N89-10103

ABSTRACT

KSC has implemented an **integrated system** that coordinates state-of-the-art robotic subsystems. It is a sensor based real-time robotic control system performing operations beyond the capability of an off-the-shelf robot. The integrated system provides real-time **closed loop adaptive path control** of position and orientation of all six axes of a large robot; enables the implementation of a highly configurable, expandable **testbed for sensor system development**; and makes several smart distributed control subsystems (robot arm controller, process controller, graphics display and vision tracking) appear as intelligent peripherals to a supervisory computer coordinating the overall system.

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 design for the Space Station and other future spacecraft is moving toward the use of robotics for operational, maintenance and repair functions while the systems are 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 reconnect 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 reconnect, 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. Therfore, a Robotics Development Team was established at KSC 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 at KSC 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 can take place to develop 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/payloads. Some of these ground operational enhancements could also be applied to space operational systems.

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 requirements of:

(1) providing real-time closed loop adaptive path control of position and orientation of all six axes of a large heavy lift (90 kilogram) robot,

(2) providing a sensor based testbed,

(3) coordinating and integrating state-of-the-art robotic subsystems through the use of a reconfigurable/expandable control and monitor system, and

(4) allowing 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. (New Berlin, Wisconsin and White Plains, New York) in conjunction with Adaptive Automation, Inc. (South Windsor, Connecticut). 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:

(1) exceed performance requirements,

(2) ensure that it would not become outdated by virtue of obsolete technology by allowing future performance capabilities to be added to the system as new technology becomes available; and

(3) use structured software modular techniques, allowing efficient and easy integration of new sensor technology.

In order to aid the systems developer in the formulation of his proposal, the KSC specification not only pointed out the type of robotic equipment NASA intended to procure, but informed him of the overall development plan for the use of the prototype equipment. The plan (Refer to Figure 1) was to **procure "off-the-shelf"** state-of-the-art robotic hardware and "intelligent" feedback control systems and to marry this hardware and software **with KSC developed work cells** incorporating sonic, infrared and tactile feedback sensors, optical transmission devices, hypergolic and cryogenic fluid couplings, and various end-effector gripper devices. It was later decided that vision control for "lines" management would not be done with an object recognition system, but would use standard KSC camera systems to enable an operator to monitor and safe the system in case of entanglement of cryogenic or electrical lines.

As delivered, Item I hardware (**Industrial Robot Arm Control**) consists of a heavy lift, servo controlled robot arm mounted on a 30 foot track, an arm controller, a teach pendant, special maintenance tools, and grippers. An identical set of Item I equipment, minus the track, was delivered to the subcontractor, Adaptive Automation, as a rental unit to allow them to perform software developmental integration

