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Apr 1st, 8:00 AM

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Robotic Applications At Kennedy Space Center

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1 Abstract

McDonnell Douglas recently performed a study, Ref [1], to find effective application of robots and their associated technology at the Kennedy Space Center (KSC). Specifically, this study was directed towards the newly planned Space Station Processing Facility (SSPF). Because the Operations and Checkout (O&C) building has a similar charter to that of the SSPF, the O&C was carefully checked for potential robotic applications. Eleven applications were discovered and a trade study developed to rate these applications. Twenty more applications external to the SSPF were found during additional studies. These robotic tasks fall into three major categories including: teleoperated robots for hazardous tasks, mobile robots for repetitive tasks and feedback compensated robots for refurbishment and inspection tasks. This paper will highlight some of the requirements for these tasks and others external to the SSPF. Additionally, the resources available at KSC will be discussed.

2 Introduction

The robotic application study performed by McDonnell Douglas revealed eleven applications for the SSPF and twenty additional applications external to the SSPF realm. These applications range from repetitive tasks not related directly to payload processing such as floor cleaning, to the more hazardous task of hydrazine fueling operations and then to tasks requiring extreme accuracy and dexterity such as inspection of flight hardware. Robotic applications at KSC are divided into the following distinct groups:

 Teleoperated Robots - These are ideal for hazardous applications at KSC, such as battery maintenance or hypergolic fuel handling. Many hazardous applications have requirements which exceed the capabilities of present robots. Teleoperated robots have the distinct advantage of removing humans from dangerous environments while leaving a 'man-in-the-loop' as the source of the robot control.

Popular examples of teleoperated robots include: Alvin, the robot which explored the Titanic, the Space Shuttle Remote Manipulator System (RMS) and nu clear 'hot' lab robots (Figure 1). As sensor technology improves and controlling hardware and software become more advanced, applications originally treated as teleoperated could become autonomous in nature. In fact, this growth path is invisioned for several advanced teleoperated systems presently under development.

2. Feedback Compensated Robots - Robots with external sensory feedback will be defined as feedback compensated robots. External sensors include: vision systems, force/torque sensors, tactile sensors, proximity sensor and others (Ref [3]). These robots could be used for a number of applications at KSC, including the inspection and refurbishment of flight hardware. Advanced robots with feedback compensation could insert and remove the various modules and racks easily accessible in the logistics containers.

Robots with feedback compensation could provide assistance in maintaining the racks, pallets and other reusable on-orbit hardware by inspecting and painting them as required. These robots would be able move heavy objects, provide highly repeatable motions, and perform tasks much quicker than a human counterpart. With adaptive feedback, many different tasks could be completed by the same robot with the proper sensors and end-effectors. Presently, the Robotics Applications and Development Laboratory, (RADL), at KSC is active in the development of feedback compensation technology.

3. Mobile Robots - Mobile robots could provide such services as building security, fire fighting, floor cleaning, hardware and tool caddy, mail courier, and trash collecting. Many of these applications are currently being developed in Jaboratories or are commercially available on the open market (Ref [4]). Robots for these redundant tasks show cost payback period in as little as three to four years. More demanding applications may include air begring tractors and hazardous spill cleanup devices.



Figure 1: The Space Shuttle Remote Manipulator System. This figure adapted from Ref [2].

Manipulators may be added to the mobile base and provide an extremely useful tool for additional applications. Often, it would be impractical or uneconomical to permanently locate a manipulator at a single location, for example at a single test stand. A mobile base would allow a manipulator to move from location to location for various tasks, greatly improving its productivity.

These three major categories share similar requirements and technologies, for example: external sensors such as force, visual and audio sensors, obstacle avoidance and automated path planning capabilities, feedback compensation technologies, knowledge based reasoning and high level command languages. Technical developments would enhance all three categories and lead to the possible development of highly capable, autonomous robots.

3 Teleoperated Robots

Teleoperated robot systems have one major advantage over traditional industrial robots in that a man is used to provide the system control. Presently, machine intelligence can not accurately emulate a human counterpart. A human is able to inference over large data sets in a real time fashion and is not adversely affected by unusual data. Computer controllers are rather simplistic devices, relying solely on the expertise of the software programmer to provide the necessary instructions to perform simple tasks.

