TOWARDS AN AUTONOMOUS HEAVY LIFT ROBOT FOR FIELD APPLICATIONS

Daniel W. Johnson, Martin Marietta Aero & Naval Systems, 103 Chesapeake Park Plaza, MP-460, Baltimore, Maryland, U.S.A. 21220

Sandor Szabo, National Institute of Standards and Technology, Bldg 220, Rm B127, Gaithersburg, Maryland, U.S.A. 20899

Harry W. McClellan, Jr., William B. DeBellis, U.S. Army Human Engineering Laboratory, ATTN: SLCHE-CS, Aberdeen Proving Ground, Maryland, U.S.A. 21005

ABSTRACT

The U. S. Army Human Engineering Laboratory (HEL), in cooperation with the National Institute of Standards and Technology (NIST) and Martin Marietta Aero & Naval Systems (MMA&NS), has developed a test-bed to study the use of robots for materials handling in the field. In June 1990, the team completed a six-axis robot capable of lifting loads as heavy as 1800 kilograms (kg) at distances as high as 9 meters. Also completed is a high level controller, based on an interactive hierarchical sensory control system architecture, capable of acquiring palletized loads autonomously from a simulated tractor trailer. This paper presents the current state of both the robot and the high level controller.

Keywords: Robotics, materials handling, control systems, robot design

1. INTRODUCTION

In the early 1980s, HEL began research into technologies applicable to autonomous handling of palletized loads. This research was conducted in collaboration with Tooele Army Depot and the National Bureau of Standards (NBS), now known as NIST. The approach was to adapt successful industrial innovations in materials handling to a rugged outdoor environment. Early research focused on using a large industrial robot equipped with sensors on the end effector to find and engage a palletized load autonomously. In 1986, HEL awarded a contract to MMA&NS to build the Field Materials-handling Robot (FMR). MMA&NS delivered the FMR (see Figure 1) to the U.S. Army in 1990.

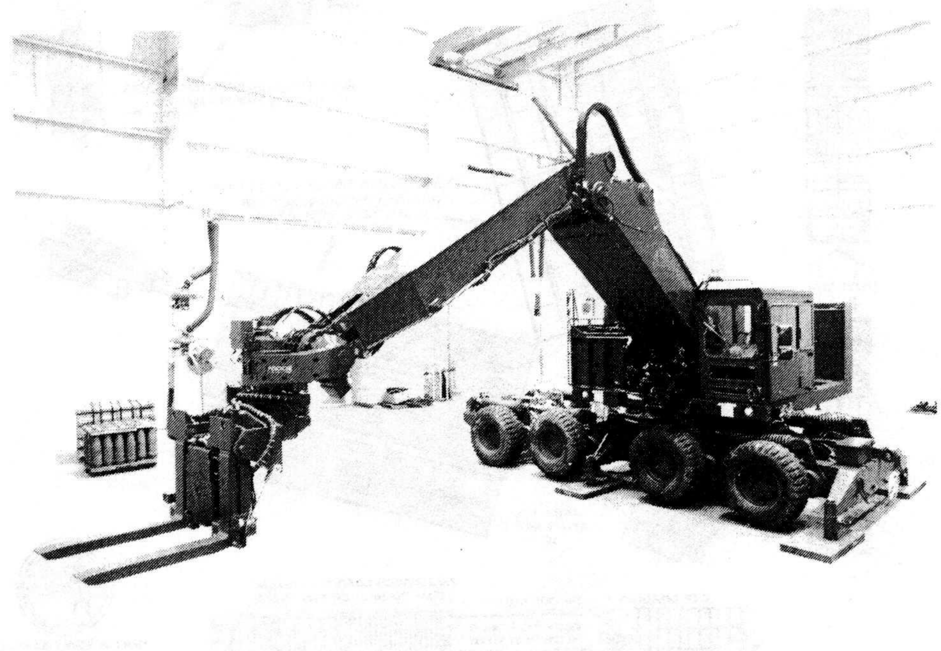

Figure 1. The field material handling robot (FMR)

Several operational requirements influenced the design of the FMR. The first is the requirement for the FMR to lift palletized loads weighing as much as 1800 kg as high as 9 meters. Other requirements were the necessity for the FMR to meet the length, width and height restrictions for transportation on the U.S. Army's C-141 cargo airplane and weigh approximately 115,000 kg. A final requirement was for the FMR to improve the cycle time for unloading tractor trailers in comparisen to the performance of human operators. The cycle time is the time required for the machine to engage a pallet, move it to a new location, and return to engage the next pallet. The FMR is designed to have a cycle time of 20 seconds for loads as great as 1180 kg, and a cycle time of 45 seconds for loads weighing as much as 1800 kg.

