

Ammunition Logistics Program

Automated Ammunition Logistics for the Crusader Program*

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ABSTRACT

The U.S. Army's next generation artillery system is called the "Crusader." A self-propelled howitzer and a resupply vehicle constitute the Crusader system, which will be designed for improved mobility, increased firepower, and greater survivability than current generation vehicles. The Army's Project Manager, Crusader, gave Oak Ridge National Laboratory (ORNL) the task of developing and demonstrating a concept for the resupply vehicle. The resupply vehicle is intended to sustain the howitzer with ammunition and fuel and will significantly increase capabilities over those of current resupply vehicles. Ammunition is currently processed and transferred almost entirely by hand. ORNL identified and evaluated various concepts for automated upload, processing, storage, docking and delivery. Each of the critical technologies was then developed separately and demonstrated on discrete test platforms. An integrated technology demonstrator, incorporating each of the individual technology components to realistically simulate performance of the selected vehicle concept, was developed and successfully demonstrated for the Army.

I. BACKGROUND/INTRODUCTION

The Army's next generation Self-Propelled Howitzer (SPH) and Resupply Vehicle (RSV) was recently given the name Crusader. In 1993 the project manager Crusader (then called Advanced Field Artillery System and Future Armored Resupply Vehicle) was looking for technology solutions that could meet the Crusader operational requirement. Design improvements were necessary for increased efficiency and safety on the battlefield. Currently, projectiles are loaded onto a resupply vehicle by hand. The vehicle then moves near the front line to rendezvous with a howitzer. Rear hatches open, and the resupply vehicle's crew manually processes the projectiles. Then the howitzer's crew transfers them from the resupply vehicle's conveyor to an onboard storage rack. The procedure is labor intensive, time consuming, and dangerous. Crew members are exposed to enemy ground-fire and to the threat of nuclear, biological, and chemical agents.

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CRING

The procedure for reloading the Crusader SPH was potentially more time-consuming because of the system's increased capacity for ammunition and the use of liquid propellant. The Crusader design also required that each projectile be weighed and identified with exterior markings to facilitate automated handling and improved firing accuracy.

Army personnel contacted the Robotics and Process Systems Division (RPSD) at Oak Ridge National Laboratory (ORNL) to investigate automating the operations required for resupplying the Crusader howitzer. ORNL has a long history of developing remotely operated equipment for use in dangerous environments. In 1993, the RPSD successfully operated the Future Armored Rearm System (FARS), which provided a means of remotely rearming an M1A1 tank. The FARS project marked the first full-scale demonstration of an automated rearm system between battlefield vehicles.

II. ASSUMPTIONS AND REQUIREMENTS

The Army provided input concerning system requirements and the relative importance of operational features. Critical requirements were derived from the Army's Operational Requirements Document. The requirements for the major operational features included the following criteria:

- All rearm operations must take place with the crew members under armor.
- The resupply vehicle must upload and process projectiles utilizing an onboard automated processing center. The processing operation for each projectile consists of removing the lifting eye, inserting the appropriate fuze, weighing the fuze projectile, and identifying the projectile's exterior with a machine-readable code.
- The resupply vehicle must upload and process 130 rounds in 45 minutes or less.
- Docking, rearming the howitzer with 60 fuze projectiles, fuel and propellant; plus

disengagement must occur in 12 minutes or less on varied terrain, resulting in no greater than a ten-degree angle between vehicles.

- The system must accommodate various round and fuze types.
- The Army requested that ORNL consider only the passive (fixed) storage option for projectiles onboard the resupply vehicle for comparison with previously tested active storage designs.

