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## LOW-LEVEL STORED WASTE INSPECTION USING MOBILE ROBOTS

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# LOW-LEVEL STORED WASTE INSPECTION USING MOBILE ROBOTS

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## ABSTRACT

A mobile robot inspection system, ARIES (Autonomous Robotic Inspection Experimental System), has been developed for the U. S. Department of Energy to replace human inspectors in the routine, regulated inspection of radioactive waste stored in drums. The robot will roam the three-foot aisles of drums, stacked four high, making decisions about the surface condition of the drums and maintaining a database of information about each drum. A distributed system of onboard and offboard computers will provide versatile, friendly control of the inspection process. This mobile robot system, based on a commercial mobile platform, will improve the quality of inspection, generate required reports, and relieve human operators from low-level radioactive exposure. This paper describes and discusses primarily the computer and control processes for the system.

**KEYWORDS:** robot, mobile robot, inspection, autonomous, computer vision, computer control

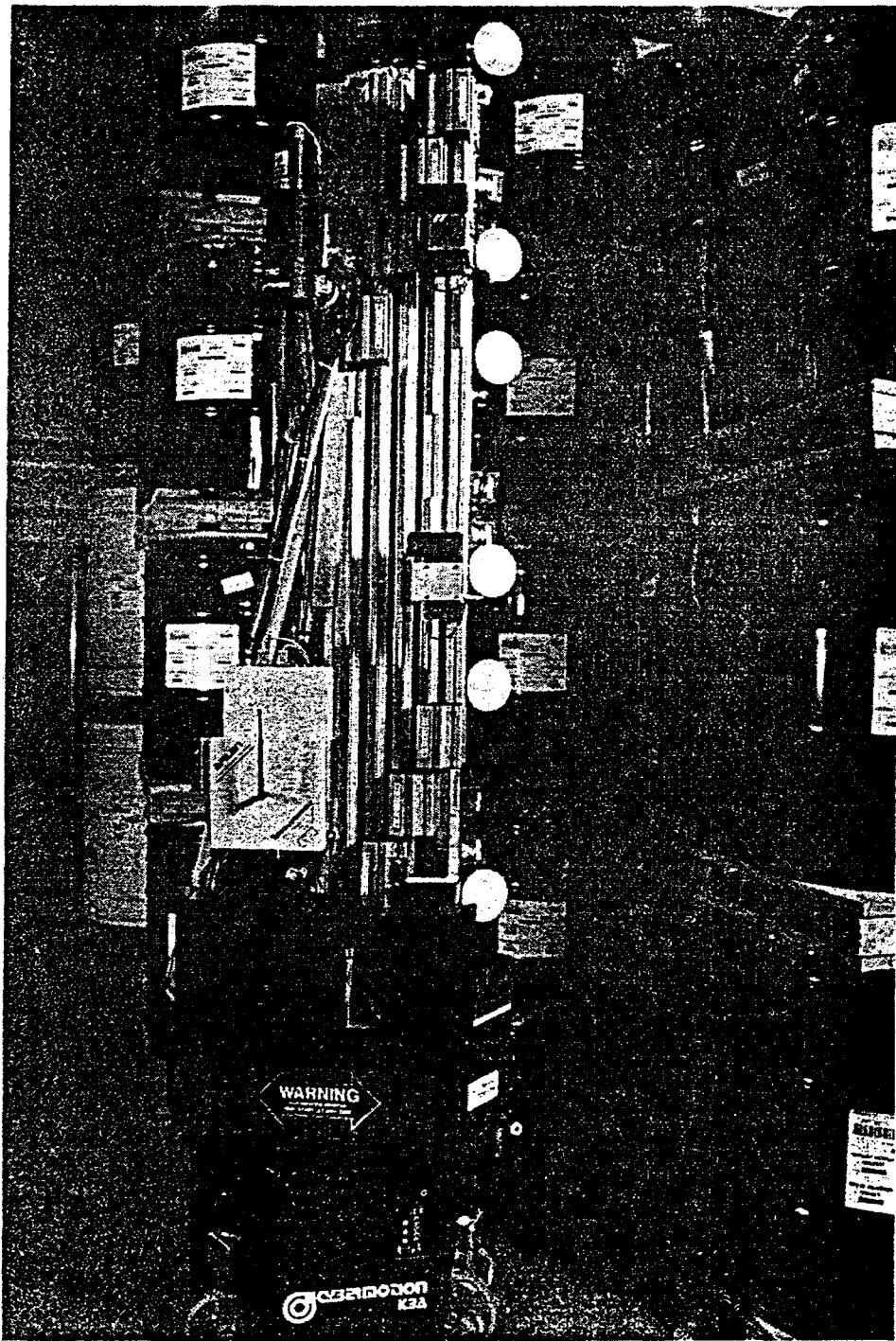
## BACKGROUND

Mixed and low-level radioactive waste is contained in 55-, 85-, and 110-gallon steel drums located at DOE warehouses throughout the United States (Fernald, Hanford, Oak Ridge, Idaho). The steel drums are placed on pallets and typically stacked four high. The columns of drums up to 16 feet high are aligned in rows forming an aisle approximately three feet wide between the rows. Tens of thousands of drums are now stored in these warehouses throughout the DOE complex. Continued operations will generate more drums of waste.

According to regulations the integrity of each drum is visually inspected weekly to determine if a drum has degraded to the condition that it should have its contents repacked into a new drum container. Currently, inspectors periodically roam the warehouses noting and reporting drum degradation. The drums are stacked such that the side seam of the drum is in full view of the inspector, since it has been found by experience that a drum shows its first signs of degradation along this welded bead. Typically the inspectors look for rust areas, streaks indicating leaks, dents, bulges, and tilting of the drums. These indicators identify *suspect* drums. Bar-code labels located to either side of the drum's seam in full view of the inspector are used for identification. The suspect

