ISSN 1340-8763

The Japan Society of Mechanical Engineers Vol.13, No.2 December 2002

Jsme News

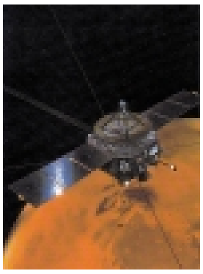
URL http://www.jsme.or.jp/English

Robotics for Planetary Exploration

Ichiro Nakatani

Professor
Institute of Space and Astronautical Science

Why space exploration? — This is an old and new philosophical question repeatedly asked since the beginning of the space development. One of the most important and strongest motivations definitely has been — and will remain to be — the human being's relentless curiosity and quest for the unknown. Human being has continuously enlarged its frontier ever since its creation and the last and biggest remaining frontier, as everyone would admit, is space.(1)



Continued on page 2

Mobile Explorer Robot for Lunar or Planetary Exploration

Takashi Kubota

Spacecraft Engineering Division,
The Institute of Space and Astronautical Science

Several missions to explore the moon or Mars by an unmanned mobile robot are being planned for scientific observation. Recently many researchers have studied and developed lunar or planetary rovers for unmanned surface exploration of planets. Especially micro-rover missions have received a lot of attention, because small, low-cost missions are typically constrained by mass, budget and schedule.

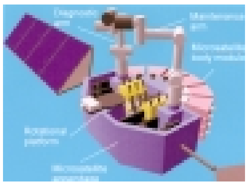
Continued on page 5

Space Robot Maintaining a Satellite Constellation in Earth Orbit

Kazuo Machida

Professor, Department of
Aeronautics and Astronautics,
The University of Tokyo

One of the most expected space robot missions in the 21st century is in-orbit servicing to space infrastructures. Information and communication network systems utilizing a satellite constellation will be required for high quality global personal and mobile telecommunications in our advancing information society as well as for the incessant flow of high-resolution images from Earth observation. These systems require a large number of satellites in low or medium earth orbit to cover the wide range servicing area. Robotics will contribute to increasing the reliability and life span of the infrastructure through maintenance, and to preserving the space environment from space debris through sweeping.



Continued on page 3

Advanced Space Robot for In-Orbit Servicing Missions

Saburo Matunaga

Laboratory for Space System (LSS)
Department of Mechanical and Aerospace Engineering
Tokyo Institute of Technology

1. Introduction

It is indispensable to develop space robots supporting space activities, such as external vehicular activities (EVA) and internal vehicular activities (IVA) for future space utilizations. Especially, EVA supporting robot is important to reduce EVA operation time. The robt should have multi-functional abilities to conduct variable tasks. Thus, we have designed and developed a reconfigurable brachiating space robot (RBR) for ground test [1,2].

Continued on page 6

Robotics for Planetary Exploration

Ichiro Nakatani
Professor
Institute of Space and Astronautical Science

Continued from page 1

Robots will play an important role in the near Earth obit assisting human activities in space as will be vividly shown in the International Space Station. In the planetary explanation, however, space robotics is not just an auxiliary technology to improve efficiency of space activities, but it is the essential element without which we would never be able even to imagine the expansion of human frontier into deep space.

The definition of robot sometimes include sensors, processors and actuators with moving mechanisms. However, the word “robot” here in this article means a much broader category and spacecraft with some kind of intelligence is assumed to be covered by robot just as NASA calls unmanned missions “robotic missions”.

The farther a robot is away from the Earth, the more intelligence he (or she) needs, because remote control and tele-operation from the Earth become less efficient. If communication delay is hours, as in the case of Pluto or Neptune, it is totally impossible to tele-operate a robot from the Earth on a real time basis. The only solution, hence, to the deep space robots is artificial intelligence. In the extreme case of exploring outer solar system, the propagation delay could be tens of years or more, in which case we will need extremely intelligent robots whose intelligence is comparable with or probably higher than that of human beings. Those robots should repair themselves, create their replacements using the available materials in other solar systems and should make very high level decisions without human intervention.

The first Japanese planetary exploration mission is “NOZOMI” which is a Mars orbiter launched in 1998 to study the interaction of Mars upper atmosphere with the solar wind. (See Fig.1)

NOZOMI, which will reach the Mars in 2004, has several autonomous operation capability as first step to develop highly intelligent spacecraft (2) : (1) introduction of smart judgment to conduct orbit maneuver, (2) autonomy for attitude maneuver, earth direction tracking and search for earth direction, (3) smart power management, (4) solar flare monitoring and the counter-measure at the time of unusual proton counting and (5) execution of command based on the house-keeping data.

