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Systems Integration for the Kennedy Space Center (KSC) Robotics Applications Development Laboratory (RADL)

V. Leon Davis Ross Nordeen

INTRODUCTION

Robotics technology is a rapidly advancing field moving from applications on repetitive manufacturing processes toward applications of more variable and complex tasks. Current directions of NASA designs for the Space Station and other future spacecraft is moving toward the use of robotics for operational, maintenance and repair functions while the spacecraft is in orbit. These spacecraft systems will eventually require processing through KSC for launch and refurbishment.

In the future, KSC will be called on to design ground processing facilities for new generation launch vehicles such as the Heavy Lift Launch Vehicle and the Second Generation Shuttle. The design of these facilities should take advantage of state-of-the-art robotics technology to provide the most efficient and effective vehicle processing.

In addition to these future needs for robotics technology expertise, it is readily apparent that robotics technology could also have near-term applications to some of the existing hazardous and repetitive Shuttle and payload processing activities at KSC.

BACKGROUND

Launch site applications of Robotics to hazardous and repetitive Shuttle processing activities will offer some unique opportunities at KSC. Commercially available robots traditionally have not allowed an easy and effective means to integrate sensors with robots in the formation of flexible control systems. Without this capability, it is very difficult to develop a system in which **robot motion** can be **controlled adaptively** in **real-time.** This real-time adaptive control is the necessary **tool** for performing **tracking** of a **Shuttle vehicle** stacked at the launch pad while it is **rocking in the wind,** in order to dock and insert umbilicals (consisting of a ganged connection of electrical and cryogenic/hypergolic fluid lines) without damage to the vehicle and without hazardous leaks.

Present "T-0" Umbilicals have to be connected during excursions caused by firing of the main engines in case of an abort (which has occurred twice already) prior to ignition of the Solid Rocket Boosters (SRB). Since it presently takes from 14 to 34 hours to re-connect various size umbilicals, there is not adequate time to safe the vehicle by draining off hazardous fuels, unless the umbilical remains connected until the Shuttle starts climbing skyward. If disconnection of these large mechanisms is done improperly, damage to Shuttle tiles or structural members could result. An orderly/controlled disconnect just prior to launch, rather than during launch, with the capability to rapidly and precisely re-connect, is the desirable approach KSC is investigating for the design of future launch vehicles. Until now such a design has been technically unfeasible, but with the advent of "peg-in-the-hole" robotics technology, high speed pipelined vision processors and real-time software control algorithms; the integration of these technologies should enable this **30 year old goal** to be accomplished.

PURPOSE

In addition to remote mate/demate of umbilical mechanisms, there are other hazardous, time consuming, labor intensive ground processing functions at KSC that could benefit from cost savings brought about by enhanced safety, productivity and efficiency through the utilization of advanced robotics technology. Therefore, a Robotics Development Team was established to determine the most feasible approach to **"capture"** the technology and to provide for implementation of a highly configurable, expandable, testbed capability to **perform robotics research and development.**

The team's initial objective was to develop a robotics laboratory that would provide a facility for training engineers in the unique characteristics and many disciplines involved in robotics technology. It was also to provide a facility where testing of robotics technology could take place to determine the feasibility of applying advanced technological solutions to current Shuttle/payload ground processing activities.

The ultimate objective of this research will be to extend the lessons learned and techniques/systems developed to support existing ground systems, and to further the development of similar systems for future ground servicing of advanced launch-vehicles. Some of these techniques could also be applied to systems in space.

Our approach was to develop, procure and install an applications development laboratory in which robotics hardware, actuators, end-effectors, algorithms, software, sensors and control systems will undergo conceptualization, development, evaluation, and checkout using a large scale test article.

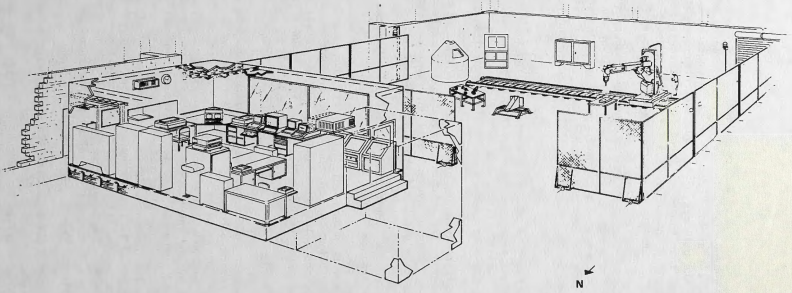
For these reasons, KSC specified a **Robotic Development Prototype System** with the following requirements. It should provide real-time closed loop adaptive path control of position and orientation of all six axes of a large heavy lift (90 kilogram) robot, provide a sensor based testbed, coordinate and integrate state-of-the-art robotic subsystems through the use of a reconfigurable/expandable control and monitor system, and allow operations beyond the capability of an off-the-shelf robot through a universal development system for varied applications.

