ROBOTIC SYSTEM FOR THE SERVICING OF THE ORBITER THERMAL PROTECTION SYSTEM

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Todd Graham, Richard Bennett, Kevin Dowling, Davoud Manouchehri, Eric Cooper, Cregg Cowan
NASA Kennedy Space Center
DM-MED-12
Kennedy Space Center, FL 32899
Tel: 407 867-7890, Fax: 407 867-1645
todd-graham@ksc.nasa.gov

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INTRODUCTION

This paper describes the design and development of a mobile robotic system to process Orbiter Thermal Protection System (TPS) Tiles. This work was justified by a TPS automation study which identified tile rewaterproofing and visual inspection as excellent applications for Robotic automation.

BACKGROUND

Robotics and automation technologies have historically not played a role in the ground processing operations of spacecraft and space systems. In part, this has been due to skepticism regarding the viability of these technologies and a strong concern for safety of flight hardware and personnel. In 1990 ground processing activities related to the Orbiter Thermal Protection System (TPS) were investigated [NASA-TPS 90]. The study identified two tasks were automation was technically possible and economically justifiable. These were rewaterproofing and visual inspection of lower surface tiles.

Rewaterproofing

The Orbiter lower surfaces is covered with tiles which are made from highly porous silica fibers covered with a glazed coating. These tiles will absorb water. The absorbed water presents several problems one of which is that it can freeze on orbit and damage the tile. As the Orbiter may be exposed to rain, the tiles must be waterproofed. This is done with, Dimethylethoxysilane (DMES), which is manually injected into a small hole in each tile by a hand held tool. A rubber nozzle is held against the tile and the chemical is forced into the tile by a pressurized nitrogen purge.

Inspection

During launch, reentry and transport tiles can be damaged. This is evident as scratches, cracks, gouges, discoloring, and (or) erosion of surfaces. This damage can impact the flight safety of the vehicle. It is critically important that all tile damage be identified and repaired if necessary. Each tile is visually inspected to see if it has been damaged.

SYSTEM REQUIREMENTS

The primary goal of this effort was to automate rewaterproofing and inspection while minimizing changes to the current methods and process parameters. It was originally considered necessary to do these tasks at any of the three Orbiter Processing Facilities (OPF) or outdoors at the Dryden mate, de-mate facility. It was decided that either automated process should take no longer than five eight hour shifts to complete. Also, it was extremely important to have a design which meets the stringent NASA safety requirements. Finally, the interface to the system must allow effortless manipulation and analysis of an extremely large data set.

At the outset, is was clear that budget constraints made it impossible to deliver a system which had completed the rigorous NASA certification process. So the design team proposed that a certifiable prototype be delivered. This strategy required that the system be designed and fabricated so that all certification requirements could be met without actually completing the required testing and documentation. Once the system design has been validated, additional funding will be sought to fully certify the prototype system.

The system was decomposed into three major sub-systems, 1) sensors and tooling, 2) a positioning mechanism, and 3) an information system. Detailed specifications were written to define the required system.

INFORMATION SYSTEM

An overview of the information system is detailed in Figure 1. Five computer systems are linked together to form the information system. These are 1) existing NASA databases, 2) the WorkCell Controller (WCC), 3) the High Level Controller (HLC), 4) the vision system computer, and 5) the rewaterproof system computer.

The WCC takes data from existing NASA databases and creates the tables which contain the data required by the robot to complete a job. The Oracle Relational Database Management System runs on both the WCC and the HLC. Data transfer between the two systems is accomplished via a temporary Ethernet connection using SQL. The WCC will interface to the Master Dimension Database (MDD) and the Tile Information and Processing System (TIPS). The MDD contains information on the geometry and location of each tile on the Orbiter. This data is used to calculate where to send the robot in order to complete a task. TIPS is a database which contains information about the Orbiter which is dynamic. The WCC utilizes a multitasking, distributed architecture. It is networked using TCP/IP and multiple workstations can be supported.

MOBILE ROBOT

Many options were examined before a mobile robotic system was chosen. This included classes of devices that allowed inspection from afar, large fixed but movable manipulators and even suction-cupped walkers. As a result of these preliminary studies the system chosen was that of a mobile base integrated with a manipulator system.