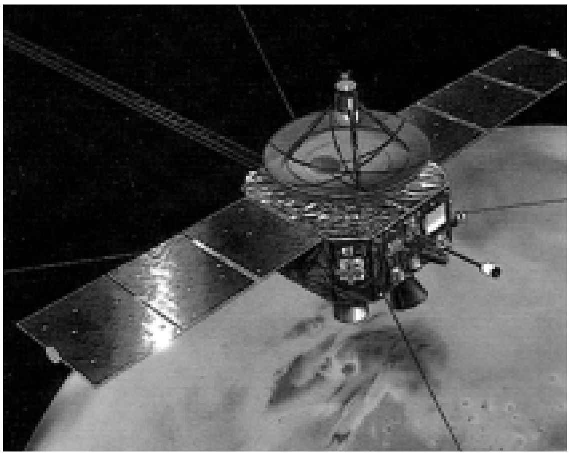


Fig. 1 Artist's drawing of Nozomi spacecraft

NASA has actively been pursuing spacecraft autonomy due to the following reasons : (1) reduction of the mission cost, (2) efficient use of communication link and (3) realization of totally new mission concept. The missions or the mission candidates for advanced autonomy to be introduced are DS1 (asteroid and comet fly-by), the exploration of Europa, one of the Jupiter’s moons, Titan exploration, Pluto/Kuiper Express and DS4 (Comet sample return).

DS1, among them all, was launched in 1998 and successfully demonstrated the on-board autonomy technology called “Remote Agent (RA)”. (4) In this experiment, the ground operators’ agent was assumed to be on-board the spacecraft and the agent was in charge of spacecraft operation to some extent. The RA is comprised of the following 4 elements : Mission Management, Planner/Scheduler, Smart Executive and Module Identification and Reconfiguration. Those functions were successfully demonstrated in May 1999 in orbit.

For planetary surface exploration, we need the technology for autonomous pin-point landing by avoiding

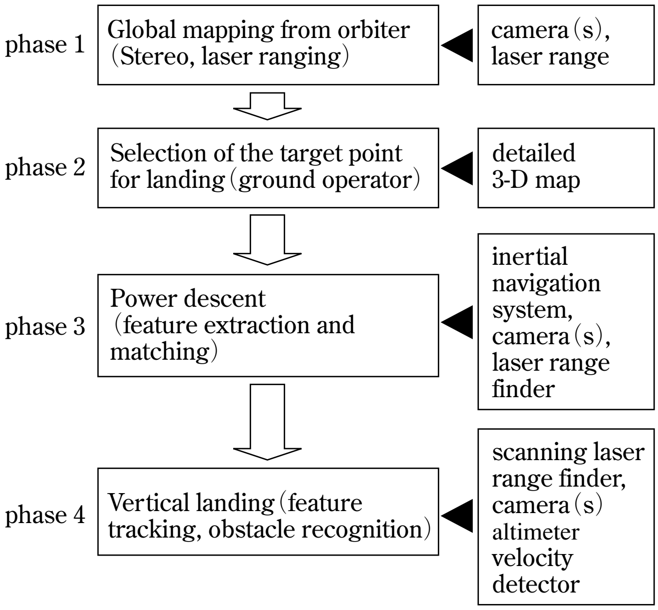


Fig. 2 Typical autonomous landing sequence

obstacles. There have been quite a few lander missions onto the moon and Mars surface. No mission, however, has ever achieved this technology. We are now proposing a technology verification mission called Selene-B which is intended for establishing the autonomous landing technology using a lunar lander. Fig.2 shows a typical autonomous landing sequence with the required functions and sensors for each of the landing phases.

The key technology here includes image processing, feature matching/tracking, and obstacle recognition. The images of the target area are usually not available in advance of the mission with adequate resolution and moreover, the different sun incidence angle could result in unexpected change of the obtained images. Hence, the reliable pin-point landing with obstacles avoided needs an extremely robust image processing scheme, which is the major reason for the lack of the actual missions which use the technology.

References

(1) Space Infrastructure Study Group: Interim Report on the Studies on Space Infrastructure, 1999 (in Japanese).
(2) Adachi, M. et al : Overview autonomies functions onboard Mars Exploration space craft NOZOMI, the 42nd Space Science Technology Joint Conference, 1998 (in Japanese).
(3) Doyle, R.J. : Spacecraft Autonomy and the Missions of Exploration, *IEEE Intelligent Systems & their Applications*, 13-5 (1998), 36-44.
(4) Nayak, P. et al : Validating the DS1 Remote Agent Experiment, *Proceedings of i-SAIRAS '99*, (1999).

