Robotic Mobile Servicing Platform for Space Station

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1. Abstract

Semi-autonomous inspection and servicing of Space Station's major thermal, electrical, mechanical subsystems is a critical need for the safe and reliable operation of the Station. A conceptual design is presented of a self-intelligent, small and highly mobile robotic platform. Equipped with suitable inspection sensors (cameras, ammonia detectors, etc.), this system's primary mission is to perform routine, autonomous inspection of the Station's primary subsystems. Typical tasks include detection of leaks from thermal fluid or refueling lines, as well as detection of micro-meteroid damage to the primary structure.

Equipped with stereo cameras and a dexterous manipulator, simple teleoperator repairs and small ORU changeout can also be accomplished. More difficult robotic repairs would be left to the larger, more sophisticated Mobile Remote Manipulator System (MRMS). An ancillary function is to ferry crew members and equipment around the station.

Primary design objectives were to provide a flexible, but uncomplicated robotic platform. One which caused minimal impact to the design of the Station's primary structure but could accept more advanced telerobotic technology as it evolves.

Figure 1. Manned Mobile Serv. .r

2. Introduction

The Space Station will undoubtedly be the largest and one of the most complex "spacecraft" ever launched by man. Bounded by a structural surface of more than 2 acres, the Station will contain many miles of electrical power, thermal fluid and data communication utility lines as well as house dozens of primary and secondary subsystems and components. Many of these elements have design lives of 20 years or more and must function reliably during this period in the hazardous environment of space. In recognition of the need to enhance the operational efficiency and reliability of Space Station, a congressionally appointed Advisory Committee [1], recommended that the initial Space Station should utilize a high degree of automation and robotics (A & R) technology. Among many of the Committee's recommendations was a suggested NASA A & R demonstration to construct "a mobile 'go-fer' robot to assist in crew tasks" [1]. The concept to be discussed in this investigation addresses this important recommendation.

Considerable work has been performed, for example see [2 to 4], in identifying teleoperator/robotic concepts and technology to assist in the on-orbit servicing and repair of spacecraft. It is clear that automated robotic work systems can considerably enhance the productivity of the flight crew. This is true, provided that the servicing tasks are well-defined, and secondly, that the required servicing mechanisms and the equipment to be serviced have been "scarred" to accommodate such automation. Furthermore, hazardous tasks, such as a propellant refueling operation, would obviously be more safely performed from a remote site.

Man's permanent presence onboard Space Station offers new and greater opportunities to repair and service in-orbit spacecraft. Robotic retrieval of satellites via free-flying robots (or robotic Orbiting Maneuverable Vehicles (OMV'S)) assisted by a teleoperated RMS are logical applications of A & R technology. However, considerable advancements in automation technology are still required, ranging from control architecture, task planning and artificial intelligence (AI) to robotic manipulator design and external sensor development [1]. Examples of how future space flight telerobots would differ from those in industry can be found in [5].

3. Space Station Inspection and Servicing

Apart from servicing orbiting payloads and spacecraft, the complexity, size and longevity of the Station warrants extensive application of automation to perform the necessary "housekeeping" and maintenance functions. Representative examples of the station's subsystems which will require periodic inspection and/or servicing are illustrated in Figure 2. Fault detection and isolation will be needed for the electrical power cables, communication and data lines, and those used for the thermal environmental control system. Detection of hazardous leaks from propulsion fuel lines or from the thermal fluid bus carrying anhydrous ammonia will also be a concern.

Micro-meteroid damage to the primary or secondary structure, solar panels, radiators, etc. must also be checked. Environmental damage such as that due to long term exposure to atomic oxygen or UV radiation to structural materials may occur as well. Contamination of optical surfaces, mirrors, and array panel surfaces can be expected. The diagnostic/maintenance list is extensive.

Reference [6] addresses many of those inspection and servicing needs of the Space Station from the standpoint of A & R. In this study, candidate A & R functions were identified, ranked and costed. Weighted assessments were made in terms of safety, productivity, IOC cost, risk, spinoff likelihood, reliability/maintainability and commonality. Table 1 is an example of one of the value ranking tables in [6], showing the priority of the first 29 of the 58 A & R candidate functions evaluated. It becomes apparent, upon reviewing this list that many of the inspection related tasks are not only important to perform but, moreover, have some of the most favorable cost-to-benefit ratios. For example, see utility run, truss/structure and thermal control system inspection items.

Another important conclusion from the study performed in [6], is that a substantial savings in crew time could be realized by automating the inspection process. According to Figure 3, automating inspection activities represent a savings of 90% of the crew's time relative to 10% for those due to repair. This finding is based on the realization that inspection related activities are both more frequent and time consuming. This is not to infer that the inspection process is necessarily more important than repair. A repair to a critical system, while not necessarily time consuming, could be critical for safe operation.