RESOLUTION METHODOLOGY

The Robotic Development Prototype System contract was performed by ASEA Robotics, Inc. in conjunction with Adaptive Automation, Inc. These companies had previously worked together to provide some unique systems for closed loop robotic control and sensor system integration. The delivery, installation, service and acceptance testing of the robotic equipment was managed by ASEA. Adaptive Automation performed system integration design and software development. They did an excellent job fulfilling specification requirements, designing the system to exceed performance requirements, avoid obsolescence by allowing future performance capabilities to be added to the system as new technology becomes available; and use structured software modular techniques, allowing efficient and easy integration of new sensor technology. The area in the high bay of the LETF where the Robotic Development Prototype System was installed is now known as the **Robotics Applications Development Laboratory (RADL).** Refer to Figure 1.

The RADL has several unique features. It has a large robot that travels on a track enabling it to access several different work cell applications. The system is **highly reconfigurable to adapt to various prototype configurations**, making it a general purpose, multi-station, research and development testbed. The robot is **integrated** through a computer and software system **to several smart distributed control subsystems** including a vision controller for tracking, a process controller

ROBOTICS APPLICATIONS
DEVELOPMENT LABORATORY
(RADL)



for work cell integration, and a smart graphics display terminal for coordination of the overall network. The laboratory **permits sophisticated control algorithms and signal processing techniques** to be applied to sensor information processing, allowing for applications that currently cannot be automated without the use of advanced sensor systems.

The initial thrust of the RADL will be to develop the systems and techniques required for automated loading and unloading of hypergolics for space vehicles and payloads during prelaunch ground operations. Future tasks undertaken by the RADL will be to extend these automated techniques to other fluids (such as cryogenic) as well as electrical power, fiber optic communication, and data system mate/demate functions. As the expertise of the engineers increases, and as requirements dictate, the capabilities of the laboratory will be increased to include equipment for three dimensional scanning, higher order image processing, AI, sonic, laser and other ranging systems, tactile systems, and mobility systems.

SYSTEMS INTEGRATION: COMPUTER HARDWARE AND SOFTWARE DESIGN OVERVIEW

ASEA Robotics Inc. (ARI) and Adaptive Automation Inc. (AAI) were very responsive to the NASA requirements of providing "real-time adaptive servo control & feedback mechanism integration." Our use of "adaptive control" implies the ability to "adapt" to real world changes as determined by sensory devices on and around the robot. The delivered system provides a **set of hardware and software building blocks** as a foundation for a general purpose sensor development testbed for robot control. The computers are **expandable** to allow for the future needs for infrared photo-optical, vision or tactile feedback devices.

In addition to hardware, AAI provided software modules to support a base-line capability from which the system could expand. The objective was to provide an open, **flexible** and **expandable** system, but one which was programmable at a high level. System operational **software** was provided in the form of **libraries of subroutines/modules** which can be used by a NASA application programmer to allow high level programming of the system without requiring the programmer to be familiar with the low level communication functions between the various subsystems. This **modular hardware/software design** approach provides ease of performance enhancement, alteration with minimal impact, and stand-alone or integrated mode functions.

INDUSTRIAL ROBOT ARM CONTROL

To accomplish early development tasks, an anthropomorphic robot arm having electric motor drives was specified. The decision was made to go with electric motor drives to avoid potential leaks of hydraulic fluids which could cause damage to or replacement of Shuttle Orbiter tiles or cause contamination by venting oil vapors. The arm was specified to be a servo-controlled mechanism since it had to be an integral part of a closed loop tracking system. We also wanted to take advantage of some common characteristics of **servo-controlled robots** which include smooth motions, controlled movement of heavy loads, flexibility of manipulation and accurate/repeatable end-of-arm positioning.

