there is no access to them. There are significant numbers of these fields passive for a certain time. Executed calculations based on analysis of the dynamics of memory access during the solution of actual problems show that 10 to 15 percent of the OZU is used actively. Another factor limiting the efficient use of hardware is the sequential nature of algorithms. If we calculate the expression

$$a + b \times c, \quad *)$$

then we should first multiply and then add. If there are an addition unit and a multiplication unit for executing multiplication operations in the computer which may operate simultaneously, then in the given case the addition unit will be idle pending completion of the multiplication unit's operation, i.e. it will not be in active use. It can be shown in this way that the essence of the algorithm with its basically unavoidable sequence is that whatever artificial procedures we use it is impossible to escape the sequential computing and the idle time of operating units associated with it. However paradoxical it seems, the statement that it is possible to construct a computer (a hypothetical one, of course) which will compute and preset algorithm in parallel can be proved. The proof of this statement is as follows. Formula *) may be thought of as the given transformation of numbers a, b and c into some other numbers $r = a + b \times c$. Not qualifying the generalization, it can be computed that numbers a, b, c and r are assigned to a binary formula. Thus, we speak of converting a given set of zeros and ones representing the series of numbers a, b and c into another given set of zeros and ones of the r series. Now we will attempt the theoretical construction of a unit with any acceptable combination of a, b and c applied to the input and immediately a combination designating the proper result r should appear at the output. As is known from Boolean algebra, it is possible to construct a disjunctive normal formula for any function. In turn, we may consider the i bit of the result r as the logic function.

$$r_i = r_i\ (a_1, a_2, \ldots, a_n, b_1, b_2, \ldots b_n, c_1, c_2, \ldots, c_n),$$

where a_j, b_j, c_j are bits representing the possible values of a, b, and c. In this case, considering that any function of r_i (any bit of r) $i = 1,2,\ldots m$, where m is the number of bits of the result, may be represented by a disjuctive normal formula with the logic operations AND, OR and NOT. It is possible to construct m processors (or m circuits) which produce the required result in simultaneous operation. We may theoretically construct such multiprocessors for each actual algorithm and it would seem that it would be possible in this way to circumvent the sequential nature of the algorithms. However, in reality there are an infinite number of actual algorithms and because of this more highly developed abstract discussions have no practical significance. On the other hand, they do make it possible to some extent to examine in general attempts to implement so-called computer environments, multiprocessor systems which are dynamically adjustable for actual algorithms. The primary capability of parallelling any algorithm justifies those efforts initiated now for practical solution of this problem within those or other limits.

The structure and architecture of third generation computers is adequately adapted for solving the problem of parallel, and this means more efficient, use of the operating units of the computer system since this structure reflects well enough the traditional view of the algorithm as a given sequence of operations.

New Level of Interaction between Man and the Computer System

The development of terminal access to computer systems, time sharing systems and man-machine dialog systems is resulting in the need to solve the problem of surmounting the language barrier which exists to this day between the mass of users and computers. In spite of the fact that the range of algorithmic languages developed until now and used for interaction with computers is very broad, nonetheless these languages must be learned and this barrier overcome. For the very reason that a general-purpose operations set is bound to lead to inefficient use of general-purpose algorithmic languages, programs are being generated that operate considerably more slowly than they would operate if the specifics of the actual subject area and the features of the actual computer were included in them. Even translators with capabilities for optimization are 1.5 to 2 times slower than meticulously composed programs in machine language.

The specifics of actual subject areas may be included by developing so-called object-oriented languages resembling a certain field understandable to specialists and specialized programming systems which "comprehend" a narrow problem category and "know how" to take this characteristic into account in designing effective operating programs. The basic design of such languages according to the evidence should include a much higher semantic content than the structures of general-purpose languages. The simple, easily formulated structures of these languages may stand for very basic concepts or simply refer in the final analysis to computations on very large programs or to the operation of entire program complexes. Such object-oriented languages, as a rule, are difficult to formalize. Interpretation of their structures or sentences very much depends on the context and for this reason they are never classified as formal. Analyzing languages in this category leads to great difficulty since this analysis requires resting ultimately on the physical rules existing in the corresponding subject field.

Along with the emergence of object-oriented languages, a new generation of general-purpose languages is appearing which to a great extent resemble meta-languages intended for describing new structures and their relationships, i.e. for describing semantics concepts.