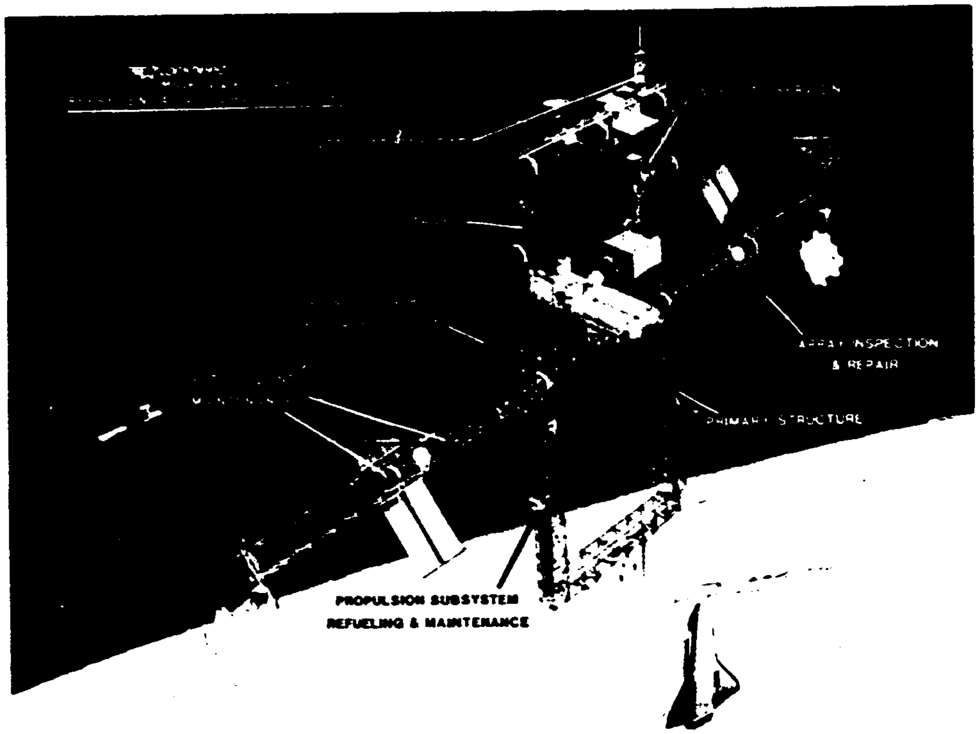

Figure 2. Representative Servicing Operations

Table 1. Benefit-to-Cost Ratio

Rank	Evaluation	Benefit to Cost Ratio	Candidate
1	67.80	3.87	•Payload-Servicing-Robot
2	67.45	5.38	•Utility Run-Inspection-Replacement
3	67.24	5.55	•Inspection-Repair-of-Trusses-and-Structures
4	63.64	0.79	•Distributed-Smart-Camera System
5	60.92	2.69	•Thermal-Control-System-Inspection
6	60.40	2.88	•Mounting Plates-Assembly-Inspection-Repair
7	58.25	2.76	•Robotic EVA-Crew-Assistant
8	57.62	1.92	•Interconnect-Inspection-Repair
9	57.45	1.84	Hazardous Material-Handling-System
10	57.38	2.26	Tunnel Inspection-for-Exterior-Damage
11	56.75	1.48	•Gimbal Maintenance
12	56.59	1.02	•Robotic Inspection-Cleaner
13	56.47	2.05	Berthing-System-Inspection-and-Repair
14	56.23	1.40	Passive Thermal-Control-Monitoring
15	56.00	0.82	Bolt Torque-Preventative-Maintenance
16	54.96	0.68	EVA Task Mission Planning Aid
17	54.55	0.22	Thermal-Control Maintenance
18	54.27	0.03	•Hazardous-Utilities Connection
19	53.63	0.01	Attitude-Determination-from Camera Video
20	53.34	0.00	Inspection-of Pressure-Seals
21	53.33	0.70	•Non Destructive-Testing-of Struts and Mounts
22	52.22	1.20	Active Thermal Control System Assembly and Operations
23	51.49	0.96	Space Station Markings Inspection Repair
24	49.92	1.24	Voice Controlled Camera Adjustment
25	49.85	2.37	Thermal Curvature Control
26	47.39	0.00	Space Station Service Vehicle
27	47.55	1.61	Space Station Coordinator
28	47.48	0.06	Structure Assembly
29	47.24	0.77	Knowledge Based System for Fault Diagnosis of Communication Systems