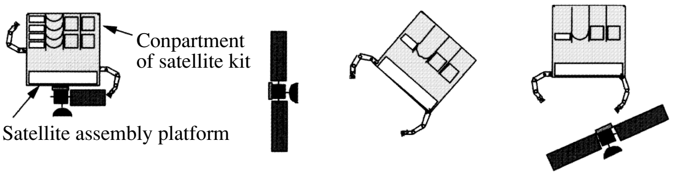
Space Robot Maintaining a Satellite Constellation in Earth Orbit

Kazuo Machida
Professor, Department of Aeronautics and Astronautics,
The University of Tokyo

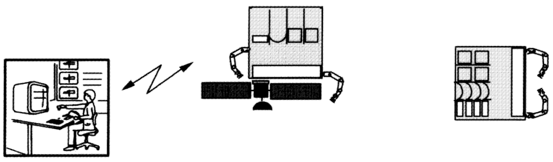
Continued from page 1

Currently, there are approximately 9000 pieces of space debris larger than 10cm in diameter orbiting the earth. The amount of this space debris increases at a rate of 300 pieces per year. With a relative velocity of approximately 10 km/s, even small pieces can cause considerable damage to the space vehicles. The amount of fragments produced by chain collision of debris is increasing, raising concerns that it may threaten the future of space activity and indicating that it is time to take measures to protect the space environment.

To meet these needs, it is necessary to develop a robust information infrastructure which is easy to maintain and to avoid any increase in the amount of debris. As a strategy to solve this problem, the "space environment preservation system" which will preserve satellites and orbits by space robots has been proposed by the author. Fig. 1 shows the system concept. A space maintenance vehicle with robots executes the assembly of several microsatellites in orbit, as well as positioning them to the required orbit. Then, it inspects the satellites periodically, and captures them for diagnosis, maintenance and supply. Also, it is used for collecting, disassembling and deorbiting of satellites at the end of the mission, helping the preservation of the space environment. The space maintenance vehicle will provide care "from the cradle to the grave" for satellite constellation.



(1) Assembly and check (2) Place into orbit (3) Capture



(4) Diagnosis, maintenance and resupply (5) De-orbit

Fig. 1 Concept of "Space environment preservation system" that takes care of satellite constellation from the cradle to the grave

Many technologies must be developed to realize the system, such as assembling, capturing, diagnosing, repairing and disassembling of the satellites by the robot. A new type of microsatellite that can be easily assembled and maintained by a robot is also required. Fig. 2 shows an example of such a robot-friendly satellite. The satellite is divided to four sections. A bus module is a core subsystem, and mission modules, an antenna panel module and a solar panel module are connected to it like branches. Fig. 3 illustrates a research model of the space maintenance vehicle. It has about 6 to 10 sets of microsatellite and their spare modules, and cares their life in orbit. It will work just like a factory and clinic for satellites. Fig. 4 shows a scene of satellite assembly by the space maintenance vehicle. The system is developed by AIST, the University of Tokyo, NT Space Systems Ltd., and Toshiba Corporation. The robot is able to assemble the satellite autonomously in 45 minutes. Strategies of "look and move" to grasp the mod-