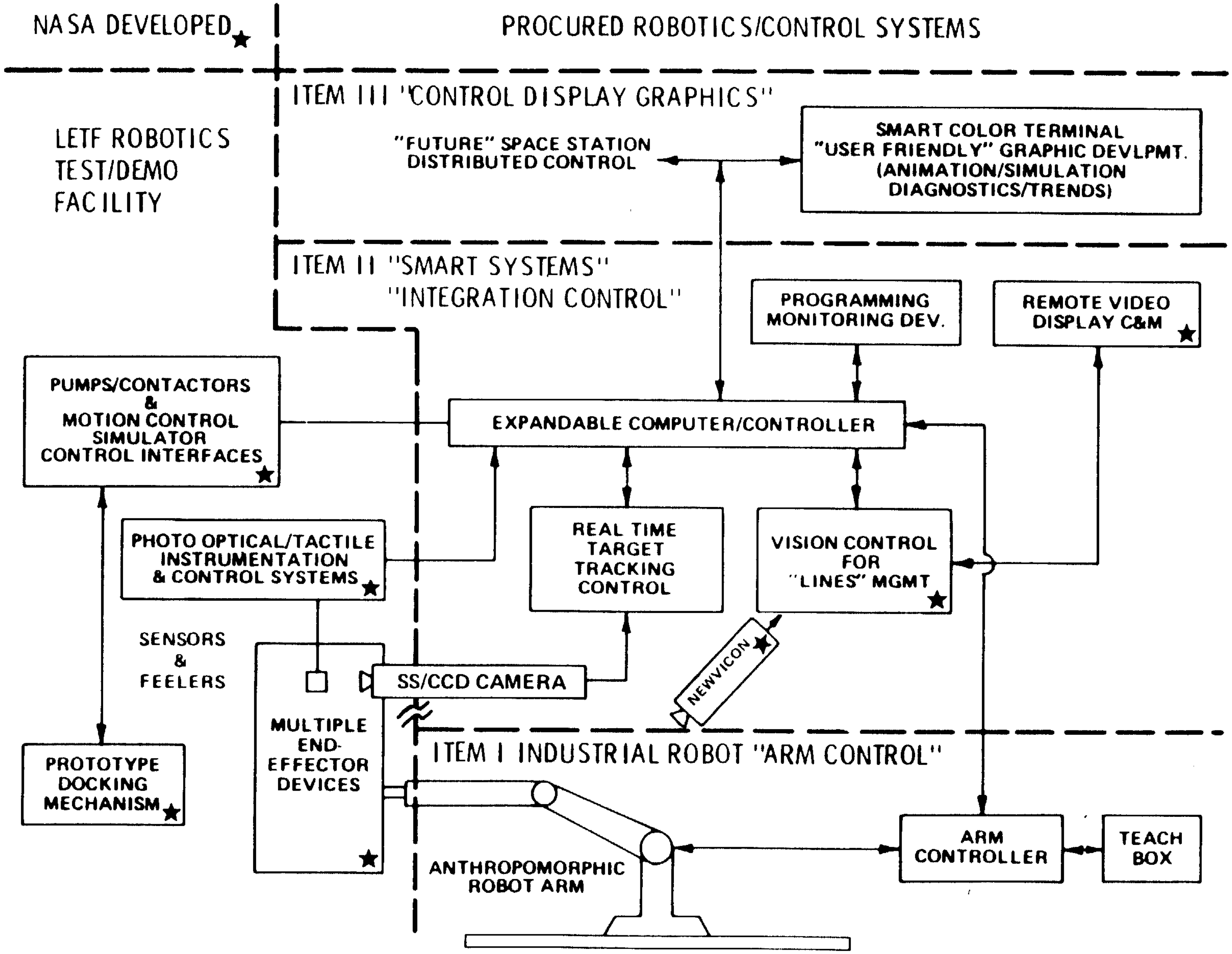
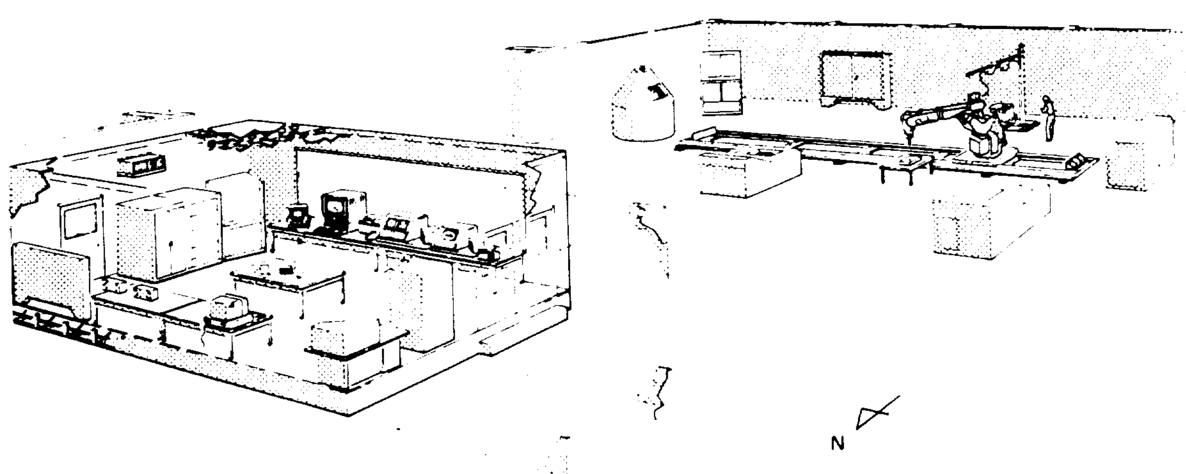


FIGURE 1. SYSTEM CONCEPT

with Item II & III equipment while simultaneously allowing NASA to gain valuable experience with the robot prior to delivery of the overall system. Item II hardware (**Smart Systems Integration**) consists of a solid state camera, a vision processor, a programmable process controller, software maintenance terminals, and a MicroVAX Supermicrocomputer. Item III hardware (**Control Display Graphics**) consists of a smart color terminal, an alarm/report message printer, and a video hardcopy color printer.