• *FUNCTIONS CAPABLE OF BEING PERFORMED BY GOFIRS*

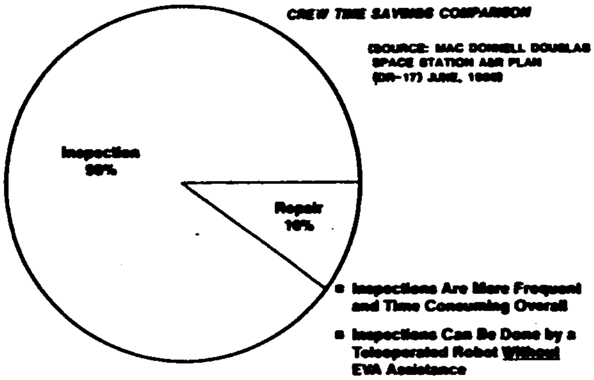

Figure 3. Inspection Versus Repair Robotic Tasks

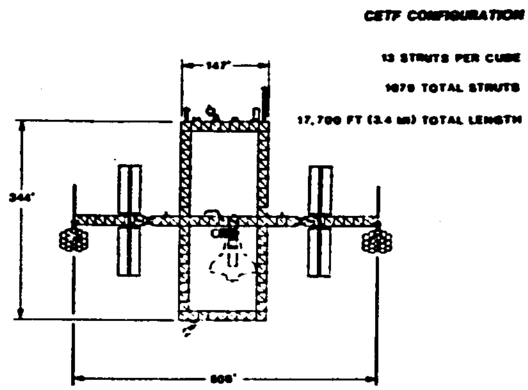

Figure 4. Inspection Travel Distances

Some appreciation of the magnitude of the inspection process can be gained from Figure 4. Considerable crew effort is involved in just examining the 3.4 miles of tubular struts which comprise the Station. Add to this the miles of electrical, thermal and data lines which could develop problems during the Station's 20, 30 or 50 year life. Fortunately, most of the required inspection activities can be performed without the need for extensive crew EVA time by utilizing a special purpose robotic mobile platform in conjunction with internal system sensors. The **Global Operational Flight Inspection/Repair System** or "GOFIRS" can perform (alone or in conjunction with a robotic MRMS) many of the inspection/servicing tasks identified in Reference [6] as listed in Table 1 (see asterisk items).

4. The "GOFIRS" Concept

In establishing the conceptual design of a robotic platform to meet the Station's needs, certain ground rules had to be established. These appear in Table 2.

Table 2. Major Conceptual Ground Rules

- **TASKS**
  - AUTONOMOUS INSPECTION ("SCOUT" FOR MRMS/TRANSPORT)
  - ASSIST CREW EVA (TOOL/ORU RETRIEVAL)
  - TELEOPERATED SERVICE & REPAIR (SMALL ORU MAINTENANCE)
  - CREW TRANSPORT (WHEN REQUIRED)
  - ACCOMODATE FTS (IF COST EFFECTIVE)
- **PERFORMANCE**
  - ACCESS STATION PRIMARY SUBSYSTEMS
  - REQUIRE NO MAJOR MODIFICATIONS TO STATION STRUCTURE
  - ON-BOARD INTELLIGENCE FOR INSITU DIAGNOSTICS OF SENSOR DATA
  - MANIPULATOR WITH ROBOTIC SENSOR (STEREO VISION FOR TELEOPERATOR SERVICING)
  - REACH ANY POINT ON STATION WITHIN 5 MINUTES (RATE=100 FT/MIN)
  - PROVIDE MINIMAL VIBRATION DISTURBANCES TO STATION
  - SATISFY ALL OTHER STATION OPERATIONAL, RELIABILITY, & SAFETY REQUIREMENTS

An important ground rule is that the GOFIRS is not intended to replace the much larger, more sophisticated MRMS/Transporter but to augment its capabilities by detecting possible mission threatening defects or faults. The ability of MRMS to perform routine inspection of the myriad of subsystems on board Station is limited by its large size (spanning more than a 5 meter bay) and its relatively slow speed (less than 2 feet/minute). A small, highly maneuverable platform capable of accessing tight interior spots could be designed to be simple enough, hence affordable, so that several GOFIRS could be on continuous patrol.

Although its primary mission is one of inspection, crew EVA assistance and transport could also be provided. Small scale teleoperated servicing and repair could also be accomplished. This could be particularly valuable if the MRMS was tied up completing an activity on one end of the Station when some system needed immediate servicing on the other end.

Another ground rule is that the GOFIRS should make maximum use of current robotic technology (sensors, computer architecture, manipulators, etc.) and yet have sufficient growth capability to accept more advanced A & R technology as it comes on line. An example of this is the Flight Telerobotic Servicer (FTS) concept to be developed as a "robotic front end" to the MRMS and OMV.

In terms of performance, the GOFIRS should be able to reach all or most of the important subsystems. It would be highly desirable to provide this mobility without disturbing the basic design of the primary structure by using miles of additional track or special cabling. GOFIRS should be equipped with sufficient onboard sensors and intelligence to perform routine analyses of inspection data and report anomalies and their location back to the command module. For example, the location of a leak in the thermal fluid lines would be identified. An onboard microprocessor would make a determination of the extent of this leak. Based on preprogrammed limits, immediate crew attention could be requested, or the anomaly could be simply "logged" for the next schedule maintenance activity.

