CONF-970469--5 SAND96-2303C

A Sensor-Based Automation System for Handling Nuclear Materials

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SEP 26 1996
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Abstract

An automated system is being developed for handling large payloads of radioactive nuclear materials in an analytical laboratory. The automation system performs unpacking and repacking of payloads from shipping and storage containers, and delivery of the payloads to the stations in the laboratory. The system uses machine vision and force/torque sensing to provide sensor-based control of the automation system in order to enhance system safety, flexibility, and robustness, and achieve easy remote operation. The automation system also controls the operation of the laboratory measurement systems and the coordination of them with the robotic system. Particular attention has been given to system design features and analytical methods that provide an enhanced level of operational safety. Independent mechanical gripper interlock and tool release mechanisms were designed to prevent payload mishandling. An extensive Failure Modes and Effects Analysis of the automation system was developed as a safety design analysis tool.

Introduction

The Weigh And Leak check System (WALS) is being developed to provide an automated system for performing remote weighing and leak checking of radioactive nuclear materials at the Mason & Hanger - Pantex Plant, a U.S. Department of Energy (DOE) facility. The materials, known as pits, are approximately the size and shape of a standard bowling ball. The system is required to perform the automated handling tasks in an attended, structured environment, with human operator interaction. These operations consist of unpacking and repacking the pits from a variety of sizes and types of containers used for storage and shipment, and transporting the pits to stations within an analytical measurement laboratory for automated and manual measurements and inspections. The weighing and leak checking operations are performed periodically to assure product integrity, safety, and inventory. Sandia is responsible for development and integration of the robotic and automated equipment for the packing, unpacking, and handling of pits, and for the sensor-based control system for WALS. Pantex is responsible for development of the weigh and leak check analytical instrumentation.

A common application of automated handling systems is to relieve humans from hazardous material handling and heavy lifting . A primary goal of the WALS system is to eliminate as much as possible the manual handling of radioactive materials. This achieves the DOE goals of reducing operator exposure to radiation and minimizing the possibilities for human mishandling. Some additional important benefits are also realized from this automation system. Once a procedure has been validated for a particular pit type, the automated control system ensures continued enforcement of the qualified procedure. Automated data entry methods reduce the need for operator interaction. These both add benefit to the system by reducing two of the largest sources of process error. Also, automated recording of product parameters and process results greatly enhances the quality assurance of the operation.

DISCLAIMER

Several challenging requirements for WALS have driven the technical design choices. The product stream to be handled has significant variability in pit and container sizes, and in processing requirements. None of the packaging fixtures or containers was originally designed for automated handling. Since all of the containers were last packed by humans, there may be substantial variability in the packaged assembly due to operator or procedural differences. The system must be designed to allow manual operation of the analytical measurement systems for those cases where automation has not been developed or qualified. Operation of the automated system will require some manual involvement, but to minimize operator training requirements, the system should direct and control these manual operations. Thus, ease of operator interaction, intuitive behaviors, and computer-guided instructions are important design considerations. The system must have the flexibility to allow frequent minor changes in process procedure and the expandability to include additional products in the future. Yet, the required software qualification, testing, and review procedures will prevent frequent software changes. Finally, a fundamental requirement on the system is the overall safety of the system for handling these extremely valuable and hazardous payloads. The design must provide measures to ensure that tools and payloads cannot be mishandled.

This paper will describe the WALS system design, focusing attention on the automation and robotics system. Software tools and approaches used for programming and development of the automation system are described. Many of the safety features and methods that are not normally employed in automated systems will be discussed.

System Description

The WALS system employs a commercial robot manipulator on a linear track, an interactive machine vision system, and force-controlled robotic motions to perform the required operations. Several custom tools were developed for handling the required materials in the workcell. Generally, the system was designed to automate those operations that cause relatively high radiation exposure to people, and to use human operators to accomplish low-dose, difficult-to-automate operations where the cost/benefit tradeoff is less attractive.