All equipment was installed at KSC prior to acceptance testing. Training on Item I equipment took place at the factory in New Berlin in December 1985. Also that month, the robot arm, track and robot controller were delivered to the Kennedy Space Center in Florida, but not installed into a high bay of the Launch Equipment Test Facility (LETF) until January 1986. Hazardous work on the Space Telescope Transporter preempted the high bay delaying acceptance testing and preliminary utilization of the stand-alone robot for several months. The Smart Systems Integration computer/controller and the Control Display Graphics equipment was delivered in September, 1986. During September and October, Items II & III equipment underwent installation into a control room built by NASA, acceptance testing was performed on the total integrated control systems, and training of NASA engineers and support contractor personnel was completed.

The area in the high bay of the LETF where the Robotic Development Prototype System was installed is now know as the **Robotics Applications Development Laboratory** (**RADL**). Refer to Figure 2.



Robotics Applications Development Laboratory (RADL)

Figure 2

The RADL is unique in that:

(1) a large robot 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;

(2) the robot is **integrated** through a computer and software system **to several smart distributed control subsystems**:

(A) vision controller for tracking,
(B) process controller for work cell integration and
(C) a smart graphics display terminal for coordination of the overall network; and

(3) the laboratory **permits sophisticated control algorithms and signal processing techniques** to be applied to sensor information processing, allowing for applications that currently can not 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 robotics engineers increases, and as application requirements dictate, the capabilities of the laboratory will be increased to include equipment for three dimensional scanning, higher order image processing, artificial intelligence, sonic, laser and other ranging systems, tactile systems, and mobility systems.

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." We are not discussing "adaptivity" which concerns the control dynamics of a robot arm relative to different weights being handled. 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. For instance, the MicroVAX provides the computing power required for the sensor processing and the interfacing hardware expandability necessary for future requirements; the Programmable Process Controller provides the present need for 248 analog and digital I/O signals and has I/O expansion capacity of over 1,000 signals; and the Vision System contains state-of-the-art computerized tracking system hardware, readily expandable for future development needs.

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 functioning of the communication procedures 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 acomplish 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 or replacement to 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. It is capable of lifting 90 kilograms and holding it 3,000 mm from its base having a repeatability of 1 mm under constant operational conditions at maximum reach and load over a large working range. All arm joints (axes) are actuated by direct current servo motor drives with closed loop feedback control through resolvers and tachogenerators. The robot is moved using simple hand motions, plain dialogue and self-instructing commands through a joystick mounted on a programmable function panel (teach pendant). The processor controls are a Motorola 68000 based system incorporating both American and Swedish technology. An extended 21K RAM memory is backed up by floppy disk and a battery providing 400 hours of memory storage. The robot controller comes with a standard adaptive control function which provides control (in local tool reference frame) of tool position only (orientation can not be controlled). The adaptive control can only operate with three analog or digital signals simultaneously. This is not enough capability for 6 dimensional (3 directions and 3 orientations) adaptive control of a sensory development testbed. However, the robot has the capability to have all 6 axes controlled from an external computer. Therefore, the robot controller's optional "external computer link software" was used to implement the task of communicating with the MicroVAX to provide the extra 3 degrees of freedom necessary to incorporate advanced docking stratagies being developed by NASA at the RADL (Refer to Figure 3).

Figure 3

The use of an **off-the-shelf** robot/controller with an integrated computer control system provides several advantages:

(1) **Development time and money is reduced** by not having to specify and build a specially designed robot to act as a tracking mechanism.

