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The *Charlotte* ™ Intra-Vehicular Robot

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INTRODUCTION

NASA has identified telerobotics and telescience as essential technologies to reduce the crew extra-vehicular activity (EVA) and intra-vehicular activity (IVA) workloads. Under this project, we are developing and flight testing a novel IVA robot to relieve the crew of tedious and routine tasks. Through ground telerobotic control of this robot, we will enable ground researchers to routinely interact with experiments in space.

PROJECT NEED

Past crew workload projections for the Space Station Freedom have exceeded available crew time by as much as 200%. Although significant effort has been expended in the transition to the International Space Station design, few readily identifiable modifications directly improve the availability of crew time for intra-vehicular activities. Flight experience from Shuttle, Spacelab and SpaceHab missions provide corroborating evidence of the need to off load crew time. Nominal crew timelines are often exceeded, particularly when contingency operations are required. And failures of experiment apparatus between scheduled crew status checks may compromise science results. Thus, we need to not only reduce the existing crew workload, but should provide for increased monitoring of experiments. Finally, much of the activity associated with such monitoring is routine and tedious, and represents a ready target for automation.

Providing this capability by individual experiment automation will add to cost, complexity, and weight without providing a robust capability for interaction. This is particularly true in applications requiring mobility and dextrous operations. Further, many experiments and systems have already been designed for crew operation. Modifications to existing crew interfaces to make them "robot friendly" would be cost-prohibitive.

Crew familiarization and training to operate onboard experiments adds to the cost of conducting space experimentation. Principal investigators must summarize potentially years of research and specialized knowledge to deal with routine and contingency operations. And during real-time support, crew observations must be relayed to the ground, interpreted, and response measures defined, transmitted, verified, and initiated. Clearly, the efficiency of operations could be improved and more ambitious experiments conducted if ground researchers had the opportunity to directly interact with their experiments.

Conduct of experiments in the crew volume requires adherence to stringent safety procedures. The cost and effort to comply with safety standards and develop supporting documentation will often exceed the cost to develop the experiment itself. The ability to remotely conduct science in a separate enclosed volume from the crew (possibly an inert or vacuum environment) could substantially reduce these costs. Further, the ability to place a module such as the SpaceHab at locations in the Shuttle payload bay other than in the front, as required by the existing connection to the crew cabin, would enhance its manifesting options, which are constrained by the combined vehicle center of gravity location for entry and landing.

OBJECTIVE

We have presented a clear need for a system that can utilize existing crew interfaces, allow preprogrammed or teleoperation and monitoring, enable telescience, and have the potential to operate in a volume detached from the crew. Our overall objective in this project is to develop a flight-rated and tested IVA robot to meet these needs at the earliest possible date. Our system will be easily adapted to the Space Shuttle, SpaceHab, SpaceLab, MIR, and the International Space Station environments. Our specific objective for 1994 has been to complete development and certification of a flight unit for demonstration on the SpaceHab 3 mission in February of 1995.

APPROACH

Our approach is to develop an IVA robot system incrementally by employing a series of flight tests with increasing complexity. This approach has the advantages of providing an early IVA capability that can assist the crew, demonstrate capabilities that ground researchers can be confident of in planning for future experiments, and allow incremental refinement of system capabilities and insertion of new technology. In parallel with this approach to flight testing, we seek to establish ground test beds, in which the requirements of payload experimenters can be further investigated.

To these ends, we have developed an affiliation with SpaceHab Incorporated, which will allow us to gain IVA robotic flight experience. A series of flight tests, beginning with the SpaceHab 3 mission, will lead to an operational subsystem, whose services can be employed by SpaceHab experiments. We are also developing a partnership with NASA to use this platform as a test-bed to develop and integrate new IVA robotics technologies into the system. Current plans seek to provide an early demonstration of ground remote operations, followed by the integration of more dextrous end-effectors, ground telepresence control modes, and active proximity and force sensing capabilities.

In 1993 we reviewed manifested SpaceHab experiments and defined IVA robot requirements to assist in their operation. We also examined previous IVA robot designs and assessed them against flight requirements. We rejected previous design concepts on the basis of threat to crew safety, operability, and maintainability. Based on this insight, we developed an entirely new concept for IVA robotics, the *CHARLOTTE* ™ robot system. Ground based testing of a prototype version of the system has already proven its ability to perform most common tasks demanded of the crew, including operation of switches, buttons, knobs, dials, and performing video surveys of experiments and switch panels.