The new generation languages are a further development of the procedural method since describing a procedure may be considered the introduction of a new construct using source reference media. However, in the old languages procedure descriptions served mainly for indicating a set of operations with several fixed data types. In general-purpose languages of the new generation there is the capability of entering new types of data, completely new projects and new interactions between them. Pascal, SLU and to some degree ALGOL-68 may be used as examples of such languages.

Computer structures of the new generation should reflect these trends toward developing general-purpose languages and toward the emergence of object-oriented nonprocedural languages. In particular, the new level of interaction between man and the computer implies the advent of display devices and voice signal complexes, i.e. image representation and concepts very far from the customary concepts of numbers and codes, as language facilities and processing equipment.

Multiple User Systems

Such systems are being developed rapidly at present and placing a number of new problems before computer and software developers. Information retrieval systems (IPS) for the most varied purposes are receiving the broadest distribution in the category of time sharing systems. At the current developmental stage of IPS's it is significant that one and the same information stored in the depths of the computer system is used by different groups of specialists for various purposes. One connection between items displayed in the stored data interests one and altogether different ones and the relationship between them interest another.

Long ago the problem of data base control emerged, understood on the logical level as the capability of describing very randomly the relationships among its elements and applying the relationships to a large amount of data.

At a much lower level this problem is induced by the task of filing, storing readjustments and organizing rapid access to the data base displayed in the auxiliary memory unit of the computer. The appearance of numerous studies and developments on systems for data base control, the appearance of specialized languages, various declaration models and corresponding programming systems speaks for itself. The path from the simplest library organization to network and relational models based on the set-theory interpretation of the dependency of element relationships has been covered only in the past 8 to 10 years and is still far from being finished.

It is thought that the problem of organizing banks, data bases and filing systems is the number 1 problem in the software systems of contemporary computer complexes. Any program system no matter how complicated rests in the final analysis on the foundation of "computer know how", i.e. on the basis of information consisting of programming modules, standard procedures, stored source data and so on. Obviously, the efficient operation of such programming systems depends to a large degree on how rapidly it is possible to reach the required data. In multiple user access systems, the problem of protecting data from unlawful interference which is part of the difficulty with the cooperative availability of facilities making it possible to change, supplement and eliminate data is very important.

Data software control is changed to a given independent software problem and should be reflected in future computer system structures.

Multiple user access to a computer system gives rise to the need to increase the number of active tasks being accomplished and also the need for dynamic reallocation of resources.

With a large number of users having simultaneous access to the computer hardware, the overhead associated with dynamic reallocation and shifting of the services may increase so much that it causes a sharp increase in delays in the system and an increase in the time spent waiting for a response.

The problem of optimum scheduling and reallocation of resources and particularly the very rapid shifting from problem to problem may be solved only by special structures and technical solutions adopted in designing new computer systems. It is impossible to say that this problem has been well enough solved in traditional third generation computers.

Linking computers in networks requires solving a whole series of problems related to the logic of interaction of the computers by telephone, telegraph and wideband communication lines. This interfacing has several levels: interaction of problems among themselves, interaction of operating systems among themselves, the organization of two-way communications and the organization of data flow in data transmission networks.

This type of computer system operation has a specific nature in addition to its software and its own criteria of efficiency and should be considered in designing new computer systems.

Technical Prerequisites in Developing Fourth Generation Computer Systems

It cannot be assumed that the problems mentioned above related to the need for increasing the efficiency of hardware use, to the requirements imposed by new intercommunication languages, to the development of software and data banks, to the organization of multiple user access and computer networks all arose suddenly and faced computer hardware specialists with the fact of the incompatibilities of third generation computers with the new requirements.

The foundation for solving the problem mentioned has been laid in one or another form in third and even second generation computer structures. We have briefly discussed experiments on grouping Minsk-22 computers operating with a common memory. In YeS computers series 1 have also been included some facilities for grouping which provide for the basic capability of performing parallel computing using several central processors. But all of this has been done within the limits imposed by the technical level of the component base available to the designers at that time. Expansion of the production of large-scale integrated circuits, the microprocessor component base, the advent of large capacity electronic memories with both very high speed response and no less important, a reduction in the cost of the listed electronic equipment and an increase in its reliability all are making it practically feasible to incorporate new structural features which solve the stated problems in computers to a considerable extent.

