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A HIERARCHICALLY CONTROLLED AUTONOMOUS ROBOT FOR HEAVY PAYLOAD MILITARY FIELD APPLICATIONS

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The U. S. Army Human Engineering Laboratory, with assistance from the National Bureau of Standards, Robot Systems Division, is developing a heavy-lift pallet handling robotic system designated as the Field Materiel-Handling Robot (FMR). The initial demonstration of the FMR will be the sensor-driven autonomous acquisition and high speed manipulation of pallets of artillery ammunition. This paper describes the FMR research and development project with emphasis on the robot control architecture and the sensor-driven autonomous operational capabilities.

1. INTRODUCTION

The U.S. Army has an interest in applying robotics technology to reduce traditionally labor intensive functions associated with the handling of logistics materiel in the theatre of operations [1]. One of the major Army programs designed to address the application of such technology is the Field Materiel-Handling Robot, or FMR, project. The FMR is a heavy-lift pallet handling robotic system with sensor-driven autonomous capabilities. The primary goal of this project is to implement advanced robotics and related technological developments in sensory-based controls, man-machine interfaces, etc., in the form of a test bed system capable of performing unmanned, fully robotic Army field materiel handling tasks. The initial demonstration of the FMR will be the autonomous acquisition and high speed manipulation of pallets of artillery ammunition weighing up to 4000 lbs. (1814 kg) and located at distances up to 25 ft. (7.6 m). These capabilities are beyond the current state of the art for robotic systems.

There are three key organizations involved in the FMR project. The lead organization and sponsoring agency is the Human Engineering Laboratory (HEL), which is part of the U. S. Army Laboratory Command. The primary contractor is Martin Marietta Baltimore Aerospace (MMBA). MMBA is responsible for design, development and fabrication of the mechanical hardware and lower levels of control, including the servo controls. MMBA is also responsible for final integration and testing. The third organization is the Robot Systems Division of the National Bureau of Standards (NBS). NBS is developing the end-effector sensor package (used to locate and acquire pallets) and the higher levels of control which utilize sensor feedback to do real-time modification of the path of the FMR.

The next two sections briefly describe the operational and system design requirements of the FMR. After that, a discussion of the FMR control system architecture and design is presented. This is followed by a description of the research and development work performed by NBS on the end-effector sensors and higher levels of control and is concluded by a discussion of the status of the project.

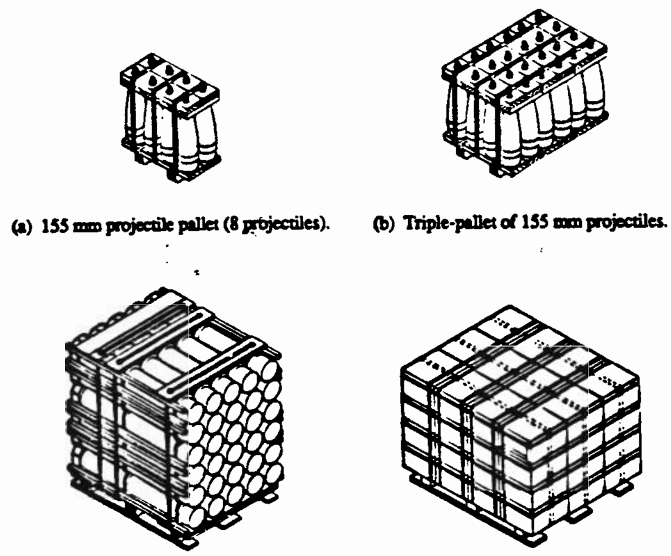
2. FMR SYSTEM OPERATIONAL REQUIREMENTS

The general operational requirements for the FMR were developed using the task of unloading pallets of ammunition from transport vehicles as one of its primary functions [2]. These requirements were also based upon a number of studies conducted by HEL regarding current field operations, type of ammunition most commonly used, necessary throughput, etc. [3].

2.1. Payload Description

The FMR is required to handle three specific types of palletized ammunition. However, the system is designed to permit acquisition, engagement and transfer of other types of palletized loads. The three specific types are: 155 mm separate loading projectiles (eight rounds per pallet), pallet-based loads consisting of 105 mm boxed ammunition (30 metal containers), and pallet-based loads consisting of boxes of .50 cal ammunition (48 boxes). Sketches of these pallet configurations are shown in Figure 1. The one additional configuration shown in this figure that the FMR will handle is three of the 155 mm pallets banded together as a unit. The weights of these four configurations are: 155 mm -- 800 lbs. (363 kg) each, 2,400 lbs. (1,089 kg) for three, 105 mm -- 2,528 lbs. (1,147 kg), and .50 cal -- 3,883 lbs. (1,761 kg).