In a number of tasks, unusual circumstances occur or slight variations in programmed motions are required for each trial. Those variations and responses to certain circumstances must be provided ahead of time and preprogrammed, which is a difficult and often impossible task.

Thus, for some special robotic applications, teleoperated systems are the only practical choice at this time to ensure successful operation and a high degree of safety. Augmenting human capabilities through the use of teleoperation as opposed to replacing him entirely, is the most reasonable method of performing difficult tasks with the current technology.

The greatest application for teleoperated robots at KSC would be for hazardous operations. Safety is a major concern at the base, not only during launch operations but also during testing and normal preparation routines. Preparing payloads for flight include a number of hazardous operations which include: the loading of hypergolic fuels, high pressure gases, ordinances, cryogenics, hazardous gases, and heavy lift operations. Most of these hazardous operations require specially trained personnel wearing protective clothing, yet the personnel could be endangered in the event of a catastrophic failure during the operation.

A teleoperated robot system consists of two major components: first the slave robot is the device which actually performs the required tasks and the second component is the master robot or more commonly, a joystick which the operator uses to control the slave robot. A variety of sensors may be used to provide telepresence between the slave robot and the operator of the joystick. Telepresence is defined as the feedback provided to the operator which gives him the feeling of being present at the worksite of the slave robot. The sensory information may include force and tactile feedback, visual feedback with stereovision or depth perception, movable points of view and high resolution zones of focus, thermal and audio feedback.

Teleoperator systems with force feedback have been in existence since the early 1950's for 'hot' nuclear laboratories. These somewhat primitive devices utilized master

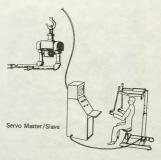


Figure 2: Master Slave Teleoperator System. This figure adapted from Ref [2].

controlled. This greatly simplified the feedback mechanism in the form of cameras fixed over the slave's work space because of the exact geometric duplication between the and a camera attached at the wrist of the robot. The commaster and slave. Any force sensed by a given joint in bined views allow the operator to better understand the the slave robot was reproduced in a scaled manner to the location of the slave within its workspace and the relationmaster robot. Likewise, any movement in a joint of the ship between the end effector of the robot and its desired master robot was duplicated by the slave in a one-to-one target. ratio. This control could be accomplished using very simple analog control strategies. Before the advent of small hazardous events astronauts are exposed to while on orpractical computer systems, this was the only method of bit. The RMS was designed to reduce the number of these control possible. Figure 2 illustrates the master/slave teleoperator system.

Through the use of computer control which communicates to both the slave and the master controller independently, a completely universal interface or joystick controller could be developed. Joy stick controlled teleoperator systems have the advantage of being able to control many robots with dissimilar geometries. For example, at the Center of Intelligent Machines And Robotics laboratory (CIMAR) at the University of Florida, a joystick composed of a handle connected to nine strings is able to control two geometrically dissimilar six degree-of-freedom robots, a Puma Unimate and MBA Associates manipulator. Another example of a completely universal joystick controller joystick providing rotational control of the manipulator. is given in Reference [9]. This design also includes a completely dissimilar geometry composed of parallel actuated modules.

Figure 3 shows a joystick controlled telerobot designed for hot lab environments.

A robotics laboratory at the Jet Propulsion Laboratory recently produced a universal joystick with scaled force feedback. It is presently used in conjunction with

robots which were scaled versions of the slave robots they CIMAR teleoperated systems incorporate visual feed back

External Vehicular Activities (EVA) are one of the most excursions, thereby reducing the number of hazards astronauts are exposed to. The RMS is used extensively in the deployment of payloads from the orbiter bay for release into orbit and to activate experiments. The RMS, operated by a mission specialist, is located in the aft area of the shuttle's crew compartment (Figure 4). The operator has direct vision from two windows looking aft into the shuttle bay and two windows directly above. Two television screens located on the control panel provide views from cameras located on the forward and aft payload bay bulkheads, and on the wrist of the RMS. The operator controls the arm by utilizing two 3 degree-of-freedom hand controllers. The left joystick provides translational motion and the right