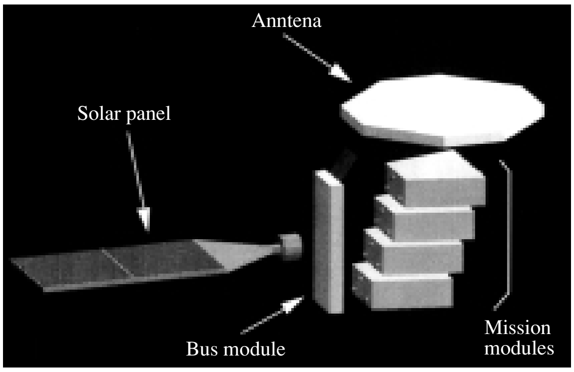


Fig. 2 Structure of modularized microsatellite for in-orbit maintenance

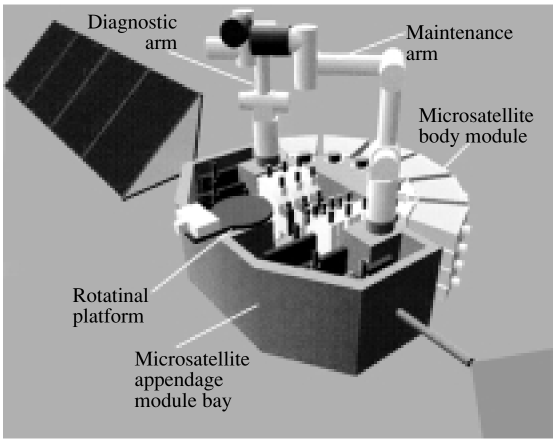


Fig. 3 Space maintenance vehicle

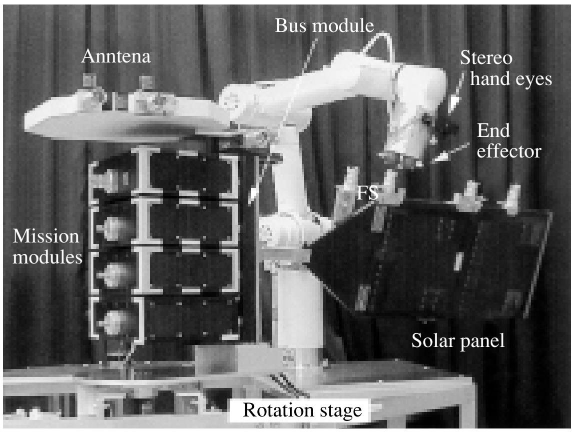


Fig. 4 Assembly of microsatellite by space robot

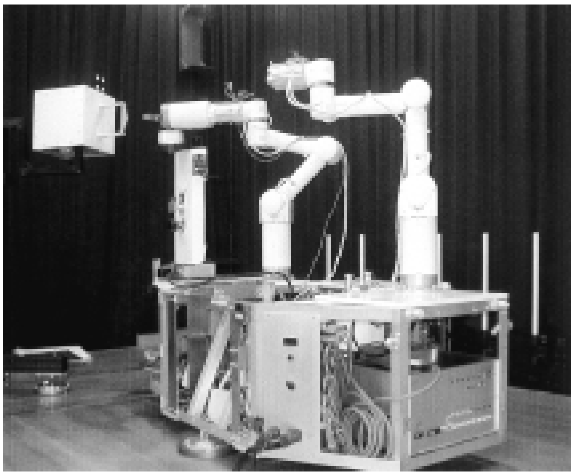


Fig. 5 Capture of rotating satellite by space maintenance vehicle on 3-dimensional weightless testbed

ules and "groping and wobbling" to exactly connect the flexible and long modules are employed. The robot attaches several instruments to arm tip, and inspects and diagnoses the satellite. An acoustic emission sensor, thermal infrared sensor, handy range finder and mass spectrum analyzer with carbon nano-tube emitter are developed for diagnostic devices.

Capturing a satellite is also important technology, and many researches are carried out at national institutes and universities. The capture of the satellite that the attitude became unstable for malfunction is difficult. Identification of relative position and motion of the satellite, proximity flying control of the vehicle, arm tracking control of the arm and a capturing tool are key technologies. Fig.5shows a scene of capturing the satellite that rotates at 1 rpm. The gripper using a wire driven adaptive finger mechanism that allows large misalignment for grasping is developed by Tohoku University, AIST and MHI.

Space maintenance system technology is expected to not only be applied to satellites, but also be evolved to a fundamental technology for the transition from disposable space systems to maintainable and recyclable space systems.

Mobile Explorer Robot for Lunar or Planetary Exploration

Takashi Kubota, Spacecraft Engineering Division,
The Institute of Space and Astronautical Science

Continued from page 1 In July 1997, as known well all over the world, NASA/JPL succeeded in Mars Pathfinder mission and the Sojourner rover could move on the Martian surface and gather and transmit voluminous data back to the Earth [1]. NASA also plans to send some rovers to Mars in 2003, 2005, 2007 Missions [2]. Figure 1 shows 2003 Mars Exploration Rover mission. Two rovers are expected to explore on Mars widely [3]. In 2005, Mars Reconnaissance Orbiter is planned. Scout missions are studied, which include airplanes or balloons. Figure 2 shows the concept of Mars Netlander to be launched in 2007.

In Japan, ISAS (Institute of Space and Astronautical Science) launched "Nozomi" spacecraft, which will be a

Mars's orbiter. ISAS plans to send Lunar-A spacecraft with penetraters to the moon. ISAS is also promoting SELENE mission with NASDA. Rover mission is not authorized yet, but under studying as a candidate of the next lunar exploration mission. Wide varieties of research on the rover have been conducted for the future missions. Candidates for scientific exploration here, not all of which, though, will be accommodated by rovers, are as follows :

1. Geology by Photo Images : topographical survey, identifying size, and shape of rocks, composition of rocks, craters etc.
2. Element Analysis : analysis of age using mass-spectrometer, element analysis using X-ray spectrometer, or γ-ray spectrometer, study of mineral composition using visible or infrared reflection spectrometer etc.
3. Wide Area Investigation : studies on magnetic anomalies using magnetometer, gravity anomalies, electromagnetic structure of the crust using VLF, seismo-logical observation using seismo-meter network etc.
4. Investigation by Manipulator : analysis of regolith, measurement of heat flux, element analysis etc.

