Engineering Notes

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Man, Teleoperators, and Robots: An Optimum Team for Space Exploration

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Introduction

THE next phase of activities on the moon following the Apollo exploration could well be its development as a base for long term astronomical and meteorological observations. However, until many of the constraints which now limit lunar exploration, such as environmental extremes, limited stay times, physiological and psychological stresses, severe reliability requirements, and communication limitations can be relaxed or eliminated, the construction and operation of long term research facilities on the moon does not appear to be practical. This paper will discuss how these limitations can be minimized by using teams of men, teleoperators, and robots.

The concept of a cooperative team as an optimum system for long duration space activities is proposed because each of the three major components, the man, the teleoperator, and the robot possess unique characteristics that, when used together, can result in maximum effectiveness. How these components could interact can be explained by first describing the principal features of each component.

Man

The highly skilled astronaut would be thoroughly trained to work with the equipment. To obtain optimum "impedance matching," the dimensions and operating characteristics of the teleoperators and robots should be compatible with those of the astronaut. The astronaut should be so familiar with the teleoperators and robots, which extend his abilities, that he would instinctively get maximum performance from the equipment even when he was confronted with abnormal situations. The astronaut's primary function would be to direct and control the team, using man's intelligence, perception, anticipation, and decision-making—all essential to the operation of the team. Only the astronaut is capable of making evaluations, and through associative thought processes, to describe unusual phenomena in terms of Earth-related experiences.

Teleoperators

Teleoperators are defined as electro-mechanical systems that can project man's manipulative and sensory capabilities across space and through barriers to permit man to operate effectively in distant or hostile environments. Teleoperators provide man with a unique capability to perform dangerous or strenuous operations without personal risk or fatigue. More than merely replacing or extending man, teleoperators, equipped with sensory feedback systems, give man a means for doing things that otherwise would be impossible. Well-known examples of teleoperators are manipulator-equipped submarines used in ocean research and manipulators used in nonroutine operations in highly radioactive areas.

Robots

Robots are electro-mechanical systems which have the mobility and manipulative capabilities of teleoperators, but in addition, have on-board computers to provide some useful level of artificial intelligence. The unique feature of a robot is that its artificial intelligence enables it to receive and process information from its immediate environment. The robot is able to relate this information to other data and instructions fed into its computer from external sources and then to determine a course of action to execute a specific task.

The concept of an astronaut-teleoperator-robot team is new and has not been studied in any significant detail. Such a team has yet to be assembled, worked, and evaluated. However, by examining and extrapolating the experience gained in developing and working with primitive teleoperators and robots, we can postulate some ideas of how an astronaut-teleoperator-robot team might operate.

Teleoperator State-of-the-Art

Operational experiences with manipulators cover a span of more than twenty years.[1,2] The advanced manipulators that are commercially available have capabilities that approach some of the capabilities of the human arm and hand in performing relatively simple tasks. There do not appear to be any major technical barriers to the development of dextrous, high fidelity master-slave manipulators equipped with tactile and force feedback systems.

Teleoperator viewing systems have used standard TV components packaged to give desirable control and display features. For example, the recent development of experimental head controlled TV systems have gone a long way toward giving the operator a "sense of presence," defined as the psychological feeling the observer has that his head and eyes are located at the camera and that he is looking directly at the scene or job to be done instead of looking at a TV monitor. This partial removal of the interface between the operator and the display is a major improvement in TV viewing, and the development of future visual systems will be directed toward completely removing the interface.

Several experimental teleoperator vehicles, equipped with manipulators and TV cameras have been built during the past 10 yr.[3,4] A recent teleoperator vehicle, the Self-Propelled Anthropomorphic Manipulator (SAM), built at a low cost from spare parts, surplus equipment, and commercial components, has been useful in demonstrating the feasibility of using teleoperators in radioactive environments.

SAM is a commercial all-terrain vehicle modified to be remotely controlled from a small portable control terminal. The "torso" is mounted on a rotating boom that can be positioned on a semicircular track to permit manipulator operations from either side and from the rear of the vehicle, as shown in Fig. 1. A switch-controlled pan and tilt unit at the base of the "torso" provides a vertical range of manipulator operations from ground level to a height of 6 ft above the ground.

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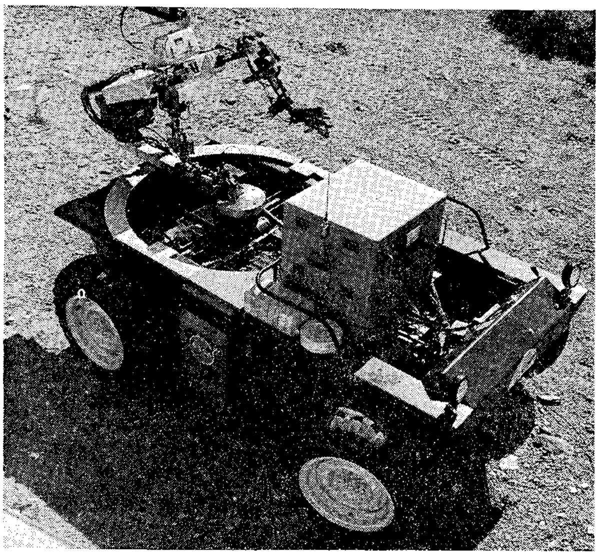

Fig. 1 Top view self-propelled anthropomorphic manipulator.