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drums are identified, retrieved and transported to the re-packing area where the entire drums are put in oversized containers.



**Figure 1.** Inspection Robot in Demonstration Area

Cost savings, reduced worker radiation exposure, improved documentation, and improved quality with inspection consistency are some of the anticipated benefits from robot inspection. The mobile robot inspector, ARIES, is designed to relieve warehouse inspectors of the tedious and mundane inspection task, and to remove inspectors from the up to 200 mrem/hour radioactive environment (Figure 1).

## DISCUSSION

### Mobile Robot

The mobile robotic system consists of a new Cybermotion<sup>1</sup> K3A [1] mobile platform, a compact subturret, an enhanced ultrasonic imaging system, a lidar navigation beacon system, and a special camera positioning system.

The Cybermotion vehicle is a proven, robust system that has been successfully employed in the areas of autonomous monitoring and security. These "SpiMaster" systems are routinely patrolling warehouses on a 24-hour basis. The basic Cybermotion system has an automatic docking/charging system. Drum-referencing algorithms and camera-positioning algorithms have been included in the primitive instruction set for the new robot.

### Onboard and Offboard Computers

The computer and control systems consist of an onboard system and an offboard supervisory system. The onboard computer system controls the inspection processes and manages other onboard activities. The onboard computer is a VMEbus system using a MIPS R3000 processor board running the VxWorks<sup>2</sup> real-time operating system. A number of the low-level primitives used by the drum navigation algorithms have been added to the instruction set of the K3A.

Offboard computers and offboard computers are networked with wireless Ethernet and provide the high-level planning, monitoring, reporting, and general supervision of ARIES. Multiple control and monitoring stations may be employed. Planning the inspection task (the *mission*) begins with the implementation of a world representation of the robot's environment (the *Robot World*). A path planner automatically generates robot path programs for user-specified paths, based on the site description contained in the robot world. The mission program, used to control the inspection process, is downloaded from the offboard system to the onboard computer where it is executed. The offboard systems may be used to monitor and control the system during the inspection process.