This paper describes the FMR development effort. It addresses the application for which the FMR was built as well as other applications that would benefit from research using the FMR test-bed. A high level design summary is presented that describes the test-bed built by MMA&NS and Martin's primary subcontractors, Koehring Cranes and Excavators, and Moog Controls. The paper then describes the control system architecture - both the manual control system for controlling the machine using two joysticks (3-degrees of freedom) in the vehicle's cab and the autonomous control system developed by NIST. Finally, the paper describes the demonstrated capabilities of both the FMR test-bed and the sensory interactive autonomous control system, which has yet to be integrated into the FMR test-bed.

2. APPLICATIONS

Research in Field Materials-handling Robot Technology (FMR-T) provides a potentially wide range of benefits to the U.S. Army's logistics community. The operational concept is for the FMR ultimately to perform loading and unloading operations at any critical supply node in a military theater of operations. The FMR is currently programmed to handle three different types of palletized loads. Operationally, the FMR would be driven to the worksite and located in a work cell configuration that facilitates rapid munitions handling. Once the work cell is defined and supporting equipment implaced, the FMR operates either autonomously or under manual control. A version of the work cell is shown in Figure 2. Simulations show that the FMR will improve ammunition flow rates by reducing the time from about 30 minutes to 6 minutes to unload a typical semi-trailer load of pallets. The work cell concept, with the FMR, eliminates the need for human "spotters" to guide forklift trucks and improves the time to unstuff containers, which will potentially lower the turnaround time for valuable transportation assets.

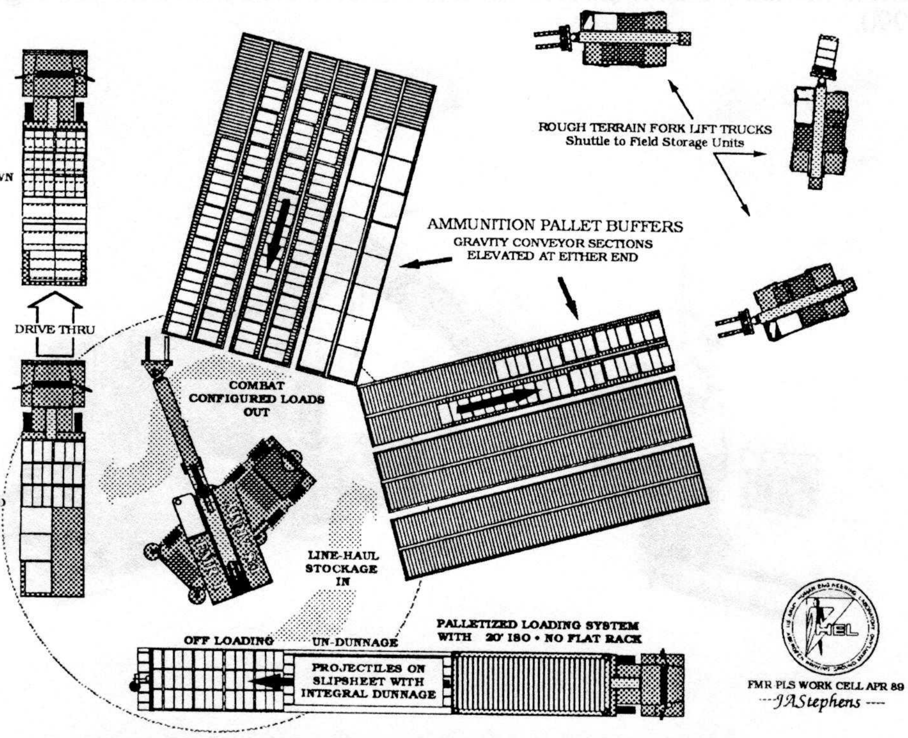

Figure 2. FMR performing in a work cell with the palletized loading system

The FMR has potential applications beyond munitions handling in the field. Talks are ongoing with the U.S. Air Force's rapid runway repair (RRR) program manager about using the FMR to develop applicable technologies for an autonomous excavator which would repair damaged runways without exposing personnel to the hazards of doing the job manually. Also, the U.S. Department of Energy (DOE) is interested in applying FMR technologies to hazardous waste site remediation. HEL and DOE officials have discussed using the FMR as a test-bed to study issues such as end effector design, sensor selection, and teleoperation from a remote location.

HEL plans to conduct field demonstrations of the FMR to show the "user" community the potential of FMR technologies, to gain reliability data, and to study the use of machine work cells in an operational field environment.

