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SDIO ROBOTICS IN SPACE APPLICATIONS

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ABSTRACT - *This paper addresses how SDIO/S/PL views robotics in space supporting the Strategic Defense System (SDS) program. It addresses ongoing initiatives which are intended to establish an initial Robotics in Space capability. This is specifically being referred to as the Satellite Servicing System (SSS). This system is based on the NASA Orbital Maneuvering Vehicle (OMV) with a Robotic* **Manipulator(s) based on the NASA Flight Telerobotic Servicer (FTS) and other SSS equipment required to do the satellite servicing work attached to the OMV. The paper also addresses specific SDIO Robotics in Space Requirements which have resulted from the completion of the SDIO/S/PL Robotics Requirements Study Contract.**

BACKGROUND

In 1987 studies were completed which looked at Space Assembly, Maintenance and Servicing (SAMS). The purpose of these studies was to investigate ways in which satellites could be maintained on-orbit. Design Reference Missions (DRMs) were developed by NASA and the AF to be representative of satellite constellations which might exist in the mid to late 1990s. Using these DRMs the contractors developed what they considered would be the best design approach to develop an on-orbit servicing system. Along with this, design concepts were investigated to determine how the satellites themselves would have to be designed and built in order to make them serviceable. Also tools, interfaces and other on-orbit servicing design needs and requirements were investigated and recommended.

Phase I of the Spacecraft Partitioning and Interface Standardization (SPIS) study was completed in 1987 for the Air Force which looked at the spacecraft sub-system designs which might be form, fit and function compatible across different types of satellites. The recommendations for sub-system standardization which resulted from this study were; battery, power control unit, inertial reference unit, reaction wheel, earth sensor and the sun sensor. Under Phase II of the SPIS the contractor is required to develop final specifications for these ORUs. The battery standard is presently nearing approval and the power conditioning unit standardization process is under way. These standardization efforts are similar to the avionics efforts initiated by the PAVE PILLAR and Modular Avionics System Architecture (MASA) programs for aircraft. Also required within this standardization process is a separate activity to define a standard spacecraft data bus, power bus and serviceability interfaces. These initiatives will then open the way to designing satellites so that they can be built in a modular and serviceable fashion.

Following the SAMS and SPIS studies the SDIO, AF and NASA began a dialog on establishing a Satellite Servicer System (SSS) which could be ready for use on-orbit in the mid to late 1990's. These discussions eventually resulted in a project based on the Orbital Maneuvering Vehicle (OMV). The concept which evolved envisioned an OMV providing the basic servicer platform. To the OMV would be attached an Orbital Replaceable Unit (ORU) and servicing carrier with a robotic front end. This robotic front end is not yet designed but will be derived from the NASA FTS program. Thus the manipulator will use components of the FTS, although it may take on a different form than the FTS, rather than becoming a new development effort. The SSS is intended to be used in a non-man tended mode when used to maintain satellites. In the case of the SDIO which has no man-in-space requirement this robotic design takes on the requirement that it must be semi-autonomous and this requirement is sometimes referred to as supervised autonomy. Supervised autonomy implies that the robot will be able to perform some tasks autonomously but will stop at predetermined points in the specific autonomous task being performed or will stop when the robot detects a non-programmed problem or interference. An operator will then have to interact with lar advantages through the use of robotics. The contractor was to accomplish this through five sub-tasks. The first sub-task was to do an overall robotics assessment of the state-of-the-art and the present shortfalls of the technology. Another task was to develop a Robotics Requirements Document for all aspects of the SDIO robotics program. This would lead into a Time-phased Implementation Plan and draft Program Management Agreements (PMA) for accomplishing the SDIO Robotics Program developed by the contractor. Finally the contractor was to develop a Robotics Video which would provide a quick way to educate personnel unfamiliar with robotics as to what the technology is, where the state-of-the-art is and what advancements are required to implement the SDIO program.

Robotics in space requirements - The main requirement for SDIO Robotics in Space will be for the robot to be robust. If the design constraints on the robot are too stringent then it will require a new robot to be designed for each application. The candidate on-orbit support missions that the robotics contractor included in this study were as follows:

1. Fuel transfer
2. Orbital Replaceable Unit (ORU) changeout
3. Counter tumbling satellite approaches
4. Uncooperative satellite retrieval/removal from orbit or neutralization
5. Ad Hoc tasks (using tools)
6. Ad Hoc and programmed task control
7. On-orbit inspection and calibration
8. Support of SSS components on-orbit such as an Orbiting Support Platform
9. On-orbit assembly
10. Reboost (Correction of Orbit/De-orbit)
11. Removable orbit insertion motor
12. Hazardous debris removal
13. Intercept vehicle reload
14. Nuclear reactor removal

In addition to the candidate missions above was added the requirement that the robot be capable of servicing any of the orbiting SDS space assets in both the near the robot to guide it on through the task or around the detected problem.

