

## Space Robot

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**Abstract:**—Robot is a mechanical body with the brain of a computer. Integrating the sensors and the actuators and with the help of the computers, we can use it to perform the desired tasks. Robot can do hazardous jobs and can reach places where it is difficult for human beings to reach. Robots, which substitute the manned activities in space, are known as space robots. The interest in this field led to the development of new branch of technology called space robotics. Through this paper, I intend to discuss about the applications, environmental condition, testing and structure of space robots.

**Keywords:**—Robots, Space Robots, Sensors, Actuators, Mechatronics

### I. INTRODUCTION

Robot is a system with a mechanical body, using computer as its brain. Integrating the sensors and actuators built into the mechanical body, the motions are realized with the computer software to execute the desired task. Robots are more flexible in terms of ability to perform new tasks or to carry out complex sequence of motion than other categories of automated manufacturing equipment. Today there is lot of interest in this field and a separate branch of technology robotics has emerged. It is concerned with all problems of robot design, development and applications. The technology to substitute or subsidise the manned activities in space is called space robotics. Various applications of space robots are the inspection of a defective satellite, its repair, or the construction of a space station and supply goods to this station and its retrieval etc. With the over lap of knowledge of kinematics, dynamics and control and progress in fundamental technologies it is about to become possible to design and develop the advanced robotics systems. And this will throw open the doors to explore and experience the universe and bring countless changes for the better in the ways we live. [1]

#### 1.1 AREAS OF APPLICATION

The space robot applications can be classified into the following four categories

1.1.1 In-orbit positioning and assembly: For deployment of satellite and for assembly of modules to satellite/space station.



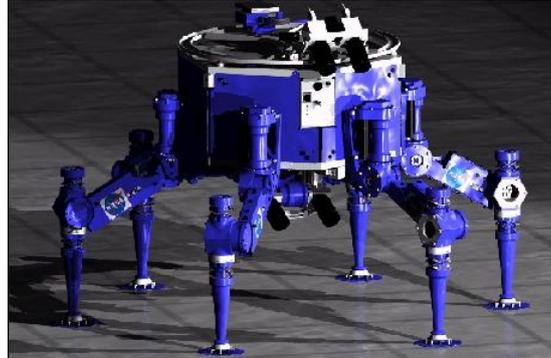
*Fig 1: Positioning and Assembly*

1.1.2 Operation: For conducting experiments in space lab.



*Fig 2: Robot for Experimental Purpose*

1.1.3 Maintenance: For removal and replacement of faulty modules/packages.



*Fig 3: Robot for Maintenance Purpose*

1.1.4 Resupply: For supply of equipment, materials for experimentation in space lab and for the resupply of fuel.

The following examples give specific applications under the above categories scientific experimentation:

- Conduct experimentation in space labs that may include
- Metallurgical experiments which may be hazardous.
- Astronomical observations.
- Biological experiments.
- Assist crew in space station assembly
- Assist in deployment and assembly out side the station.

Assist crew inside the space station: Routine crew functions inside the space station and maintaining life support system.

Space servicing functions

## 1.2 Refueling.

Replacement of faulty modules

- Assist jammed mechanism say a solar panel, antenna etc.
- Space craft enhancements
- Replace payloads by an upgraded module.
- Attach extra modules in space.
- Space tug
- Grab a satellite and effect orbital transfer.
- Efficient transfer of satellites from low earth orbit to geostationary orbit.
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## II. SPACE SHUTTLE TILE REWATERPROOFING ROBOT TESSELLATOR

### 2.1 Tessellator

Tessellator is a mobile manipulator system to service the space shuttle. The method of rewaterproofing for space shuttle orbiters involves repetitively injecting the extremely hazardous dimethyloxysilane (DMES) into approximately 15000 bottom tile after each space flight. The field robotic center at Carnegie Mellon University has developed a mobile manipulating robot, Tessellator for autonomous tile rewaterproofing. Its automatic process yields tremendous benefit through increased productivity and safety.