The layout of the robotic workcell is shown in Figure 1. The workcell was modeled and operations simulated using the IGRIP Robot Simulation environment. The robot manipulator is a six-axis, 20 kg payload device (Model S-700, Fanuc Robotics of North America), mounted on a 7.5 m linear track. The linear workcell layout was chosen to accommodate the large number of stations, allow expansion for future devices, and meet the maintenance and separation requirements for the weigh and leak check stations. Gripper, tool, and parts storage stations on both sides of the track are accessible to the robot. The containers to be unpacked and repacked are positioned on the floor next to the robot's path of travel on the track. No floor chocks or static fixtures are required for locating the containers in the cell.

The robot end-of-arm tooling is shown in Figure 2. The tooling components consist of a six-axis force/torque sensor, a pneumatic safety clutch, a pneumatic tool change adapter, and a video camera used for computer vision operations and video monitoring. Custom grippers and tools have been designed to meet the needs of individual payloads; the tool changer is used to make the multiple tool changes required during operation. Figure 2 also shows a typical container/fixture/payload configuration used in WALS.

The fixture assembly and disassembly station (ADS) was designed to work in conjunction with the robot to manipulate the fixture components in order to extract the bare pit from, and reinstall the bare pit into, the packing fixture. At the ADS, the robot delivers and removes the payload and fixture components, and operates a pneumatic torque wrench for the bolting operations. The ADS uses pneumatic actuators and single axis stages to hold the fixture in place during bolting, and to control the position of the components and bolts during reassembly of a fixture around a pit. A critical operation during reassembly requires telerobotic guidance of the robot motion to place a fixture component around the pit. Multiple cameras are used to assist as the component is guided into place by the operator's motion directions, subject to velocity and distance constraints imposed by the control system.

The control system is separated into two physical locations. The VME real-time control system communicates directly with the robot controller, monitors the numerous input sensors, and operates the various output actuators used in the cell. This controller is located in the workcell, along with a networked terminal for barcode data entry and display of workcell setup instructions. The supervisory control system is located in a console inside a remote control room. Closed-circuit video monitors and a shielded glass window provide visual access into the workcell for the control room operators during automated handling.

The block diagram in Figure 3 shows the components of the control and automation system. The primary user interface in the control room is a UNIX workstation (Sun Microsystems Sparc20) that also functions as the supervisory control computer for the system. The machine vision operations that extract geometric features and dimensions from video images are also performed on this computer. The vision system uses several workcell cameras, a programmable video switcher, and image capture hardware resident in the workstation. A magnetic stripe and barcode badge reader system is also interfaced to this primary user interface. This workstation is networked to five additional computers in order to control the workcell operations. Three of these are separate PCs that independently control the weigh and two leak check subsystems.

The real-time workcell control computer is based on the VMEbus architecture, and operates under the VxWorks multi-tasking real-time operating system. WALS uses two real-time CPUs based on the Motorola 68030 (Force Computers Model 30 and 33) in the VMEbus to perform force/torque sensor data processing and control the nearly two hundred workcell input/output devices. This VME system also performs the serial command interaction with the Fanuc robot controller (Model R-J) that runs the Karel robot program language. The distributed nature of the computing architecture, the demand for real-time access, and the need for the multi-tasking behavior of VxWorks and UNIX are all driven by the needs to service the sensory requirements of the system (such as force-sensing and vision), which are ultimately driven by the system requirements for safety, flexibility, and versatility.

Programming for the VME and UNIX systems is done in C++. Modern graphical user interfaces are employed throughout for direct operator interaction. The software architecture of WALS is shown in Figure 4. Up to three pits are processed asynchronously under control of the three pit task schedulers (PTSs). Each PTS performs the required operations on an individual pit by directing the actions of the system through commands to the various server modules. Each PTS is able to adapt to the specific pit type by accessing pit type information in a configuration file.