Clearly, deciding a course of action based on real time sensory inputs would embrace the new and growing technology of Artificial Intelligence or AI. If corrective action is needed, a GOFIRS equipped with the appropriate teleoperator/telepresence sensors, cameras and manipulator, could make the repair under the control of a human operator. If the repair could not be made remotely from the command module, then the GOFIRS could transport a crew member to the site to make the repair. In a more futuristic version of this scenario, the repair could be made autonomously by GOFIRS under the automatic control of an "expert system".

Due to its mobility, GOFIRS would offer a secondary benefit of being able to ferry the crew and needed equipment, tools or ORU's around the Station for EVA. A minimum nominal travel rate of 100 feet/minute (1.1 miles/hr.) would enable any point on Station to be reached within 5 minutes. Of course the mass and acceleration rates must be sufficiently small as not to induce significant vibrational disturbances into the Station.

Table 3. The "GOFIRS" Concept

GLOBAL OPERATIONAL FLIGHT INSPECTION REPAIR SYSTEM

- SELF-INTELLIGENT, SMALL, HIGHLY MOBILE INSPECTION & ROBOTIC REPAIR PLATFORM
  - WHEEL (OR MAST) DRIVEN, TABLE-TOP SIZED VEHICLE WHICH CAN ACCESS MAJOR AND MINOR SPACE STATION SUBSYSTEMS.
  - EQUIPPED WITH ON-BOARD SENSORS & TELEMETRY TO AUTONOMOUSLY PERFORM ROUTINE INSPECTION.
  - EQUIPPED WITH CAMERAS & MULTI-DEGREE OF FREEDOM ROBOTIC MANIPULATOR TO PERFORM EITHER TELEOPERATOR OR TELEROBOTIC SERVICING OR UTILIZE FTS AND ORU'S
  - PROGRAMMABLE MICROPROCESSOR TO PERFORM ASSIGNED TASK, TRACK CURRENT LOCATION AND PERFORM ROUTINE ANALYSIS OF INSPECTION SENSOR DATA.
- MULTIPLE "GOFIRS" CAN CONTINUOUSLY PATROL DESIGNATED SEGMENTS OF SPACE STATION.
- CAN ASSIST MSC/TRANSPORTER AND ASTRONOUTS IN EVA ACTIVITIES.
- CAN FERRY CREW FROM POINT TO POINT
- "LOW LEVEL" GOFIRS CAN BE DEVELOPED IN THE TIME FOR FLIGHT EXPERIMENT DEMONSTRATION.

Features of the GOFIRS concept which meet the above ground rules are summarized in Table 3. It is envisioned that there may be a need for multiple GOFIRS to "patrol" various segments of the Space Station in a relatively slow "inspection" mode. It is also envisioned that one GOFIRS may be assigned to each of the outboard rotating solar wings while one or two more units will patrol the fixed central portion of Station.

This would circumvent the need to devise a means for crossing the alpha rotary joints. For example, 4 such GOFIRS dispersed in this manner could make a complete inspection of the Station's primary structure in approximately 60 hours at an inspection rate of 2 feet/minute.

Another point to be made is that a "low level" GOFIRS type system utilizing current state-of-the-art robotics technology could be developed in time for a shuttle flight demonstration prior to launching the Space Station.

5. Description of Capabilities

A conceptual illustration of a "wheel driven" GOFIRS appears in Figure 5. A description of features and capabilities is summarized in Table 4. On board microprocessor capability will be needed to perform the inspection/repair functions, control the GOFIRS motion, and to perform in situ diagnostic analysis of sensor data. This data can be logged and telemetried back to the crew capsule or ground using data compression techniques at some later time or at once if an emergency requires immediate attention. Location of the defect and information for guidance could be obtained by encoded magnetic strips like "bar codes" circumscribing the struts. Optical sensors could be used in place of these magnetic strips.