In our country intensive research and development are being done on new generation computers. Apparently, it is possible to speak of four main conceptual directions for these developments. The first direction of evolution is associated with the development of series 3 computers in the framework of the common YeS computer program discussed earlier. The main idea behind this direction is the enlargement and modification of the internal structure of this series while retaining program continuity with series 1 and series 2 computers so as to satisfy by this means the main requirements for future use of the computers in multiprocessor computer complexes and in computer networks producing output for data transmission networks and expanded communications with remote users. Expanding the range of virtual operating environments included in the series 3 computer is the direction associated with the emergence of object-oriented languages and systems.

The second direction is related to the failure of the traditional third generation computer structure and an approach to developing multiprocessor computer systems with internal instruction systems similar to high-level languages and manifesting their procedural nature and block structure. With this direction are classified El'brus computers which will be discussed in more detail below.

The third trend is associated with the development and establishment of rearranged uniform multiprocessor computer facilities adapted for solving problems subjected to parallel processing at the input algorithm level. A picture of such a multiprocessor complex may be obtained from the study in the footnote *) where its structure is described as follows. The central computer system consists of a uniform control field and a uniform decision field. Each field is a set of single-type specialized blocks implemented on an integrated microcomponent base.

The control field element is concerned with instruction processing and each such instruction processing block (BOK) may execute its operation independently. The control field blocks may process instructions of several different common memory fields. In essence, each BOK is equivalent to the control circuits of traditional computer in function and is involved in selecting an instruction from the memory, decoding it, computing the effective address, selecting operands and so on.

The decision field consists of single-type elements representing an arithmetic-logic unit capable of executing logic and arithmetic operations on several types of data. Each such arithmetic unit may operate autonomously and independently of its own neighbors in the field.

The control field modules prepare the order queue for the decision field. An order consists of the operating instructions and operands underlying the conversion. From the overall order queue generated by the control field, any free element of the decision field selects a request for execution, sets up a connection with the proper control element, executes this request and transfers the result to the element initiating it.

The special operating system modules allocate parallel branches of a single task among the control field elements.

Translators or the user should be responsible for seeing that the source problem written in high-level language is divided into branches executed in parallel. A special processor which executes operating system functions is part of the system.

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*) Prangishvili, I. V.; and Ryazanov, V. V. "Mnogoprotsessornyye upravlyayushchiye kompleksy s perestraivayemoy strukturoy" [Multiprocessor Control Complexes with Rearranged Structure], Moscow, ITM i VT, 1977.

The control and decision fields may contain a different number of elements. The productivity of the system with maximum marshalling is 100 million operations per second. A main memory with modular structure equally accessible to all of the control blocks of the decision field is part of the system.

A dual-processor complex based on an SM-2 minicomputer is used as the processor which executes the operating system functions making it possible to interface the series of external units of the ASVT-M system with the system.

The organizing principles described above make it possible in the computing mode to reallocate resources both of the control and of the decision fields and to achieve versatile rearrangement of the system as a whole also. This also allows the accomplishment of multiprogram computing.

The most complicated problem in using systems organized this way efficiently is synchronization of the branches of a single task using common data arrays and scheduled division of the control field elements into subbranches or independent tasks for the purpose of loading the decision field elements more efficiently. Thus, in the operating system of the given multiprocessor complex there is a complicated problem classed with discreet programming problems. At present, the subject of approximating the computer structure to the high-level programming languages and also transferring a number of software functions to the computer hardware is widely discussed among specialists associated with computer hardware and programming. These questions are being studied particularly intensively right now when the potential has appeared for implementing the most complex logic operations on a single large-scale integrated circuit chip. At present the following structural circuit of a software system has been constructed to some extent consisting of several self-regulated operations or blocks.

The first block is control programs which organize the input of source data and its storage in the input field. In this block is located control of the inquiry logic of the data sources: a punchcard reader and remote terminals, users terminals and consoles. Those components of time sharing monitors which control reception from individual users consoles may be grouped in this block. The input unit also accesses the file system for resources to allocate the obtained input data to a buffer memory.

The next large software circuit block accessing the input field organizes the translation of programs from various languages to the object language of the loading module. The translated module is allocated to a storage field of the object modules for which resources should be selected from the file system.