The system uses a commercial relational database engine for logging system activity. The log database is divided into a system log used for reporting operational events, and a diagnostic log for recording lower level system activity that is useful for diagnosing system problems after they have occurred. The WALS primary user interface offers access to a graphical user interface for querying the log database during system operation.

The relational database system is also used for maintaining a robot database that is used for managing robot motion via stations, points, and paths. A robot path editor (RPE) was developed for UNIX platforms that allows uploading of Karel robot points and paths from the teach pendant, editing on a workstation, storage in the database, and downloading back to the robot controller. The editor extends the capability of the robot by providing developers with the ability to embed the control parameters used for reactive and compliant force-controlled motions into the native robot controller's paths.

Each workcell station contains a toolplate mounted to its structure. All robot paths for that station are relative to the coordinate frame defined by the toolplate. Methods were developed that allow the robot system to mate automatically to the toolplate, under force control, with sufficient repeatability for updating the location of a station. This method offers an easy-to-use method for operators to verify and modify station positions, as needed, without the need for an extensive robotics background and training.

Process Description

The WALS automation and robotics system performs the operations of pit unpacking, packing, and transfer among the measurement subsystems. Prior to system operation, an operator delivers up to three pits into the workcell for subsequent automated operations. Each pit is held inside an assembled shipping fixture that is housed in the external container. The operator uses a barcode system and a graphical user interface on the WALS supervisory control computer to identify the pits and containers, schedule the operations to be performed, and initiate the operations. The operators perform some preliminary container unpacking operations, such as label and seal removal, and radiation sampling. Prior to leaving the workcell area, the operators also load output fixture stations with components for later assembly.

The WALS machine vision system uses a camera mounted on the robot end-effector to confirm the container type based on its measured dimensions and to locate the fixtured pit within the container for subsequent robot handling operations. The robot begins the unpacking operations by removing the fixtured pit from the container and aligning the shipping fixture with the system tooling. The machine vision system is used to locate specific fixture features but also to allow operator interaction for process confirmation and help with difficult configurations. A manual inspection station is available where the pit and fixture may be inspected or manipulated by the operator in cases where automated operations are not practical, such as for tape removal or identification of stamps. The robot works together with the ADS to unbolt the fixture and separate its components. Following disassembly of the fixture, the pit is returned to the manual operation station for any required cleaning and radiation monitoring. Finally, the pit is moved to the weigh and leak check subsystems and to staging locations. The WALS automation system coordinates and directs the operations of these subsystems that perform the measurement and data analysis, but allows the subsystems to retain their full operational autonomy. Following the measurements, the automated system repackages the pits into new fixtures and staging/shipping containers. The system programming is designed to allow operator intervention in the process for pit inspection and cleaning in the event that an analytical measurement results in an unsuccessful test.

System Safety Considerations

Because the WALS robotic system will handle material that is both hazardous and valuable, the safety of the operations is of utmost importance; assurance must be given that personnel will not be harmed and that the materials and environment will be protected. The primary robotic safety issues are related to the need to handle the materials safely by preventing uncontrolled robot motions or dropping of payloads during handling. Safety is implemented through system design, mechanical design, and integration of safe practices into control software. Sensors are integrated into the system to provide information to the control system about the state of the workplace environment. Mechanical tool interlocks are used to provide independent safety mechanisms. The fundamental approach is to provide additional information to the software control system in order to make intelligent decisions for safely handling these hazardous materials, but ultimately, to provide mechanical and electrical means to ensure safe operation without reliance on software. Additional details of the system's safety features may be found in Reference [1].

