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Demonstration of the Smart Crane Ammunition Transfer System[1]

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ABSTRACT

The purpose of the Smart Crane Ammunition Transfer System (SCATS) project is to demonstrate robotic/telerobotic controls technology for a mobile articulated crane for missile/munitions handling, delivery, and reload. Missile resupply and reload have been manually intensive operations up to this time. Currently, reload missiles are delivered by truck to the site of the launcher. A crew of four to five personnel reloads the missiles from the truck to the launcher using a hydraulic-powered crane. The missiles are handled carefully for the safety of the missiles and personnel. Numerous steps are required in the reload process and the entire reload operation can take over an hour for some missile systems. Recent U.S. Army directives require the entire operation to be accomplished in a fraction of that time. Current development of SCATS is being based primarily on reloading Patriot missiles.

SCATS development integrates robotic control and sensor technology with a commercially available hydraulic articulated crane. SCATS is being developed with commercially available hardware as much as possible. Development includes adding a 3-Degree-of-Freedom (D.F.) end-effector with a grapple to the articulating crane, closed-loop position control for the crane and end-effector, digital microprocessor control of crane functions, simplified operator interface, and rectilinear motion operating mode. SCATS operation has been successfully demonstrated. Ultimate plans are for this technology to be transferred and utilized in the military fielding process.

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DISCLAIMER

INTRODUCTION AND BACKGROUND

Missile resupply and reload have been manually intensive operations up to this time. Reload missiles are delivered to the site of the launcher by truck. The truck typically carries enough missiles for one reload, and may tow a trailer with enough missiles for another reload. The truck has a hydraulic crane for lifting and handling the missiles. Typically, a crew of four to five personnel is required to reload the missiles from the truck to the launcher. The missiles are handled carefully for the safety of the missiles and personnel. The entire reload operation takes over 1 hr. for some missile systems. Recent U.S. Army directives require reload to be accomplished in a fraction of that time. The potential exists to significantly improve missile reload time, safety, and utilization of personnel using robotic technology for missile reloading.

The current SCATS development work is focused primarily on Patriot missile reload. Patriot missiles are handled inside rectangular steel canisters for reloading. The canisters are approximately 1.07 x 1.00 x 6.10 m (3.5 x 3.3 x 20 ft), and weigh approximately 1701 kg (3750 lb), including missile. The missiles are fired out of these canisters on the launcher, so the empties must also be handled. The reload truck, called the Guided Missile Transport (GMT), is equipped with a hydraulic-powered articulating crane with a hydraulic powered hoist.

This paper summarizes the current status of the SCATS project at the Oak Ridge National Laboratory (ORNL). Additional information on project background and requirements has been described previously (Bradley, et al., 1995).

DEVELOPMENT APPROACH

The general approach being taken for development of SCATS is to integrate state-of-the art digital controls technology with the hydraulic crane. As currently developed, the SCATS includes: 1) digital microprocessor control of the articulating crane, 2) addition of a 3 D.F. end-effector with a grapple to the crane, (3) closed-loop position control for the crane and end-effector, (4) simplified operator interface, and (5) rectilinear or straight line movement operating mode. The SCATS equipment is assembled on the GMT, replacing the standard hydraulic crane for the demonstration. Planned future developments include load sensing, compliant control, automated operation, obstacle avoidance, and tipping prevention.

SYSTEM DESCRIPTION

SCATS is being developed with commercially available hardware for the hydraulic actuators, control valves, instrumentation, and the articulating hydraulic crane. Using commercial hardware where possible reduces development costs and improves maintainability of the system. The following is a summary description of SCATS hardware and controls.

Mechanical Hardware

The mechanical hardware being developed for SCATS consists of the missile grapple, a 3 D.F. end-effector, and ancillary mechanical equipment. A custom design grapple was built for the Patriot missile canister. The missile grapple, shown in Fig. 1, is a hydraulically powered grapple, which reaches around the missile canister with four arms to couple into existing fork-lift slots on the bottom of the canister. Two hydraulic cylinders power the grapple arms. The grapple arms are designed so that when loaded, the load acts to keep the arms closed. Alignment guides are provided to assist in positioning of the grapple on the missile canister.

The 3 D.F. end-effector, Fig. 1, consists of a commercial 2 D.F. actuator with a custom design pitch actuator to interface with the crane boom. The commercial 2 D.F. wrist provides yaw and roll positioning. All end-effector actuators are hydraulic. The hydraulic control valves for the end-effector and grapple are mounted on the end of the crane boom.