Lunar rovers are expected to travel in wide areas and explore the surface in detail. Exploration requirements for lunar rovers are as follows, large area exploration, underground exploration, long term exploration, sample collection and analysis, placement of scientific instruments, exposed surface exploration such as craters

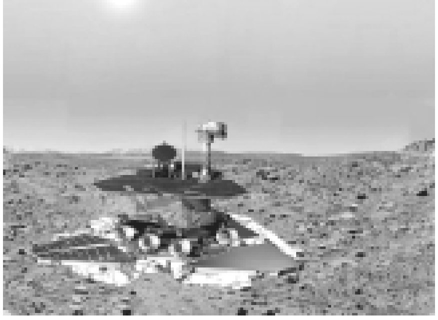


Fig. 1 2003 MER Mission [2] (NASA/JPL/Caltech)

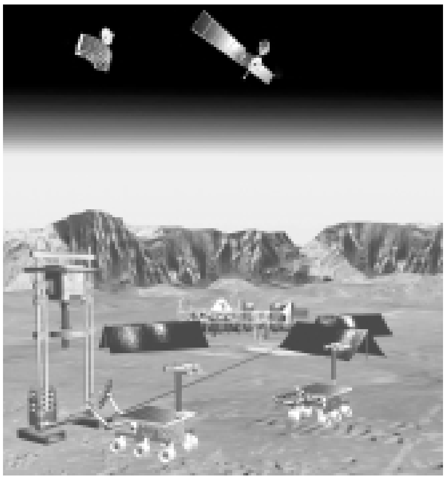


Fig. 2 Mars Netlander [2] (NASA/JPL/Caltech)

As a part of a development program, tele-operation or autonomous navigation technologies are earnestly studied for realizing a rover to be able to move on an unknown lunar or planetary surface. Recently rover field tests have been performed for evaluating the planetary rover performance. In December 1996, NASA/JPL demonstrated the field tests by the Rocky 7 in the Mojave Desert. The Rocky 7 navigation is based on operator way-point designation and on autonomous behavior for movement to the specified targets. In June 1997, CMU rover Nomad navigated about 200 [km] of the planetary-like Atacama Desert in South America while under the control of operators in North America. ISAS rover research groups also have done a long-range test for the perfect autonomous rover at a slag heap in Izu-Ohshima in Japan.

Planetary rovers have been studied, that can travel safely over a long distance on rough terrain. The rover R&D group of ISAS, Meiji University and Chuo University have developed a small, lightweight micro-rover with a new mobility system, which is called "Micro5" [4]. The weight of Micro5 is about 5 [kg]. The developed rover measures about 0.53 [m] wide, 0.55 [m] long and 0.25 [m] high. The wheel diameter is 0.1 [m]. Micro5 has the sampling system. The light-weight manipulator with a camera has been developed, which is attached to the front of the rover. Some scientific instruments are under development. A multiple-rovers mission based on buddy system has been proposed as shown in Fig. 3. The proposed buddy system would lead to higher reliability and safety for exploration mission of the moon or planets. Cooperation by multiple rovers can also make it possible to extend the exploration areas. Various kinds of tasks such as crater exploration, cliff exploration, sample collection, digging, can be realized by cooperation of multiple rovers.

In-situ observations of small bodies like asteroids or comets are scientifically very important because their sizes are too small to have high internal pressures and temperatures, which means they should hold the early chemistry of the solar system. In recent years, some rendezvous or sample-return missions to asteroid have received a lot of attention in the world. So far, NEAR (USA, Launched in 1996), Deep Space 1 (USA, 1998) and Stardust (USA, 1999) were successfully launched. Contour (USA, scheduled in 2002) and Rosetta (Europe, 2003) are ready to be launched. Other small body exploration missions are under studying. NEAR spacecraft was successfully put into the orbit of asteroid 433 Eros in February in 2000. After precise remote-sensing observations, NEAR spacecraft succeeded in hard-landing on the surface of EROS in February in 2001.