In this project, a 2D-vehicle workspace covering and vehicle routing problem has been formulated as the Travelling Workstation Problem (TWP). In the TWP, a workstation is defined as a vehicle which occupies or serves a certain area and it can travel; a workspace is referred to as a 2D actuation envelop of manipulator systems or sensory systems which are carried on the workstation; a work area refers to a whole 2D working zone for a workstation. [3]

### 2.2 THE OBJECTIVE OF THE TWP

- To determine the minimum number of workspaces and their layout, in which, we should minimize the overlapping among the workspaces and avoid conflict with obstacles.
  - To determine the optimal route of the workstation movement, in which the workstation travels over all workspaces within a lowest cost (i.e. routing time).
- The constraints of the problem are
- The workstation should serve or cover all work areas.
  - The patterns or dimensions of each workspace are the same and
  - There some geographical obstacles or restricted areas.

In the study, heuristic solutions for the TWP and a case study of Tessellator have been conducted. It is concluded that the covering strategies, e.g. decomposition and other layout strategies yield satisfactory solution for workspace covering, and the cost-saving heuristics can near-optimally solve the routing problem. The following figure shows a sample solution of TWP for Tessellator.

### III. ROBOTS TO REFUEL SATELLITES

The US department of defense is developing an orbital-refueling robot that could expand the life span of American spy satellites many times over, new scientists reported. The robotic refueler called an Autonomous Space Transporter and Robotic Orbiter (ASTRO) could shuttle between orbiting fuel dumps and satellites according to the Defense Advance Research Projects Agency. Therefore, life of a satellite would no longer be limited to the amount of fuel with which it is launched. Spy satellites carry a small amount of fuel, called hydrazine, which enable them to change position to scan different parts of the globe or to go into a higher orbit. Such maneuvering makes a satellites position difficult for an enemy to predict. But, under the current system, when the fuel runs out, the satellite gradually falls out of orbit and goes crashing to the earth. In the future the refueler could also carry out repair works on faulty satellites, provided the have modular electronic systems that can be fixed by slot in replacements.[1]

#### 3.1 SPACE ROBOT CHALLENGES IN DESIGN AND TESTING

Robots developed for space applications will be significantly different from their counter part in ground. Space robots have to satisfy unique requirements to operate in zero conditions (lack of gravity), in vacuum and in high thermal gradients, and far away from earth. The phenomenon of zero gravity effects physical action and mechanism performance. The vacuum and thermal conditions of space influence material and sensor performance. The degree of remoteness of the operator may vary from a few meters to millions of kilometers. The principle effect of distance is the time delay in command communication and its repercussions on the action of the arms. The details are discussed below.

#### 3.2 ZERO EFFECT ON DESIGN

The gravity free environment in which the space robot operates possesses both advantages and disadvantages. The mass to be handled by the manipulator arm is not a constraint in the zero environments. Hence, the arm and the joints of the space robot need not withstand the forces and the moment loads due to gravity. This will result in an arm which will be light in mass. The design of the manipulator arm will be stiffness based and the joint actuators will be selected based on dynamic torque (i.e.; based on the acceleration of the arm). The main disadvantage of this type of environment is the lack of inertial frame. Any motion of the manipulator arm will induce reaction forces and moment at the base which inturn will disturb the position and the altitude. The problem of dynamics, control and motion planning for the space robot is considering the dynamic interactions between the robot and the base (space shuttle, space station and satellite). Due to the dynamic interaction, the motion of the space robot can alter the base trajectory and the robot end effector can miss the desired target due to the motion of the base. The mutual dependence severely affects the performance of both the robot and the base, especially, when the mass and moment of inertia of the robot and the payload are not negligible in comparison to the base. Moreover, inefficiency in planning and control can considerably risk the success of space missions. The components in space do not stay in position. They freely float and are a problem to be picked up. Hence, the components will have to be properly secured. Also the joints in space do not sag as on earth. Unlike on earth the position of the arm can be within the band of the backlash at each joint.[4]

#### 3.3 VACUUM EFFECT AND THERMAL EFFECT

The vacuum in space can create heat transfer problems and mass loss of the material through evaporation or sublimation. This is to be taken care by proper selection of materials, lubricants etc., so as to meet the total mass loss (TML) of <1% and collected volatile condensable matter (CVCMM) of <0.1%. The use of conventional lubricants in bearings is not possible in this environment. The preferred lubricants are dry lubricants like bonded/sputtered/ion plated molybdenum disulphide, lead, gold etc. Cold welding of molecularly similar metal in contact with each other is a possibility, which is to be avoided by proper selection of materials and dry lubricants. Some of the subsystem that cannot be exposed to vacuum will need hermetical sealing. The thermal cycles and large thermal variations will have to be taken care in design of robot elements. Low temperature can lead to embrittlement of the material, weaken adhesive bonding and increase friction in bearings. Large thermal gradients can lead to distortion in structural elements and jamming of the mechanism. This calls for the proper selection of the materials whose properties are acceptable in the above temperature ranges and the selection of suitable protective coatings and insulation to ensure that the temperature of the system is within allowable limits.