In any software system in one or another form there is a block with static loader functions which assembles the program from the block-modules and allocates it to a problem field prepared for dynamic loading and solution

The next block, the system supervisor, controls multiprogramming solution of problems changed into active form, taken from the problem queue and prepared for solution. In the solution process the results of computing are accumulated in the output field, resources for which are all selected from the same file system in the dynamics of computing. Finally, there is a large block in the software system which performs the required editing and output of the results in a print-out and to peripheral systems.

This very rough software circuit may be given in detail when necessary.

The principle of transferring software functions to the hardware may be examined not only from the point of view of increasing the level of the internal machine language. There can be an attempt to develop a nonuniform multiprocessor system consisting of specialized processors which efficiently execute the operations of each large block of the software system. In this fourth direction of developing nonuniform multiprocessor systems, research and development are also being done.

2. El'brus Multiprocessor Computer Systems

In developing these systems attention was focussed primarily on three problems: "efficiency of equipment use, the capability of accomplishing maximum productivity and the development of highly reliable subsidiary structures having the capability of gradually increasing the productivity based on adaptation to solved problems".*

Here we will give a brief account of the complexes mentioned with which it is possible to some extent to speculate on structural solutions adapted for achieving the indicated goals.

The El'brus system with a productive capacity of from 1.5 million operations per second to 10 million operations per second and the high-productivity El'brus-2 system with an overall high-speed response of more than 100 operations per second are part of the series of multiprocessor computer systems.

The El'brus-1 and El'brus-2 systems are constructed on the very same structural principles; their modules are functionally identical and their processors have an identical instruction system and functionally identical unified operating system (EOS).

The main modules of the El'brus computer system are: 1-2 central processors, main memory modules (4-32), input-output processor modules (PVV) (1-4), data transmission processor modules (PPD) (1-16) and modules for controlling drums and disks forming a system for bulk storage control.

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* Burtsev, V. S. "Printsipy postroyeniya mnogoprotsessornykh vychislitel'nykh kompleksov El'brus" [Principles of Constructing the El'brus Multiprocessor Computer Systems], Moscow, ITM i VT, 1977.

The main memory of all the system's processors is accessed through a program distributor in which the functions of elimination of malfunctioning memory blocks and placing reserve blocks in operation are also located. Reliability of the computations is ensured by developing a hardware control system to control both the processor operation and the data transfer operation in all levels of the system.

The instruction system of the central processor is based on the principle of push-down memory access and on hardware implementation of the stack. The internal machine language is suitable for inverse use of prefix notation and operating codes executed on the operations positioned at the top of the stack. Not the operands themselves but references to procedures which compute the values of the required operand may also be found at the top of the stack. In its construction principles the central processor instruction system is similar to the instruction system of such computers as the KDF-9 and Burroughs whose structure is usually considered nontraditional. At the same time, the instruction system and data organization have inherent differences in the direction of more developed hardware for description of data types, their protection and memory allocation methods. The stack mechanism is used widely not only for dynamic memory allocation to accommodate local targets of the programming blocks and procedures, but also for recall of control data in converting to a lower level of indenture of procedures and for recall of data on the address environment of problems during interrupts and switching from problem to problem. In the El'brus instruction system there has been further development of the descriptor hardware reflecting such high-level language constructs as procedure, array and data declarers.

Each data item in the memory is supplied with additional control digits (tags) containing information about the data type and different control tags including tags for read and write protection. The extensive use of the stack mechanism, descriptor and declarer hardware and the capability of indicating the level of indenture all make it possible to construct so-called "clean" reenterable (recycled input) procedures or programs in which references to the address of items in the mathematical or physical memory are not explicitly present.

This is very important in organizing computing in multiprocessor systems since it allows the very same program material to be used simultaneously by several processors operating with different data. The descriptor and indirect reference hardware make it possible for different programs to have simultaneous controlled access to common data which is useful in solving some complex problems.

In developing the El'brus system great attention was given to the problem of synchronization during parallel execution of branches of a single problem on common data, i.e. the problem of process synchronization. Many synchronization operations are carried out at the hardware level.