Mechanical System

The size constraints of the vehicle coupled with the close quarter navigation needs for operating in the OPF required a locomotion system of high maneuverability. A wheeled system utilizing Mecanum wheels was selected. This device utilizes novel roller wheels to obtain three-degree-of-freedom (DOF) motion in the plane. The drive trains for locomotion are within the diameter of the wheel hub. A locking hub allows the operator to disengage the wheels from the drive train completely. This enables the machine to be pushed or towed out of the way in an emergency. The base is formed by a very rigid welded steel frame. The design was deflection driven to provide a very stiff base from which to operate the manipulator. Figure 2 shows a general outline of the sub-systems of the mobile robot. The base also supports two enclosures for electronics and rewaterproofing equipment as well as an on-board nitrogen tank and a battery cage .

Manipulation

When the base reaches a particular work area stifflegs are deployed. The manipulator then deploys itself from it's stowed configuration. The manipulator provides a number of motions to reach the tiles. As shown in Figure 2 the first vertical motion is termed the Major-Z. Linear rails connect the two Major-Z actuators to give a vertically raised rigid platform that can move the rest of the mechanism along the length of the robot. A second vertical motion (Minor-Z extend) is then used to lift the later sections of the manipulator. The two vertical motions are used because a single telescoping device could not provide the combination of stroke length, short unextended height, payload and accuracy needed. Atop this motion is a 360 degree rotating motion (Minor-Z rotate). From this rotate motion a boom nearly a meter in length extends to a stow-deploy link. This link only swings the wrist and toolplate into position for the work. The need for this motion stems from the height requirements and the need to package the robot within the constraints imposed by the facilities. The wrist is a modified Rosheim wrist that provides a hemispherical non-singular workspace. It is capable of moving and accurately positioning the end-effector (25 kg). Precise positioning of the robot relative to the Orbiter is needed to achieve accuracy's of 1mm across the lower surface of the Orbiter. An approach that utilizes two systems delivers the required accuracy. A rotating eye-safe laser scanner reads bar code targets that are precisely located in the facility. Triangulation from three or more of the many targets can give us robot position with a few centimeters. This will position us precisely enough to find a specific tile. The tile positions are known with respect to the shuttle and we can register the tile position with the vision system.

Computing Systems

Three of the on-board computers are VMEbus based real-time systems: a robot controller which controls the base and manipulator motions and monitors the overall health and status of the robot; a vision system which performs the registration and inspection tasks; and a rewaterproofing system which controls the rewaterproofing injection system. The two computer systems which directly control actuator motion (robot controller and waterproofing system) employ "safety circuits" between the computer servo outputs and the motor amplifiers. The fourth on-board system is the High Level Controller (HLC). The HLC is responsible for planning the course of action to complete a given task. In the case of an error or failure in any system, primary safing is performed via the safety circuits, and the HLC performs recovery actions. The HLC also maintains a graphical operator interface.

Electrical Systems

The electronic design is driven by two major constraints: It must 1) run untethered for up to 10 hours, and 2) meet the NEC Class 1 Division II group D requirements for operating in a hazardous atmosphere. Fifteen kilowatt-hours of energy are required to meet the first requirement. Standard gelled lead acid batteries were chosen since they offer good power density. To meet the NEC requirements, all of the electronic enclosures are purged and pressurized, including the battery pack. Additionally, excess heat will be removed from the main electronics enclosure with heat pipes .

REWATERPROOFING SYSTEM

The rewaterproofing system was designed to automate the current manual rewaterproofing process. The system was designed to be fail safe to ensure that tiles were not damaged and that the proper amount of fluid was injected in each tile's rewaterproofing hole(s). It utilizes force control with redundant sensing to ensure that proper contact force is maintained between the rewaterproofing nozzle and the tile surface during the injection process. The nozzle is surrounded by a containment system seal and a slight negative pressure to capture any DMES from a failed injection. The containment system helps to minimizes unnecessary DMES from being vented to the local environment. Process completion is verified through redundant sensing of injection force and DMES injection pressure.