The 155 mm pallets are two-way entry pallets, i.e., the fork tines can be inserted under the pallet from only two directions. The two pallet-based loads are four-way entry. In all cases, the semitrailer loads will be of the same pallet configuration, i.e., no mixing of individual and banded 155 mm pallets and no mixing of 155 mm, 105 mm, and .50 cal pallets. Also, all blocking and bracing (dunnage) will be manually removed prior to unloading by the FMR.



(a) 155 mm projectile pallet (8 projectiles). (b) Triple-pallet of 155 mm projectiles.

(c) 105 mm ammunition pallet (30 containers). (d) .50 cal pallet (48 boxes).

Figure 1. Illustration of the four pallet configurations.

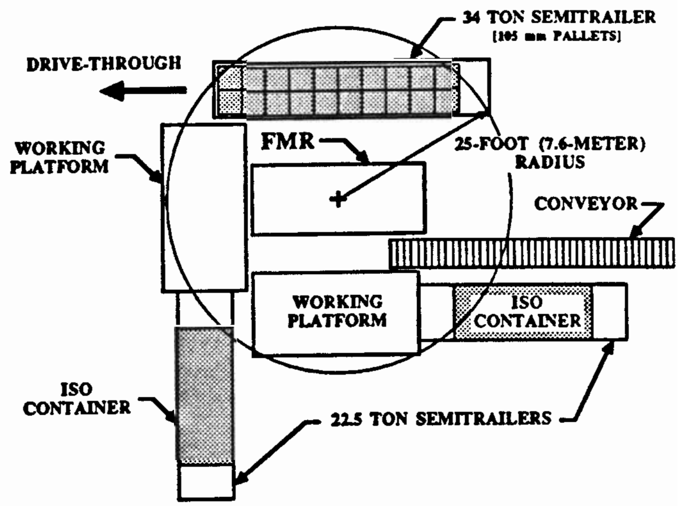


Figure 2. Example of possible workstation layout.

2.2. Workstation Layout

Although the final workstation configuration has not been established (this will be done by MMBA after evaluation of various trade-offs), Figure 2 illustrates an example of a possible workstation layout. The workstation consists of two slip-sheet working platforms, a semitrailer drive-through area, an output conveyor and the FMR. Pallets are delivered to the workstation either in ISO containers loaded on semitrailers or directly on flat-bed semitrailers. Pallets loaded in ISO containers are pulled out of the container on a slip-sheet and onto the working platform. The pallets are unloaded from these three work sites by the FMR and transferred to the conveyor. From the conveyor, the pallets are put in temporary storage or transferred to another ammunition resupply vehicle.

For this scenario, the FMR is unloading and transferring pallets at heights typical of truck beds [approximately 56 in. (1.4 m)]. Since other applications may not involve this exact scenario, the FMR is also required to handle pallets located on the ground.

2.3. System Design Requirements

Satisfying the operational requirements for the unloading of palletized ammunition just described establishes a number of system design requirements. These requirements relate primarily to the reach, payload and operational performance of the FMR.

2.3.1. Mechanical Design

The FMR must handle very heavy loads over long distances and be capable of operating at as many as three work sites without moving, i.e., parked in one spot. The two primary factors driving the mechanical design are the payload and operational work volume requirements. The FMR must handle payloads up to 4000 lbs. (1813 kg) at distances out to 25 feet (7.6 m) and heights ranging from the ground to truck bed height [approximately 56 in. (1.4 m)]. This places some severe design requirements on the FMR.

The specific requirements, which must be met when carrying the maximum payload of 4000 lbs. (1813 kg), are as follows [2]:

(1) The manipulator shall have no less than six degrees of freedom (three translational and three rotational).

(2) The horizontal reach shall be no less than 25 ft. (7.6 m) from the principal manipulator rotational axis to the end-effector mounting surface.

(3) The minimum horizontal reach shall be no more than 10 ft. (3.0 m) from the principal manipulator rotational axis to the tip of the end-effector tines.

(4) The upper limit of vertical reach shall be no less than 9 ft. (2.7 m) above ground level.

(5) The lower limit of vertical reach, with the end-effector tines parallel to the ground, shall be no less than 6 in. (15.2 cm) below the ground plane at a horizontal reach of 10 ft. (3.0 m).

(6) The manipulator rotation about the principal axis shall be no less than 375 degrees.

(7) The FMR must weigh less than 50,000 lbs. (22,680 kg).

The requirement for the end-effector is that it provide some means of load engagement for the various types of palletized payloads. Implied in this is the requirement that the end-effector be capable of carrying the maximum payload and provide a means for adjusting for different size pallets. The FMR end-effector is a fork with two tines. The positions of the tines are servo-controlled to adjust the spacing according to the type of pallet being acquired.