A well publicized teleoperator application was the successful retrieval of a malfunctioning satellite, Solar Maximum Mission, during STS-41C, April 1984. A special end effector was designed for the Space Shuttle Remote Manipulator System, to grapple the satellite. The teleoperated RMS was at first unable to grapple the satellite because it had a mild wobble. Two days later, ground crews were able to reduce the wobble and a successful grapple was made on a six degree-of-freedom Puma Unimate. Both the JPL and April 10 by the RMS. The satellite was then immediately

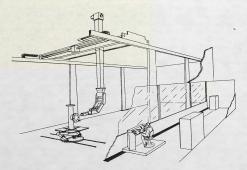


Figure 3: Joystick Controlled Teleoperator System. This figure adapted from Ref [2].

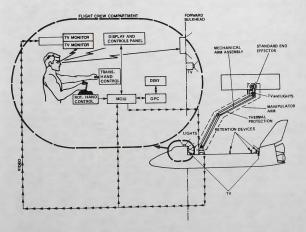


Figure 4: The Space Shuttle Remote Manipulator System. This figure adapted from Ref [2].

lator foot restraint, which turned the RMS into the equivalent of on orbit 'cherry picker' (Ref [10]). Possibly with improved sensory feedback and a greater degree of telepresence the entire task could have been performed with the RMS.

Other research laboratories have incorporated various sensors on the salve robot to warn the operator of impending obstacles. Infrared, sonar, and tactile sensors have been placed on various portions of the slave for this purpose. In addition to obstacles perceived by either the operator or warnings from the various sensors, an automated warning system has been developed which utilizes a CAD based model of the slave's environment. The position and orientation of the robot, as measured from the joint encoders, is animated on a high resolution display terminal in real time, and obstacles from the CAD based model change from a passive green color to a bright red when the robot encroaches within a preset limit (Ref [11]).

Various hazardous tasks are performed routinely at KSC and include the loading and unloading of hydrazine fuels, hypergolic fuels, high pressure gases, the loading of ordnances, and many others. These applications have similar task requirements that can be divided into several generic groups, including:

- · removing or inserting bolts, pegs, hose's and plugs into their perspective receptacles
- · insertion and removal of modular devices on board assemblies
- · turning valves, nuts and bolts
- · removing or replacing protective caps and covers on components
- · monitoring test equipment

Many of these tasks could be easily simulated and practiced by the operators off line in special teaching facilities. New end-effectors could be designed and fabricated so that they may be used for several different tasks. In some instances, existing equipment may have to be adapted so that teleoperated systems could more safely and efficiently manipulate the work pieces. For example, a chamfer may be added to a peg so that it may be more easily inserted into a hole. Advanced design for automation certainly improves the chances for successful robotic applications. However, by improving teleoperator technology a number of existing tasks using the existing tools may be performed with robotic systems.

The RADL at KSC is a highly integrated robotic system test bed. The laboratory includes: the slave manipulator, sonar, visual and force/torque feedback sensor (Ref [5]). In

docked on a special ring so repairs could be made. This addition, a high speed computer is currently directly interwas done by two EVA astronauts, standing in a manipu- faced to the robot controller, and all of the devices in the system. The RADL facility represents an excellent opportunity for developing and testing a teleoperator controller. A joystick controller implemented in the current architecture would functionally appear as simply another device in the system. Proposals to expand the facility to include a teleoperated controller are now being developed.

Teleoperated systems offer one major advantage over traditional direct hazardous processing: removing humans from hazardous environments. The operating personnel would be completely removed from possible hazards while still maintaining direct control of the hazardous process. The slave robot could manipulate objects that are much heavier than human rated loads with greater accuracy. The slave robot could also be designed to work in adverse environments such as intense heat, a composite treating oven for example, underwater for SRB retrieval applications or corrosive environments where manipulators come in contact with corrosive fuels, acids, vapors, etc.

As machine intelligence capabilities expand in the future, teleoperated applications may grow to complete autonomous operation. The sensory information available to the human operator will also be available to the any high level processor. However, adjustments must be made in reducing and interpreting the sensory information. The actual teleoperators may be used as experts to input information into expert system based controllers. Thus it is obvious that teleoperation should occur before complete automation is possible. This the only reasonable and achievable path to reaching automation of difficult tasks.