#### 3.4 OTHER FACTORS

One of the prime requirements of space systems is lightweight and compactness. The structural material to be used must have high specific strength and high specific stiffness, to ensure compactness, minimum mass and high stiffness. The other critical environment to which the space robot will be subjected to are the dynamic loads during launch. These dynamic loads are composed of sinusoidal vibrations, random vibrations, acoustic noise and separation shock spectra. The electrical and electronic subsystems will have to be space qualified to take care of the above environmental conditions during launch and in orbit. The components must be protected against radiation to ensure proper performance throughout its life in orbit.

The space robots will have to possess a very high degree of reliability and this is to be achieved right from the design phase of the system. A failure mode effect and critical analysis (FMECA) is to be carried out to identify the different failure modes effects and these should be addressed in the design by

- Choosing proven/reliable designs.
- Having good design margins.

- Have design with redundancy.

### 3.5 SPACE MODULAR MANIPULATORS

The unique thermal, vacuum and gravitational conditions of space drive the robot design process towards solutions that are much different from the typical laboratory robot. JSC's A&R Division is at the forefront of this design effort with the prototypes being built for the Space Modular Manipulators (SMM) project. The first SMM joint prototype has completed its thermal-mechanical-electrical design phase, is now under construction in the JSC shops, and is scheduled for thermal-vac chamber tests in FY94.

FY93 was the SMM project's first year, initiating the effort with a MITRE Corporation review of the existing space manipulator design efforts (RMS and FTS) and interaction with ongoing development teams (RANGER, JEM, SPDM, STAR and SAT). Below this system level, custom component vendors for motors, amplifiers, sensors and cables were investigated to capture the state-of-the-art in space robot design. Four main design drivers were identified as critical to the development process:

1. Extreme Thermal Conditions;
2. High Reliability Requirements;
3. Dynamic Performance; and
4. Modular Design.

While these design issues are strongly coupled, most robot design teams have handled them independently, resulting in an iterative process as each solution impacts the other problems. The SMM design team has sought a system level approach that will be demonstrated as prototypes, which will be tested in the JSC thermal-vacuum facilities.

The thermal-vacuum conditions of space are the most dramatic difference between typical laboratory robot and space manipulator design requirements. Manufacturing robots operate in climate controlled,  $\sim 20^\circ\text{C}$  factory environments, where space manipulators must be designed for  $\sim 75\text{K}$  temperature variations with  $1500\text{ W/m}^2$  of solar flux. Despite these environmental extremes, the technology to model and control robot precision over a wide temperature range can be applied to terrestrial robotic operations where the extreme precision requirements demand total thermal control, such as in semiconductor manufacturing and medical robot applications.

Thermal conditions impact reliability by cycling materials and components, adding to the dynamic loading that causes typical robot fatigue and inaccuracy. MITRE built a customised thermal analysis model, a failure analysis model using FEAT, and applied the fault tolerance research funded by JSC at the University of Texas. The strategy is to layer low level redundancy in the joint modules with a high level, redundant kinematic system design, where minor joint failures can be masked and serious failures result in reconfigured arm operation. In this approach, all four design drivers were addressed in the selection of the appropriate level of modular design as a 2-DOF joint module.

The major technical accomplishments for the FY93 SMM project are:

- Conceptual and detailed design of first joint prototype;
- Detailed design and fabrication of thermal-vacuum test facility;
- Custom design of thermal-vac rated motors, bearings, sensors and cables; and
- Published two technical papers (R. Ambrose & R. Berka) on robot thermal design. [3]

## IV. SYSTEM VERIFICATION AND TESTING

The reliability is to be demonstrated by a number of tests enveloping all the environmental conditions (thermal and vacuum) that the system will be subjected to. Verification of functions and tests will be conducted on subsystems, subassemblies and final qualification and acceptance tests will be done on complete system. The most difficult and the nearly impossible simulation during testing will be zero simulation.