SYSTEM DESCRIPTION

The Charlotte robot system is shown in Figure 1. Its design was driven primarily by the requirements for a compact and lightweight system which could safely operate in conjunction with crew members in a large workspace volume.

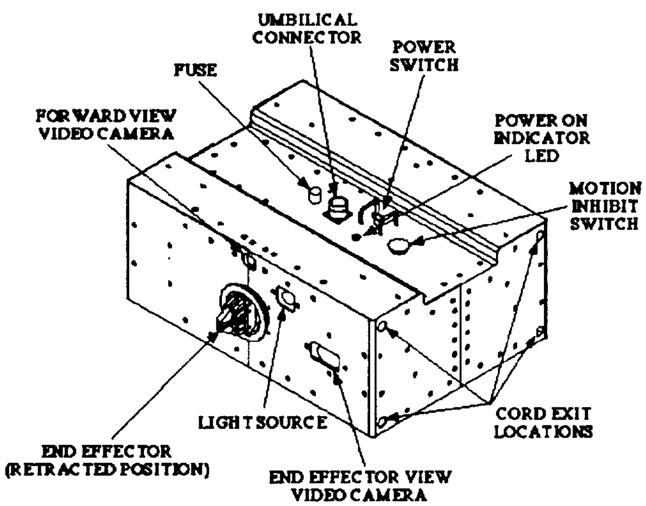

Figure 1. - The Charlotte robot.

Functionally, the system consists of a six-degree-of-freedom (DOF) motion platform with an attached 3-DOF end-effector. Eight servo controlled cables emanate from the corners of the frame to support the robot. Coordinated control of the cables allows the robot to translate and rotate within a workspace defined by the cable anchor points. The end effector is attached to the front of the frame, and consists of an extendible gripper with an infinite roll capability. The take-up spool mechanisms, drive components, control and operational computing capability are all contained within the robot's frame. A video subsystem with two CCTV cameras is also integrated inside the frame to provide views of the workspace and end-effector. The flight unit weighs less than 40 lb and measures approximately 8 x 19 X 14 inches. Power and data lines are the only external connections.

Designed as a parallel redundant cable driven manipulator, the Charlotte robot offers a number of unique features. Foremost among these for space applications is safety. Because motion in any direction requires coordinated control of all servo motors, the system has a high immunity to joint runaway. Because the manipulator is redundant, it is also highly reliable. In the unlikely event of a cable break or jam, the system will still retain full 6-DOF control, although the effective workspace volume and stiffness may be affected.

While not readily apparent, another striking characteristic of the system is its high rigidity and repeatability. The use of high modulus cables ensures a high, albeit varying stiffness throughout the workspace volume. At the center of its workspace, the Charlotte robot exhibits a stiffness greater than 1000 lb /inch. In general, as the robot moves toward the edges of the workspace, the stiffness in that direction and the normal direction increases, while the stiffness in the opposite direction decreases. These characteristics can often be exploited to great opportunity in a variety of situations.

Coupling the high stiffness with a high bandwidth position-based control system using velocity and acceleration command shaping results in very precise control and high repeatability. Cable lengths are theoretically controlled to better than 1/64000 of an inch. Positioning repeatability within the workspace has been demonstrated to be better than 0.005 inch. Angular positioning repeatability is on the order of 0.04 degrees. The current system can be controlled at rates as low as 0.001 inch/second. To minimize crew hazard, the unit has been sized to keep the applied force less than 40 lb., thereby defining the acceleration limit. Command shaping also allows the system to be controlled to minimize micro-gravity disturbances. Nominal power consumption is less than 54 watts with a 180 watts peak.

Production and maintainability of the Charlotte robot are facilitated by the use of commercial off-the-shelf components that are integrated into modular, easily replaceable units. This approach enabled us to complete a working prototype system within four months of concept development. A standard industrial computer chassis with a Intel-486 based CPU card, an electronic disk drive emulator, and multiple commercial servo-amplifiers are employed to effect motion control. A video subsystem and two CCTV cameras are also integrated into the robot. The spool and drive mechanisms have been integrated into eight identical and interchangeable cable control modules to simplify production, sparing, and logistics.