The PVV module, the input-output processor, is a specialized computer with its own local memory and the capability of accessing the main memory. It controls the interface of the system with peripheral equipment. Parts of the PVV are rapid channel blocks and standard channel blocks. On its part the rapid channel block consists of four selector channels serving up to 64 high-speed users each. The selector channels are designed for interface with such units as high-speed magnetic drums and floppy disks. The standard channel block contains 16 channels serving up to 256 external users. A standard channel provides multiplex service to comparatively slow peripheral devices such as magnetic tape, input-output units and so on. In addition there is a unit for connection to data transmission processors (up to 4 channels).

The main function of the PVV is to relieve the central computing system of the operations of organizing transfer queues, of reacting to interrupts on input-output, of optimizing servicing of transfer request queues. One PVV provides maximum transfer speed on a high-speed channel of up to 4 million bytes/second and on a standard channel and a channel connecting with the PPD of nearly 1 million bytes/second.

The data transmission processor, the PPD, is a specialized computer unit with versatile program control and a productive capacity on the order of 700,000 operations per second. It has its own local memory in which control programs providing service to 160 telephone and telegraph communication lines are located.

As many as 10 grouped couplers may be part of the PPD each of which is designed to serve up to 16 telephone or telegraph lines. This unit performs the function of monitoring and program control adaptation to different data transmission systems. The data transmission processors may serve primarily for constructing remote processing and remote access systems. A communication received or transmitted via telephone or telegraph lines is subjected to multistage hierarchical servicing in the following circuits: modem, grouped couplers, the central processor of the PPD, the coupling unit of the PVV, the main memory and the system's central processor. This kind of hierarchy sets the higher stages free from routine operation related to the detailed analysis of incoming signals, their careful monitoring and a continual increase in the level of logic control.

The operating system constitutes the software base for the El'brus computer system. The organizational structure of the central processors makes it possible to have an operating system in a single unit without depending on their number. Since dispatcher input-output control functions are transferred to specialized processors of the PVV and PPD, resource control, problem flow scheduling, processor resource allocation, monitoring of viability and reservation control operations are located in control programs executed by the system's central processors. Process operation control and its synchronization is an important function of the central operating system. The central operating system also executes ordinary call functions of programming systems, memory allocation, dynamic call of procedures and required arrays and file system control. The high-level languages ALGOL-60, FORTRAN, COBOL, PL-1, ALGOL-68, SIMULA-67 and Pascal should be part of the programming system of an El'brus computer system. In addition, the El'brus assembly language, a procedure-oriented, machine-dependent language comparable in its capabilities to high-level languages, is part of the programming system. In El'brus assembly language are included capabilities permitting the design of well-constructed programs. For systems mathematicians a network description language SETRAN has been developed which automates programming of control algorithms for the data transmission processor during development of remote processing systems and writes control programs for receiving and transmitting operations in different data transmission systems.

An integral part of the central operating system is the data base control system which provides multiple access to the files and is based on a network model of data structures.

The newspaper MOSKOVSKAYA PRAVDA of 8 April 1978 reported that production has begun in the Soviet Union on El'brus-2 fourth generation general-purpose multiprocessor systems with an overall productive capacity of more than 100 million operations per second and that at the present time still more highly-productive general-purpose computers are being developed. This report made by TASS confirms the great value given in our country to developing high-productivity computers.

Progress in the field of research and development on systems of this type is proceeding in various directions and this promises the successful solution of great and difficult problems facing scientists in the process of the technical revolution and brought to life by the growth of modern industry and the important problems facing society.

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PUBLICATIONS

SATELLITE COMMUNICATIONS IN THE 10TH FIVE-YEAR PLAN

Moscow SPUTNIKOVAYA SVYAZ' V DESYATOY PYATILETKE in Russian 1979 signed to press 15 Mar 79, pp 2, 64

[Annotation and Table of Contents from the book by A.D. Fortushenko, professor and Phd in the engineering sciences, Znaniye Publishers, 1979, 40,320 copies, 64 pages]

[Text] Modern satellite systems, which are intended for transmitting and relaying television, telegraph and telephone signals, as well as data and other types of information transmission for weather services, time services, telemetry, etc. are described in the brochure. The construction of satellite communications equipment is briefly discussed and some ideas of the prospects for the development of satellite systems are presented.

The material is designed for a broad circle of readers.