Feedback Compensated Robots

Typical applications of robots in industry have been for tasks which require a great deal of repetition. The auto industry is a prime example. Runs of 100,000 or more units are typical for production lines incorporating robots. Because the auto industry is the mainstay for many robot manufacturers, most robots are designed by the criteria imposed by the auto manufacturers. In most instances, the auto industry does not have the accuracy requirement that the aircraft and spacecraft industries have insisted on. However, many applications in the aircraft and spacecraft industry have been recently discovered. Instead of completely redesigning current robots, users are adapting robots with sensors to meet the more stringent requirements of the aircraft and spacecraft industry (Ref [5]).

Feedback compensated robots are defined as programmable robots that have sensory feedback to provide enhanced capabilities over traditionally controlled robots. These capabilities include the ability to alter the current robot motion due to disturbances in the operation. Disturbances normally include force and related system defor-

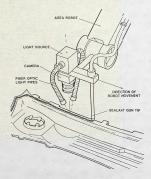


Figure 5: Typical Robot With Feedback Compensation. This figure adapted from Ref [3].

sensors described for the teleoperated robot system includfeedback compensated robot. A distinct difference between teloperated and feedback compensated robots is that the robots with feedback compensation could operate repetitively, with minimal human intervention after being initially programmed manually. The advantage with feedback testbed with the following sensors: compensation is tasks where large varying loads are found may be adequately handled.

Robots with feedback compensation are found in some manufacturing environments. Typically, force/torque sensors are used for many of the metal removal applications including grinding, routing and deburring. Visual techniques are used quite often for assembly processes. Sonar feedback may be used in applications where the gross locations of objects are required, painting and materials handling for example. Laser interferometers could be used in applications where a high degree of positional accuracy is required, particularly in alignment applications and inspection operations.

The feedback compensation of robots is a fairly recent area of research, but the intensity of research has increased as new applications for robots are found. Many of these new applications have requirements that typical off the shelf robots cannot meet without some type of additional sensory feedback. Most automation applications using robots at KSC would require the addition of feedback compensation because of the unique and expensive hardware involved.

These applications would range from the inspection and refurbishment of payload racks and pallets, to resupplying

mations. The feedback sensors include many of the same the logistic elements of a cargo resupply module. Because these robots would be working directly with flight harding: vision, force/torque, sonar, infrared, tactile, etc. Fig- ware, special precautions and adaptive sensors would have ure 5 illustrates the placement of sensors on a prototype to be included to prevent costly damage due to accidental contact. Some of the feedback compensation strategies for these applications would include a combination of sensors and algorithms currently under development.

Presently, the RADL has an excellent sensory feedback

- · 6 degree-of-freedom force/torque sensor
- · vision system with 3 degree-of-freedom tracking algorithm
- · sonar displacement transducer

In addition, the ASEA robot incorporates a compensation feedback architecture in the controller for the first three axes, the base, shoulder and elbow joints. Figure 6 shows the RADL system in block diagram form.

Feedback compensation strategies require special algorithms to be written to take the measured sensory information and convert it to robot commands at the individual joint levels. In some cases, feedback control may improve the internal performance of the robot by increasing the positional accuracy or dynamic response. Other feedback control schemes are used to eliminate errors outside of the robot's control, external compensation. Additional schemes may be used to eliminate a combination of internal and external sources of error.

An example of feedback compensation used to improve the internal performance of a robot is presented here. Sensor feedback was used to improve the positional accuracy of a standard industrial manipulator at the Machine Tool

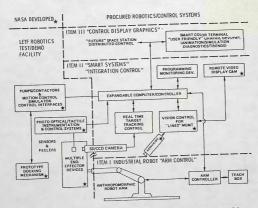


Figure 6: RADL System Block Diagram. This figure adapted from Ref [5].

of positional error were revealed and modeled, and feedback compensation schemes implemented for each case. One source of error was due to the structural flexibilities of the robot structure. When forces are applied to flexible structures, deformations occur in the form of positional errors. By modeling the flexibilities of the robot structure, and measuring the applied forces in real time, these positional errors could be eliminated in real time with feedback control (Ref [6])

Feedback compensation of robots can also be used to correct errors out of the robot's control or external compensation. A common example would be that robots are often used to retrieve objects off of moving conveyor belts. In some instances, the objects may not be at the correct location for the preprogrammed retrieval operation. Without adaptive control, the robot would blindly grope for the object with little chance of success. However, feedback control in the form of a vision sensor could augment the robot's preprogrammed path and direct the gripper to the object for a successful retrieval operation. This type of feedback compensation has been implemented repeatedly in industry. Obstacle avoidance would be a special case under this square inch per frame. A robot must be used to accurately category of feedback compensation.