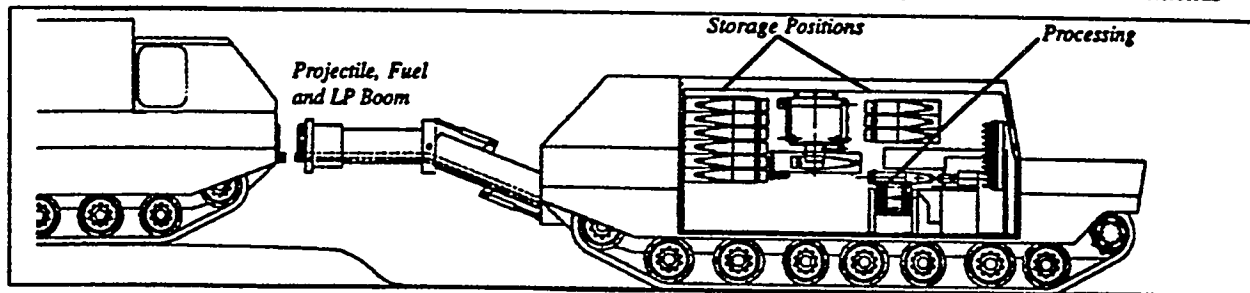
III. CONCEPT DESCRIPTION

ORNL's first challenge on the Crusader project was to select an overall concept for automating the resupply functions. This concept would demonstrate the necessary processing and delivery tasks. Computer visualizations and time/motion studies of proposed operations were conducted to provide additional means of comparison. During this phase, concepts were evaluated and verified systematically through decision analysis.

The concept selected, shown in Figure 1, features a 6-degree-of-freedom (D.O.F.) articulated arm that extends from the front of the resupply vehicle to upload unprocessed projectiles via conveyors. Fuzes and liquid propellant are loaded through access panels on the side of the resupply vehicle. The types of projectiles and fuzes and their lot numbers are input into the control system computer during upload. Fuel, both for the RSV and for the eventual transfer to the SPH, is also taken on during the upload process.

Projectiles are then processed within the dry and secure interior of the vehicle. A pick-and-place robot moves the projectiles to an automated processing center comprised of stations where each operation is performed. All processing and storage of projectiles takes place horizontally and in-line with the transfer arm. The processed projectiles are then placed in a secure storage cell by the robot.

Once the arm is retracted, the resupply vehicle is prepared to rendezvous with a howitzer on the battlefield. There, the articulated arm extends



and is mated to the resupply port on the howitzer. The type and quantities of projectiles, propellant, and fuel requested by the howitzer crew chief are transferred onboard. The projectiles are removed from their storage cells by the robot and placed onto the delivery conveyor. An inventory management system tracks the storage locations of the assembled rounds (projectile and fuze assembly) and ensures delivery of the correct rounds to the howitzer.

IV. TECHNOLOGY DEVELOPMENT

Specific technology areas of concern were automation of projectile processing operations, such as projectile fuzing, marking, and weighing and the eventual docking and delivery of ammunition from the RSV to the SPH. Each of these areas will be discussed in more detail in the following sections.

A. Projectile Processing

Automation of the weighing, marking, and fuzing operations was developed initially on separate test stands. The weighing system selected for demonstration consisted of a cantilever beam-type load cell in conjunction with a dual-axis inclinometer to measure the angle of misalignment from true horizontal. Readings from the two devices were then used by preprogrammed angular compensation algorithms to calculate the actual weight of the projectile.

Identification of the ammunition to permit rapid automated handling was investigated. Use of matrix symbols applied via labels or directly printed onto the projectile's surface was evaluated under various conditions. These markings proved to be very reliable provided the surface of the ammunition was not wet or dirty. Since these conditions are not guaranteed in a battlefield environment, ORNL also investigated the use of machine vision-based techniques to recognize each ammunition component based on its existing exterior physical features. A detailed description of each of the aforementioned activities is provided.¹

Another of the key technologies to be automated was fuzing. The projectiles were initially unfuzed, and a fuze had to be inserted and threaded into the projectile as part of the processing. A constraint on the design solution was that the ammunition could not be modified to simplify automation. Projectile fuzing is addressed.²

B. Docking and Delivery Arm

Based on the Artillery school's desire to keep the soldier under armor during the rearm operation of the SPH, ORNL proposed a 6-D.O.F. docking and delivery system to mate the RSV and SPH and to rearm the howitzer. The delivery system must have the ability to dock with the SPH and transfer 60 projectiles and associated propellant without requiring the crew to leave their respective vehicles.