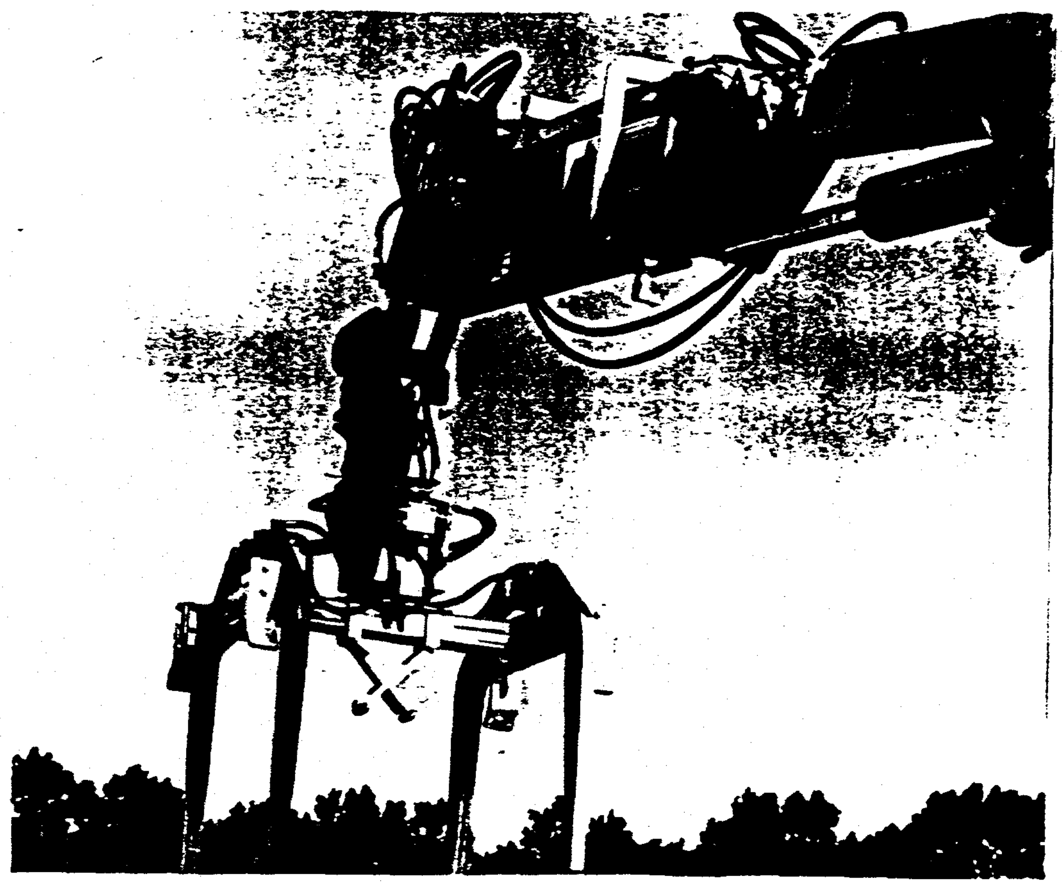

Figure 1. SCATS 3 D.F. End-effector and PATRIOT Missile Canister Grapple

Hydraulic Controls

The SCATS hydraulic system is a conventional heavy-equipment system with some modifications to provide electric control and improve dexterity for robotic operations. The valves selected are high-performance proportional valves that offer a manual override lever along with their electric control. The system is currently using the constant volume pump which is standard for the GMT.

To reduce the hose handling problem, the valve stack was split into two stacks, one mounted at the base for the crane actuators, and the other mounted at the end of the boom for the end-effector and grapple. This also improves performance by reducing the hose length between the end-effector valves and the actuators.

Counterbalance valves are installed on all actuators to provide safety features and performance improvements. The safety features prevent collapse of the boom in case of a hose rupture, and individual pressure reliefs prevent overexertion of the actuators for particular directions. These valves also provide a purge function which removes air and contamination from the hoses. Counterbalance valves also smooth out high inertia loads without the need for compensation from the computer.

For back-up manual operation, in case of computer failure, all of the hydraulic valves have manual override handles. However, since the end-effector valves are mounted on the crane boom, they may sometimes be inaccessible. A future planned capability is for manual control for the end-effector valves to be provided by an electric switch box instead of the computer, for fall-back end-effector operation.