3. FMR DESIGN SUMMARY

The FMR is a full-scale, electrohydraulically actuated, experimental manipulator (see Figure 1) ruggedized for use as a heavy lift robotics test-bed in the field. With the addition of the real-time control system (RCS) developed at NIST and the incorporation of ultrasonic range sensors and optical proximity sensors, this robot is capable of transferring autonomously in 6 minutes the same amount of materiel that a four-person crew using conventional forklifts could move in 30 minutes. In its present state, the operator drives the manipulator to a work site using the vehicle controls in the cab. After raising the vehicle onto its outriggers, the operator switches the system from travel mode to manipulator mode and uses the robot arm to download palletized cargo from arriving trucks onto conveyor systems at the work site.

The manipulator arm consists of a 3-degrees of freedom wrist developed by Moog, an end effector, upper arm and lower arm developed by MMA&NS, and a rotating base developed by Koehring Cranes and Excavators. The wrist provides pitch, yaw, and roll motion to the end effector using three seal-type, rotary vane, hydraulic actuators. The end effector is designed to efficiently handle a variety of palletized ammunition payloads by incorporating continuously adjustable tines and load cells for pallet and pallet weight identification. The arms were fabricated from optimally tapered ASTM-A710 steel skins minimizing weight while meeting high stiffness requirements. The arms are actuated by hydraulic motor-driven, high precision, low friction roller screws to provide axial stiffness and strength and positional accuracy, while maintaining low power consumption. To meet packaging requirements, the manipulator arm was designed to fold back for stowage between the cab and engine compartments on the rotating base.

The rotating base is mounted on a high stiffness bearing and actuated by a piston-type, hydraulic motor through an anti-backlash, dual pinion reduction drive. For each drive in the manipulator, special care was taken to mount the controlling servo valves as close as possible to their associated hydraulic motor-actuator, through specially designed manifolds, to minimize oil entrapment and maximize hydraulic stiffness. Each joint of the FMR is equipped with a resolver, a tachometer, and two pressure transducers to supply feedback to the servo level control system. In addition, limit switches are incorporated in the outer five joints have to prevent motion when hard stops occure. Moreover, a mechanical brake is used in each drive to assure fail-safe operation during loss of power.

The vehicle's undercarriage, which was built by Koehring, incorporates the trailing arm design from Standard Manufacturing, Inc., to achieve vibration and shock isolation for the delicate manipulator and on-board electronic components during travel mode. The four wheels on each side of the undercarriage are actuated with two hydraulic motors allowing speeds of 32 kilometers per hour (kph) on improved surfaces and 4 kph on 20% sloped surfaces. The suspension system enables the operator to control the height of each wheel independently so that the vehicle system can be leveled before deploying the outriggers. Once deployed, the wheels are lifted in order to put the weight of the FMR on the outriggers for stable manipulator operation.

The power sources for both manipulator and vehicle operation are split between the rotating base and the undercarriage. A Detroit diesel turbocharged 6V-53T engine, located on the rotating base, supplies 280 horsepower at 2500 revolutions per minute to drive four Abex piston pumps, also located on the rotation base. In manipulator mode, these pumps provide 31 to 76 gallons per minute (g/min) flow at 3000 to 3500 pounds per square inch (lbs/in^2), with one pump dedicated to each of the three hydraulic motors and with one pump dedicated to the wrist actuators and end effector as a unit. In travel mode, only two of the Abex pumps, providing 76 g/min at 4500 lbs/in^2, are used. A lever in the cab switches between the four-pump circuit and the two-pump circuit so that the same pumps can be used for both manipulator mode and travel mode.

When travel mode is selected, the manipulator hydraulic circuits are blocked and two of the pumps are re-routed to supply power to the right and left travel drives. A fifth pump, a utility pump, supplies power for the suspension and brakes on the undercarriage. All the pumps draw oil from a 90-gallon reservoir on the rotating base are pressurized to permit pump operation at maximum engine speed without inlet cavitation. The power required to operate the electronics for manipulator operation is supplied by a diesel driven 7.5 kw Onan auxiliary generator on the undercarriage. A rotary hydraulic manifold and an electrical slipring allow for the passage of hydraulic and electric power between the rotating base and the undercarriage while also allowing for continuous base rotation.