The articulated conveyor or ammunition transfer arm retracts into the vehicle for storage and extends to dock with the SPH for ammunition resupply. The first arm section remains inside the vehicle and is attached to the track which the arm rides on to extend and retract. The second and third arm sections make up the 6-D.O.F. jointed arm. The transfer arm tested is shown in Figure 2.

The joint between the first and second sections (shoulder) has $\pm 20^\circ$ pitch and yaw motions (1 D.O.F. and 2 D.O.F.). The joint between the second and third sections (elbow) has $\pm 18^\circ$ pitch and yaw motions (3 D.O.F. and 4 D.O.F.). The third section contains an 18-in. extension (5 D.O.F.) and also houses the docking port which incorporates a roll joint of $\pm 10^\circ$ (6 D.O.F.). The docking port requires the roll joint to accommodate the alignment and mating of the fuel and liquid propellant ports on the SPH.

One of the main concerns for a device of this size is weight. The second and third sections of the arm are cantilevered, and therefore the pitch actuator at the shoulder must be able to support the moment arm created by the combined mass of sections two and three. For this technology demonstrator, the second and third sections were fabricated out of 2219 aluminum to take advantage of its high strength-to-weight ratio. Gas springs were used on section 2 to counteract the load seen by the pitch actuators due to the weight of sections 2 and 3. These springs were designed such that no load would be seen by the pitch actuators when the arm joint angles were at 0° . These steps ensured that commercial actuators could be used for each of the joints.