ANTHROPOMORPHIC ROBOT

The robot delivered was an **IRB-90/2** manufactured by ARI in the United States. The use of an **off-the-shelf** robot/controller with an integrated computer control system provides several advantages. **Development time and money is reduced** by not having to specify and build a specially designed robot to act as a tracking mechanism. The robot controller can perform kinematic/dynamic matrix transformations using its internal processor capability and thereby **free up the**

MicroVAX computer for supervisory tasks. It can be used as a **"stand alone"** system or integrated with other computerized control systems in a **distributed network.**

ROBOT TRACK

In order to make the laboratory a **multi-station developmental testbed,** the robot was placed on a track. The RADL installation was the first use of an IRB/90 on a track and the installation was completed without degrading the robot's repeatability performance. The track uses an electric motor acting as a seventh axis enabling the robot to service various workcells. Several experiments can be located along and around the 9 meter (30 foot) track. This flexibility increases its efficiency and eliminates the necessity of purchasing additional robots for each developmental project.

SMART SYSTEMS INTEGRATION

The computer hardware and software subsystems were specified as two basic blocks: a Computer/Controller and a "Real-time Target Tracking Controller." They were to allow servo control, tracking, and feedback mechanisms integration providing the capability for **supervisory coordination** of various smart control systems, **I/O hardware interfaces** for integration of work cells that NASA will implement to control peculiar tasks such as docking motion control simulation mechanisms, and Adaptive Path Control of docking mechanisms through **real-time visual feedback.**

The Computer/Controller function was satisfied by 2 separate computer systems operating in an integrated manner. The systems are a DEC MicroVAX II microcomputer and an ASEA MasterPiece 280 Programmable Process Controller. The target tracking was supported by the MicroVAX interfacing with a hybrid system made up from a Motorola 68010 computer controlling DATACUBE vision processor hardware.

SUPERVISORY COMPUTER

The supervisory computer is the **heart** of the RADL system integrating the various "smart" subsystems, allowing them to talk to one another and making them appear transparent to the user. AAI chose to implement the supervisory computer using a **DEC MicroVAX II computer.** All software was developed in the VAX C programming language because it supports a high-level programming environment while providing low-level bit manipulation necessary for control.

SYSTEMS INTEGRATION SOFTWARE

There were separate and distinct requirements regarding the software that were levied upon the contractor. Software for operation, demonstration and acceptance testing of the integrated systems had to be delivered to the Government for all furnished subsystems in the form of modular subroutine libraries. Software was required to be easily programmable and to be developed in a top-down, structured manner with sufficient annotation to allow clear understanding of its operation. Diagnostic software programs were required to verify operational status of the communication links to the various subsystems, to enable debugging and to allow troubleshooting of the integrated systems.

AAI fulfilled those requirements by providing 9 major computer system software functional modules. **Operator interface modules** provide easy use of menu driven displays that allow command visibility, descriptive terminology and operator prompts. A status window, located in the lower portion of the screen, displays any messages in understandable phrases. **Configuration file processing modules** are text files that contain parameters that need to be changed often by the operator. **Robot**

communication module software provides sophisticated real-time target tracking robot position motion command functions that allow for direct control of all 6 axes of the robot arm's velocity, orientation and position. **Vision system communication modules** support a master/slave relationship with the MicroVAX being the master and the vision subsystem the slave. **Programmable process controller communication modules** allow individual data items as well as groups (data sets) of functionally similar items to be transferred to/from the MicroVAX. **Simulation modules** provide performance data (obtained during any target tracking experiment) which can be archived onto the MicroVAX disk and transferred ("played back") to the color graphics display subsystem through the programmable controller subsystem. **Exception handling modules** enable the operator to immediately determine the cause of an exception and to take the appropriate action. All error conditions are displayed in the system status window through the use of simple, readable messages. **Diagnostic modules** aid the operator in identifying hardware problems and in monitoring system performance. **Closed-loop control modules** provide real-time 2-D tracking control of the robot arm using coordination between the MicroVAX, vision subsystem, and robot controller.

PROGRAMMABLE PROCESS CONTROLLER

The NASA specification identified the need for a **dedicated control processor** with flexible programming and ease of expansion. AAI determined that a Programmable Process Controller (PPC) would provide a cost effective solution to work cell integration while offloading the supervisory computer for more time critical tasks such as interfacing the robot and vision control systems. Sensors need to be interfaced directly to the MicroVAX's Q-bus only in time critical situations. The PPC can incur all the overhead involved in processing I/O signals and can transfer only exception data or requested application display information to the MicroVAX. Work cells will be interfaced to the robotic systems through the PPC to provide closed loop control of each test apparatus. Overall systems display information will be processed by the PPC to a "slave" color graphics display system.