Digital Control System

Since the control system will ultimately be deployed in the field, the system must be rugged enough to withstand the extremes of vibration, temperature, and weather. For this application a VMEbus architecture using single height (3U) boards was chosen for compactness. The VME-based system should provide not only the computing power currently required but flexibility for future enhancements. Low-power CMOS boards with extended temperature ranges of 0 to 70°C were chosen for the application. Taken together, these result in a system that is small, generates little heat, withstands higher temperatures than normal, and therefore should require minimal cooling. The computer enclosure is environmentally sealed for all-weather operation. Cooling is provided through a sealed heat exchanger mounted in the top of the enclosure.

Mounted inside the environmental enclosure are the VME system, the hydraulic amplifiers, the power regulator components, and a watchdog circuit to automatically shut down the system in case there is a problem. The input/output (I/O) signals are routed through environmentally sealed connectors to the hydraulic arm and end-effector.

The VME system is made up of a CPU card, an ethernet card, and various I/O cards. The CPU card contains a 40-MHz 68030 processor, a 40-MHz 68882 floating point unit, 4 MB of dynamic random access memory (RAM), and 1 MB of battery-backed, tri-ported static RAM. A separate ethernet card is utilized for communication with the software development system (the ethernet card would not be required in a developed system). The analog and digital I/Os are provided through plug-in modules on 3U baseboards. This provides flexibility in the "mix" of I/O utilized. The balance of the VME system is made up of four resolver-to-digital boards and a resolver reference supply. All of the I/O boards are isolated from the VME bus and require minimal power. The total power required for the VME system is estimated at less than 50 W— which is several times over than "typical" VME systems.

Currently, input to the control system is provided by resolvers on all but two joints, which use potentiometers to provide position. Pressure sensors in the hydraulic lines will be used to compensate for nonlinearities in the system. While this should be adequate for teleoperation, additional instrumentation will be necessary for some of the future planned automated operations.

The environment for software creation and debugging is based on the VxWorks cross-platform development package. The host system is a Sun Sparcstation with SunOS and OpenWindows/Motif networked to the real-time VME target through ethernet. The host is used to edit, compile, link, and store the code. The code is then downloaded to the run-time system for execution and debugging. The VxWorks run-time system is based on a real-time, multitasking kernel. The application code for this project is being developed in the C++ programming language.

A pendant-type operator interface is being used for the initial prototype. It simplifies a type of interface that operators are familiar with and gives the capability to walk around and view the equipment from various perspectives while controlling the system. The pendant is a 6 D.F. controller implemented with two, 3 D.F. rate-control joysticks. These joysticks are arranged to provide "intuitive" motions in that the stick is moved in the direction the end-effector is moved. A similar arrangement was used on the Teleoperated Small Emplacement Excavator at ORNL with very good results (Thompson, et al., 1993).

Control

The control scheme utilizes input from the pair of 3 D.F. joysticks, one for translational control, the other for rotational control. In the ideal case, the control system would simply transform the Cartesian commands from the joysticks to the joint velocities to send to the hydraulic valves. Unfortunately, a number of things, e.g., valve nonlinearity, friction, oil temperature, etc., prevent the load from being moved in the proper direction with enough accuracy. To provide the necessary control on SCATS, the input from the joystick was used to generate a planned path that the crane then follows. This planned path represents the path the crane would take if the actuators worked perfectly. As the

crane attempts to follow this planned path, an error signal is generated from the deviation from the desired path. This error signal is subtracted from the joystick commands as a compensation to bring the crane back on the path. For example, if a slow lift joint caused the crane to lag below the intended path, the error compensation would add a vertical component that would give the lift joint a larger signal and bring the crane back to the path. A new path is generated whenever the operator changes the joystick inputs.

In addition, each of the hydraulic valves in the system was individually modeled and characterized to compensate for nonlinearities. It was found that there was enough variation in the proportional control valve response curves that it significantly affected their response. A second order curve was used to model the valves, with separate parameters for negative and positive directions. Compensation for the dead-end associated with each valve was also provided.