The hydraulic circuits were carefully designed to maintain system integrity. A 125-hp, engine-cooled radiator is used to maintain a nominal hydraulic oil temperature of 170° Fahrenheit, and special valving restricts flow at the lower temperatures while allowing free flow at high temperatures. Full flow return filters maintain contamination levels well within the requirements of the valves and rotating equipment, while bypass valves protect return line components. Similarly, a pump suction strainer and bypass valve system screen out contaminants disturbed in the reservoir by vibrations. Manifold-mounted blocking valves, cross-port relief valves, and anti-cavitation valves protect the actuation systems during emergency stopping and back-driving conditions. Mechanical brakes are protected from the violent hydraulic loads encountered during an emergency stop by closing blocking valves before the actual application of the mechanical brakes.

The operator interface, located in the cab mounted on the rotating base, includes a video monitor, two joysticks, an emergency stop switch, an array of lighted pushbutton switches and indicators, and engine-vehicle functions. The video monitor is switch selectable for displaying either system status information and prompts or for displaying video from end effector cameras. The joysticks each have 3-degrees of freedom for controlling pallet motion, thumb switches to control cursor motion on displays with system prompts, and a grip sensor switch as a "deadman" safety feature to allow the control system software to distinguish between desired and inadvertent joystick movements. The emergency stop switch is a large, red, mushroom-capped, two-position pushbutton used to halt all system functions. Other switches include one for resetting the system after a stopped condition and one for temporarily pausing system operation. The pause switch stops low level servo control, applies the mechanical brakes, and allows immediate resumption of operation if desired. The indicators are used to display status pertaining to brake engagement, emergency stop or pause conditions, and travel or manipulator mode operation. The controls for engine and vehicle functions include a steering wheel, throttle, and status displays of critical engine data such as oil temperature, filter pressures, and fluid levels.

The electronic control system, also mounted on the rotating base, is contained in a weatherproofed, thermally managed enclosure. The electronic control system for the FMR is a distributed microprocessor based system which implements all required levels of control. Most of the 54 boards in the system, 24 of which are single board computers, were custom designed to optimize the processing required to capture of sensor data and to transmit actuation signals. However, the complex control algorithms were all implemented on off-the-shelf boards including several of Intel's iSBC 386/31 and 386/21 single board computers. Hence, it is possible to modify the software on these boards to implement new algorithms without having to know special hardware functions.

The electronic control system is divided into four major subsystems: (1) the autonomous RCS developed by NIST (not currently integrated) used for generating autonomous motion commands from end effector sensor data; (2) the manual control system (MCS), used for generating motion commands from joystick inputs and for coordinating overall system operation; (3) the servo level control system used primarily for tracking the motion commands from either the RCS or MCS; and (4) the safety control system which is responsible for monitoring redundant system safety functions. Each subsystem is physically separated on individual back planes. A high speed, serial data link provides communications between subsystems.

Each subsystem contains a serial communication controller board which provides the necessary protocol and message overhead functions for a 4-megabit per second, token-passing, ring topology local area network developed in accordance with the IEEE 802.5 standard. The task of each subsystem is further divided into subtasks and implemented on the aforementioned single board computers. This distributed architecture allows every board within a subsystem to process data independently and share results at least once during the system-level 20-millisecond (ms) communication cycle.

The lowest level boards communicate at a rate of once every 5 ms. Test functions are provided on most of the single board computers to diagnose component failures on the board or to diagnose inconsistencies with correct system operation. A remote pendant designed into the system provides additional safety. This pendant contains remote start and stop controls for the main diesel engine and redundant emergency stop and pause pushbuttons. The electrical signals for the remote pendant pass through the electrical slip ring. A fiber optic slipring can support an enhanced remote control station consisting of two joysticks controls and video feedback.

4. CONTROL SYSTEM ARCHITECTURE

The overall control system architecture for the FMR is based on research about developing architectures for intelligent machines started at NIST in the early 1970s. The NIST paradigm for such architectures is the hierarchical controller [BA]. The role of any level in the hierarchy is to break complex tasks into simpler subtasks to be executed by the next lower level. This approach minimizes the complexity of any single level, promotes modular development of software with robust interfaces, and is highly suited for multiprocessing environments.

The system architecture for the FMR is shown in Figure 3. The system consists of the four major subsystems: the autonomous control system (ACS), the MCS, the servo level control system, and the safety control system.