The manipulators are powered orthotic arms[5] converted into anthropomorphous ("human-like") manipulators. The manipulators are controlled by an exoskeleton system using the same type of orthotic arms equipped with position sensors but not powered. The human operator, located at a distant and safe distance, can wear the control arms as a walk-around exoskeleton. A photograph of the exoskeleton control system is shown in Fig. 2.

The visual system for the recently modified SAM is a head-controlled TV camera mounted at the top of the torso. The camera's location with respect to the manipulator was selected to simulate the location of a human operator's head in relation to his arms. The anthropomorphic configuration of the manipulators and TV system was selected because the SAM manipulator and television control systems have a total of 16 degrees of freedom. Therefore the only practical way to control all of the motions simultaneously is to use an anthropomorphic exoskeleton technique which is an extension of the human eye-hand correspondence.

The vehicle control is a simple system using commercial linear actuators and position sensing potentiometers. A commercial 64 channel digital PCM-FM radio link is used for commanding and controlling the vehicle.

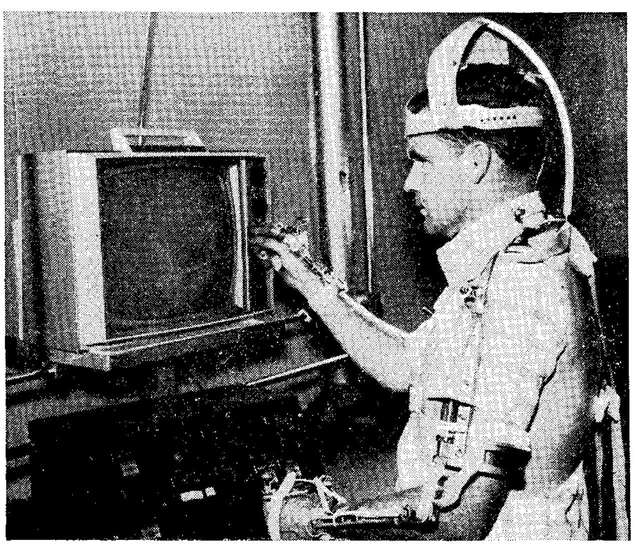

Fig. 2 Control station—SAM system.

Robot State-of-Art

The state-of-the-art of robots, is primitive and limited to a small number of experimental devices built in university laboratories. Most information is based on theory rather than actual experience. Since the technologies required for mobility and manipulation are reasonably advanced, virtually all of the robot research and development work currently in progress is in the area of computer sciences. Current efforts are being applied to the development of techniques for the information processing that will be required for a practical robot.

Among the many problems already identified in information processing, the four key problems appear to be: a) the analysis of visual scenes, b) the autonomous control of complex moving vehicles, c) the programing of two computer systems for effective sharing of computational tasks, and d) the design and construction of suitable on-board computers.

Probably the best-known example of a contemporary robot is Stanford Research Institute's Shakey. Shakey's abilities are limited to coping with large wooden objects in an uncluttered room. Another example of contemporary robotry is an experiment in progress at the computer sciences laboratory at Stanford University. In this experiment a computer-television-manipulator-system, essentially a robot, has been "trained" to do some very simple tasks, such as stacking blocks within a prescribed accuracy of alignment. Progress has been slow, but it appears inevitable that highly competent robots, will be developed.

Description of Astronaut-Teleoperator-Robot Team

It appears that practical teleoperator and robot teams can be developed and combined effectively to operate in space. Such a team can be flexible in that man, teleoperator or robots can be used individually or in different combinations. For example, 1) teleoperators can be used by astronauts on the moon, or 2) teleoperators controlled from a ground station can assist astronauts on the moon, or 3) astronauts on the moon can control teleoperators on the moon while working cooperatively with robots on the moon, etc. Furthermore, the numbers of astronauts, teleoperators and robots in a team can vary according to need.

Such a team could have a major impact on future space planning. With versatile and flexible capabilities available, the scope of space activities could be much broader than the activities currently being considered and will permit the development of the moon for the benefit of man.

A credible lunar development project must be economically justifiable. In order to be so lunar facilities must be constructed and equipped so that they can be operated continuously over a period of many decades. This assumption precludes the continuous presence of astronauts because of the limitations of life support systems and physiological and psychological constraints. Earth-controlled teleoperators would normally be used to maintain and operate the facilities on a continuing basis. Also assumed is an economical and reusable shuttle between Earth and moon.