PROGRAMMABLE PROCESS CONTROLLER SOFTWARE

The only **application** program requirements specified by NASA, were to receive data from the MicroVAX and transfer it to the color graphics display system. The application software developed to support the RADL color graphics display was separated into functional modules, generated on the MasterAid, implemented on the MasterPiece PPC and displayed on the color graphics CRT. Data sets were defined to group similar types of information onto one screen for quick access, straightforward clarification, and for an overview of the latest configuration of control parameters. The programs provide the following displays. A **tracking grid display** reads previously recorded tracking error data and robot arm positions, and dynamically replays this data onto a multi-colored grid to depict tracking error. Scaling is variable and grid areas are dynamically highlighted to illustrate the difference between camera position and target location. A **robot status display** provides a graphic representation of the robot's current position on the track. It also provides robot controller status information such as the positions of the robot axes, the robot's operating mode, robot programming information and diagnostic data. **Data set displays** provide information concerning the system's serial **communication parameters** between the MicroVAX, robot, vision and programmable process controller. Other **data set displays** provide information concerning current **closed loop control parameters** of both the robot and vision systems.

REAL-TIME TARGET TRACKING CONTROLLER

The NASA specification emphasized the importance of this subsystem to provide rapid and precise control of the robot arm. It was required that the system be a real-time servo loop consisting of a small solid state camera, mounted on the robot's end-effector, which views a docking target and uses centroid error signals to process command signals to servo controls in order to make the end of the arm track a moving mechanism. After identification of the target, the vision control system will only involve processing of target tracking errors. This simplification, together with simplified centroid or **equivalent target location** calculations, will eliminate much of the arithmetic and the discrimination operations which slow down most "vision-control" systems, to enable it to provide "real-time" position control. After the end-effector is "locked" onto the target, distances and angles will be determined by either the vision control subsystem or later augmented by NASA developed photo-optical, laser or tactile devices; and integrated with the Target Tracking Controller and the Arm Controller, through the Computer/Controller, to initiate final insertion sequences. The solution was to obtain a low cost system that provided the **necessary tools** to determine the distance, tolerance and compliance capabilities required for the design of remote umbilical mechanisms. NASA also plans to use the system to provide a **technology base** for future development of advanced tracking control capabilities for other applications.

TRACKING SYSTEM COMPUTER

AAI selected the **Motorola System 1000** as the vision system computer interfacing a DATACUBE image processing board set. The vision system is supported by the Motorola VERSAdos operating system: a real-time, multiuser, multitasking operating system with features necessary for the support of the image processing boards. These features provide servicing of directly connected interrupts, intertask communication, system utilities, memory allocation and task management services.

IMAGE PROCESSING HARDWARE

The RADL vision system uses four boards selected from the **DATACUBE MaxVideo** line of image processing products. They use a pipeline design approach providing a high performance image processing capability with the flexibility to accommodate more modules without impacting the capability to process images at the scan rate of the camera. The initial image processing configuration uses the following hardware/firmware boards: an **image digitizing board**, a **pipelined linear signal processing board**, a **feature extraction board**, and an **image storage board.**

TRACKING SYSTEM SOFTWARE

Firmware on the image processing boards was integrated with Motorola based software modules developed to control and monitor target tracking tasks. Their modularity allows them to be used later in different combinations for future image processing tasks. The tracking system modules provide the following functions. **System initiation modules** allocate shared memory blocks for intertask communication and starts the other vision system tasks. **Command processing modules** examine commands received from the operator's terminal. **Vision system communication modules** implement system protocol with the MicroVAX. **Target tracking modules** determine the location of significant edges and determine the centroid of the edges.

SOLID STATE CAMERA

A Charged Coupled Device (CCD) camera was provided with software offsets to enable remounting on various end-effector devices.

CONTROL DISPLAY GRAPHICS

The RADL control room houses all computer control equipment with the control and monitor (C&M) devices positioned along a 5 meter picture window overlooking the robotic test area. Devices available there are the MasterAid C&M CRT for the PPC, a TV monitor for display of camera and tracking system data, a DEC VT220 terminal for online C&M of the MicroVAX and tracking vision systems, and a smart color terminal. NASA has added a DEC VT240 terminal for offline programming of the vision system and is installing control panels for work cell integration and a remote video display C&M panel. The various CRT terminals provide a **"bird's-eye view"** for programming and troubleshooting of both the supervisory MicroVAX computer, the Motorola vision computer and the programmable process controller. The smart color terminal is an interactive, high speed, color graphics CRT which provides operating personnel with **real-time status of the processes** under their control.