The force/torque sensor connected to a computer is used in several ways to enhance safe operation of the system. First, the force/torque sensor is used to verify expected forces and moments when a payload is picked up but before the robot moves away from the pickup location. Second, the force/torque readings can be used to control the robot directly and modify its motion in real-time [2]. Two methods are used. In the *reaction* mode, software monitors the sensor readings to *stop* a controlled robot motion when a specific set of force/torque values is achieved. This mode is typically used to signal completion of a movement that places a tool or payload. In the *compliance* mode, software is used to *adjust* the robot motion in continuous response to the sensor readings. This mode is frequently used for precisely positioning a payload into a specific location by "feeling" the forces encountered during the placement. Finally, an additional, independent computer in the VMEbus system is used to monitor the force/torque sensor and trigger the robot's emergency stop (E-stop) circuit if force/torque limits are exceeded during robot motion in the workspace. Thus, if the robot control system failed, force/torque sensing can still stop the robot's motion through the primary E-stop circuitry.

WALS is designed with an electrical interlock circuit that prevents activation of the pneumatic tool release mechanism unless every tool is in its proper storage location in the workcell. This prevents an inadvertent air system activation from causing a release of a tool. Each tool has a unique electrical identification code that is interrogated by software when the tool is initially picked up.

An important safety requirement is to prevent a spurious or inadvertent electrical signal, or a software or computer error, from opening a gripper and releasing the payload at an incorrect location. In WALS, every gripper that handles pits is equipped with a mechanical latch mechanism that physically prevents the gripper from opening except at particular locations where the part may be released safely. These locations in the workcell have a cooperating mechanism that releases the mechanical safety latch; the release is activated either by a software command or as a result of the mechanical positioning of the gripper at the location. In this way, spurious signals or inadvertent computer commands to open the gripper cannot cause an unsafe action. Also, the pneumatic actuation of the gripper system is designed so that the payload is held in the case of a loss of air pressure or electrical power.

Although WALS contains multiple layers of safety features that are independent of software, the system is fundamentally controlled by software, and thus software is involved in various safety-related features of the system. A rigorous software development methodology was used to help ensure reliable and safe operation. The software was developed using a standard software engineering process with requirements definition, design, implementation, and testing phases. Each phase included a verification component to identify and correct defects as early as possible. Formal inspections were performed on documents and software components. During the formal inspections, strict attention was paid to safety-related issues and concerns. At the inspections and throughout all software development activities, decisions were made with careful considerations regarding the impact on system and software safety. Configuration management methods were used throughout to ensure proper software operation.

The system contains an independent software process that is responsible for monitoring various safety-related aspects of the system and generating a robot E-stop if an unsafe condition is detected. As discussed earlier, this process monitors real-time force and torque data from the robot's sensor. The process also monitors robot gripper activity (i.e., get, put, open, and close) in order to detect and report the activation of electrical and mechanical devices associated with grippers. To ensure that the system cannot operate without the safety monitoring process, a hardware-based watchdog timer is used that will stop the robot if the software process is not operating.

The system designers have worked with risk assessment analysts at Sandia to develop an extensive Failure Modes and Effects Analysis (FMEA) for WALS [3,4]. The process of developing an FMEA involves determining possible failures of the system (failure modes) and the responses (effects) of the system to each of the failures. For each failure mode, the failure mechanisms are determined. Then for each failure mechanism, appropriate detection and compensation schemes are identified. Next, the failure effect is noted. Then a hazard level is assigned based on a qualitative estimate of the likelihood that the failure will occur as well as the severity of the consequences of the failure. The process of determining failure mechanism, detection, compensation, and effect is repeated for each failure mode and involves significant effort and cooperation between the project team and the analysts. When completely developed, the FMEA provides a very detailed picture of the safety features of the system and can point out areas of weakness in the safety design as well as areas where unnecessary redundancy may reduce the system reliability.

Summary

The WALS automated system is being developed for handling large payloads of radioactive nuclear materials in an analytical laboratory. The automation system performs unpacking and repacking of payloads from shipping and storage containers, and delivery of the payloads to the stations in the laboratory. The system uses machine vision and force/torque sensing to provide sensor-based control of the automation system in order to enhance system safety and achieve easy remote operation. Through a combination of extensive design analysis, independent mechanical interlocks, redundant computer monitoring, advanced sensor integration, and rigorous software engineering methods, the system should provide an enhanced level of operational safety.