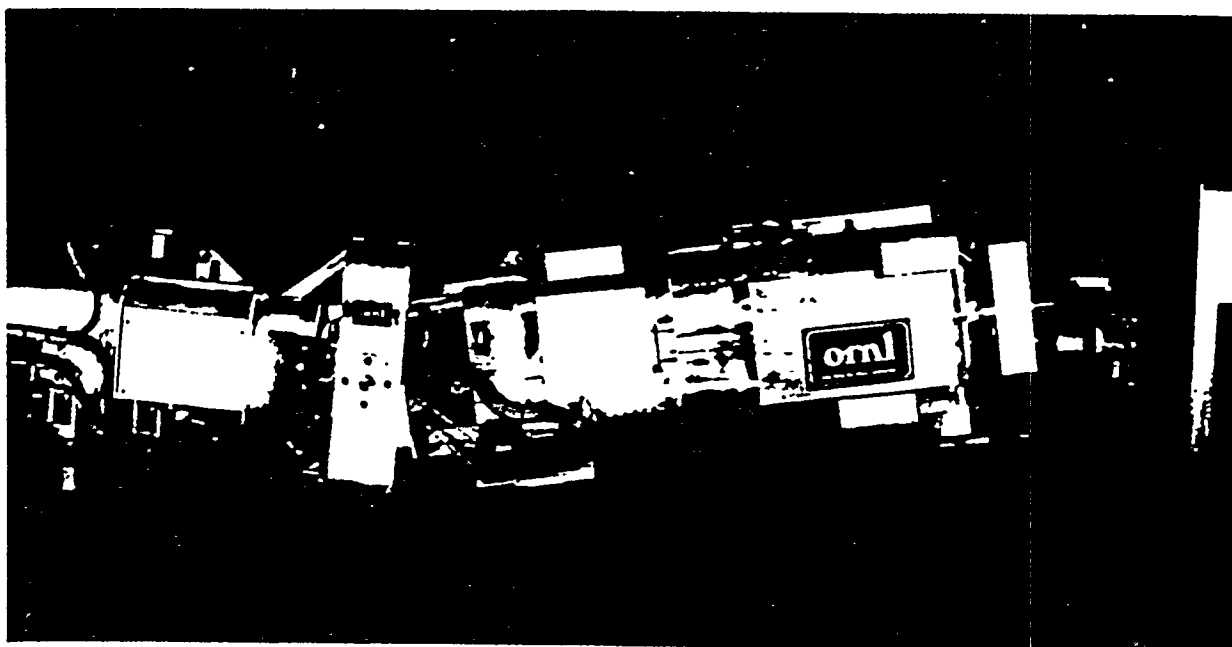


Figure 2. Delivery Arm Selected Concept

To achieve a precise level of control, linear thrust actuators driven by an electric servo motor were chosen for joint control instead of hydraulics. The linear motion of the actuators is converted into joint angle motion by a lever arm formed by the two pitch/yaw joint gimbal assemblies. The extension joint has linear motion, and its actuator moves the extension directly. The docking port roll is similar to the pitch/yaw actuator.

Ball screw actuators were chosen for the yaw and the extension degrees of freedom, while acme screw actuators were chosen for the pitch D.O.F. The ball screws reduce the arm stresses by allowing the joints to backdrive during the clamping together of the docking and resupply ports by the docking clamp latches, while the acme screws prevent undesirable backdrive in the pitch planes. An absolute position sensor was mounted to each actuator to ensure that joint position is always known. These sensors provide the feedback necessary for both manual and computer-aided docking.

C. Automated Docking

The robotic expertise developed at ORNL in nuclear fuel processing environments was used extensively in developing autodocking technology.

The automated docking system initially developed was a laboratory prototype intended to demonstrate the feasibility of autonomous docking (autodocking) for Crusader resupply missions.

The ORNL autodocking program began in June 1993 with a 3-month feasibility study to determine if autonomous docking was possible using commercially available hardware. ORNL engineers recognized that the additional hardware needed to support autodocking on a robotic arm was small. The engineers devised an architecture that uses a digital image processing system to calculate the position and orientation (pose) of a special docking port.

The autodocking system itself does not initiate or control any robotic arm movements during autodocking. Its sole function is to supply the port's pose to the external control system, which uses the pose to move the transfer arm. By separating the path planning process from the motion control function, the system can be easily adapted to different mechanical arms.

The system prototype was initiated in February 1994, using a single video camera and a unique target to simulate the docking port. The first remote pose measurement was demonstrated in June 1994.

The system, modified for increased accuracy and reliability, was completed in June 1995. The system was mounted on a small, commercial robot in an experiment to emulate resupply docking. The demonstration of small-scale autodocking proved that the concept was sound. After the tabletop version of autodocking was successfully demonstrated, the system hardware and software were used to demonstrate full-scale autodocking on the transfer arm.

The incremental effort to incorporate autodocking into the transfer arm was minimal. A software algorithm was created to convert the pose vector to a desired path of travel for the boom. This path generator determines the exact path of motion needed to dock the boom from any random position in the docking envelope. The path directions are sent to the inverse kinematics algorithm, which, in turn, drives the individual transfer arm linkages, as shown in Fig. 3.

In the transfer arm control architecture, the robot motion control module remained unchanged with the addition of the autodocking module. Either the manual joystick or the autodocking system can provide path data to the motion control module. The choice of manual or autonomous docking is software selectable by the operator.

A simulated SPH port, as shown in Fig. 4, was fabricated with eight lab markers in order to make an accurate pose measurement from both the maximum and minimum camera range. The SPH port could be used for manual and autodocking without modification. The camera was mounted on the inside

of the boom on a pivot arm that is rotated out of the path during ammunition transfer, as shown in Fig. 5.