(2) The robot controller can perform kinematic/dynamic matrix transformations using its internal processor capability and thereby **free up the MicroVAX computer for supervisory tasks.**

(3) 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 track was subcontracted to ESAB North America Robotic Welding Division in Fort Collins, Colorado. 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. Sensors will be used along the track as inputs to the integrated control sytem to define areas where obstacles must be avoided. Also, if there is a problem with one experiment, the robot can simply be moved along its track to another work station. This flexibility increases its efficency and eliminates the necessity of purchasing additional robots for each developmental project. Since the smart systems computers enable adaptive control of position, velocity and orientation of all six axes, the robot can be made to simulate a spherical or cartesian robot. NASA can determine tolerances required, robot characteristics, and control system strategies necessary for a prototype system prior to releasing a specification for an aerospace application, therefore, saving time and money.

SMART SYSTEMS INTEGRATION

The integrated computer hardware and software subsystems were specified as 2 basic blocks: a "Computer/Controller" (or a combination) and a "Real-time Target Tracking Controller." They were to allow servo control, tracking, and feedback mechanisms integration providing the capability for:

(1) **supervisory coordination** of various "smart control systems,"

(2) **I/O hardware interfaces** for integration of work cells that NASA will implement to control peculiar tasks such as prototype docking motion control simulation mechanisms, and

(3) "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 Digital Equipment Corporation (DEC) MicroVAX II supermicrocomputer 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. The delivered system provided a baseline capability to demonstrate the functioning of target tracking. NASA is currently upgrading the hardware and software for advanced tracking development.

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** configured with a 70 Mb hard disk, 2 Mb of RAM memory, a 95 Mb tape unit and a Q-bus with 9 serial ports and one parallel port. The system was configured with the Micro VMS operating system because it provided the best combination of supporting a multiple user and a multiple process environment, while providing relatively good real time response. All software was developed in the VAX C programming language because it supports a structured, high-level programming environment while providing low-level "bit manipulation" necessary for control. This hardware/software combination offers a wide range of potential product enhancements, meets stringent throughput requirements and provides a system that can be easily documented and maintained.

SYSTEMS INTEGRATION SOFTWARE

Software for operation, demonstration and acceptance testing of the integrated systems was required 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:

(1) **Operator interface modules** provide easy of use 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.

(2) **Configuration file processing modules** contain parameters that need to be changed often by the operator. These modules reside in the MicroVAX and allow both flexibility and ease of operation. There are several parameter files including robot, vision, closed loop control, programmable controller, and graphic display parameters. They are extremely "user friendly" "text" files and can be read, printed, rearranged and easily modified.

(3) **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. To ensure that the robot controller is never waiting for a motion command from the MicroVAX, a second command is transferred to the robot controller before the motion of the current command has been completed. A specially developed math library allows sensor positional information to be transformed into a "quaternion" representation for use by the ASEA robot controller. Also provided are robot communication functions for operator tasks such as upload of robot programs from the robot controller, download of robot programs from the computer, change of the current robot mode, synchronization of the robot and monitoring of robot status.

(4) **Vision system communication modules** support a master/slave relationship with the MicroVAX being the master and the vision subsystem the slave. These modules maximize the throughput rate by minimizing the length of commands and responses, ensure data integrity through parity and checksum techniques and allow for expansion of vision functions.

(5) **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. The communication protocol is an ASCII protocol designed by ASEA.

(6) **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. The robot's position and current tracking error can be examined in more detail and viewed repeatedly in "simulation" mode.

(7) **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. Exception handling modules are separated by their causes and by their level of severity to ensure that errors are detected, correctly classified, and properly handled.

(8) **Diagnostic modules** aid the operator in identifying hardware problems and in monitoring system performance. An extensive set of diagnostic routines have been written to examine all communication between the MicroVAX and the other system components and to store normal/abnormal performance data for display.

(9) **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. The vision subsystem calculates target error information every 33 milliseconds, the MicroVAX closes the loop using PID (proportional, integral, and derivative) feedback and sends a new motion command to the robot approximately every 90 milliseconds. Algorithms in 6-D are presently being formulated to perform dynamic umbilical mate/demate.