The automated system will perform the automated handling tasks in an attended, structured environment, with human operator interaction. Use of the system will reduce operator exposure to radiation, eliminate heavy lifting, and minimize the possibilities for human mishandling. The automated control system also ensures enforcement of qualified procedures. Automated data entry methods will reduce the need for operator interaction. Together, these reduce two of the largest sources of process error. Also, automated recording of product parameters and process results will enhance the quality assurance of the operation.

Acknowledgment

This work was performed at Sandia National Laboratories and supported by the U. S. Department of Energy under Contract DE-AC04-94AL85000.

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Figure 1. WALS Workcell Schematic Layout

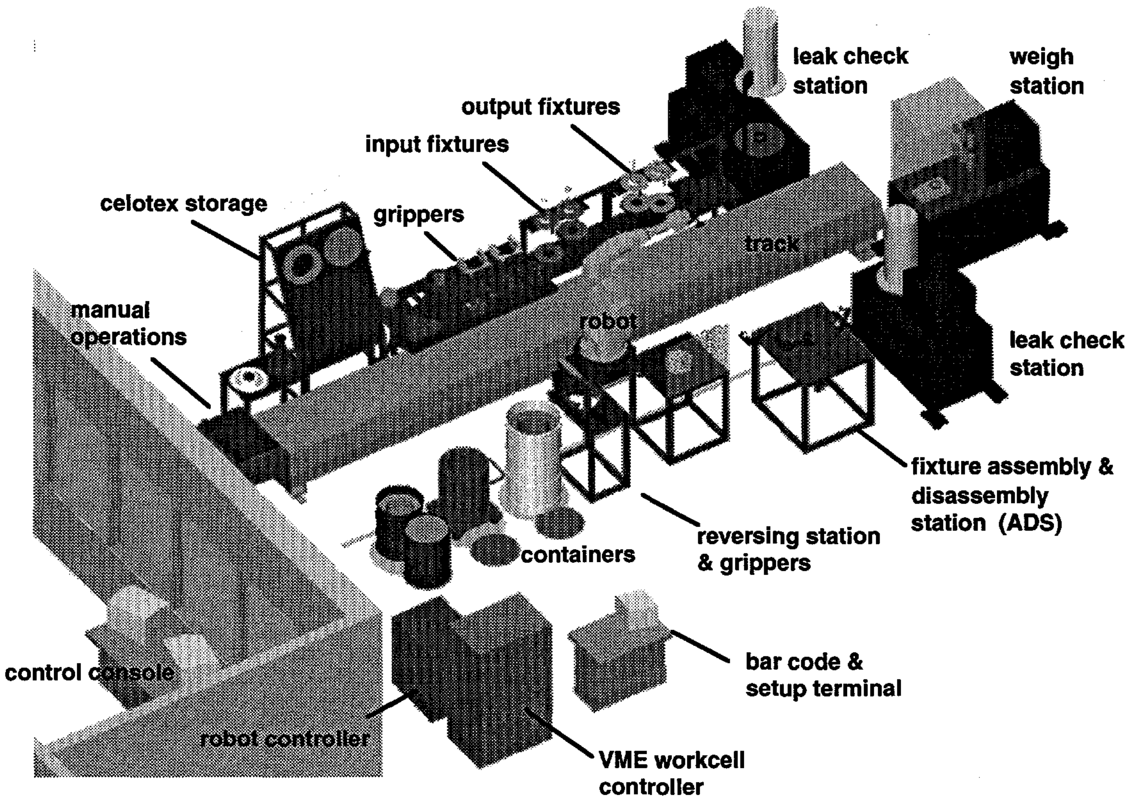

Figure 2. End-of-arm Tooling Configuration

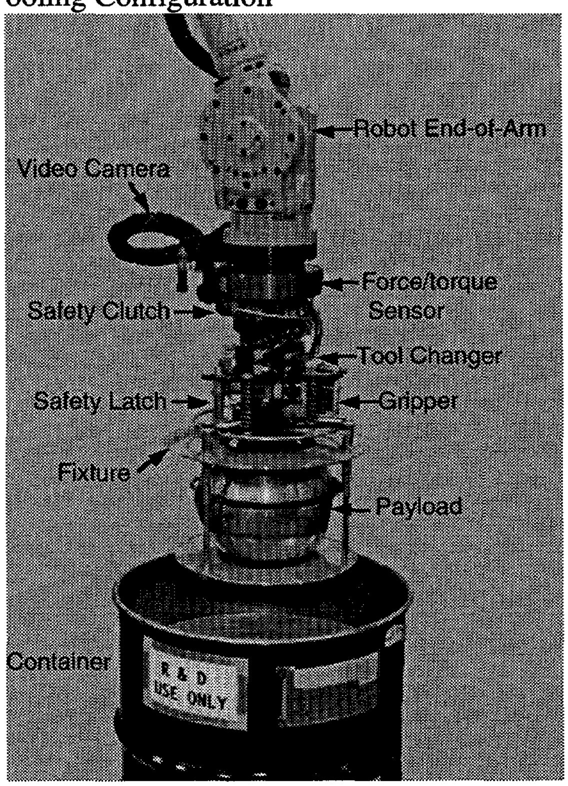

Figure 3. Control System Block Diagram

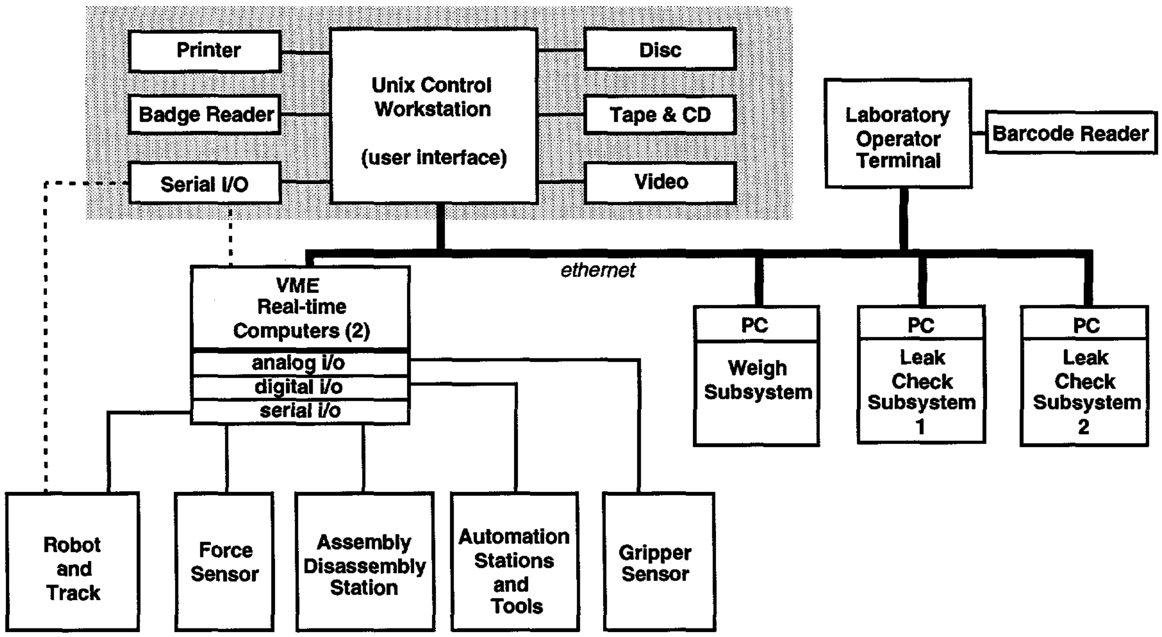

Figure 4. Software Architecture Block Diagram