A final type of feedback compensation would eliminate a combination of both types of errors mentioned above. Cur- end effector of the robot, the position of the robot would rently, this area of research is being pursued at KSC for an have to be accurately known at all times. Presently, large automatic umbilical reconnect system. The heavy umbilindustrial robots suitable for an application such as this

Laboratory, University of Florida. Three particular sources ical plate will cause changes in the dynamic performance and positional errors due to structural deformation of the robot. These are internal errors. Because the target (the Shuttle) is dynamic, positional errors outside of the robot's control will be introduced also.

A three degree-of-freedom visual tracking system, a six degree-of-freedom force/torque sensor and a single degreeof-freedom sonar displacement device are used to provide the sensory input to the adaptive feedback control. Algorithms take the sensory information and convert it to joint level control, and the robot is able to accurately track a target in real time as a simulation to the actual umbilical reconnect process. Without the feedback compensation, target tracking would be impossible for standard robots.

Robotic inspection of flight hardware is an excellent automation application. Inspecting large structures such orbiter payload racks and pallets represent a challenging task. For the resolution required, multiple views must be made if video imaging techniques are used. The more advanced vision systems offer 1024 by 1024 pixel resolution per image. If the desired resolution of the inspection is 0.001 inch, then the vision system can inspect only approximately one move the camera from point to point.

Because the camera would be rigidly mounted to the

feedback compensation scheme would use an external positioning system to accurately locate the camera within 0.001 inch through out the entire work volume of the robot.

Even though much flight hardware is similar in description, each may be configured entirely different. Racks for example, describe hardware used to support and contain flight hardware and experiments. Each flight may require several differently configured racks. For a return from flight inspection, it would be impractical to manually reprogram the inspection routine for each rack. Instead, a vision system could be used to scan the rack for the various configurations and have the controller automatically generate a inspection routine from a library of inspection subtasks. This would be an example of a high level feedback compensation scheme.

ing with flight hardware, obstacle avoidance is of extreme techniques and vehicles with this capability are considered importance. Various sensors would be installed on the semi-autonomous. Semi-autonomous capabilities allow the robot to provide the necessary information to detect ob- AGVs to deviate from their predetermined programmed stacles and cause the controller to either warn the operator path when abnormal conditions are encountered. Figure 8 or plan an alternate path avoiding the obstacles. Obstacle provides a view of a mobile system with various sensors detection and avoidance has been under development for several years in the area mobile robots, and is quite successful and commercially available. This technology could be effectively transferred to these applications.

Feedback compensation of robots is presently being pursued by a number of institutions, private industry and government supported laboratories, including the RADL at KSC. The benefits of feedback compensation are clear, expanded applications, improved performance and accuracy. Feedback compensation has an excellent track record and has brought robots into fields far beyond their standard abilities. Tasks requiring feedback compensation have been identified at KSC and more applications are being discovered regularly. Compensation techniques provide for a system which can respond to and maintain accuracy when unpredicted disturbances are present. This allows the robots to be used in more demanding, higher-value tasks.

Mobile Robots

Mobile robots have had an active role in industry for approximately 10 years. They are commonly used to transport materials in a variety of environments, from semiconductor clean rooms to shop floor of foundries to a number assembly line applications. These component transporters are referred to as Autonomous Guided Vehicles (AGV) and typically follow paths that have been mechanically applied to the floor, a form of low level control (Ref [3]). Most AGVs also include a higher level of control, incorporating active sensors for obstacle detection and avoidance. Figure 7 shows a typical AGV.