To dock with the port, the location of the optical center of the camera with respect to the boom docking plane has to be accurately determined. This is because the system measures the position and orientation of the SPH port with respect to the camera. However, the robot motion control module needs the position and orientation of the port with respect to the contact tabs of the arm since that is the surface that will make first contact during docking. Therefore, all pose measurements must be converted to the arm's coordinate frame.

To accomplish this, a coordinate transformation matrix is created. First, the geometric position of the light-emitting diodes (LEDs) lights with respect to the SPH port center is accurately determined. Starting from the docked position, the boom is retracted to bring the LED into the camera field of view. Knowing the calculated position of the camera from the pose and the actual distance the boom (and thus the camera) has been retracted, the distance from the optical center of the camera to the boom mating face can be determined. The coordinate transformation matrix is retained until recalibration is needed. Normally, recalibration is necessary only if the camera position or orientation on the boom is changed.

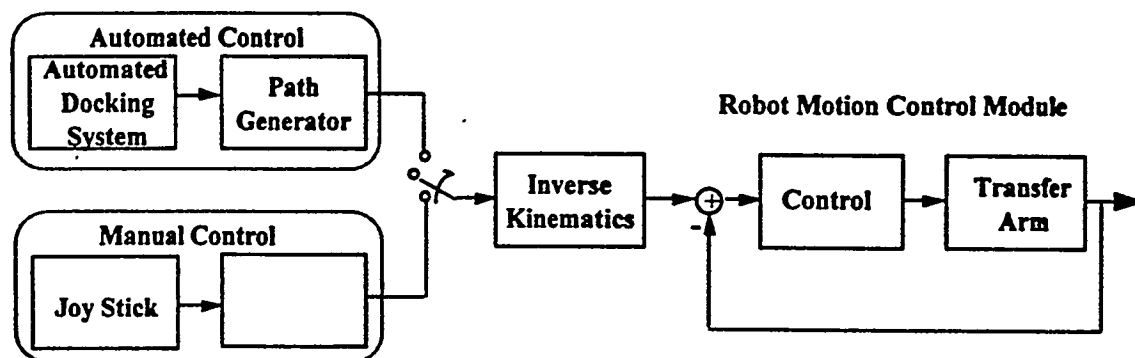


Figure 3. Flow Chart of the Transfer Arm Control Architecture.

Autodocking was accomplished in two stages. With the boom retracted, a pose measurement of the SPH port is obtained from the autodocking system. Because the measurement accuracy is proportional to the target range, it is desirable to take another pose measurement closer to the port. From the initial pose reading, a new position, directly in front of the port and approximately 10 in. away, is calculated for the second and more accurate pose measurement. The arm is then actuated to this new position, where the final pose measurement is taken. The coordinates of the port are computed from the pose measurement taken at the closer location. The arm can then be autodocked with the port. The camera must be kept fixed relative to the boom during all pose measurements. The time required to complete an autodocking is less than 40 s from initiation of the autodocking command to camera retraction.

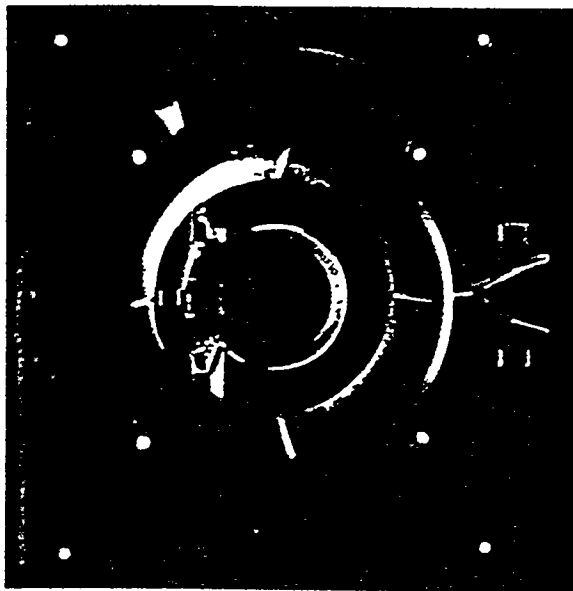


Figure 4. View of the Simulated Docking Port

D. Control System

A distributed control approach was implemented based on lessons learned from previous projects where subsystem development and system-level designs progressed in parallel. The distributed control architecture and a modular software design permitted maximum flexibility while it significantly reduced system cable requirements.