ONGOING RESEARCH IN THE RADL

The integrated RADL system **provides an easy to use testbed for NASA sensor integration experiments** and successfully fulfilling its initial target tracking requirement. Advanced target tracking development is in progress concerning the mating of umbilicals used during space vehicle launch. Studies are underway to use the laboratory's capabilities to **enhance the safety, productivity and efficiency of KSC facilities** for Shuttle and Space Station ground processing operations.

VISION SYSTEM UPGRADES

For the delivered system, the robot must be positioned so that the target is entirely within the field of view for the tracking function to perform. Target identification or object recognition is not performed, and orientation control is not provided; but the capability is available within the integrated systems. **Future system expansion** to provide these capabilities is presently in progress. New boards will provide real-time determination of the centroid of multiple targets and will allow discrimination between many different targets. Software is currently being developed to utilize 4 dots to determine position, distance and orientation. This will enable **upgrade** from 2-D **to 6-D tracking** control. 3-D tracking has recently been implemented by NASA engineers using the existing hardware and software.

FORCE-TORQUE SENSOR UPGRADES

We are also working to develop force-torque sensor techniques and control algorithms to provide tracking servo control of the RADL robot after docking an umbilical with its moving target. Note that before docking, the system has to use vision techniques; after docking, the target does not move relative to the vision system on the robot, therefore it is **necessary to switch from non-contact vision control to force tactile control** in order to maintain tracking. In effect, the target will then lead the robot "around by the nose" with slight forces and not impart any unnecessary loads to the target vehicle. Integration of tactile and depth sensors with the vision system is also necessary to effect mate techniques. Vision and force control may momentarily work together or may need to be switched right after latching has occurred. Dr. Rees Fullmer, from Iowa State University, is working this summer at the RADL with the Robotic Development Team to develop control techniques and to devise generic tests to determine which of these strategies is best for our application.

EXISTING KSC APPLICATIONS

Robotic work cell development applications at KSC are currently focused on tracking and docking development, remote umbilical plate mate/demate, large connector/QD development, hazardous panel operations and end-effector/gripper development. Florida Institute of Technology is performing **end-effector research** based on previous NASA concepts developed at Langley Research Center and at Marshall Space Flight Center, as well as some innovative concepts of their own. Automated Dynamics Corporation has a contract to develop a computer controlled "Universal End-effector with Torque Feedback" for the operation of hand valves in hazardous environments. NASA is working with scientists at the Controlled Ecological Life Support System facility at KSC to **develop robotic techniques** for Plant Growth Chamber automation which may eventually aid extraterrestrial crop production.

ROBOTIC APPLICATIONS UNDER REVIEW

Studies on hazardous, time critical and labor intensive problems peculiar to KSC are being conducted for several applications. **Automation and robotics studies** are being performed on Space Station ground processing facilities. The use of **mobile robotics** for security, fire fighting and hazardous spill operations is being investigated. Robotic techniques to improve "Shuttle Orbiter **payload inspection** and closeout verification" (operations involving possible damage to payloads with expensive "return from Pad" consequences) are being investigated. Non-destructive test sensors, vision systems and various kinds of distance ranging sensor systems can be integrated with the RADL systems to develop the **prototype concepts for integrating robot parameters with large data based graphics** and **artificial intelligence** (AI) **software** systems. For instance, the RADL robot can position a sensor with precise accuracy, report that position and orientation, provide distance sensory data and integrate machine vision "electronic photographs" with graphics and AI software to furnish computer printouts providing automatic sizing and highlighting of exception data. This type of system is being proposed for a number of possible projects such as **nondestructive testing** for Solid Rocket Booster joint and seal verification, Shuttle Orbiter radiator **damage inspection,** Orbiter tile damage/debonding assessment and Orbiter **contour measurements.** The manual methods employed presently in these operations are very labor intensive and produce expensive serial-time flow problems.

SIGNIFICANCE

Implementation of the computer hardware and software systems in the Robotic Applications Development Laboratory system at KSC is for the **development and application of advanced robotic control technology.**

KSC not only launches spacecraft, but services these spacecraft on the ground: designing the support equipment, launch accessories and computer hardware/software for ground spacecraft servicing. Several of the technologies undergoing development in the RADL have similarities to **autonomous control, docking** and **refueling** tasks being developed for Space Station and satellite servicing applications.

Large operational cost savings are possible through the integration of advanced technologies for ground processing operations such as Orbiter tile and radiator damage assessment (as described above in ROBOTIC APPLICATIONS UNDER REVIEW). The **RADL** is an **ideal test-bed** where the government can work with private and aerospace contractors to establish the feasibility of these cost saving approaches.