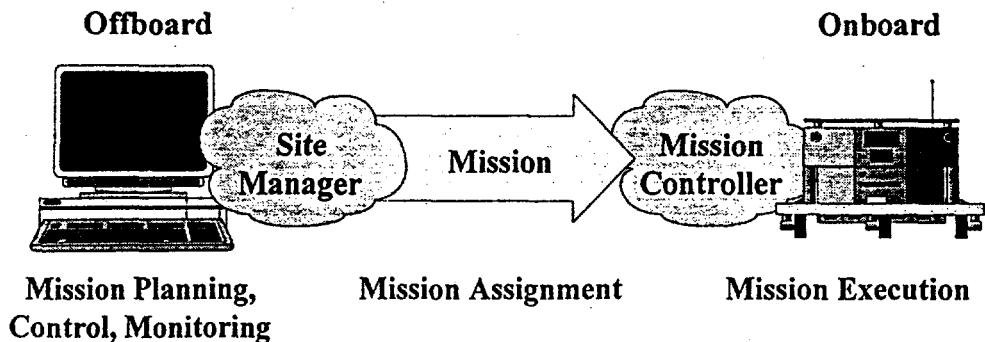
The *mission* represents the system description of the tasks to be performed by the robot (Figure 2). The mission is created by the Site Manager (*mission planning*), down-loaded to the robot, (*mission assignment*), and executed by the onboard Mission Controller. The Site Manager may be used off-line to plan and create a mission or on-line to control and/or monitor the operation of the robot. It is the users primary access to the system at the task level. The mission controller carries out the mission in an autonomous fashion.

The planning takes place offboard, using the Site Manager. Mission planning depends on the use of information stored in both the Robot World and the Drum Database. Mission assignment is the process of down-loading the mission information to the onboard system. While all actual communication is done by the communications software, it is informative to view this as a peer level system in which the various offboard components communicate directly with their onboard counter parts.

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<sup>1</sup> Cybermotion, Inc., 115 Sheraton Drive, Salem, VA 24153, (703) 562-7626.

<sup>2</sup> Wind River Systems, 1010 Atlantic Ave., Alameda, CA 94501.



**Figure 2.** The Mission

The mission consists of *(i)* the mission script, a high-level description of the mission used by the onboard Mission Controller, *(ii)* the Path Library, a set of path programs that may be used to travel between the nodes included in the survey area, and *(iii)* a local copy of the drum list.

The Site Manager uses the information contained in the Robot World, together with user input, to create the mission. It is invoked from the main control program. The primary functions of the Site Manager are to *(i)* provide a high-level programming interface to the system, *(ii)* support general queries concerning the state of the warehouse, including the visual inspection tour, and *(iii)* provide for control of the report generator. Programming a mission for a robot is largely visual with defaults supplied for many of the parameters.

The Mission Controller is the onboard program which is charged with the task of carrying out the mission. It is a peer of the Site Manager in that it receives the mission. It differs in that it is primarily a real-time program since it directly controls the robot during the survey. The Mission Controller executes the procedural part of the MDL mission script, using the information contained in the non-procedural part.

While AutoCAD is used to represent the warehouse, it is less suitable for the drums due to their dynamic nature. The information required to define the drums is kept in the drum list, a part of the Robot World that is managed by the Site Manager. The drum are linked lists which contain drum information needed for navigation (drum location, size) as well as specific information on each drum. The drum list are organized by the bottom (or reference) drum since the floor projection (2-D location) is of primary interest. Each reference drum entry also contains entries for all other drums stacked on it. The specific drum information is obtained from the Drum Database. The Site Manager also maintains navigation information in the Robot World in the form of the LIDAR beacon locations. It may maintain the docking beacon information although this also can be done be the Dispatcher.