PROGRAMMABLE PROCESS CONTROLLER

The NASA specification identified the need for a **dedicated control processor** with flexible programming and ease of expansion. It even identified the amount and type of I/O support required. 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 input/output (I/O) signals and can transfer only exception data or requested application display information to the MicroVAX.

AAI selected a **MasterPiece 280 PPC** manufactured by ASEA Industrial Systems (AIS). It is a Motorola 68000 based system (similar to a smart Programmable Logic Controller) providing logic control, process control, data handling, and PID functional capabilities. 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. The distributed control approach is evident in that the PPC will do what it can do best (process all input data and control routines efficiently within 50 milliseconds) and the graphics system will do what it can do best (process and display real-time performance data to a color screen), each system sharing duties and offloading processor functions from one another.

Programming of the MasterPiece is done using function blocks (a "higher level" programming method than relay ladder logic). Programming is accomplished by a **MasterAid 214** system which is a portable Motorola 68000 based system that has its own display screen, keyboard, and floppy disk drive. The MasterAid and associated printer is used during program execution to provide real-time display of the internal programs and for troubleshooting. It is used during program development for off-line design and debug.

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:

(1) A **tracking grid display** reads previously recorded tracking error information 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.

(2) 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.

(3) **Data set displays** provide information concerning the system's serial **communication parameters** between the MicroVAX, robot, vision and programmable process controller. The data set entries contain such information as baud rate, number of data bits, and port number.

(4) Other **data set displays** provide information concerning current **closed loop control parameters** of both the robot and vision systems. These data sets contains entries such as PID constants, robot scale factors, camera position, and the time period for the robot arm to move in its approach to the target.

NASA is developing more application programs to integrate new test cells as they come on-line.

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. The specification stated, "During docking tasks, the arm will be commanded to near full-extension and tracking-control processing will be initiated. Therefore, the servo loop will mostly involve wrist movements but may involve minor elbow movements. After identification of the target, the vision control system will only involve processing of target tracking errors. These simplifications, 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." Tracking performance tolerances were not specified since NASA intends to develop docking mechanism requirements. The solution was to obtain a low cost system that provided the **necessary tools** to determine the distance, tolerance and compliance capabilites required for the design of remote umbilical mechanisms. NASA also plans to use the system to provide a **technology base** for future developement of advanced tracking control capabilities for other applications.

Again, AAI satisfied requirements quite well by implementing the vision system with the highest power vision processing boards available at the time, interfacing them with a high performance computer, and developing general purpose modular software to support a real-time system while allowing the flexibility to support a wide range of future vision applications.

TRACKING SYSTEM COMPUTER

AAI selected the **Motorola System 1000** as the vision system computer interfacing a DATACUBE image processing board set through a VME bus. The System 1000 is configured with a Motorola 68010 10 MHz processor, a 15 Mb hard disk, a 512 Kb RAM memory, a 655 Kb floppy diskette, 3 serial ports, and 1 parallel port. 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 (30 images per second). The initial image processing configuration uses the following hardware/firmware boards:

(1) DIGIMAX - An **image digitizing board** performing A/D and D/A conversions at a 7.16 MHz rate from a standard RS-170 video signal. The analog input signal is software filter selectable and conditioned with programmable gain and offset circuitry. It provides graphics overlays, dynamic input multiplexing and transparent switching of Input and Output Look Up Tables.

(2) VFIR - A **pipelined linear signal processing board** for time critical processing at 144 million arithmetic operations per second. It performs a 3 X 3 convolution operator to the image to enhance its edges. A full frame of video data is processed in much less time than the 1/30th of a second it takes the camera to scan the image.

(3) FEATUREMAX - A **feature extraction board** that counts the number of occurrences of many different events and stores their x and y coordinates in a 64 Kb block of memory. The board also provides histogram recording of the locations of up to 16 K features. The feature extraction board receives the enhanced edge image and records the coordinates of every point in the image that has a value higher than a preset threshold value. The Motorola computer uses this data to calculate centroids by vector summing the xy coordinate pairs and dividing by the total number of pairs.