The commonly used simulations for zero  $g$  are

**4.1 Flat floor test facility:** It simulates zero  $g$  environments in the horizontal plane. In this system flat floor concept is based on air bearing sliding over a large slab of polished granite.

**Water immersion:** Reduced gravity is simulated by totally submerging the robot under water and testing. This system provides multi degree of freedom for testing. However, the model has to be water-resistant and have an overall specific gravity of one. This method is used by astronauts for extra vehicular activities with robot.

**4.2 Compensation system:** Gravitational force is compensated by a passive and vertical counter system and actively controlled horizontal system. The vertical system comprises the counter mechanism and a series of pulleys and cables that provide a constant upward force to balance the weight of the robot. However, the counter mechanism increases the inertia and the friction of joints of rotating mechanism.

## V. PERFORMANCE ASSESSMENT AND CALIBRATION STRATEGIES FOR SPACE ROBOTS

Predictable safe and cost efficient operation of a robotic device for space applications can best be achieved by programming it offline during the preparation for the mission. Computer aided design techniques are used to assure that the movement of the robot are predictable. A software model of the robot and its work cell is made and this must be compatible with the model of the environment in which the robot must perform. Cost efficiency requirements dictate that a robot be calibrated, after which its performance must be checked against specified requirements. Proper use of miniaturized sensing technology is needed to produce a robot of minimum size, power requirement and consumption and mass. This often requires minimizing the number and the type of sensors needed, and maximizing the information (such as position, velocity, and acceleration) which is gained from each sensor.

The study of methods of assessing the performance of a robot, choosing its sensors and performing calibration and test, ESA passed a contract with industry. Results of this work are applicable to any robot whose kinematics chain needs accurate geometrical modeling. [1]

### ROBOT PERFORMANCE ASSESSMENT

The objectives of robot performance assessment are

- To identify the main source of error which perturb the accuracy of the arm.
- To decide if the arm or the work cell must be calibrated.
- To compare the expected improvement in accuracy in calibration.

The performance of the robot is assessed by making mathematical model of the characteristics of the error source in each of its sub system such as the joint, the robot link or its gripper. From these the effects of errors on the positioning accuracy of end effector (the functioning tip of the robot arm) can be evaluated.

Error sources are identified by a bottom up analysis, which take account of the capabilities of state of the art production technology. For each robot subsystem error sources are identified and are sorted into three categories.

Systematic error which do not vary with time, such as parallelism, concentricity and link length.

Pseudo systematic error, which are time variant yet predictable such as temperature induced effects.

Random errors, which vary with time and cannot be, predicted such as encoded noise.

Once the error source have been classified and its magnitude defined, various statistical methods may be used to evaluate its effects when they work in combination. Simply adding all the errors, take no account of their statistical nature and gives an estimate which is safe but unduly pessimistic; misapplication of statistics can produce an estimate, which is too optimistic.

Accuracy of some painting mechanism is frequently estimated by separately eliminating the root mean square value of each of the three error types identified above and adding them. In the case of AMTS project, all error sources were considered as statistical variables and a single root mean square error at the end effect or was of interest. The bottom up approach used to establish the contribution of each power source error source was validated taking the case of manipulator for which a worst case accuracy of 2.7mm was predicted. This was very close to its average accuracy of 2mm.

### 5.1 ROBOT CALIBRATION

If the performance prediction has shown that calibration is needed to compensate for errors, a proper calibration approach is required.

Ideally, all calibration must be done on ground. In orbit calibration procedures should be limited to crosschecking the validity of model developed on ground and if necessary correcting for errors such as microslip page or pressure gradient.

To keep the flight hardware simple, the in orbit calibration should be achieved using sensors already available in the robot. Calibration is performed in five steps:

Modeling, in which a parametric description of the robot is developed, introducing geometric parameters such as link length and non geometric parameters such as control parameters.

Measurement, in which a set of robot poses (position and orientation) and encoder data are measured using real robot to provide inputs to the identification test step.

Identification, which uses the parametric model and the measured data to determine the optimal set of error parameters.

Model implementation, which may be done either by updating the root controller data or by correcting the robot pose with expected standard deviation of the error.

Verification, that the improvement in the positioning accuracy of the robot in all three axes have been achieved.