2.3.2. Operational Performance

The operational performance requirements are specified in terms of cycle time and end-effector positional accuracy and repeatability. These requirements are given as a function of payload, velocity and acceleration.

The cycle time is specified for the autonomous operational scenario previously described. The time allotted corresponds to the total time it takes for any transfer cycle, starting when the tines are retracted from a pallet placed on the conveyor until the next pallet is set down on the conveyor. For payloads less than 2600 lbs. (1179 kg), the maximum cycle time is 20 seconds. For payloads between 2601 and 4000 lbs. (1180 and 1814 kg), the cycle time is load dependent and can vary up to a maximum of 45 seconds for the maximum payload of 4000 lbs. (1814 kg).

The positional performance requirements are given in terms of the maximum deviation of the actual location of the end-effector relative to the commanded location. The maximum deviation is specified as a function of velocity and acceleration. The reason for this is that during high speed, high acceleration operations, e.g., rotating from the working platform to the conveyor, exact positioning of the manipulator is not critical. However, for low speed, low acceleration operation, e.g., setting the pallet on the conveyor, finer control of the manipulator position is important.

Tables 1 and 2 give the maximum deviation (± x in inches) as a function of velocity (v_x) and acceleration (a_x) for unloaded and loaded conditions, respectively. These tables give the required repeatability along the x axis. The same values apply for motions along the y and z axes. The absolute accuracy requirement is ± 5 in. (± 12.7 cm); however, this only applies when the manipulator is stationary (i.e., $v_x = 0$ and $a_x = 0$).

To further illustrate this, the x-coordinates of a typical trajectory are shown in Figure 3. This trajectory is for a simple move in which the x-coordinate changes from a stationary value at x_1 to another stationary value at x_2. The commanded trajectory consists of a set of x-coordinates, a new value approximately every 20 msec. The error bounds defined in the tables are illustrated by the curves above and below the commanded trajectory. In the regions where the commanded x-coordinate value is stationary ($v_x = 0$ and $a_x = 0$), the error bound is small. In regions where the commanded x value is changing ($v_x \neq 0$), or where the slope of the commanded x value is changing ($a_x \neq 0$), the error bound is larger. The actual value of x is required to be inside the error bounds at all times. Thus, these error bounds define the following error, overshoot, and settling time that is allowed at any point in the trajectory.

2.3.3. Mobility/Transportability

The FMR is designed to be mobile so that it can be driven to the pallet unloading work site. The specific requirements are: a minimum travel speed of 15 mph (24 km/h) unloaded and with the manipulator stored (a speed of 20 mph (32 km/h) on paved road is desired), capable of traveling at any heading on a 20% slope with a

Table 1. Maximum position deviations -- no load.

Velocity, v_x, in./sec.	Acceleration, a_x, in./sec.^{2}					
	0	1	3	10	30	>30
0	0.2	0.4	0.6	1.0	3.0	5.0
1	0.4	0.6	1.0	3.0	5.0	7.0
3	0.6	1.0	3.0	5.0	7.0	9.0
10	1.0	3.0	5.0	7.0	9.0	11.0
30	3.0	5.0	7.0	9.0	11.0	13.0
>30	5.0	7.0	9.0	11.0	13.0	15.0

NOTE: Table values correspond to ± x in inches.

Table 2. Maximum position deviations -- loaded.

Velocity, v_x, in./sec.	Acceleration, a_x, in./sec.^{2}					
	0	1	3	10	30	>30
0	1.0	2.0	3.0	5.0	7.0	10.0
1	2.0	3.0	5.0	7.0	10.0	12.0
3	3.0	5.0	7.0	10.0	12.0	14.0
10	5.0	7.0	10.0	12.0	14.0	16.0
30	7.0	10.0	12.0	14.0	16.0	18.0
>30	10.0	12.0	14.0	16.0	18.0	20.0

NOTE: Table values correspond to ± x in inches.

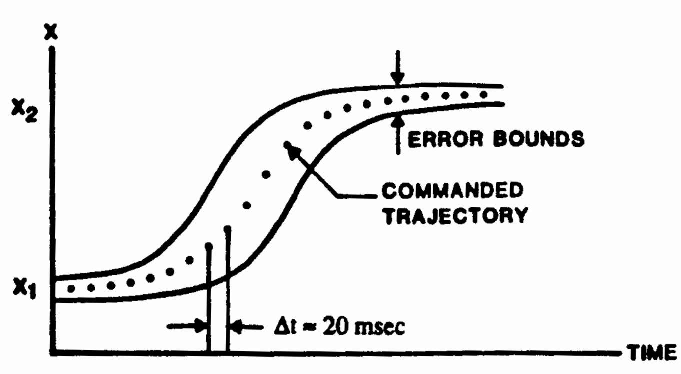


Figure 3. Example of commanded trajectory and allowable error bounds.

minimum speed of 2.5 mph (4 km/h), and moderate off-road cross-country mobility.