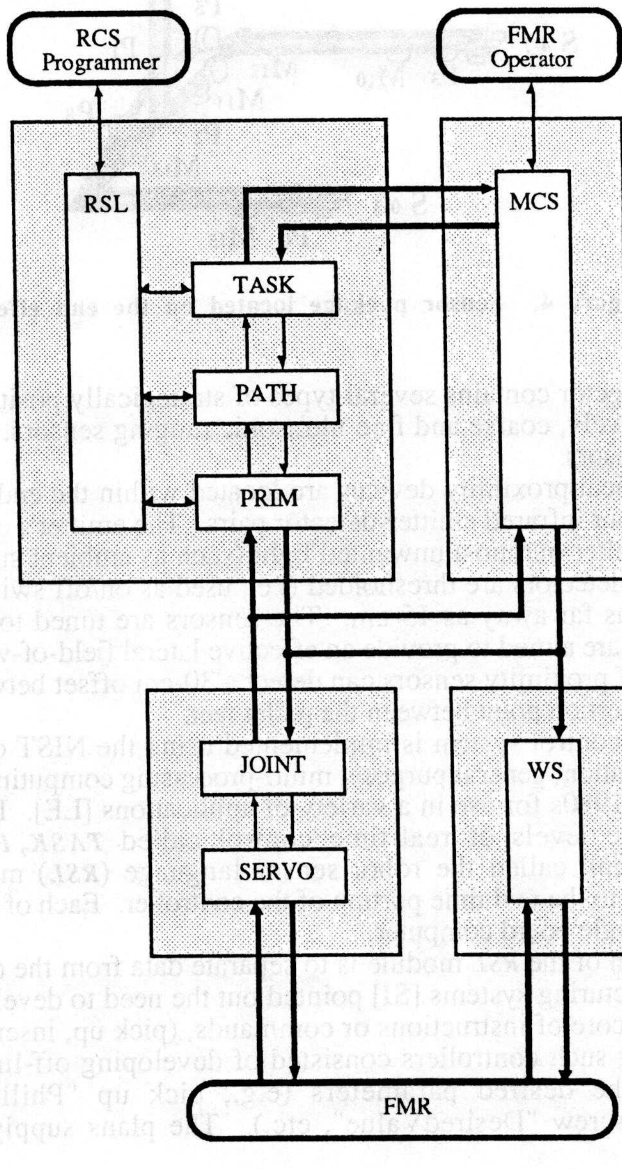

Figure 3. The control system architecture FMR.

Autonomous Control System

The purpose of the FMR ACS is to acquire pallets automatically (i.e., locate the pallet and insert the fork tines) and to transfer pallets within the work cell. The system developed by NIST consists of a sensor package and a second generation RCS (RCS-2) computing platform.

The sensor package consists of several ultrasonic ranging devices and two arrays of optical proximity devices strategically mounted on the FMR's end effector as depicted in Figure 4. The ranging devices are clustered into two groups: a forward looking cluster is used for aligning with the pallets, and a downward looking cluster is used for aligning with truck beds. Two types of range sensors are employed. A low resolution sensor (operating range of 25 cm to 3 m, 0.25 cm resolution, ±10° field-of-view) provides coarse acquisition of surfaces, and a high resolution sensor (operating range of 5 cm to 35 cm, 0.08 cm resolution, ±8° field of view) is used for fine acquisition.

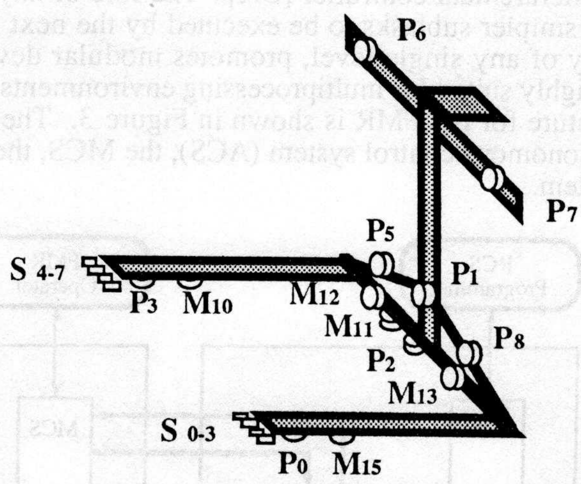

Figure 4, Sensor package located on the end effector.

The FMR end effector contains several types of strategically positioned sensors. The P and M sensors are, respectively, coarse and fine ultrasonic ranging sensors. The S sensors are arrays of optical proximity sensors.

The arrays of optical proximity devices are located within the ends of each fork tine. Each array is comprised of four infrared emitter-detector pairs. The emitter's energy is modulated which allows the detector to filter out most unwanted light (such as ambient sunlight), providing a more robust operation. The detectors are thresholded (i.e., used as on/off switches) to receive reflected energy from surfaces as far away as 15 cm. The sensors are tuned to detect the pallet support structures at 10 cm and are aimed to provide an effective lateral field-of-view of approximately ±15 cm. Thus, the arrays of proximity sensors can detect a 30-cm offset between the end effector fork tines and the desired insertion point between the pallet feet.