This supervised autonomy is necessitated by SDIO and AF satellites which are in orbits which could, because of the combination of distance and electronic or mechanical processing, have communication delays in the neighborhood of several seconds. These delays are difficult to learn how to handle by an earth based operator in a totally teleoperated mode and necessitate that the entire system be slowed down to ensure safety to the robot and the satellite. Therefore in the interest of economy of time and resources it will be necessary to allow the robot to do certain repetitive functions autonomously at a higher speed with the operator teleoperated slowdown only being required when absolutely necessary.

At the start up of the negotiations with NASA on SSS the SDIO realized that its requirements might be more restrictive than NASA's due to the supervised autonomy requirement as well as the relatively more robust satellite environment. Also the need for teleoperation from the ground rather than from on-orbit in the Space Station or the Space Shuttle implies that the SDIO and AF requirements for the servicer be more restrictive. This led the SDIO to contract for a study to define the SDIO requirements for a SSS robot. In addition this study developed robotic requirements for ground and manufacturing in relation to the SDIO Strategic Defense System (SDS) and its followon components. However only the requirements developed for the SSS are of consideration in this paper.

SDIO ROBOTICS PROGRAM FOR SSS

Overview - The robotics contract required that the contractor look at several aspects of the SDS and its followon systems. These included areas within the ground systems where robotics could play a key role in reducing manpower requirements without sacrificing flexibility, capability or security needs. In addition the contractor was directed to look at ground launch operations, on-orbit servicing and manufacturing areas which could gain simi-term and future. This means that the robot be capable of servicing the near term assets of experiments (such as Zenith Star and a proposed Neutral Particle Beam (NPB) experiment in the mid-1990s), the Boost Surveillance and Tracking System (BSTS), the Space Surveillance and Tracking System (SSTS) and the Space Based Interceptor (SBI) as well as those assets anticipated for the future (such as lasers, Space Based Radars (SBR) and NPBs). As one can readily see this is necessarily a very robust environment. Robust in the sense that the robot must be capable of servicing vastly different sizes and styles of spacecraft as well as very different payload requirements and hence their attendent ORU and servicing differences. This robust environment then requires an equally robust robot or else multiple designs for the robotic front end to the SSS. The above translates into the following requirements if a single design is to be able to accomplish all of the above support missions:

1. Volume and weight of ORUs that the manipulator must handle - maximum is 1000 kg and minimum is 1 kg
2. Manipulator arm reach - maximum is twenty meters and minimum is 1 meter
3. Number/types of end effectors/tools - up to five
4. Degrees of freedom - up to seven
5. Human control interface parameters including time lag, tactile and force reflection, and vision feedback are recognized requirements but further study is required before specific quantization may be added
6. Knowledge base to accommodate geometric descriptions of assets to be supported and action to be taken for routine ORU change out and selected contingency manipulations
7. Manipulator hardware and control system capability to provide the desired accuracy and response to constants
8. Provisions for four-color capability including necessary space-to-ground communications bandwidth.

In addition to the above requirements for the manipulator it is recognized that the manipulator design may be simplified if the serviced satellite is designed to be robotically friendly. This means that the satellite must be modular, have a hard-dock capability, have ORUs designed to be robotically removable, be capable of fault detection and isolation to a single ORU 99% of the time and be able to determine a friendly servicer from an unfriendly ASAT vehicle. Most of these requirements are more stringent than the NASA requirements where NASA is working with friendly satellites which may be brought back to the space station or STS for additional support from IVA/EVA astronauts. If NASA requires that the servicer maintain satellites which are not easily brought back to the space station or STS such as the Polar Orbiting Platform (POP) than their requirements will begin to approach SDIOs except for the uniquely military aspects of the SDIO requirements.