These devices are usually taught manually with a teach

has a positional accuracy of approximately 0.100 inch. A pendant, much like a standard industrial robot. The controllers record such information as: velocity, location and duration of desired stops, and locations of turns to branch paths. Low level sensors are used to detect the path, which is formed by wires embedded in the floor, stripes painted on the floor or other reference based techniques. Typically encoders in the wheels keep track of the gross location of the vehicle and fiduciary marks periodically update the controller with more precise location information.

Because AGVs are typically used in dynamic environments, where obstacles are sometimes encountered, additional sensors and control strategies are incorporated. Often sensors are used to detect obstacles in the desired path and either the controller will direct the AGV to remain stationary until the obstacle is out of the path or an alternate path around the obstacle may be developed. For the automation applications which have robots work- This requires active real time sensors and robust control installed. Sensors used for obstacle detection include:

- · Machine Vision A major sense for autonomous capabilities, it provides brightness in two dimensions over an image. Two dimensional vision is useful for object recognition, inspection and robot guidance. Machine vision requires real time data processing to effectively utilize the vast amount of information produced by the camera.
- · Proximity Sensors A number of sensors can be used to provide proximity location of obstacles, including ultrasonic and infrared sensors. These sensors are quite inexpensive and can give a gross detection obstacles. Many cameras incorporate this technology for automatic focusing. Often 10 or more of these devices are set on the periphery of a mobile platform to provide a mapping of its surroundings.
- Tactile Sensors Externally applied forces can be measured to discover obstacles. Whiskers or bumpers are used on some mobile bases for this purpose.

Presently, new applications dependent on AGV technologies are commercially available or under development such as: mail couriers, lawn cutters, garbage collectors, hospital drug and meal dispensers, floor sweepers, sentries, underground mining applications, etc. The devices would be taught desired paths, but they would not follow a stripe or wire in the ground. They would instead would require high level, real time sensor capabilities and advanced control systems for full time semi-autonomous operation.

Several highly repetitive tasks have been identified at KSC. Though not directly related to payload processing,

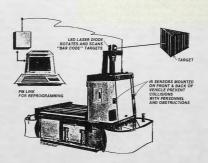


Figure 7: Typical Automated Guided Vehicle. This figure adapted from Ref [7].

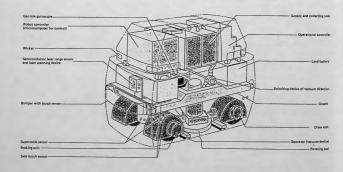


Figure 8: Diagram Of Mobile Robot Structure. This figure adapted from Ref [8].

following applications show cost savings within three to four years: automated contaminant removal systems for cleanroom areas, intrusion detectors, logistic applications and mail courier.

Applications involving the processing of space shuttle payloads include: air bearing tugs (devices used to propel and steer air bearing devices), tools and component caddies and emergency hazardous fuel cleaner for accidental spills. While these devices may improve the efficiency and safety of the processing environment, it is somewhat harder to provide cost justification.

These semi-autonomous devices may eventually be updated to fully autonomous systems, which would greatly increase the number of potential applications. A fully autonomous device would be able to take a high level command as, 'Go to room 123, retrieve object X and return to Q,' divide that command into various sub tasks and proceed automatically. This level of automation requires a great deal of sensor enhancement, data compression and enhanced control strategies.

6 Conclusions

Traditional robotic applications in industry have been deeloped for highly repetitive tasks with rather moderate design criteria. However, robotic applications at the Kennedy Space Center are unique in nature. Low volume and demanding performance requirements are the norm. Fragile flight hardware with toxic fuels and gases must be delicately handled. Little room for error is available and mistaks are costly and dangerous.

Automation and robotics can offer enhanced safety, improved reliability and cost savings for many applications. Many of the applications found are within the state-ofthe-art and could be developed and tested at the RADL. Additional equipment would be required to carry out the development of several applications mentioned above, induding: an advanced joystick for teleoperation, obstacle detection sensors, a position feedback device and a mobile platform. Software would then have to be developed to gather sensory information and effectively utilize it in real time.

Primary benefits to KSC are reliable inspection and safer working environments for Space Shuttle, Space Station and Payload processing personnel. Removing humans from hazardous work areas is an obvious benefit. Feedback compensation is required for high value, difficult applications where random disturbances are presented. Not only will this technology be useful for applications at KSC, industry will be able to expand commercial applications of robots.

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