FLIGHT OPERATIONS

From an operational perspective, the system is compact, lightweight, easy to transport, and quickly installed. The crew can remove the robot from its flight locker and install it in an operational configuration in less than five minutes. The unit is transported with all cables reeled in, holding the anchor pins to the cable feed grommets at the corners of the robot enclosure. Installation is accomplished by powering up the unit, pulling each cable in turn to reel them out under active control, and attaching the anchor pins to anchor points at the boundary of the workspace. Figure 2 shows the Charlotte robot in the deployed configuration in the SpaceHab module.

Once deployed, command and control of the robot is initiated through a portable personal computer which is used as a communications terminal and operator interface to the control software that resides within the on-board master computer. Crew members will initially test the robot in a teleoperated mode, using keypad mapped controls to test the robot in each translation and rotation axis, and execute relative-move and move-to commands. Visual observation of the robot, digital position information displayed at the portable computer, and CCTV images from the robot's video cameras will be used to monitor these actions. Image recognition is used for visual calibration. Next, scripted command sequences will test the

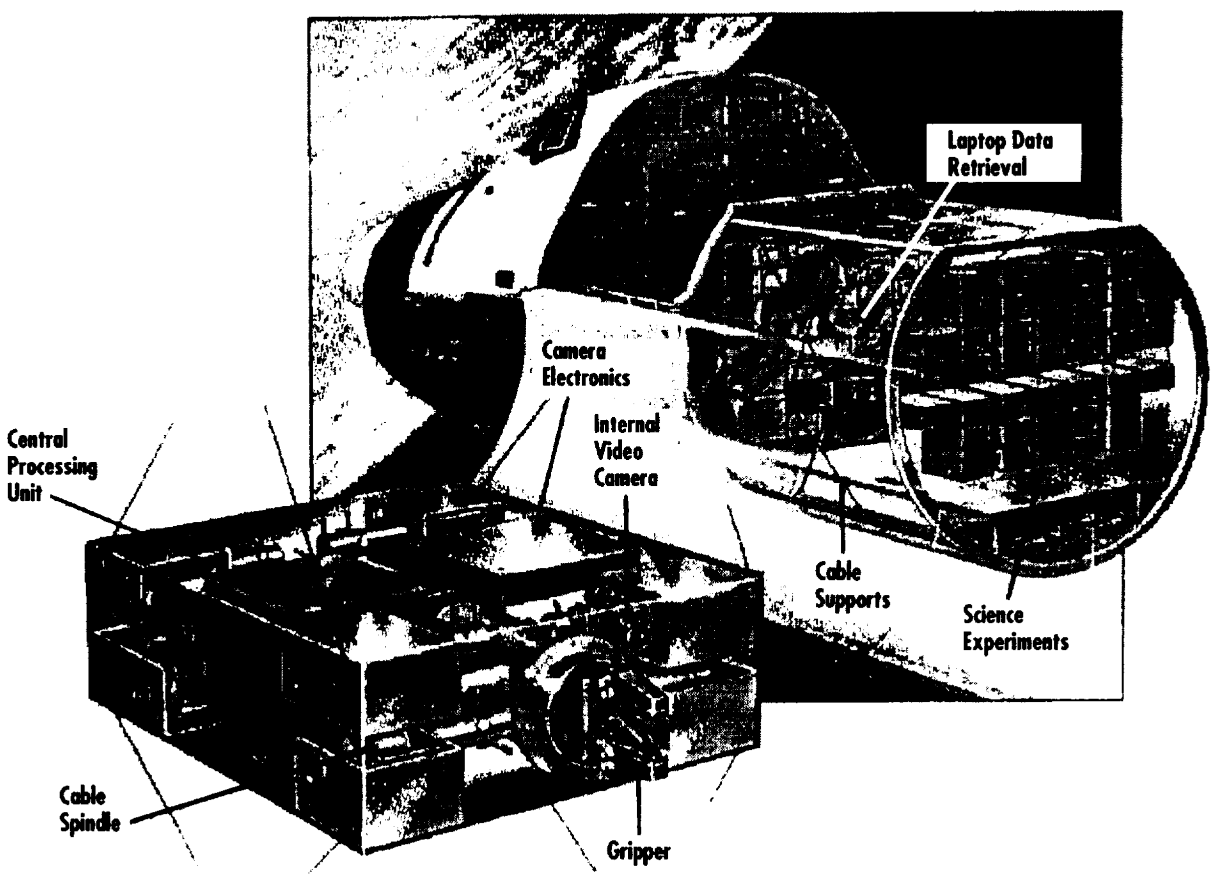

Figure 2. - The Charlotte IVA robot and its deployed configuration in the SpaceHab module.