The autonomous control system is implemented using the NIST computing platform. The RCS-2 is a second generation, general purpose, multi-processing computing environment that NIST developed in the early 1980s for use in a variety of applications [LE]. In the FMR hierarchy, the RCS consists of three levels of real-time control called ***TASK***, ***PATH***, and ***PRIM***, and a programing environment, called the robot sensor language (***RSL***) module, which provides a language and interfaces to the real time portion of the controller. Each of these components runs on a separate Intel 8086 single board computer.

One main function of the ***RSL*** module is to separate data from the controller. Early research about complex manufacturing systems [SI] pointed out the need to develop robust controllers that can reliably perform a core of instructions or commands, (pick up, insert, torque screw, etc.). At that time programming such controllers consisted of developing off-line plans that "called" the specific tasks with the desired parameters (e.g., pick up "PhillipsScrewDriver", insert "ScrewXYZ", torque screw "DesiredValue", etc.). The plans supply the data that drive the controller.

Each level in the FMR has its own command set. The primary ***TASK*** level command, **TRANSFER**, is used to move pallets from a source location to a destination location. Each **TRANSFER** command is broken into subcommands such as: **APPROACH_PICKUP**, **DEPART_PICKUP**, **APPROACH_RELEASE**, and so forth. These commands are sent to the ***PATH*** level. The ***PATH*** level retrieves the plans (stored in common memory by the ***RSL***) which specify how to execute an **APPROACH_PICKUP**. Each plan is uniquely identified by the command parameters; for example, the plan for **APPROACH_PICKUP** "155 PALLETS" will have a different set of instructions than for "BOXED AMMUNITION." Beside the FMR plans, the RSL module also maintains other important data, such as predefined locations in the FMR work space and models of the different sensors.

A general **APPROACH_PICKUP** plan consists of a sequence of path point commands (PPC). The basic PPC is the **goto** command. A sequence of **goto** commands is used to *teach program* the FMR. Each **goto** command, with the destination goal pose and motion parameters, is sent to the ***PRIM*** level where trajectories that take the end effector from the current pose to the goal pose are generated. The ***PRIM*** level calculates intermediate goal poses, typically along Cartesian straight lines within the position, velocity and acceleration limits of the motion parameters, once every 20 ms. Each intermediate goal is sent to the servo level control system which drives the end effector along the desired trajectory. It is important that the ***PRIM*** level must generate a correct new pose every 20 ms. If the ***PRIM*** level misses a cycle and the same pose is output consecutively while the end-effector is moving at a high speed, the robot will execute an instant deceleration causing potential damage to system components. The role of the safety control system is to detect such errors and override normal control.

Teach programming the FMR is not adequate for acquiring pallets autonomously. Special PPT commands employ the various sensors to analyze the environment, define the surface of the truck bed, locate edges of pallets, locate the correct entry side of a pallet and so forth. The **range** and **equate** commands illustrate the basic capabilities of the sensors. The pertinent **range** command parameters are the sensor name, a coordinate vector specifying direction and a desired range. During execution of the **range** command, the ***PATH*** level requests range data from the sensor processor, calculates a goal pose based on the current range and the input parameters, and sends the command to the ***PRIM*** level. While the ***PRIM*** level is generating the intermediate goals poses, the ***PATH*** level continues to execute the range command (in parallel with the ***PRIM*** level) until the desired range is achieved. The **range** command is used to move the end effector to a specific height above the trailer bed. Like the **range** command, the **equate** command uses two range sensors. In the **equate** command, the difference between two range readings is used to calculate a rotation about the specified coordinate vector. The **equate** command is used to adjust the pitch and roll of the end effector with respect to the trailer bed.

Manual Control System

The MCS provides the sole interface to the operator and controls the operational state of the FMR system. This subsystem continuously monitors manipulator status and displays the appropriate information on the monitor in the cab. The MCS was designed to be compatible with the RCS and overrides the RCS only when the operator selects a manual mode option or when unsafe conditions arise. In manual mode, the operator moves the manipulator from the cab using the two 3-degrees of freedom joysticks. The individual joints may be controlled directly in this way, or the operator may select a tool frame of reference in which the three translational and the three rotational degrees-of-freedom of the payload can be controlled directly by the joysticks. The resulting joystick motions are interpreted as velocity commands by the MCS as it generates trajectory data. For safety purposes, manual motion speeds are restricted. Only in the autonomous mode, when the operator is not permitted in the cab, are full payload speeds as fast as 120 inches-per second allowed.