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8225
CSO:1870

PUBLICATIONS

NEW BOOK ON MAN IN OPEN SPACE

Moscow NA ORBITE VNE KORABLYA ("In Orbit Outside of the Transport Ship") in Russian 1977 signed to press 12 Sep 77 pp 175-176

[Annotation, introduction and table of contents from book by Yu. N. Glazkov, L. S. Khachatur'yants and Ye. V. Khrunov, Zhaniye, 100,000 copies, 176 pages]

[Text] Preparation was begun after the first space flights in the "Vostok" program in our country to conduct one of the most important operations: Space walking by man. A large number of problems solved in open space, the specific nature of the acting factors and working conditions introduced their corrections to the cosmonaut training system. The problems of a cosmonaut's activity outside the sealed compartments of a spacecraft (station) are considered in this book and the hardware which support work in open space is described. The authors of the book are engineer-cosmonauts and a physician.

Introduction

[Text] A new step in mastering outer space was made in the Soviet Union on 18 March 1965 in accordance with the space research program. Pilot-cosmonaut Aleksey Leonov was the first to step bravely into open space.

"Why? We had still not become quite familiar with space and already a space walk!"

The years passed. Cosmonauts and astronauts took space walks many times and worked in space according to the Voskhod, Gemini, Soyuz and Apollo programs. The question "why?" was answered by practice.

On 14 May 1973 the long-term Skylab Orbital Station was launched into a circumterrestrial circular orbit. Three crewmen were to work in the station. Hundreds of millions of dollars were expended and the enormous labor of large collectives of scientists, engineers and workers was invested. And yet, the meteorite and heat shield of the station was destroyed during orbital injection of Skylab. Jammed by a fragment of the meteorite shield, one of the solar panels did not open. The temperature inside the station increased and an energy shortage was predicted. The launch of the first crew was delayed. What to do? Utilize the capabilities of man. Man had to fly to the station, inspect it and make repairs.

And astronauts repeatedly made space walks and conducted repair operations at an altitude of approximately 400 km. The solar panel was released and opened. Instead of the destroyed heat shield, a shield delivered from the earth was installed. The station's efficiency was restored. A human, who went into open space with tools in hand, saved the scientific research program.

Thus, the answer was given by practice. Another question arises. An emergency related to disruption in functioning of the external systems occurs on a space object. Can man, located in the relatively safe situation of the spacecraft cockpit, direct special automatons to eliminate it. He can. Only with the single stipulation that if he knows before launch that this part will fail, then this process requires interference. But this is hardly probable. The crew of the Apollo-13 spacecraft were trained to correct a large number of failures, but the unexpected happened during the flight.

How and what a cosmonaut can do, leaving the spacecraft in orbit, what are the results of his labor and what is the change of main psychological functions -- our book is devoted to these problems.

In the first section, considering the problems of space walks and a complex of operations which man should perform outside the spacecraft, we tell about the main methods of emerging from the spacecraft in orbit and about the technical basis of accomplishing them.

Outer space creates a number of conditions which oppose a cosmonaut's space walk; therefore, the characteristic features of human functioning in open space are analyzed in the second section of the book. We determined two complexes of acting factors. These are the physical factors of environment and factors related to its effect on the mental state of man.

Human activity in open outer space and the program of transfer of two crew members from spacecraft to spacecraft during flight are considered in the next sections of the book. In the first case the results of studying the psychophysiological, emotional and biomechanical characteristics of crew activity are outlined in detail and a subjective account and the results of engineering-psychological analysis are given in the second case.

In conclusion, experimental investigations of promising equipment and principles of locomotion in open space is related.

The reader will see that the authors, illustrating one or another idea, frequently present examples from foreign technology. And this is not accidental since, we feel, models of foreign spacecraft and their onboard systems are less known to the reader than is Soviet space technology.

The fate of the book naturally disturbs the authors. And we do not want to transform our book into a manuscript of man's making it another step into unknown, but hostile, weightless and essentially unoriented outer space. We analyze, make conclusions and make suggestions.