A critical technology area not previously discussed is the control philosophy adopted and implemented. Certain basic principles guided the development and implementation of the control

architecture. Key among these was the concept of a control architecture that supports all of the discrete demonstrations and can be easily enhanced to facilitate an integrated demonstration of the various subsystems. A different, but related, objective was to maximize the reuse of software between subsystems.

The control system was designed so that hardware dependency was minimized. During the early stages of design and development, detailed knowledge of the hardware was not available. Because of the relatively fast-paced development effort undertaken, the control system had to be developed in parallel with the system hardware design and fabrication.

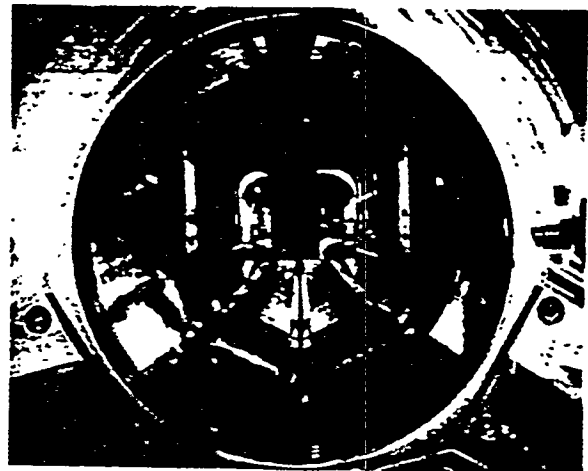


Figure 5. View Looking into the Transfer Arm.

A system monitoring and debugging capability was integrated into the control system. The monitoring capability permits the system developers and integrators to verify the correct operation of the various low-level control signals in a nonintrusive manner during operation of the equipment. The debugging capability permits modification of system parameters and direct entry of low-level commands.

The control system is a hierarchical system built on a multiprocessor, network-based architecture that provides significant benefits in the development, implementation, and integration of the control system. The modular and hierarchical nature of the hardware/software architecture facilitated development of certain portions of the control system in the absence of accurate or complete information on the hardware to be controlled. It also provided a convenient method to integrate and test the system as various hardware components are completed.

The VxWorks operating system was used throughout the control system except in the operator interface CPU, which runs OS/9, in order to leverage some previously developed operator interface experience. A UNIX (SunOS) host machine provides a development environment for all of the software running on the VxWorks target machines.

All control systems software was written in C and C++. Where practical, object-oriented design practices were used in conjunction with the C++ language to produce reusable modules that encapsulated their data.

V. Technology Demonstrator

The final phase of the project brought the various subsystem components together to form an integrated technology demonstrator that simulated operations on board a resupply vehicle. The demonstrator, shown in Fig. 6, consisted of the transfer arm mounted to the floor by way of a base assembly. The processing equipment was located above on a mezzanine structure. A pick-and-place robot for moving projectiles was also mounted on the mezzanine, as were two storage racks, each capable of holding four projectiles. After installation, extensive work was necessary to interconnect the various controls and mechanical systems. In November of 1995, the system was successfully demonstrated for Army personnel.