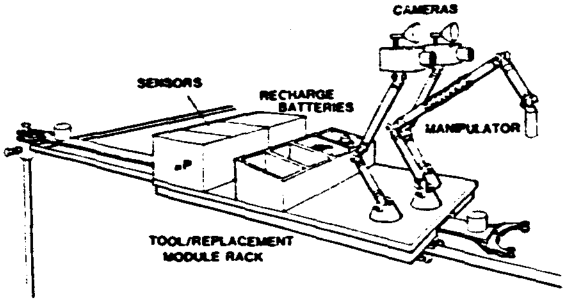

Figure 5. Global Operation Flight Inspection Repair System

Table 4. Capabilities

- SELF-INTELLIGENT MOTORIZED PLATFORM
  - ON-BOARD ROM FOR ITINERARY & INSPECTION/REPAIR FUNCTION
  - ON-BOARD ROM FOR MOTORIZATION, PIVOTING SEQUENCE & SELF-DIAGNOSTIC
  - ON-BOARD INSPECTION/DETECTION SENSOR & DIAGNOSTIC WITH TELEMETRY CAPABILITY (AMMONIA DETECTOR, TUBE DEFECT X-RAY DETECTOR, ETC.)
  - ON-BOARD GUIDANCE (MAGNETIC STRIP POSITION LOCATOR)
- TELEROBOTIC FUNCTIONS/ROBOTIC MANIPULATION (6 D.O.F.)
  - SEMI-AUTONOMOUS OR TELE-OPERATOR REPAIR/COMPONET REPLACEMENT (BI-NOCULAR CAMERA/FORCE-FEEDBACK MANIPULATOR)
  - ROUTINE EMERGENCY SERVICING FUNCTIONS (ALPHA BRG PACKAGE, FLUID MODULE, ROLL-RING CHANGEOUT, ETC.)
  - ON-BOARD "TOOL CHEST" REPLACEMENT PART CAROUSEL
- ELECTRO-MECHANICAL DESIGN FEATURES
  - "STEERABLE" & "LATCHABLE" DRIVE CASTOR WHEEL BOGIES } OR COLLAPSIBLE
  - POLYMER-COATED WHEELS (LIGHTLY SPRING LOADED) } MAST PROPELLED
  - NODAL PIN PIVOT LATCH MECHANISM
  - TUBE CLAMP MECHANISM FOR LARGE TORQUE REACTION
  - RECHARGABLE BATTERY PACK

Teleoperator or telerobotic repair would be accomplished with one or two dexterous manipulators having the appropriate tactile/force feedback sensors and utilizing multiple cameras (stereo-vision). Tools and replacement parts would be carried to facilitate either crew EVA or telerobotic On-orbit Replaceable Unit (ORU) changeout.

The platform would be motorized being either a wheel driven or propelled by a coilable mast arrangement to be discussed later. In the wheel driven variant, two "steerable" and "latchable" drive wheel bogies (See Figure 6) would be lightly spring loaded against the tubular strut with soft polymer coated wheels. The allowable contact pressures to prevent damage to the struts would be determined by extensive tests. However, in-house tests of a protype, aluminum-clad, carbon-graphite epoxy tube of the required size sustained a point load of over 200 pounds without damage. Anticipated wheel loads for the GOFIRS would be at least one order of magnitude lower than this. A tube clamp mechanism with a large footprint could be incorporated if needed to react large torques during part removal and replacement.

The large MRMS/Transporter will make use of pins attached to the truss nodal connectors to crawl along the station. These same pins, as shown in Figure 7 could be used to pivot the GOFIRS from strut to strut. In one arrangement, shown in Figure 8, a simple jaw type grip, equipped with a gear drive could swing or pivot the platform about the pin. The steerable wheel bogie (Figure 6) can "spiral" the platform to a sideface (see Figure 7) and the pivoting action can then take place. Diagonal members (not shown) can be reached by pivoting 45 degrees. Pivoting 180 degrees will permit continued motion along the same longeron. Thus through various combinations of pivoting and spiraling virtually any strut member can be reached without additional tracks or alterations to the primary structure.

Rechargeable batteries would provide energy for locomotion, microprocessing and robotics functions. A power bus outlet could recharge the batteries after a predetermined tour.

