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ABSTRACT

In the same way that the launch of Yuri Gagarin in April 1961 announced the beginning of human space flight, last year's flight of the German ROTEX robot flight experiment is heralding the start of a new era of space robotics. After a gap of twelve years since the introduction of a new capability in space remote manipulation, ROTEX is the first of at least ten new robotic systems and experiments which will fly before the year 2000.

Biting Off Too Much

Historically, the space robotics community has pursued the goal of creating fully autonomous, self-contained robotic systems with considerable onboard intelligence as the next major objective in space robotics evolution. Systems such as the Flight Telerobotic Servicer (FTS) were intended to provide near-human levels of intelligence and dexterity, capable of interpreting very high level command structures and autonomously executing the commands without human intervention. The robot was designed to replace a full-time human operator with automated sensing, perception, planning and reasoning sufficient to conduct daily operations.

Since the initiation of the FTS and similar

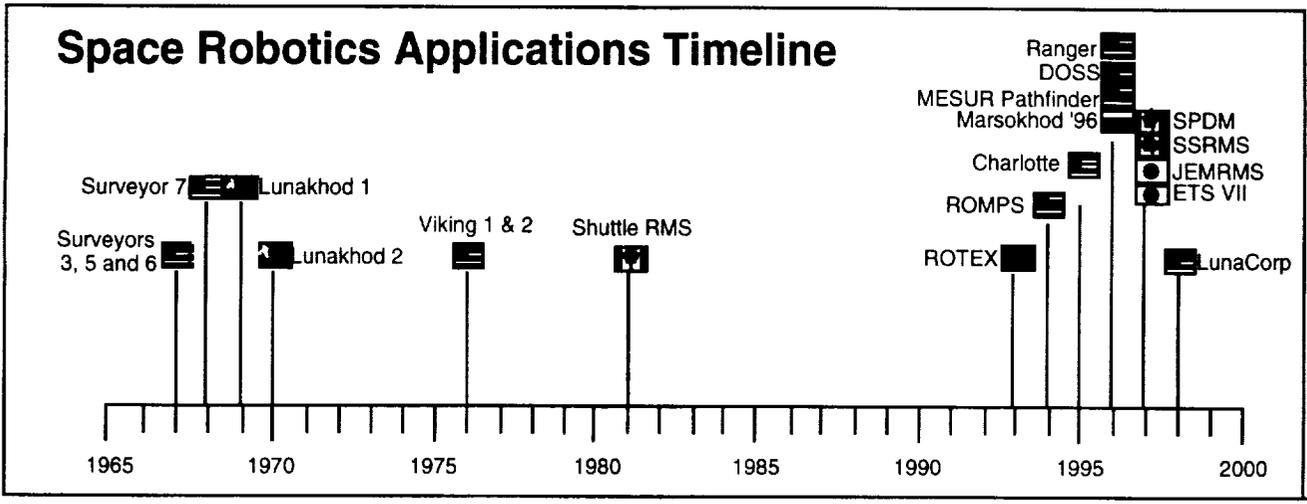
ambitious undertakings, the robotics community has gained new understanding of the research still required to create the technologies needed for such systems.

A New Focus

While the technology to support fully autonomous intelligent robotics is not yet available, operational needs for capable remote manipulation and locomotion still exist. In the space robotics arena, a significant paradigm shift is taking place to contend with these needs. Rather than attempting to force the use of immature technology to emulate the "smarts" of a local astronaut operator, the new focus is to utilize advanced teleoperation technology to move the operator from close proximity on-orbit to the ground. Technology elements including predictive displays, low-level reactive planners, sensor-based command execution and dynamic world modeling enable the ability to contend with problems associated with relocation of the operator, such as time-delayed communications, limited viewing options and limited command stream bandwidth. While there is still a long-term goal of developing intelligent autonomy for robots, the short-term goal has become the development of technology to push forward "intelligent teleoperation."

The major impact of this shift in development philosophy is the new opportunity to move robotics out of the laboratory and into the field. The maturation of advanced teleoperation technologies has helped increase confidence in

Space Robotics Applications Timeline



the ability of robotic systems to robustly perform real tasks. With this increased confidence has come the acceptance of the potential benefits offered by space robotics technology, and the challenge to “fly it and prove it” with a series of robotic flight experiments and demonstrations. The new push to “get things flying” will yield multiple new space robotic systems before the end of the 1990’s.

Robotic systems to be flown during the next five years fall into three categories: Extra-Vehicular Robotic (EVR) servicers, science payload servicers, and planetary rovers.