In addition to velocity constraints, there are mechanical design constraints imposed by accelerations, and third-derivative constraints are applied to improve the tracking accuracy of the servo level control system by generating additional smoothness in the resulting commands. Joint space velocity commands from the joysticks are processed by a non-linear filtering algorithm to achieve these constraints precisely. Tool space velocity commands are first converted into the equivalent joint space velocity commands, using an inverse Jacobian approach, and then processed by a non-linear filtering algorithm which includes a scale back feature to achieve the constraints precisely, while accurately preserving tool space directions. In either case, the resulting commands are passed down to the servo level control system after being passed through the FMR forward kinematics to obtain world space commands that are compatible with those generated by the RCS.

Servo level Control System

The primary objective of the servo level control system is to follow the commands generated by the MCS (or the RCS, once it is integrated and the autonomous mode is selected). To do this, world space commands are passed through the FMR inverse kinematics to obtain the equivalent joint space trajectory and to scale back the commands if any velocity or acceleration constraints are exceeded (this is only likely if the commands were RCS generated). The commands are then interpolated, smoothed, and differentiated to produce the desired joint positions, velocities, and accelerations, which are passed to a sophisticated feedback control algorithm to produce the commands to the servo valves for each drive.

The 6-ton arm can pick up two tons. This payload-to-arm weight ratio of 1:3 introduces significant dynamic effects, including both structural and hydraulic vibrations, which must be considered in the development of robust low level, closed loop control algorithms. Controlled flexibility is necessary if the robot arm is to be light enough to transport and power in the field. In addition, such structurally flexible manipulators offer the advantage of faster response times and lower production and operation costs because of smaller actuators, smaller power supplies, and less arm material. The FMR low level control system successfully handles these flexibility effects as well as the complexities of having closed kinematic chains, tightly coupled, and highly non-linear rigid-body interactions among the joints, electro-hydraulic actuation, and load and speed-dependent friction.

The FMR trajectory tracking controller follows trajectory commands accurately through the application of a non-linear feedback control strategy that uses internally generated mathematical models (i.e., inverse dynamics) and local sensory information (e.g., resolver data) to adapt to some of the time-varying properties of the robotic system. The FMR controller includes a highly accurate, predominantly feed forward-type control signal as verified through extensive open loop testing of the manipulator. Accurate feedforward control allows lower feedback gains since tracking errors are small and prevented from accumulating. The lower feedback gains, in turn, result in decreased interactions with low-frequency structural and hydraulic modes of vibration, thereby increasing stability and accuracy. Moreover, the adaptive properties of our "feed forward" algorithm results in rapid adjustments of unexpected variations in variables not easily known (e.g., payload) or controlled (e.g., pump pressures).

In addition to its primary function, the servo level control system includes a tine spacing controller, a pump pressure controller, a payload weight estimator, and a large variety of monitoring functions including additional constraint checks and failure detection. Limits of torque, power and joint position are checked and produce either a slowing of manipulator motion or an emergency stop as appropriate. Failure indications such as large following errors, large reductions in pump pressure or engine speed, loss of critical sensors or electrical power, severe underloading or overloading of the tines, communication and processing faults, and potential collisions between the manipulator and itself or its environment, always shut down the system through the application of an emergency stop.

Safety Control System

The safety control system (SCS) adds redundancy to the failure detection in the other subsystems by duplicating all the critical error checks in a separate subsystem. The SCS includes a redundant electrical network to monitor and use certain sensors such as the joint resolvers. The most significant duplication is the forbidden volume processor. This board uses internally generated polytopic and half space models of vehicle, manipulator and work space objects to detect impending collisions.

An on-board algorithm [GI] is used to precisely calculate the distances between all potentially colliding object pairs, and to shut the system down if either objects become too close to each other or approach each other at too great a speed. Whereas the safety control system uses real resolver measured joint positions to kinematically calculate object locations, the forbidden volume processor in the servo-level control system uses commanded joint positions to perform these calculations.

5. DEMONSTRATED CAPABILITIES AND CURRENT WORK

Manual Motion Test bed

A variety of fully coordinated maneuvers employing motion in all six joints of the FMR manipulator was used in testing the electronic control system, with emphasis placed on the lowest level control algorithms. A real time data-acquisition system on board the FMR collected sensor and command data so that proper evaluation and refinement of the controller could occur. Plots of tracking accuracy for each maneuver indicated good performance over a large range of maneuver speeds and payload weight.