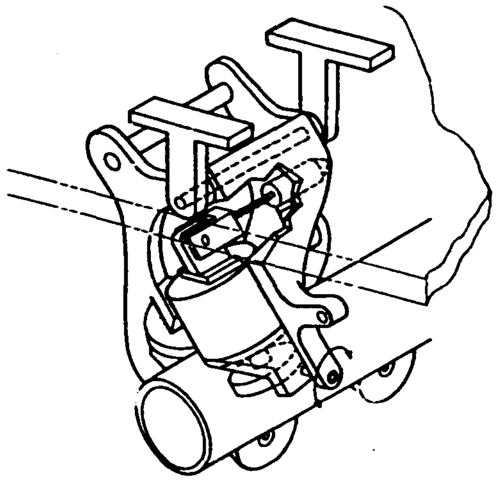

Figure 6. Wheel Bogie

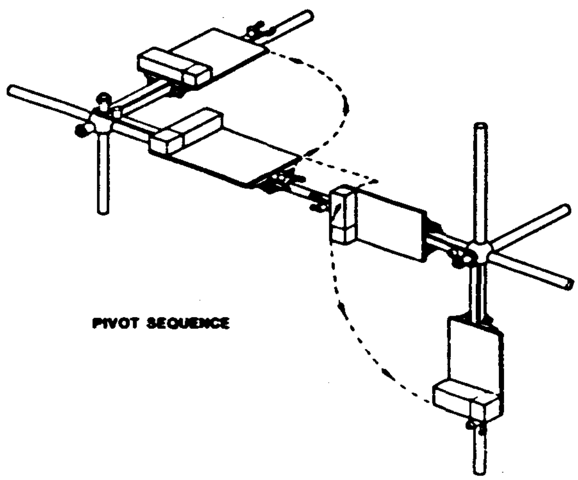

Figure 7. Pivot Sequence

Additional capabilities such as detecting, replacing and/or cleaning solar array panel segments could be achieved with GOFIRS as illustrated in Figure 9. Here the GOFIRS shuttles back and forth on a tubular strut supported by two expandable masts. Scanning across the array, "window washer fashion", the infrared sensors on board the manipulator are mapping temperatures to isolate malfunctioning solar cells.

In the event that the tubular struts themselves cannot be used for support, a twin mast driven platform is envisioned, as illustrated in Figure 10. Appropriately expanding and contracting the masts will provide linear motion. These coilable masts are similar to those conventionally used to deploy flexible solar arrays. A turn-table bearing will permit the platform to assume any planar orientation. The pivoting function will occur in the same manner as before with the exception that the forward mast segment will translate and fold (see Figure 10) to allow motion along the side face. Stiffness and buckling strength of the twin masts are not anticipated to be a problem. Adequate cycle life of the flexible battens must be established.

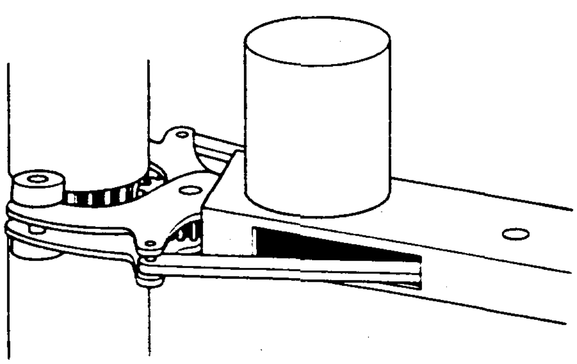

Figure 8. Nodal Pin

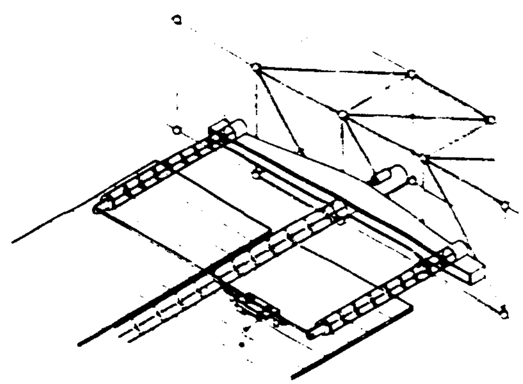

Figure 9. Solar Array

6. Telerobotics

In another variant, as shown in Figure 11, the GOFIRS serves as a combined crew transport and man-controlled servicer. Here the astronaut has a direct visual link with the repair or changeout activity while crew members aboard the Station or on the ground can participate if need be. The system is equipped with one or possibly two dexterous manipulators to facilitate teleoperator repairs.