system's ability to operate a representative set of SpaceHab experiment switches, buttons, dials, and knobs. A second set of scripts will demonstrate the robot's ability to perform video surveys of experiments in the SpaceHab module.

Following successful completion of the first phase of tests, ground command and control of the robot will be evaluated. Using the services of the SpaceHab and Space Shuttle data and communications subsystems, a second phase of testing will be initiated by ground controllers. The primary purpose of this testing will be to demonstrate the ability to operate the robot independently of the crew. This will enhance experiment monitoring and crew scheduling flexibility by enabling ground controlled operations during crew meal and sleep periods.

SCHEDULE

Final assembly of the Charlotte robot flight unit and early safety reviews for the SpaceHab 3 flight were completed by May 1994. A series of unit test and flight safety reviews remain to be conducted, culminating in a Flight Readiness Review in January 1995, with a expected launch in February of 1995 on the SpaceHab 3 mission on STS-63.

FUTURE SPACE INITIATIVES

Plans are underway for follow-on flights. We expect that successful completion of the first flight's objectives will lead to designation of the Charlotte robot as an operational subsystem of each SpaceHab module on subsequent missions. We are also planning a series of robot technology flight experiments to extend and enhance the system's capabilities. A project plan is under development that seeks to integrate robot technology developed at NASA centers and several small businesses with the basic Charlotte platform. Capabilities added may include a serpentine manipulator arm to enhance dexterity, ground telepresence control utilizing a virtual reality environment, and active on-board proximity and collision detection.

To facilitate this use of the Charlotte robot as an experimental test-bed, we intend to develop a number of industry-standard modular interfaces for structural, power, and data interconnects with the robot. Ultimately, it is hoped that this approach will lead to the development of a complement of end-effectors and tools that can be employed by researchers in conducting space telescience. To facilitate and expedite this development, we seek to develop a set of international ground test-beds, in which 1-g capable versions of the Charlotte system can be employed as research tools.

TERRESTRIAL APPLICATIONS

Many terrestrial uses of the system are also envisioned. Most of the desirable features of the Charlotte system transition well from space to terrestrial applications. The system is inherently scaleable, allowing us to consider both larger and smaller units. Large scale applications are envisioned requiring cable lengths of several hundred feet and payload capacities of several thousand pounds. The Charlotte robot might find applications in industries with requirements for systems with large workspace volumes, controlled transport, or precise positioning, such as aircraft production and maintenance, construction, and warehousing (Figures 3 and 4).

Smaller scale applications envisioned for the device include certain machining, materials handling, and laboratory applications. In general, Charlotte derived systems are best suited to applications with large, uncluttered

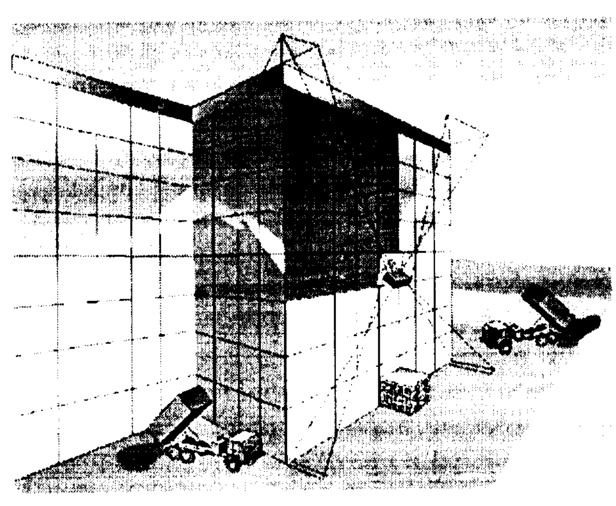

Figure 3. - A Charlotte robot could transport and install siding material for construction.