VISION SYSTEM

The vision system has two primary functions. One is to accurately determine the relative position and orientation of the robot tooling with respect to Orbiter tiles. The other is to perform post-flight visual inspections. The vision system uses a two step process to accurately position itself with respect to a tile. First, it uses its laser light projectors to determine the perpendicular distance from the robot tool plate to the tile surface and the orientation of the optical axis with respect to the tile surface. This information is used by the HLC to move the camera to the proper position and orientation so the remaining 3 degrees of freedom can be calculated. These remaining degrees of freedom are calculated with image matching techniques that utilize the current and baseline tile images. The vision system performs visual inspections by comparing pre- and post-flight time images to identify areas in a tile images whose visual appearance has changed. It does this by first aligning the pre and post flight images very accurately. The differences between these images are calculated. These differences are then processed and the differences in the tile's visual appearance are reported to operations personnel. Currently the vision system is capable of identifying missing tile coating and missing pillow type gap fillers.

CONCLUSION

A prototype mobile robotic system for space shuttle servicing has been configured, designed and is currently undergoing system integration and testing. This robot system, when implemented, will mark the beginning of a new era in the ground processing of critical space flight hardware at NASA's Kennedy Space Center.

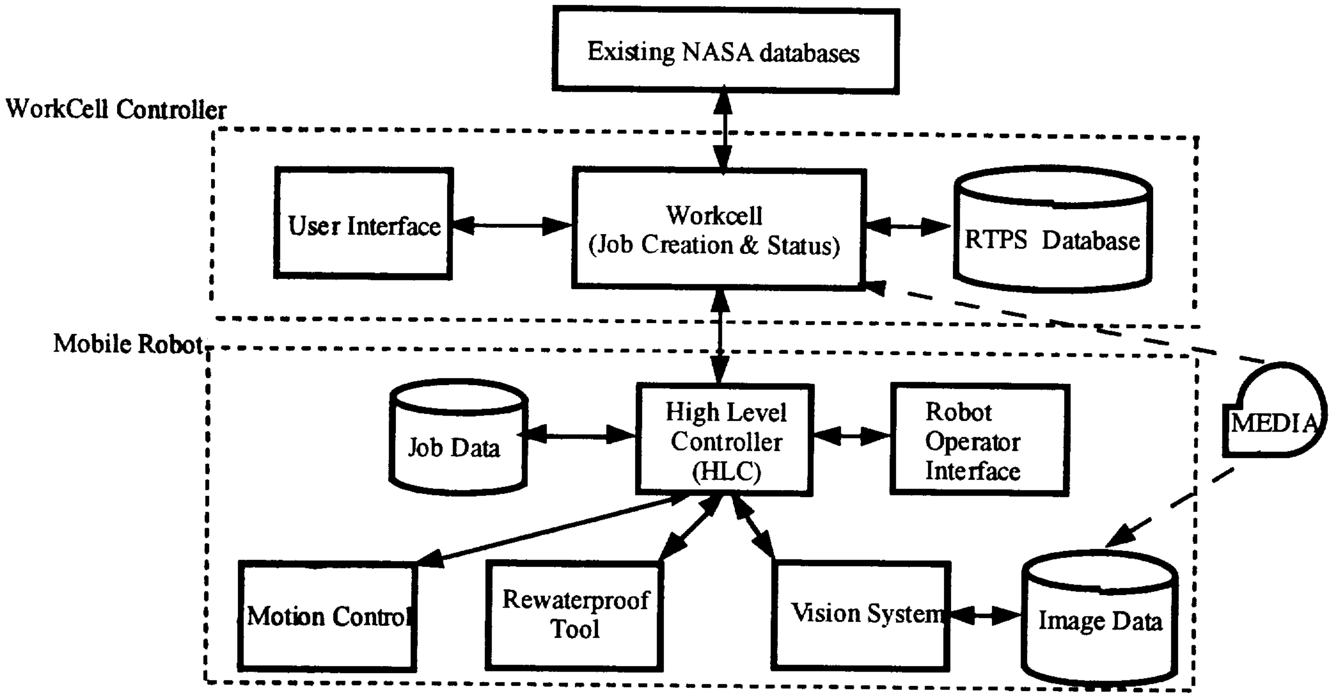

Figure 1 Information System Architecture

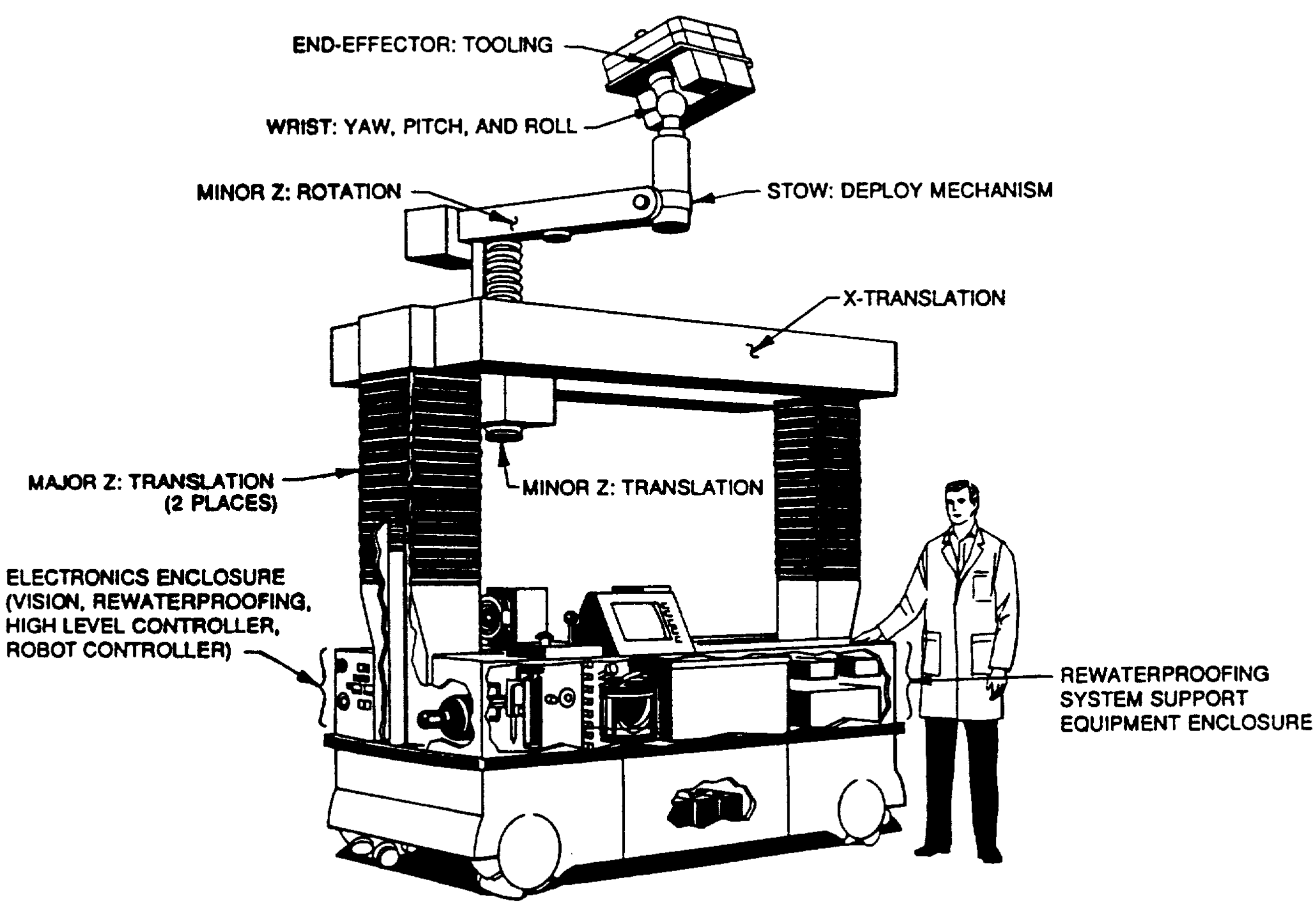

Figure 2 Mobile Robot System

Teleoperations/Telepresence