A method for calibrating each axes independently has been successfully developed in the frame of the contract. This method uses independent measurements of motions along each of the three axes. Advantage of this approach compared to others such as those requiring all robot joints move simultaneously is that it subdivides the general problem of robot calibration into a set of problems of lower complexity, thus achieving good stability and numerical precession. The calibration software is parametric and is suitable for calibrating any open robot kinematics chain. [2]

### 5.2 PERFORMANCE EVALUATION

As part of a verification procedure, specific performance tests were carried out on a robot by Krypton under contract to ESA. The first was an accuracy test in which the robot had to adapt a specified pose and aim at a point, key characteristics for predictable offline programming. The second test evaluated the repeatability with which the robot could reach a pose it had been taught to adopt. This is essential for performing repetitive and routine tasks. Finally, the multidirectional pose accuracy was tested to establish the effect of random errors and to establish the limits of calibration procedure. The performance of the robot was measured before and after calibration.

Procedures for calibrating robots on ground and in orbit have been developed, and the performance of the robotic devices has been successfully tested. The robot calibration procedure proved to work well resulting in an improvement in performance by a factor of ten in some cases. The calibration software is versatile and it can be used to calibrate and evaluate most kinematics chains ranging from a simple two axes antenna gimbals mechanism to a ten axes manipulator. These software procedures are now used by Krypton for applications in most motor industry and elsewhere.

## VI. STRUCTURE OF SPACE ROBOTS

### 6.1 DESCRIPTION OF STRUCTURE OF SPACE ROBOT

The proposed robot is of articulated type with 6 degrees of freedom (DOF). The reason for 6 DOF system rather than one with lesser number of DOF is that it is not possible to freeze all the information about possible operations of the

payload/racks in 3D space to exclude some DOF of the robot. Hence, a versatile robot is preferred, as this will not impose any constraints on the design of the laboratory payload/racks and provide flexibility in the operation of the robot. A system with more than six DOF can be provided redundancies and can be used to overcome obstacles. However, the complexities in analysis and control for this configuration become multifold.

The robot consists of two arms i.e. an upper arm and a lower arm. The upper arm is fixed to the base and has rotational DOF about pitch and yaw axis. The lower arm is connected to the upper arm by a rotary joint about the pitch axis. These 3 DOF enable positioning of the end effector at any required point in the work space. A three-roll wrist mechanism at the end of the lower arm is used to orient the end effector about any axis. An end effector connected to the wrist performs the required functions of the hand. Motors through a drive circuit drive the joint of the arm and wrist. Angular encoders at each joint control the motion about each axis. The end effector is driven by a motor and a pressure sensor/strain gauges on the fingers are used to control the grasping force on the job.

## 6.2 DISCRPTION OF SUBSYSTEMS

The main subsystems in the development of the manipulator arm are

- Joints
- Arm
- Wrist
- Gripper

### JOINTS

A joint permits relative motion between two links of a robot. Two types of joints are Roll joint rotational axis is identical with the axis of the fully extended arm. Pitch joint rotational axis is perpendicular to the axis of the extended arm and hence rotation angle is limited.

The main requirements for the joints are to have near zero backlash, high stiffness and low friction. In view of the limitations on the volume to be occupied by the arm within the workspace, the joints are to be highly compact and hence they are integrated to the arm structure. To ensure a high stiffness of the joint the actuator, reduction gear unit and angular encoders are integrated into the joint. Each joint consists of Pancake type DC torque motors (rare earth magnet type) which have advantage over other types of motors with respect to size, weight, response time and high torque to inertia ratio. Harmonic gear drive used for torque amplification/speed reduction. These gear drives have near zero backlash, can obtain high gear ratios in one stage only and have high efficiency.

Electromagnetically actuated friction brakes, which prevent unintentional movements to the arms. This is specifically required when the gear drive is not self-locking. In space environment, where the gravity loads are absent (zero  $g$  environment) brakes will help to improve the stability of the joint actuator control system. i.e. the brake can be applied as soon as the joint velocity is less than the threshold value. Electro optical angular encoders at each axis to sense the position of the end of the arm. Space qualified lubricants like molybdenum disulphide (bonded film/sputtered), lead, gold etc. will be used for the gear drives and for the ball bearings.

### ROBOT ARMS

The simplest arm is the pick and place type. These may be used to assemble parts or fit them into clamp or fixture. This is possible due to high accuracy attainable in robot arm. It is possible to hold the part securely after picking up and in such a way that the position and the orientation remains accurately known with respect to the arm. Robot arms can manipulate objects having complicated shapes and fragile in nature.