In Japan, ISAS plans to launch an asteroid sample and return spacecraft MUSES-C [5] toward a near Earth asteroid 1998SF36 in 2003. In MUSES-C mission, the spacecraft will make a dynamic touch down the surface of the target asteroid and then collect samples automatically by using novel sampler system. The MUSES-C

Fig. 3 Cooperative Exploration by Multiple Rovers

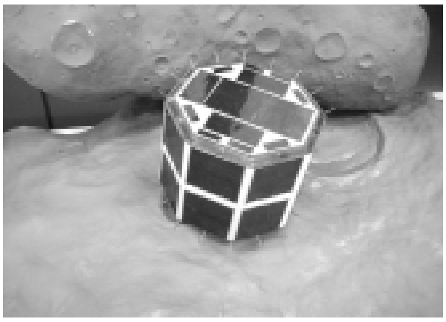


Fig. 4 Asteroid Exploration Rover MINERVA

spacecraft will also take a small rover MINERVA to the asteroid and deploy it onto the surface to explore the surface in detail. Figure4 shows the overview of MINERVA. MINERVA can move and explore by hopping function.

In space exploration, new era comes, to explore deep space widely and in detail. Planetary rovers would make a very important role in deep space exploration. Robotics missions will receive more and more attention. Subsurface exploration and sample return missions would be realized in the near future.

References

[1] http;//mpfwww.jpl.nasa.gov/

[2] http;//www.jpl.nasa.gov/

[3] C.R.Weisbin, D.Lavery, G.Rodriguez, "Robotics Technology for Planetary Missions Into the 21st Century" Proc. of i-SAIRAS'97, pp.5-10, 1997.

[4] Y.Kuroda, K.Kondo, K.Nakamura, Y.Kunii, T.Kubota, "Low Power Mobility System for Micro Planetary Rover "Micro5"," 5th Int. Symposium on Artificial Intelligence, Robotics and Automation in Space, pp.77-82, 1999.

[5] http://www.isas.ac.jp/

Advanced Space Robot for In-Orbit Servicing Missions

Saburo Matunaga

Laboratory for Space System (LSS)

Department of Mechanical and Aerospace Engineering

Tokyo Institute of Technology

Continued from page 1

The RBR is designed to be capable of walking on ISS (the International Space Station) and of reconfiguring its structural topology in order to assist various astronaut activities. Typical tasks include (1) walking inside the pressurized module or outside the exterior of the exposed facility, (2) accessing the power and communication port on ISS, (3) changing configuration of RBR suitable for required tasks such as assembly and inspection, (4) providing visual information to the crews.

The short article outlines the research and development of the RBR system as well as its application to a multiple robot satellite system for in-orbit servicing. The former RBR research work was funded by a part of "Ground Research for Space Utilization" promoted by National Space Development Agency of Japan (NASDA) and Japan Space Forum. This was a joint project with Tokyo Institute of technology, Tohoku University, Toyota Technological Institute, National Aerospace Laboratory, Communications Research Laboratory, Toshiba Corporation, Kawasaki Heavy Industry, Shimizu Corporation, Nissan Mortor Co., Ltd. (IHI AeroSpace), and NASDA. The latter research was supported by the Grant-in Aid for COE Research Project of Super Mechano-Systems by the Ministry of Education, Culture, Sports, Science and Technology (MEXT).

2. Design and Development of RBR

One RBR arm is composed of the six joint modules in roll or pitch configurations, an end-effector and a pivot as shown in Fig. 2. The basic design criterion is "modularized unit" by integrated electronic devices into mechanical parts including a DC servomotor, a harmonic drive, a rotary encoder and photo micro sensors in a compact form. The end-effector and the pivot can be connected mechanically and electrically. The pivots are placed on ISS as well as on a satellite, and they provide electric power and communications signals to the end-effector through the connector. A miniature-sized CCD camera is installed inside the end-effector for precise position control of the arm to grasp the handrail or to reconfigure the RBR system.

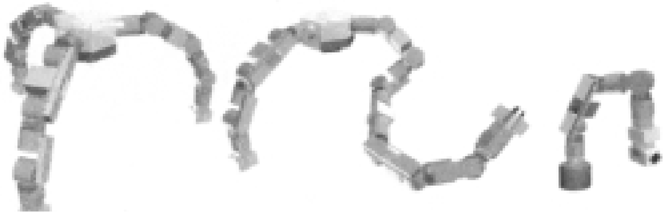


Fig. 1 RBR configurations

One of the most important key technologies required for realizing the reconfigurable function is a system of distributed controllers for the joint's motor drivers and joint-to-joint or arm-to-arm communications. Two-type serial network methods, TIA/EIA-485 and Ethernet, are adopted for a RBR network system. Each arm has hierarchical two layers using these serial networks, as shown in Fig. 3. The top layer is a main controller named Communication Controller (CC), and the other seven sub-controllers named Device Controller (DC) for the six joint modules and the end-effector. Fig. 4 shows developed CC and DC. The CC is utilized as a high-end PC and a communication interface. Most components used are embedded by PCMCIA, which makes extension and/or repairing of functional parts by exchanging to other PCMCIAs. The DC is composed of a 16-bit MPU (Hitachi H8) with a TIA/EIA-485 transceiver and an H bridge circuit. All the seven DCs of the joint modules and the end-effector communicate with the CC through the TIA/EIA-485 bus line.