(4) FRAMESTORE - An **image storage board** containing 3 (384H x 512V pixel) frame storage buffers to hold digitized video images. It is used to provide a window (mask) which is gated with the data output from the pipelined linear signal processing board to reduce the "area of interest" processed by the feature extraction board. It also draws a cross hair on the operator's TV monitor to allow him to view what the vision system is calculating as the center of the target.

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:

(1) **System initiation modules** allocate shared memory blocks for intertask communication, allocates system queues to allow transfer of messages between tasks and loads/starts the other vision system tasks.

(2) **Command processing modules** examine commands received from the operator's terminal which can set vision system parameters and stop the target tracking task. They are essentially message processor modules invoking routines to initialize, request status, set/request parameters, start and stop target tracking and set the area of interest window.

(3) **Vision system communication modules** implement system protocol with the MicroVAX. AAI developed a protocol in which one MicroVAX command generates continuous vision system responses. This mode transfers target tracking coordinate information from the vision system to the supervisory computer. Termination can be by either the MicroVAX, the operator or a vision system error. An additional "window" command allows the MicroVAX to dynamically control the size of the camera view, as the distance from the camera to the target changes.

(4) **Target tracking modules** compute the spatial derivatives of the image, 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. Since target edge data is used to determine the location of the target, the camera is equipped with an auto-iris lens to provide compensation for variations in lighting. The vision system provides target location information in a plane perpendicular to the line of sight of the camera.

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 (Reference Figure 2) 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 video panel will provide black and white video displays and joystick control of 4 high-contrast cameras placed around the outside of the robot test area. A color stereo camera mounted on the shoulder of the robot will send color data to a 3-D monitor providing a display image for depth perception. 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 a focal point for demonstration purposes providing a **"big-picture" display** of the overall process.

SMART COLOR TERMINAL

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. It permits operator interaction in a timely and responsive manner through displays which include: process graphics with color coded status/control parameters, process diagnostics using color and blink for ease of interpretation, emergency and alarm conditions for fast corrective action, and exception data for real-time statistical analysis. The need for this device is to reduce the display software "intensity" of the various work cells and subsystems being controlled.

The color graphics display system chosen was the **MasterView 820** which is designed to interface with the MasterPiece PPC system. It is configured with a Motorola 68000 based processor, memory, floppy disk, 19" color display unit, color "frame-grabber" printer, battery backup and keyboards for operation and display generation. The MasterView system is specifically designed to provide user friendly graphics development for overall systems status, exception data, diagnostics, simulation and trend displays.

All software required to build and configure **user displays** is included with the system. The system includes a packet of standard displays which can be easily configured by the user: 6 overview displays containing 10 groups each with 10 objects, 60 group displays with 10 to 100 objects each, 7 types of object displays, 20 trend displays, 10 to 20 application specific displays and event and alarm lists. Special displays can be rapidly set up from a choice of preprogrammed items (pumps, valves, special symbols, etc.) or can be "drawn" by a person with little programming knowledge via the system's line drawing and text creation capabilities. AAI provided a tracking error demonstration program and other application displays (refer to PROGRAMMABLE PROCESS CONTROLLER SOFTWARE). NASA is providing display graphics in accordance with future work cell development.

ONGOING RESEARCH IN THE RADL

The integrated RADL system is **currently providing an easy to use testbed for NASA sensor integration experiments** and successfully fulfilling its initial target tracking requirement (Refer to Figure 4). Advanced target tracking development is in progress concerning the mating of umbilicals used during space vehicle launch. Programmatic 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 such 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. Newly developed image processing boards (for implementing real time large kernal operations) and enhanced software (for more robust, noise free, reliable edge detection) are being installed. At the same time, a faster processor (Motorola 68020) and a new VME backplane is being installed **to accommodate the latest special purpose hardware.** These 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.

EXISTING KSC APPLICATIONS

Two robots have been developed at KSC: a small pneumatic control robot to test Electronic Security System cards and an Electrostatic Robotic Test Cell (ERTC) to measure electrostatic charge retention on nonconductive materials. The ERTC was installed in an environmental test chamber at KSC and has increased measurement repeatability, accuracy and productivity in a program inspecting thousands of material samples.