One must also be aware that in addition to the above SSS requirements for a robotic servicer that there are additional technology requirements which must be addressed in both the near term and the future in order to insure that there are no "show-stoppers" as one proceeds into the SSS design. These technology issues may be broken down into five areas; systems integration, computer control system, sensors, actuation systems, and man-machine interface. In order to eliminate the possibility of "show-stoppers" the following issues must be addressed in a technology program:

1. Systems Integration Issues
   a. The sensor feedback time lag between ground-based human commands and sensor feedback from the space-based servicer
   b. Architecture definition for the coordination of ground-based and in-space control computers
2. Computer Control System Issues
   a. Suitable uplink to load control programs
   b. Adequate response bandwidths to implement human instructions, and anticipation of manipulator movements where significant time lags between manipulator actions and human controller responses occur
   c. Adequate ground monitoring capability
   d. Communications protocols between SDS space assets and the servicer
   e. Provisions for ensuring safe operation of actuator systems.
3. Sensor Issues
   a. Weight and space adaptation and packaging of available sensor technology into an on-orbit servicer
   b. Adaptation of sensors for satellite stabilization.
4. Actuator System Issues
   a. Development, design and construction of manipulator arms of sufficient dimension
   b. Weight and space adaptation of actuation systems
5. Man-machine Interface Issues
   a. Time lags associated with direct control of the robotic servicer
   b. Input speed due to data throughput speed limitations
   c. Execution precision of commands using direct control
   d. Data saturation due to critical and trivial feedback
6. Unresolved Servicer Issues
   a. What kind, how many and the design required for fluid and electrical connectors for interfacing the servicer to the spacecraft being serviced
   b. What type of docking mechanism shall be used
   c. Final docking sensor developments such as laser ranging, radar, etc.

Each of the above technology issues must be solved as they apply to the SDIO SSS robotic servicer requirements. This means that for an on-orbit servicer to be effective requires that the SDIO initiate parallel efforts in both technology development and SSS development to ensure an effective SSS can be fielded in the mid-to-late 1990's for support of the SDS space assets.

SDS Robotics Program - Due to budget constraints the starting up of an ambitious robotic development program is nebulous. Therefore the SDS Robotics Program must be accomplished with as little cost as possible. This implies some innovative funding must be accomplished. The key is to have the already ongoing NASA/AF/SDIO SSS program carry the bulk of the SDIO requirement satisfaction. In addition there must be some technology programs instituted in order to insure that the SSS program succeeds. These technology requirements can be met by leveraging off of existing programs such as are found within the SDIO's small business and innovative science and technology programs. Also other agencies have on-going robotics efforts which may be useful in achieving the necessary SDIO technology goals with little or no SDIO funding required. These agencies would include DARPA, NASA, and AFSC/WPAL for instance. Efforts are now underway to investigate the feasibility of this approach. Any potential SDIO technology program will probably have to wait until the 1990 budget year regardless.

Applications of SDIO Robotics - A few words about the SDIO applications will help to substantiate the need for robustness of an SSS robotic servicer. The most near term requirement for a SSS in the SDIO program will be to support the mid to late 1990's experiments. The most ambitious of these are the Zenith Star and NPB experiments. These are large vehicles that will likely be too large for a single launch vehicle and thus will require assembly on-orbit. Also the weight limitations may mean that fuel and other depletables will be minimized in order to ensure that the experiment is a success. It would appear that if these satellites were to have provisions for on-orbit servicing that not only could their on-orbit lifetime be extended but also provision for ORU changeout may provide for a way of upgrading or changing the satellites design should that be necessary to ensure success. The next application would be to the SDS Phase I implementation in the mid to late 1990's. This would include the BSTS, SSTS and SBI satellite programs. Several studies such as the SAMS study have shown that the capability to be able to service satellites on-orbit would provide for life-cycle cost savings. This savings comes from being able to keep the satellites alive after replenishable depletions, to provide a way of repairing a failed satellite without launching a new satellite, to provide for upgrading the satellite with new ORUs without having to design, develop and launch a new constellation and other possibilities which will become obvious once designers realize that their satellites are accessible after launch. And finally application to the followon SDS assets which will have another set of requirements associated with them such as on-orbit assembly, alignment, and calibration requirements that do not exist on the more near term satellites.

Conclusion - The SDIO has been investigating the feasibility of on-orbit servicing through a succession of studies and design and development efforts. Paramount to these efforts achieving their goals is that a proper robotic front-end be available to the SSS. The SDIO's robotic study has developed the necessary requirements that this robotic servicer must meet in order to achieve these on-orbit servicing goals. Only through judicious and innovative application of scarce funds can we hope to have a successful robotics program and associated SSS program.