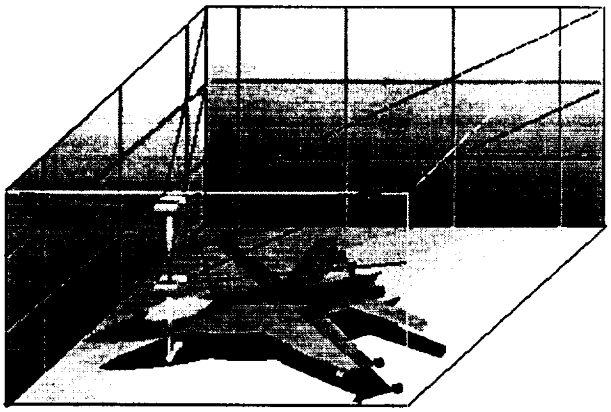

Figure 4. A Charlotte derived robot may be employed in single or multiple work cells to affect aircraft refurbishment and maintenance.

workspaces relative to the size of the objects to be manipulated, but with precise positioning needs; those which require only temporary use of robot; or in environments with evolving task or workspace requirements which need an easily reconfigurable robotic system.

CHALLENGING NEW FRONTIERS

One of the most exciting uses of the Charlotte robot currently in development employs it as a force feedback device in a man-in-the-loop simulator. The application is being developed by the Automation and Robotics Division of NASA's Johnson Space Center, and seeks to evaluate the use of virtual reality in astronaut training. This type of training must provide the appropriate visual environment and some of the sensory stimulus of weightless operations. Traditional training methods include flying parabola's in aircraft to achieve brief periods of weightlessness and, primarily, the use of neutral buoyancy facilities (water tanks) with immersed test subjects and hardware mockups. Underwater test facilities have several shortcomings, including the need to manufacture hardware mockups, the limited size of the tank, the cost to maintain and operate the facility, and the viscous damping effects which prevent objects from responding to applied forces as they would on-orbit.

The alternate approach under investigation uses virtual reality to simulate interaction with the visual environment, and uses the Charlotte robot to provide tactile sensory stimulus. Sensors are used to measure forces applied to the robot, a computer model computes the motion that would result, and the robot is commanded to move accordingly. Complicated dynamic interactions involving spacecraft systems can be modeled in the host computer. Reflecting this motion as movement of "virtual" objects in a helmet mounted display and physical motion of handholds or other crew interfaces mounted on the Charlotte robot allow the astronaut to "see and feel" simulated zero gravity effects. (Figure 5). Such simulators have the advantage of being easily reconfigurable to a variety of simulation scenarios with minor changes in data loads and visual models. Similar techniques can be applied to other training or entertainment applications.

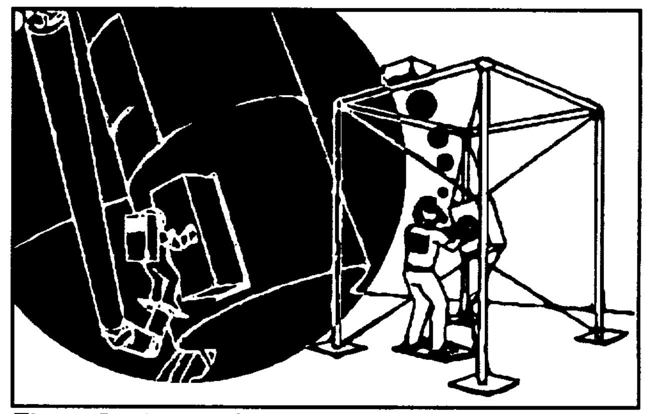

Figure 5. - A test subject wearing a helmet display in a laboratory experiences the exertion and visual sensations associated with an EVA task.

SUMMARY

A novel approach has been described to fulfill space intra-vehicular robotic needs. The solution is elegant in its simplicity, but surpasses other approaches in the intrinsic safety it provides and its ratios of workspace volume to weight and power requirements. The exceptional stiffness of the robot enables it to be highly precise, especially with regard to its workspace volume. Easily transportable, the device can be installed quickly, and its cables attach points can be configured to optimize performance for a variety of tasks. United States and international patents are pending.

Robotics Technology