A Benign Earth Observation Facility

The establishment of an Earth observation facility on the moon would permit the acquisition of enormous amounts of data over a period of many decades. Working in conjunction with various types of satellites, such an observation facility could receive data from the satellites, correlate it with its own observations, process the data, and send the results of the processed data back to earth.

In constructing and operating such a facility, site selection surveys would include aerial reconnaisance from an orbiting spacecraft, augmented by surface surveys, made by teleoperators which in turn are controlled by astronauts operating from a lunar module on the surface. The teleoperator would provide the detailed data about surface characteristics that could not be obtained from an aerial survey. It could determine powdery or jagged rock out-croppings and the size and distinguishing features of the craters.

The team of astronauts and teleoperators working on the moon would examine candidate sites in detail to determine susceptibility to moonquakes, the depth and bearing strength of granular material, and the presence and strength of large rock formations.

The preparation of the selected site for the facility would take many months, much longer than astronauts could stay on the moon. The site preparation would be accomplished by robots and Earth-controlled teleoperators. Robots would grade the soil compaction and do the trenching. Earth-controlled teleoperators would assemble and maintain the robotic construction equipment and control the over-all operation. The permanent control center and a habitat for astronauts would be built. It is expected that astronauts would return to the moon for this phase of construction, which would be a complicated installation requiring the intelligence and adaptability of men. The astronauts would use teleoperators to transfer prefabricated sections of the control center and habitat from the lunar shuttles to the previously prepared foundations. Astronauts and teleoperators would then work together carefully assembling and testing the control center and habitat.

Astronauts would later return to the moon to perform the checkout and activation operations, using teleoperators where required. Astronauts would provide the on-site expertise and judgement needed for activating the facility. Although the robots intended to operate the facility would have been proven and "trained" in a simulation facility on the Earth, the astronauts would work closely with the operating robots during the initial operations to ensure that the robots are able to operate the Earth observation facility for an extended period of time.

Astronauts would not be needed to operate the facility on a routine basis, since the robots would maintain the facility, receive and warehouse supplies and spare parts, and ship scientific data and records back to Earth. During these extended unmanned operating periods, Earth-controlled teleoperators would be used to maintain and repair the robots to adjust, align, calibrate, and repair experiments and facility equipment. Astronauts would return to the facility only when on-site operations are required to refurbish it or to install and check out new experiments, sensors, or computing systems.

The creation of astronaut-teleoperator-robot teams will provide a practical technique for constructing large space facilities, and operating the facilities over several decades. Similar approaches can eventually be used for exploring and developing the planets. The robots can rove and do simple tasks. The teleoperators can extend man's sophisticated capabilities across great distances. Man can use his experience, judgement, and associative thinking abilities to construct and operate large and complex facilities in space. The integration of man, teleoperators, and robots will create flexible teams with composite abilities far superior to those of the individual components.

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Air Film Cooling in a Nonadiabatic Wall Conical Nozzle

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Nomenclature

c_p = specific heat
h = heat-transfer coefficient
K = constant in Eq. (3)
m = mass flow rate
P = pressure
R = nozzle radius
S = slot height
T = temperature
u = velocity
x = distance along wall from coolant slot
z = axial distance from coolant slot
α = thermal diffusivity
η = adiabatic wall film cooling effectiveness
η' = nonadiabatic wall film cooling effectiveness
$\phi, \phi_1, \phi_2, \phi_3$ = exponents defined by Eqs. (3–6)

Subscripts

c = coolant condition at slot
L = based on local conditions
w = wall condition
0 = stagnation condition
∞ = freestream condition

Superscripts

$*$ = geometric throat
o = condition with no film cooling

Introduction

FILM cooling techniques provide a means of preventing structural deterioration of components such as turbine blades and rocket nozzles which experience very high local heat fluxes. Two procedures have been followed in predicting the effects of film cooling on heat transfer; namely, correlation methods[1–3] and various boundary-layer theories.[4,5] Boundary-layer methods will undoubtedly receive increased emphasis, particularly when the coolant flow rate is critical to performance; however, in many applications it is acceptable to apply the simpler correlation methods.

Using the apparatus of Ref. 6, the present study evaluates various forms of a correlation method as applied to an air film-cooled conical nozzle operating with a heated-air main stream and a water-cooled wall.

Several film cooling studies in the literature have dealt with nonaccelerated flow over adiabatic walls. In many of these studies, correlations of the Hatch-Papell[1] type were applied with reasonable success. It has also been shown that a satisfactory correlation of film cooling data in the highly accelerated flow of an adiabatic-wall rocket nozzle could be obtained with a slight modification of the method of Ref. 1.[2] Lieu[3] modified the film cooling effectiveness η in order to

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