The major advantage of the system is that the number of cables inside the arm is only fourteen: two for the power line, four for the Device Controller line, four for the Communication Controller line and four for spare for advanced usage. The wire number reduction is the key of the RBR system realization.

3. Demonstration Experiments

We conducted many function evaluation experiments including aircraft microgravity test and show the reconfigurability and brachiating functions of the RBR using two RBR arms as shown in Figs. 5 - 6.

RBR concept can be applied to multiple robot satellite cluster for advanced in-orbit servicing such as inspection, observation, capture, recovery, repair and de-orbit of uncontrolled satellites and construction of large space structures [3]. We have developed a ground experiment system named DISC (Dynamics and Intelligent Simulator for Clusters) that consists of satellite simulators with gas thrusters, a ground station system, and a position determination system. Using the system combined with the RBR arm, we demonstrated the system reconfiguration and transportation capabilities as shown in Fig. 7, in which D1 means DISC #1 and so on.

Fig. 2 Joint module, End-effector and Pivot

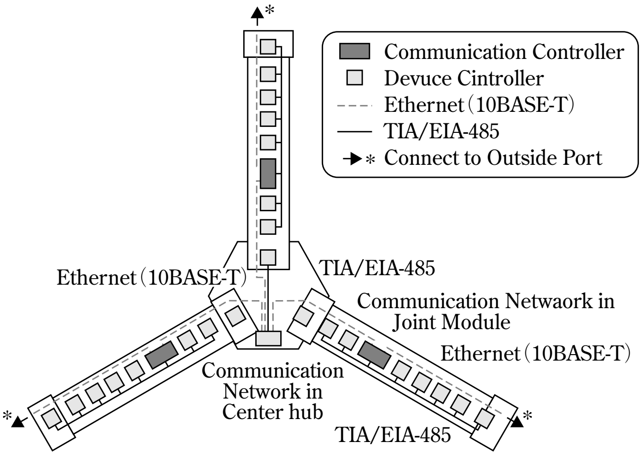


Fig. 3 Communications network

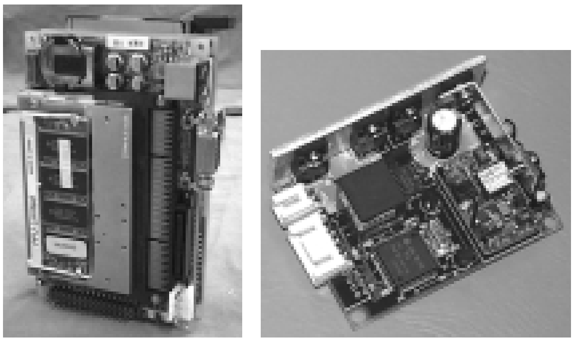


Fig. 4 Communication and Device Controllers

4. Conclusion

The design concept, the system architecture, and the major characteristics of the Reconfigurable Brachiating space Robot (RBR) have been briefly presented and its versatile applicability is shown with some demonstrations. Next step is to clearly define robot supporting

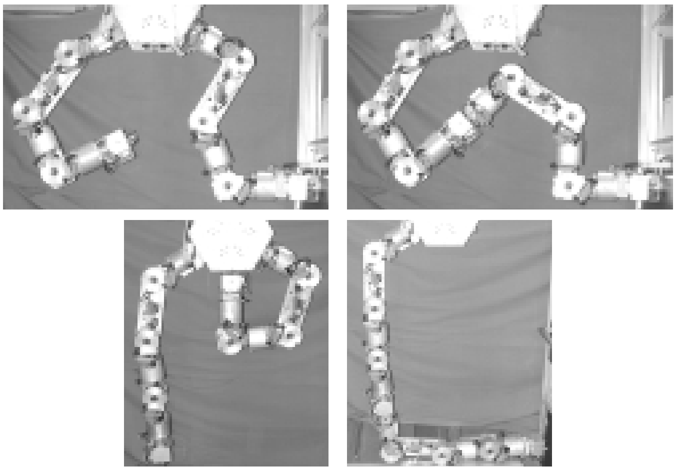
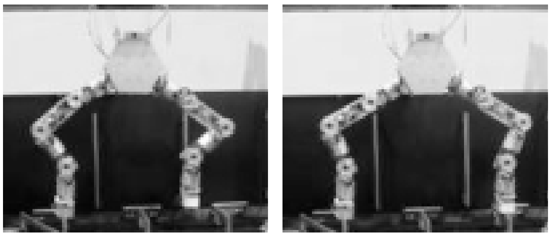
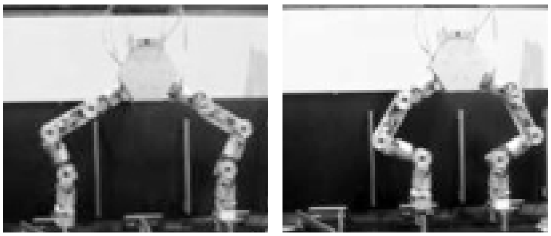