EVR Servicers

The EVR servicer systems are robotic systems deployed in Earth orbit for use outside of pressurized, controlled environments. Such systems are typified by the Shuttle RMS, which was first flown on the STS-2 mission in 1981. Target applications for these systems include on-orbit satellite assembly, maintenance, repair and servicing, robotic enhancement of Shuttle payload bay operations, and ground-control robotic servicing of external Space Station payloads.

Canada is providing two space robots for use on the International Space Station. The Space Station Remote Manipulator System (SSRMS) is a 55-foot long, 7-Degree Of Freedom (7-DOF) manipulator similar to the Shuttle RMS. Designed to maneuver and locate large payloads along the Space Station truss structure, the SSRMS can transfer power, data and video signals from attached payloads via

the latching end effectors at both ends of the arm.

The second Canadian system is the Special Purpose Dexterous Manipulator (SPDM), a dual-arm dexterous robotic system composed of two 7-DOF manipulators, a Power-Data Grapple Fixture, and supporting structures and tooling. The SPDM is controlled during teleoperations with two 3-DOF hand controllers and via keyboard entry and/or preprogrammed sequences for automated trajectory control. Each manipulator is controlled separately, in addition to independent control for the SPDM body and the SSRMS (during operations where the SPDM is positioned by the SSRMS).

At the same time, Japan is preparing a dual-manipulator system as an element of the Space Station Japanese Experiment Module (JEM). Composed of the Main Arm and Small Fine Arm, the JEM Remote Manipulator System (JEMRMS) is intended to provide maintenance, servicing and changeout of science packages placed on the JEM exposed experiment carrier. The Main Arm, similar in configuration to the SRMS and SSRMS, is a 6-DOF positioning tool used to transport large payloads and provide coarse positioning for smaller, more dexterous manipulators. The Small Fine Arm is a 6-DOF manipulator which can be operated either from the end of the Main Arm, or from a fixture on the exposed experiment facility.

Under development by Martin-Marietta Corporation and the NASA Johnson Space Center, the Dexterous Orbiter Servicing System (DOSS) is being developed to provide dexterous manipulation capability for

operations in the Space Shuttle payload bay. The DOSS is a MPESS-mounted robot that can operate from a fixed base or from the end of the Shuttle RMS. The purpose of this 7-DOF manipulator is to provide the Shuttle crew and mission controllers with a tool to augment and potentially replace selected EVA activities in the payload bay. These activities include EVA worksite setup, nominal and contingency payload operations (ie. opening lens covers, removing GAScan lids, etc.), and technology development activities.

Ranger is being integrated at the University of Maryland, under sponsorship of the NASA Telerobotics Program. Scheduled for flight in late 1996 aboard an expendable launch vehicle, Ranger is a dual-arm free flying telerobotics flight experiment which will conduct on-orbit validation and verification of many of the technologies developed by the NASA program. Utilizing telepresence ground-based control, coordinated manipulator operation, automated rendezvous and docking technology, and a hybrid propulsion system, Ranger will conduct a simulated satellite servicing exercise to characterize the operational capabilities of free-flying robotic systems. The project will correlate neutral buoyancy robotic simulations by developing nearly identical underwater and space flight units, and performing identical tasks in both environments.

Japan is also developing a free-flying robotic servicing experiment, scheduled for flight in 1997 aboard a H-II rocket. A target vehicle and chase vehicle will be deployed to exercise technologies including GPS receivers, rendezvous radar, proximity CCD sensors, docking mechanisms and onboard guidance computers. Simultaneously, a 6-DOF manipulator mounted on the chase vehicle will be used to demonstrate cooperative control of the chase vehicle attitude as it reacts to manipulator position, ground-based teleoperation of the manipulator, demonstration of on-orbit satellite servicing including fuel transfer and battery exchange, and target vehicle acquisition, grapping and restraint.

Science Payload Servicing

Science payload servicing robotics differ from the EVR systems in that they are designed to maintain experiment payloads in controlled

environments, and are specifically designed as elements of nominal experiment operations (i.e., the robot is intended to be a functional component of the overall experiment, performing tasks such as reagent replenishment, product harvesting, sample collection, etc.), and not just as contingency and repair systems in the event of experiment failure or malfunction.