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6521
CSO: 8144/1276

PUBLICATIONS

SENSORS AND AUXILIARY SYSTEMS OF SPACE APPARATUS, ROBOTS AND MANIPULATORS

Moscow TRUDY 8-OGO MEZHDUNARODNOGO SIMPOZIUMA IFAK PO AUTOMATICHESKOMU UPRAVLENIYU V PROSTRANSTVE: DATCHIKI I VSPOMOGATEL'NYYE SISTEMY KOSMICHESKIKH APPARATOV. ROBOTY L MANIPULYATORY in Russian 1978, Vol 4 signed to press 8 Aug 79 pp 3-4, 163-164

[Annotation, foreword and table of contents from book edited by B.N. Petrov and V. Yu. Rutkovskiy Izdatel'stvo "Nauka", 1150 copies, 164 pages]

UDC 62-50:629

[Text] The fourth volume contains material on the design of locomotion systems: robots and manipulators. Also considered are problems of making new sensitive elements of systems for stabilization, orientation and guidance of space apparatus, such as star sensors, special optical sensors and sensors of attack and sideslipping angles. The contents are intended for a wide circle of engineers, post-graduate students and scientific workers in the area of automatic control.

Foreword

The 7th International IFAC [International Federation for Automatic Control] Symposium on automatic control in space took place from 17 to 21 May 1976 in Rottach-Egern, FRG. The mission of the symposium included the exchange of scientific information and discussion of new results in the area of theory and practice of automatic control of complex dynamical objects, obtained in various countries during the period after the 6th IFAC Symposium, which took place in August 1974 in Tsakhkadzor, USSR. At the symposium reports were presented embracing a wide range of problems of the theory and practice of space apparatus navigation and control, control of descent into the atmosphere, optimization of control processes, design of robots and manipulators, etc. The symposium materials are presented in four volumes.

In the fourth volume considerable space is given to material devoted to problems of the construction of star sensors, optical sensors with screened mass, digital systems for space telescope guidance and attack and sideslipping angle sensors.

Problems of the motion of locomotion robots and manipulators are considered. Methods of synthesis of robot-exoskeleton control systems are given, and semiautomatic manipulator control systems are considered. New material on the development of the French manipulator MA 23 is given. This manipulator has several virtues and is undoubtedly of interest to specialists working in the area of locomotion engineering.

Preparation for publication of the Russian edition of the collected transactions of the 7th International IFAC Symposium and translation of the reports of foreign authors was done by members of the Institute of control problems V.S. Kosikov, A.A. Kotenko, V.G. Khromov, V.M. Sukhanov, V.V. Churilova, V.A. Putintsev, N.D. Litvinov, Ye. M. Firsova, V.M. Glumov and N.K. Ol'manskiy.

UDC 629.78
Issledovaniye algoritmov upravleniya dvizheniyem avtonomnogo planetokhoda metotom matematicheskogo modelirovaniya [Study of motion control algorithms for an autonomous planet vehicle by the mathematical modelling method]. Valil'yev, V.F.; Gurvich, P.M.; Lupichev, L.N.; Shamanov, I.V. (USSR). Datchiki i vspomogatel'nyye sistemy kosmicheskikh apparatov. Roboty i manipulyatory. Moscow, "Nauka" 1978.
For studying the algorithms for motion control of an autonomous planet vehicle a complex mathematical model is proposed. A block diagram of such a model and the basic principles of construction of the separate algorithms comprising it are given. Some modelling results are presented. 7 illus., 3 ref.

UDC 629.78
Avtomaticheskoye upravleniye kompleksom dvizhushchikhsya planetokhodov [Automatic control of a set of moving planet vehicles]. Benesh, I.; Kolar, P. (Czechoslovakia). Datchiki i vspomogatel'nyye sistemy kosmicheskikh apparatov. Roboty i manipulyatory. Moscow, "Nauka", 1978.
An autonomous set with several separate moving elements, planet vehicles, intended for studying the surface of a planet is described. The planet vehicles are connected by metal cables. The set is supposed to reach a goal, i.e. a given region or place where some parameter of a physical field attains an extremal value; in doing this it overcomes or skirts randomly placed obstacles. The principle of hierarchic organization is not used in controlling the set. The behavior of the set is studied as the behavior of a special type of cellular automaton which uses a random search in its algorithm of transitions. Results of computer experiments are given which support the good capacity for work of the set. 10 illus, 2 ref.

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SENSORS AND AUXILIARY SYSTEMS OF SPACE APPARATUS

ROBOTS AND MANIPULATORS

9251
CSO: 1870

END