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. A graduate student is working with NASA contractor personnel on the development of **orientation control algorithms** utilizing vision data based on changes to the shape of a circle. 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 been given a Small Business Innovation Contract to develop a computer controlled "Universal End-effector with Torque Feedback" for the operation of hand

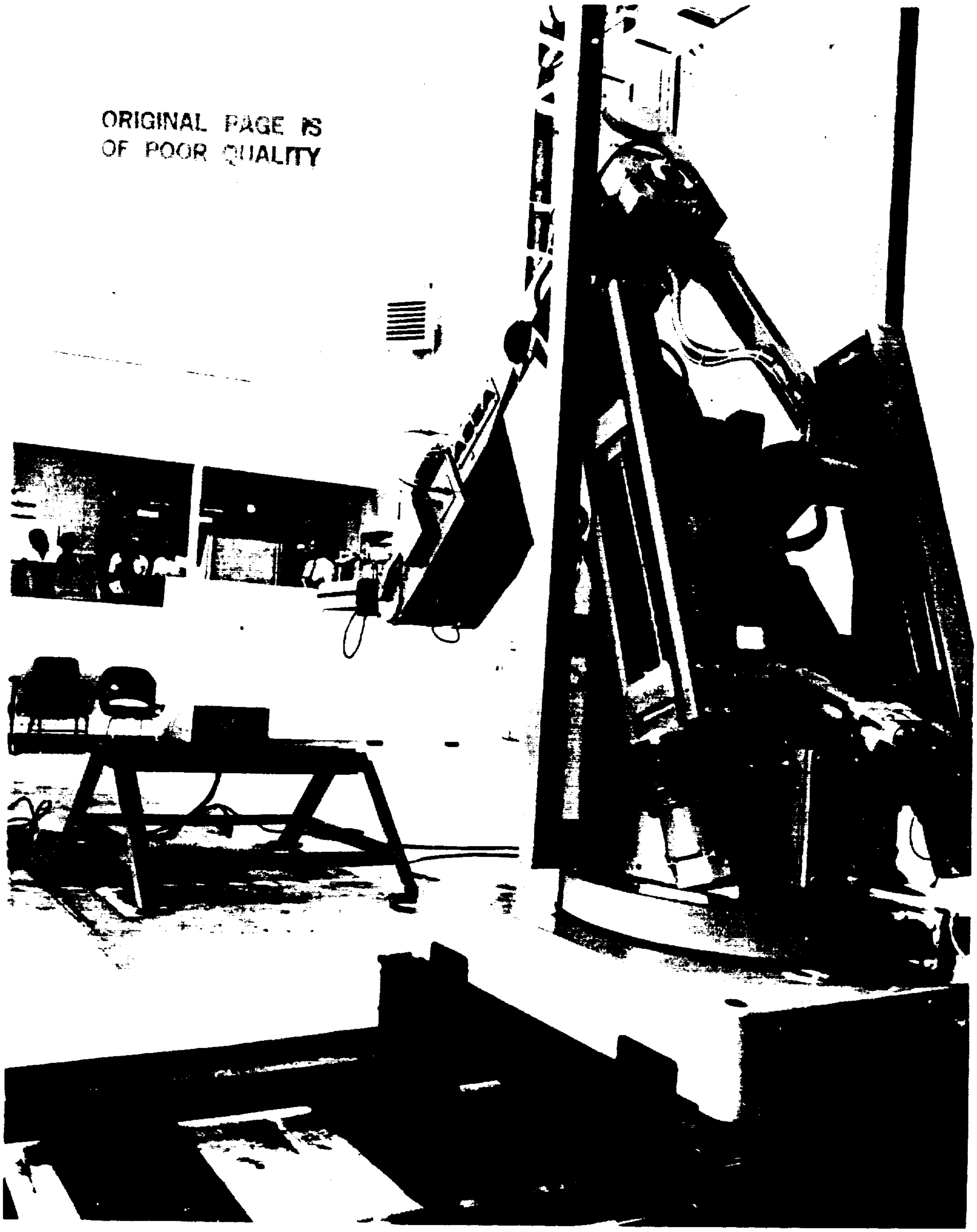


Figure 4

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.