Fig. 5 Reconfiguration Motion



(a) First Step (b) Grasp Next



(c) Second Step (d) Final

Fig. 6 Brachiating Motion

(a) Arm Connects to D1 (b) D2 approaches to D1

(c) Arm connects to D2 (d) Arm disconnects from D1

Fig. 7 RBR Transportation Demonstration

tasks for in-orbit servicing and to design and develop a RBR system considering space environment under a well-defined project. A "Useful and robust" robot system is indeed desired for space development and Japan must conduct it forward with the strong leadership of the world.

References

[1] Ryoichi Hayashi, Saburo Matunaga and Yoshiaki Ohkami, "Design Concept and System Architecture of Reconfigurable Brachiating Space Robot," J. of Robotics and Mechatronics, Vol.12, No.4, pp.425-431, 2000.

[2] Ryoichi Hayashi, Saburo Matunaga and Yoshiaki Ohkami, "Experimental Evaluation of Reconfigurable Brachiating Space Robot," J. of Robotics and Mechatronics, Vol.13, No.5, 2001, pp.548-553.

[3] Saburo Matunaga, Osamu Mori, Shingo Tsurumi, and Hideto Okada, "Robot cluster system and its ground experiment system", 51st. Congress of the International Astronautical Federation, IAF-00-A. 3. 06, 2000.

[4] Website of Matunaga Lab at Tokyo Institute of technology: http://horse.mes.titech.ac.jp/index.html

MEETING CALENDAR

Sponsored or Joint Conferences & Symposiums

DATE	CONFERENCES & SYMPOSIUMS	LOCATION
2003.03.16-20	The 6th ASME-JSME Thermal Engineering Joint Conference (AJTEC2003) http://www.jsme.or.jp/ted/AJ2003.html	Hawaii, U.S.A.
2003.04.20-23	The 11th International Conference on Nuclear Engineering (ICONE-11) http://www.jsme.or.jp/pes/icone11	Tokyo, JAPAN
2003.06.15-18	2003 JSME-IIP/ASME-ISPS Joint Conference on Micromechatronics for Information and Precision Equipment (IIP/ISPS Joint MIPE) http://www.jsme.or.jp/iip/IIP-ISPS-Joint-MIPE.html	Yokohama, JAPAN
2003.07.06.-10	4th ASME/JSME Joint Fluids Engineering Conference http://www.asme.org/conf/fed03/	Hawaii, U.S.A.
2003.08.19-22	International Symposium on Speed-up and Service Technology for Railway and MAGLEV Systems (STECH2003) http://translog.jsme.or.jp/stech03/	Tokyo, JAPAN
2003.09.10-13	International Conference on ADVANCED TECHNOLOGY in EXPERIMENTAL MECHANICS 2003 (ATEM '03) http://atem.mech.nagoya-u.ac.jp	Nagoya, JAPAN
2003.11.03-05	International Conference on Leading Edge Manufacturing in 21st Century (LEM21) http://www.jsme.or.jp/mmt/callforpapers.pdf	Niigata, JAPAN
2003.11.09-13	International Conference on Power Engineering-2003 (ICOPE-03) http://www.jsme.or.jp/pes/ICOPE-03/	Kobe, JAPAN
2003.12.01-03	International Symposium on Micro-Mechanical Engineering -Heat Transfer, Fluid Dynamics, Reliability and Mechatronics- (ISMME 2003) http://www.jsme.or.jp/ted/ISMME.html#English	Tsukuba, JAPAN

JSME
News
Vol. 13
No. 2

Editors:Hiromasa Ishikawa,
Ken Okazaki
International Activities Committee
Published by The Japan Society of Mechanical Engineers
Shinanomachi-Rengakan Bldg, Shinanomachi 35,
Shinjuku-ku, Tokyo 160-0016, Japan

Fax:81-3-5360-3508

URL http://www.jsme.or.jp/English