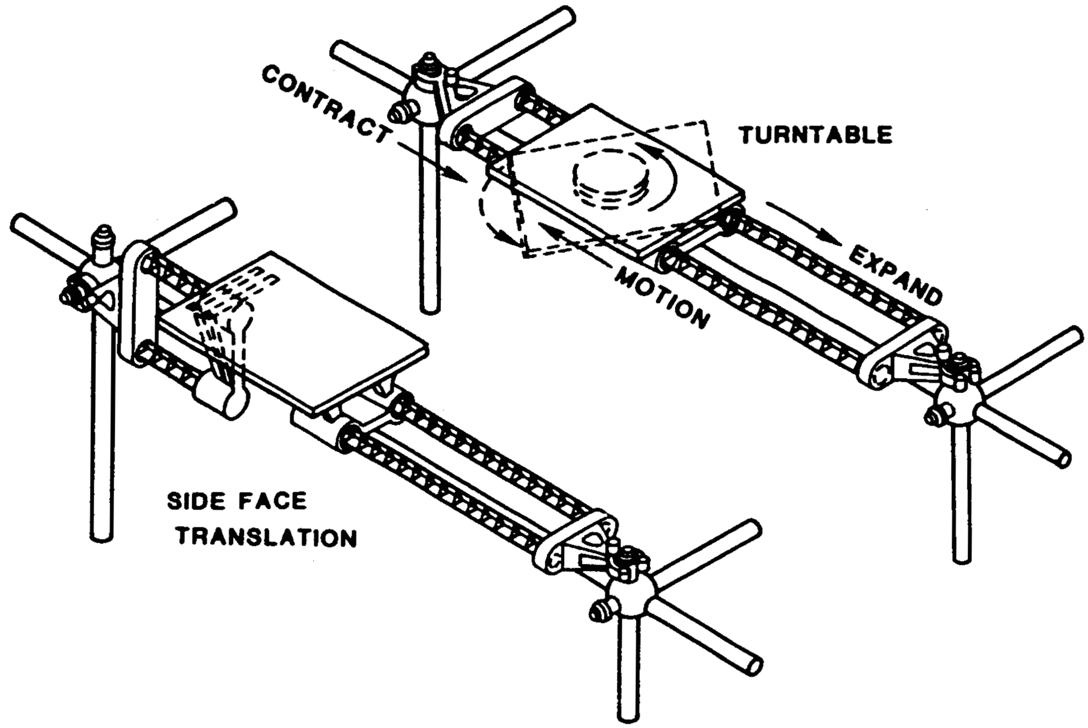

Figure 10. Twin Mast Propelled Platform

Figure 12 illustrates a more advanced telerobotic service configuration for GOFIRS. In principle, the robotic unit pictured here can be the same as that developed for the MRMS or Robotic OMV. The addition of the robot strengthens the GOFIRS capability in performing repairs and making replacements but will undoubtedly add to the cost and size of the platform. A cost-to-benefit assessment of the degree of robotic sophistication will be needed.

Figure 11. Crew-Controlled Servicer and Transport

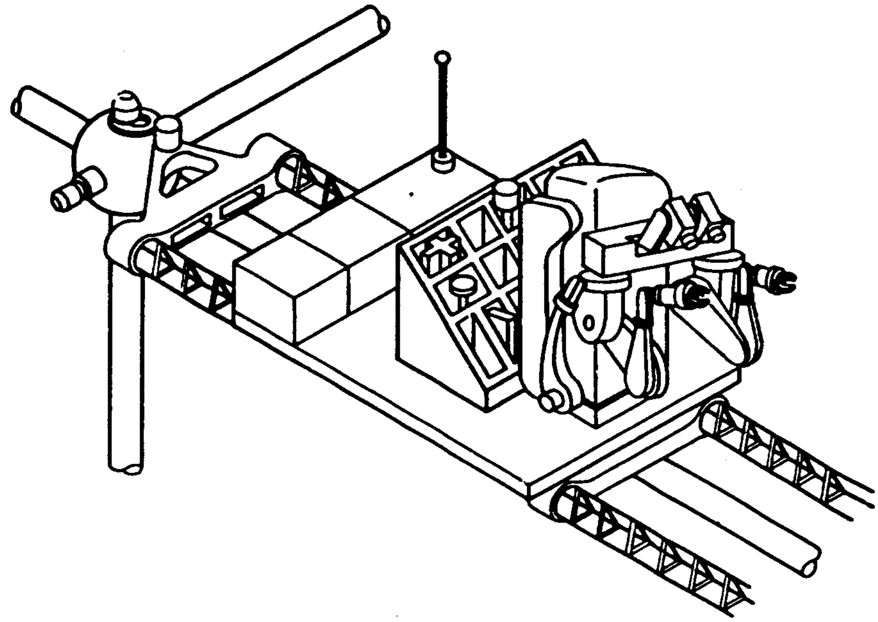

Figure 12. Flight Telerobotic Servicer Mounted Platform

7. A & R Technology For Space

Substantial progress has been made in the development and application of automation and robotic technologies for ground based applications. Industrial robots are now commonplace in factories. However, the repetitive, well structured, highly defined tasks that shop robots are well suited to perform are not commonplace in space. In space applications the tasks are often very diverse, less frequent and highly complex.

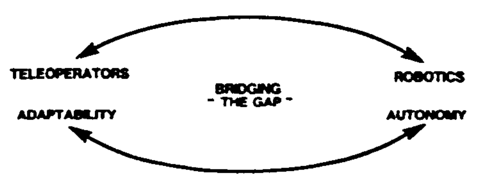

Figure 13. The A & R Challenge!

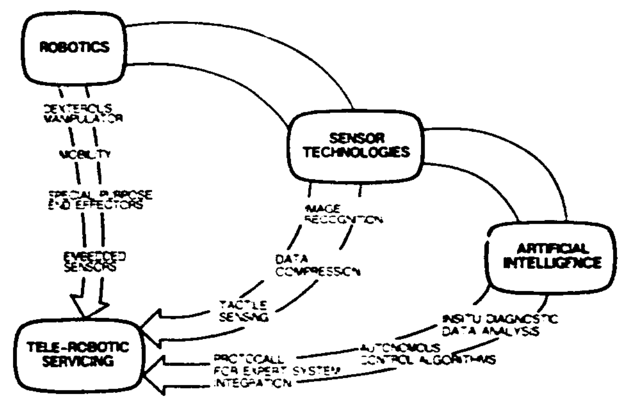

Figure 14. Enabling Technologies

Figure 13 best illustrates this dichotomy of needs. On one hand, robots are ideally suited to *autonomously* perform well-structured tasks. On the other hand, teleoperated manipulators, such as those used in the nuclear industry, can be *adapted* to perform less structured tasks due to their human operators. However, the price for this adaptability is the expenditure of dedicated operator time, a precious commodity aboard the Space Station.