At least two such systems are currently in the final stages of preflight integration. McDonnell-Douglas has recently completed development of Charlotte. Charlotte is a small robot physically connected to its work environment with a series of eight Kevlar strands. The strands extend from the corners of the robot's rectangular body to hard points at the extreme corners of the workspace, which may be the interior of SpaceLab, SpaceHab or a space station module. By increasing and releasing tension on selected strands, the body of the robot is able to translate throughout the entire volume of the workspace.

The Robotic Operated Materials Processing Systems (ROMPS) is a joint project between the NASA Goddard Space Flight Center, the Michigan Space Automation and Robotics Center, and the Zymark Corporation. ROMPS will demonstrate low-cost on-orbit processing through the use of robotics to autonomously produce semi-conductor materials. Scheduled for launch on STS-64, this GAScan experiment will investigate zero-gravity annealing of semi-conductor thin films. The robot will utilize low-level automation to maintain the materials furnace, supply source substrates to the furnace and harvest processed thin films.

The European Space Agency is investigating the incorporation of a large-scale science payload maintenance robot into the Columbus module of Space Station. This system would have a work envelope encompassing the entire interior of the module, and would provide logistics support for science experiments and materials production systems.

Planetary Surface Systems

Planetary surface robotics is the area in which the largest breadth of knowledge exists, although it is somewhat dated. As early as 1967, the Surveyor missions carried simple

remotely-operated manipulators to the surface of the Moon to collect samples of the Lunar regolith. Followed by the Russian Lunakhods in 1969 and 1980, and the Viking missions to Mars in 1976, these early efforts identified the fundamental environmental constraints and technology obstacles to be surmounted to enable the development of robust, long-lived planetary surface robotics.

It was traditionally accepted that the next generation of robotic rovers for unmanned Lunar and Mars missions would be large (800-kg or more), monolithic, highly intelligent and autonomous devices which would require significant development and operational support in terms of technology, budget, computational and human resources. Then in 1989, a small group of rogue technologists at MIT and JPL began a new initiative in micro-rover technology based on subsumption architectures. Making use of progressively smaller computers, increasingly advanced sensors, and maturing mobility systems, a series of micro-rover testbeds was developed which culminated in the MESUR (Mars Environmental Survey) Pathfinder Rover. This six-wheeled 5 kg-class rover is scheduled for launch to Mars in 1996, and will perform technology validation experiments in addition to science investigations and instrument deployment. Control for the rover will be shared between Earth and the limited onboard intelligence of the rover. By combining sensory input with predefined "behaviors" the rover will autonomously navigate between the waypoints, avoiding rocks, crevasses and other impassable terrain.

Scheduled for flight in 1998, Russia intends to launch the Mars '98 mission which will include the Marsokhod rover. Being developed by the Institute for Space Research (IKI) and the Babakin Center of NPO Lavochkin, the Marsokhod is a six-wheeled, 100-kg rover that will use radioisotopic thermal generators (RTG) for power generation and thermal control. Because of the RTGs, the rover will be able to operate during the Martian night, and is expected to have a long surface lifetime (one year or more) with a potential total excursion distance of over 100 kilometers. The Marsokhod enables exceptional mobility characteristics through the use of unique bi-conic titanium wheels and a segmented three-

part chassis.

In addition to these Mars-bound rovers, LunaCorp has announced plans for a lunar rover project slated for launch in 1998. Rather than driven by science needs, the incentive for this project is primarily entertainment - the goal of the project is to provide the world's first interactive space exploration event by giving the public the opportunity to drive the rover on the moon. The rover will be remotely operated via telepresence control from workstations located in theme parks around the country. Capitalizing on NASA rover technology developments, LunaCorp is working with Carnegie-Mellon University to transfer these technologies into the first commercial lunar rover application.

Technology Requirements for Future Systems

With the advent of these new experimental and operational space robotic systems, the ability for remote manipulation to offer significant improvements to mission operations, cost effectiveness and mission safety will be proven. But these will still be early generations of advanced space robotic applications. As successive waves of space robotic applications are deployed beyond the year 2000, the goal of intelligent, autonomous space robotics will become more and more important. Technology drivers for these systems include enhanced collision detection and avoidance, advanced local proximity sensing, task level control workstations, improved command and control architectures, fault tolerant architectures, reduced mass and volume, worksite recognition and representation, improved robotic dexterity, advanced supervisory control, and improved overall system robustness.

By combining these next-generation technologies with the operational knowledge gained from applications being flown in the next few years, the first intelligent space robotic systems will be within reach. By then combining the technologies with the development procedures utilized by the current suite of applications, the next generation of space robotic applications will be affordable, even within the ever-tightening budget environment of today's space program.

Commercialization

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