Field testing at the U.S. Army Aberdeen Proving Ground (APG) was conducted in October 1990 as part of the annual U.S. Army Materiel Command's (AMC) Technology Exposition. Coordinated closed loop control of all six axes, as well as successful pallet acquisition, transfer, and release under manual mode were first publicly demonstrated at that time.

Autonomous Motion Test-bed (FMR-X)

In parallel with the design and fabrication of the FMR, NIST developed a test-bed, called FMR-X (eXperimental), to characterize the high level control system and sensor package. Initial work was performed with a Puma 760 robot, whereas the current configuration uses a Unimate 4000 robot. The Unimate robot has a work envelope and payload capacity sufficient to handle full sized, light weight mockups of 155-mm ammunition pallets. The robot, during various phases of testing, has been mounted on a trailer flatbed, both indoors and outdoors, and on concrete floors.

The FMR-X autonomous control system differs slightly from its implementation on the FMR. Comparing the FMR-X to the FMR architecture (see Figure 3), the ***JOINT*** level resides within the RCS (as opposed to the servo level control system). The ***SERVO*** level resides in the control system provided with the Unimate. A serial line interface (called SLAVE) is used to send and receive joint angles once every 28 ms. In addition, the upper interface to the ***TASK*** level is a terminal from which the operator types in the task command (as opposed to receiving commands from the MCS via network communications).

The FMR-X currently resides at the HEL's robotics laboratory, at APG, Maryland. It supports algorithm development, demonstrations, and future integration with the FMR.

RCS Integration with the FMR

Current efforts seek to integrate the ACS and the RCS with the manual motion controllers in the FMR. The modularity of the hierarchical controller simplifies this integration demonstrated by the ease with which the controller was transitioned from the Puma robot to the Unimate robot. In this case, only the kinematic transformations performed by the ***JOINT*** level had to be changed. No changes were made in the ***PRIM*** , ***PATH*** , and ***TASK*** levels.

The ***JOINT*** level was included in the FMR electronic control system design, as part of the servo level control system to support Cartesian based commands from both the ***PRIM*** level and the MCS. The interface between the ***PRIM*** and ***JOINT*** level remains functionally identical. Work is also continuing in modifying the ACS to communicate via the fiber optic network. The network provides the communications link to both the ***TASK*** and ***PRIM*** levels.

6. CONCLUSIONS

The FMR-T provides a wide range of benefits to the U. S. Army's logistics community, to others whose tasks are to handle hazardous materials, and to general heavy materials handling in the field. The forklift has existed for many years, and it has even been programmed for automated operation. However, the FMR has matured technology for use in the field, and the FMR-T program could significantly advance the state of the art of heavy lift material handling. The FMR demonstrated manual control in 1990, and the high level controller is internally integrated and ready to be implemented on the FMR.

7. ACKNOWLEDGEMENTS

The authors wish to recognize the accomplishments of the people associated with the development of the FMR. We commend the current MMA&NS technical team: Mr. Edmund N. Holt II, who developed the system level requirements and was responsible for all the early system level testing; Dr. John J. Murray, who was responsible for developing efficient, accurate mathematical models for both the simulation studies and the final on-board controller; Mr. Peter R. Peterman, who was the chief architect of the hardware used in the electronic control system; Ms. Karen Goodrich, who developed most of the software design for more than 100,000 lines of code in the present system; and Mr. Thomas P. Andreychek, who conducted the final system level testing and mechanical engineering. We also commend the fine work of the primary FMR program manager, Dr. Abraham Orbach (formerly of MMA&NS), and thanks to Mr. Roger Kilmer of NIST and Mr. Harry McCain (formerly of NIST) for their consistent support throughout the developmental process. We especially acknowledge the contributions of Mr. John Stephens and Mr. Chuck Shoemaker, of HEL, who initiated the FMR program and led its development.

REFERENCES

[BA] Barbera, A. J.; Albus, J. S.; and Fitzgerald, M. L.; "Hierarchical Control of Robots Using Microcomputers", Proceedings of the 9th International Symposium on Industrial Robots, Washington, DC, March 13-15, 1979.

[SI] Simpson, J. A.; Hocken, R. J.Albus; "The Automated Manufacturing Research Fa:ility of the National Bureau of Standards", Journal of Manufacturing Systems, Vol. 1, Number 1, 1982.

[LE] Leake, S. A.; Kilmer, R. D.; "The NBS Real-time Control System User's Reference Manual", Ver 2.2c, August 1988.

[GI] Gilbert, E. G.; Johnson, D. W.; Keerthi, S. S.; "A fast procedure for computing the distance between complex objects in three dimensional space", IEEE Journal of Robotics and Automation, Vol. RA-4, pp. 193-203, 1988.