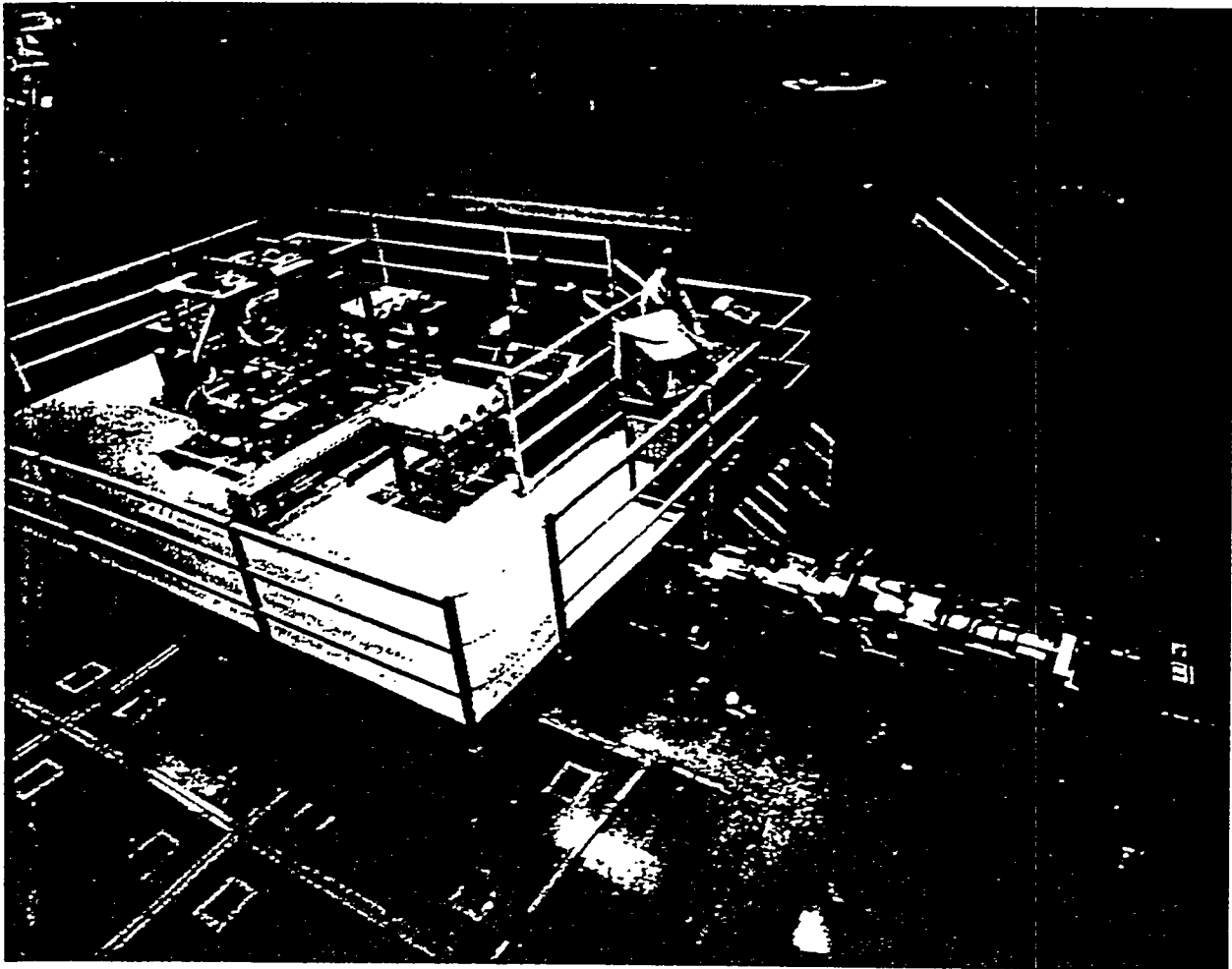


Figure 6. Integrated Technology Demonstrator

VI. CONCLUSIONS

From concept development through demonstration of a complete system, this project presents new opportunities for safe and efficient ammunition resupply for the Army's next generation of field artillery systems. Successful implementation of the ORNL-developed technologies onto the Crusader system will help the U.S. Armed Forces maintain their record of having the most advanced ammunition logistics system in the world.

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