The "challenge" is to bridge the gap between the adaptability afforded by a teleoperator and the autonomy offered by a robot. Some see this bridge as a "tele-robot", one system offering both capabilities, while leaning toward more teleoperation in the early years.

The GOFIRS concept presented here enbodies this duplicity of capabilities. Moreover, it offers the opportunity to have a *distributed* robotic capability about the Space Station, in the same manner as robotic machines are distributed about our factories. Consider the effectiveness and reliability of several smaller machines, simultaneously performing a sequence of simpler tasks in comparison to one super-sophisticated machine required to alone perform the cumulative tasks of the team of smaller robots.

Despite significant on-going progress in many areas of A & R technology, our current level of technology would only support a space based telerobot having relatively low level capabilities. A partial, by no means complete, list of areas where strengthening is warranted appears in Figure 14. The work needed in the robotics area can most quickly be envisioned by the somewhat facetious notion of adapting a 2-ton shop robot to become a space-qualified, flight manipulator. One that has sufficient dexterity to remove a defective circuit board from a delicate instrument if required. Reliabilities associated with today's industrial robots are far from those required for precision space mechanisms. Few, if any, have been designed to operate in a vacuum. Unfortunately, the effort needed to develop and demonstrate the relevant electro-mechanical technologies for a space-worthy, multidegree-of-freedom robot is sometimes under-appreciated.

Other areas requiring continued attention include a range of sensor and detector technologies, with high emphasis on vision related systems for teleoperation (see Figure 14). A whole family of inter-related activities fall under the area of machine intelligence, including task planning and reasoning, control execution, human interfaces and system architecture. The ability to make in-situ, real time, autonomous assessment of sensory inputs will be particularly important in enhancing crew productivity.

8. Conclusion

A concept for a self-intelligent, mobile platform is presented which can perform many of the inspection and maintenance activities envisioned for Space Station. Routine inspection related tasks can represent the single greatest expenditure of crew time given the shear size and complexity of Station's support systems. Several sensor-equipped, mobile platforms or GOFIRS working together with health monitoring sensors internal to these subsystems would be of great value in identifying not only the location but, moreover, the extent, hence urgency, of the defect. In this way, GOFIRS performs as a "scout" for the crew and relieves scheduling of the large teleoperated MRMS.

Features of the concept include the ability to move about Station without the need for special tracks or cables. Virtually all exterior and interior areas within the Station's framework are accessible.

The GOFIRS concept is modular, accomodating more advanced robotic capabilities as they evolve. In its simplest form, GOFIRS is an inspection cart with some crew and tool transport capabilities. Rudimentary teleoperation capability can be added with the addition of a flexible manipulator and vision equipment. Later, a more advanced flight telerobotic servicer unit could be accommodated. In this way a stepping stone approach can be taken. The advantage is the ability to demonstrate the concept at some low level with technologies available today at minimal risk.

The next phase of the work is to establish the performance requirements of a GOFIRS type system in relation to operational inspection and servicing activities to be scheduled on board the Station. This will set the frame work of preliminary design to arrive at the balance between cost, risk and capability. Suitability for early flight demonstration would also be assessed.

REFERENCES

[1] Advanced Technology Advisory Committee, "Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy", Volumes 1 & 2, NASA TM-87566, March, 1985.

[2] A. J. Meintel, Jr. and R. T. Schappell, "Remote Orbital Servicing System Concept, Satellite Services Workshop", NASA Johnson Space Center, June 22-24, 1982.

[3] L. M. Jenkins, "Telerobotic Work System Concepts", Proc. AIAA/NASA Symposium on Automation, Robotics and Advanced Computing for the National Space Program, September 4-6, 1985. Washington, D.C.

[4] R. E. Olsen and A. Quinn, "Advanced Orbital Servicing Capabilities Development", Aerospace Environmental Systems, paper number 860992, Proc of the 16th ICES Conference, July 14-16, 1986, pp. 719-732.

[5] H. L. Martin, D. P. Kuban, D. M. Williams, J. N. Herndoin and W. R. Hamel, "Recommendations for the Next-Generation Space Telerobot System", Oak Ridge National Lab TM-9951, March 1986.

[6] D. R. Flaherty, "Automation and Robotics Plan (DR-17)", Space Station Definitions and Preliminary Design, Work Package Number 2 McDonnell Douglas MDCH2036A, June 1986.