### WRIST

Robot arm comprises of grippers and wrist. Wrist is attached to the robot arm and has three DOF (pitch, yaw, and roll). Wrist possesses the ability to deform in response to the forces and the torques and return to equilibrium position after the deflecting forces are removed.

### GRIPPER

Gripper is attached to the wrist of the manipulator to accomplish the desired task. Its design depends on the shape and size of the part to be held.

## VII. OPERATION

### 7.1 SPACE SHUTTLE ROBOT ARM (SHUTTLE REMOTE MANIPULATOR SYSTEM)

#### USE OF SHUTTLE ROBOT ARM

- The Shuttle's robot arm is used for various purposes.
- Satellite deployment and retrieval
- Construction of International Space Station

Transport an EVA crew member at the end of the arm and provide a scaffold to him or her. (An EVA crew member moves inside the cargo bay in co-operation with the support crew inside the Shuttle.)

Survey the outside of the Space Shuttle with a TV camera attached to the elbow or the wrist of the robot arm.

Shuttle robot arm observed from the deck

## 7.2 ROBOT ARM OPERATION MODE

SRMS is operated inside the Space Shuttle cabin. The operation is performed from the aft flight deck (AFD), right behind the cockpit; either through the window or by watching two TV monitors. To control the SRMS, the operator uses the translational hand controller (THC) with his or her left hand and manipulates the rotational hand controller (RHC) with his or her right hand.

### THE RHC

How does the Space Shuttle robot arm grasp objects? Many people might think of human hand or magic hand, but its mechanism is as follows. At the end of the robot arm is a cylinder called the end effector. Inside this cylinder equipped three wires that are used to grasp objects. The object to be grasped needs to have a stick-shaped projection called a grapple fixture. The three wires in the cylinder fix this grapple fixture at the centre of the cylinder.

However, a sight is needed to acquire the grapple fixture while manipulating a robot arm as long as 45 feet. The grapple fixture has a target mark, and a rod is mounted vertically on this mark. The robot arm operator monitors the TV image of the mark and the rod, and operates the robot arm to approach the target while keeping the rod standing upright to the robot arm. If the angular balance between the rod and the robot arm is lost, that can immediately be detected through the TV image. End effector and grapple fixture Robot arm's payload acquiring sequence

## 7.2 FREE FLYING SPACE ROBOTS

The figure below shows an example of a free flying space robot. It is called ETS VII (engineering test satellite VII). It was designed by NASDA and launched in November 1997. In a free flying space robot a robot arm is attached to the satellite base. There is a very specific control problem. When the robot arm moves, it disturbs the altitude of the satellite base. This is not desirable because, The satellite may start rotating in an uncontrollable way. The antenna communication link may be interrupted.

One of the research objectives is to design robot arm trajectories and to control the arm motion in such a way that the satellite base remains undisturbed or that the disturbance will be minimum. Free flying space robots

## SPACE STATION MOUNTED ROBOTS

The international space station (ISS) is a sophisticated structural assembly. There will be several robot arms which will help astronauts in performing a variety of tasks.

### JEMRMS

The figure shows a part of ISS including the Japanese Experimental Module (JEM). A long manipulator arm can be seen. The arm is called JEMRMS (JEM Remote Manipulating System). A small manipulator arm called SPDM (Special purpose dexterous Manipulator) can be attached to JEMRMS to improve the accuracy of operation.

### SPDM

Space robotics is one of the important technologies in space developments. Especially, it is highly desired to develop a completely autonomous robot, which can work without any aid of the astronauts. However, with the present state of technologies, it is not possible to develop a complete autonomous space robot. Therefore, the teleoperation technologies for the robots with high levels of autonomy become very important. Currently, the technologies where an operator teleoperates a space robot from within a spacecraft are already in practical use, like the capture of a satellite with the shuttle arm. However, the number of astronauts in space is limited, and it is not possible to achieve rapid progresses in space developments with the teleoperation from within the spacecraft. For this reason, it has become highly desired to develop the technologies for the teleoperation of space robots from the ground in the future space missions. [4]

## VIII. CONCLUSION

In the future, robotics will make it possible for billions of people to have lives of leisure instead of the current preoccupation with material needs. There are hundreds of millions who are now fascinated by space but do not have the means to explore it. For them space robotics will throw open the door to explore and experience the universe.

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