Mission planning begins with the selection of the area to be surveyed. The Site Manager, using the 3-D AutoCAD description from the Robot World, provides a 2-D floor plan. The survey area is selected by enclosing the desired area on the 2-D layout of the warehouse. The Mission Planner then *(i)* creates a path abstraction of the selected (survey) area, *(ii)* uses the Path Planner to create a route through survey area, together with the path library programs required to implement the path, *(iii)* creates mission script used by the Mission Controller, and, finally, *(iv)* creates the onboard version of the Robot World.

The path abstraction (or path description) of the warehouse contains the beacons, nodes, and paths. The drum lists for a given aisle are attached to the appropriate path defining that aisle. From the general path abstraction, a subset containing the information required for the survey area is created. This structure provides the navigation information contained in the mission script. The path abstraction also provides a mechanism for determining the manner in which the robot will react to a given situation. It is possible to associate with each node or path both attributes and behaviors. This provides a mechanism by which the same instruction can cause a different response when executed in a different environment. This is done by attaching to each path component the appropriate attributes and procedures. For instance, the width would be an attribute which could be attached to a given path. Each attribute or procedure would have a scope equivalent to that of the path (or other component) to which it was attached. This would allow general conditions to be attached to the entire route and modified as appropriate in smaller sections.

### Inspection Payloads

*Camera positioning system (CPS).* The mobile platform will transport an application payload that includes a mechanical deployment system designed specifically for this project [2]. The CPS consists of four separate inspection modules, one for each drum in a four-high stack. Each module includes a camera, bar-code scanner, and strobe lighting. For the drum inspection process, at each stack of drums the CPS extends up and folds out to deploy the four inspection modules at various heights on the drums required by the vision system. Inspection modules for the three top drums are positioned by two linear actuators, a cabling system, and an interlocking five-rail mechanism. The inspection module for the bottom drum at floor level is positioned with a parallelogram special-case four-bar linkage. Two "photo" positions are required for each drum. These positions are determined by requirements of the computer vision inspection system and are programmed as a table in the primitive instruction set.

The CPS is retracted to a more compact position for maneuvering around the warehouse en route to inspection assignments and between drum aisles. It has an overall height of approximately eight feet in this collapsed position. Since the drum aisles contain three sizes of drums (55-, 85-, and 110-gallon capacities), the control system will determine the size of each drum stack and position the CPS accordingly.

*Vision system.* A major module of the inspection process is the vision system [3]. The overall function of the vision module is to locate *suspect* drums and to report these conditions. Once drums have been located by the robot's navigation system, visual assessment of drum condition is primarily an autonomous assessment of visible and quantifiable surface characteristics. The visible surface blemishes which indicate potential drum failure are rust patches of at least 0.5 x 0.5 inch size, paint blisters indicating internal surface rust, and physical dents. A color image system is used. The variability in ambient lighting and power limitations of the mobile robot requires the use of an efficient strobe-based image acquisition system. A learning algorithm is provided which initially adjusts the inspection parameters according to information given by a human tutor.

*Radiation Hardening.* Requirements for the low-level drum inspections do not dictate radiation hardening, since the radiation levels of the inspection environment are low.

However, future uses of such a mobile system in other applications, such as decontamination and decommissioning operations, may require a radiation-hardened vehicle for operation in high radiation areas. Therefore, a radiation hardening study and cost analysis has been performed to determine the requirements for fabricating a radiation-hardened version of the mobile inspector [4].

## CONCLUSIONS

Current mobile robot technology, computer technology, and mechanical design technology have been integrated by a university/industry team to produce a practical commercial mobile robot system to be employed by the U.S. Department of Energy in their environmental management programs. The Phase 2 prototype will be tested and evaluated at a DOE warehouse storage site. After evaluation and enhancements commercial mobile systems will be available for DOE from Cybermotion, Inc. The system and its components will be evaluated for potential use for other tasks such as decontamination and decommissioning.

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