Another variable affecting control of the crane was the flow of hydraulic fluid to each joint. The flow required for each joint to produce a required motion was predicted based on a model of the joint. If the sum of the predicted flows exceeded the capacity of the hydraulic system then all flows were scaled back appropriately. Likewise, if the flow required for an individual joint exceeded the capacity for that joint, then all of the outputs were scaled back. This helped to prevent starving individual joints and improved the ability to track along a generated path.

PHASE 1 TECHNOLOGY DEMONSTRATION

The Phase 1 Technology Demonstration was successfully completed at ORNL, Fig. 2. For the demonstration, empty missile canisters were handled. The equipment had been fully load tested previously to 125% of required capacity. The canisters were unloaded from a simulated launcher and transferred from the GMT to the simulated launcher as would be done during a normal reload. The rectilinear motion control was successful, and operations were performed using only two operators.

This was the first demonstration of SCATS equipment, and the purpose was to demonstrate the feasibility of this application and the potential to improve current missile handling. Though handling the canisters appeared to be faster with SCATS, quantifying the improvement in reload time was not an objective of this demonstration. A Patriot Launch Station wasn't available for the demonstration, and all of the planned capabilities to improve speed had not been implemented in SCATS.

Planned improvements to the motion control should provide further improvements in the reload speed. Docking with a canister can be extremely difficult without resolved motion control. Although the current accuracy is usable for the task, any improvements to the accuracy of the resolved motion control would provide corresponding improvements in the ease of use. Planned improvements for the next phase of the project include adding resolvers to two joints that currently sense joint

position using potentiometers. Resolvers provide significantly better data than the potentiometers and this improvement should significantly improve the ability to accurately control the position of the grapple. Also, an accumulator will be added to the system to smooth out pressure variations in the system. The next phase of the project will address these and other improvements to the system as well as automation of operations such as stowing and deploying the system.

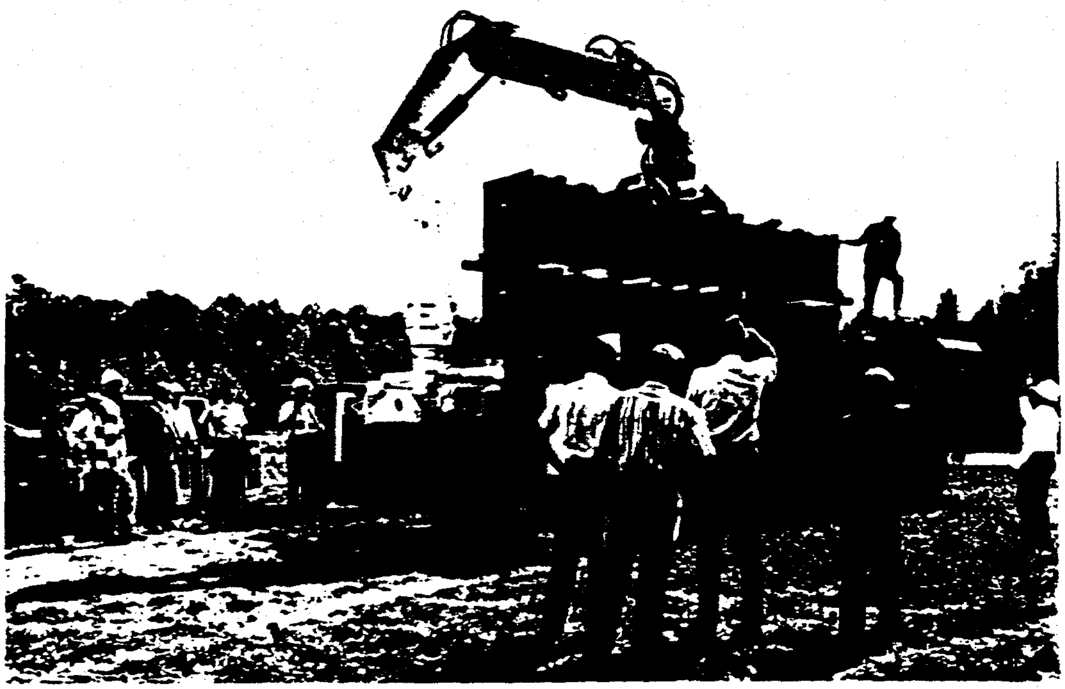

Figure 2. SCATS Phase 1 Technology Demonstration

CONCLUSION

SCATS has been successfully demonstrated at ORNL. Future demonstrations are planned as development progresses. Following completion of the development, the technology will be transferred to the U.S. Army for fielding.

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