In terms of transportability, the requirements are that it must be capable of: (1) being towed; (2) highway movement worldwide when loaded on a U. S. Army M871 semitrailer; and (3) meeting C141 aircraft cargo volumetric and weight constraints [L = 840 in. (2,134 cm), W = 123 in. (312 cm), and H = 109 in. (277 cm) and less than 50,000 lbs. (22,680 kg)].

3. AUTONOMOUS CAPABILITIES

The FMR is required to perform autonomous location, acquisition and transfer of pallets of ammunition. The sensors required to perform these tasks and a more detailed breakdown of the operational scenario are presented below.

3.1. Sensor Configuration

The sensory requirements discussed here are those necessary for autonomous acquisition of pallets. These sensors are mounted on the end-effector. The general requirements for these sensors are to provide data to permit the following: (1) level the end-effector with the working platform or truck bed; (2) locate the pallet or array of pallets; (3) orient the end-effector with the pallet to be acquired; (4) insert the tines without hitting the pallet; and (5) verify that the pallet is on the end-effector.

The necessary data are obtained using eight acoustic ranging sensors, five forward-looking and three down-looking, and optical proximity sensors at the tip of the tines and at the base of the fork. The basic sensor configuration is illustrated in Figure 4. The acoustic ranging sensors provide range information with a resolution of approximately 1/4 in. (0.64 cm) over a range of 1 to 10 ft. (0.3 to 3.0 m). The down-looking acoustic sensors are used to level the end-effector with the truck bed. The forward-looking acoustic sensors are used to locate the pallet and orient the end-effector with it. The optical proximity sensors are close range [maximum of 4 in. (10.2 cm)] and supply only binary information. That is, the output of the sensor changes state when it crosses a preset threshold range. The optical sensors at the tip of the tines are used for fine centering adjustments before tine insertion under the pallet and for guidance adjustments as the tines are inserted. The optical sensor at the base of the fork is used to verify that the pallet is on the end-effector.

3.2. Autonomous Operational Scenario

The primary function of the FMR is to autonomously unload truck loads of ammunition to a conveyor system. This is accomplished in individual steps in which a single pallet (or a group of pallets strapped together) is unloaded. The basic operational scenario of the FMR is as follows: assuming the FMR has just placed a pallet of ammunition on the conveyor, it must swing to the approximate location of the next pallet, use sensory feedback to determine the precise location of the pallet, pick up the pallet, deliver it to the conveyor and set it down.

These steps are carried out autonomously with extensive use of sensor feedback to adapt manipulator motion to the variations in the task environment. A more detailed

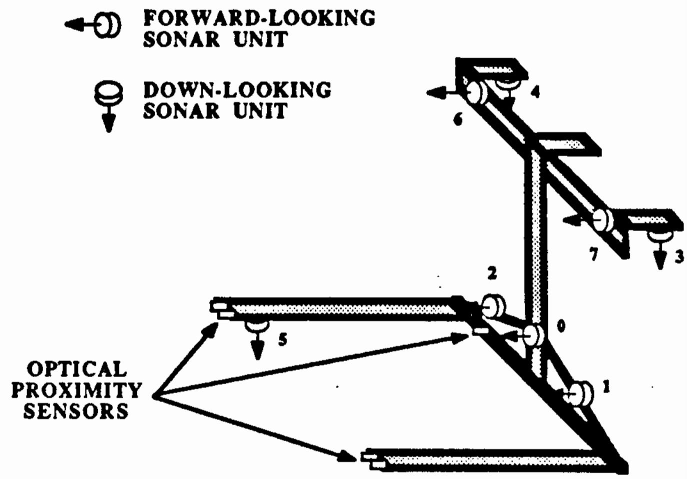


Figure 4. End-effector-mounted sensor configuration.

description of the task scenario is listed below:

(1) Move to a known starting position.

This is only necessary at the beginning of the entire unload task.

(2) Orient the fork with the truck bed or working platform.

This is also only necessary at the beginning of the unload task and allows the FMR to level the fork with a new truck bed or previously unaccessed work platform. This is done with the aid of the down-looking fork-mounted ranging sensors. Once this is accomplished, the FMR can retain this information for the entire unloading process.

(3) Scan the truck searching for a pallet.

The use of this step depends on the payload configuration. If each pallet in the truck load is randomly oriented then this step is required each time. The strategy employed is that the FMR sweeps its end-effector past the entire load and employs its forward-looking ranging sensors to determine the approximate location of the closest pallet. This closest pallet is then selected as the next to be unloaded.

The scan step is not required for each pallet in the case of tightly configured array of pallets. In this case, the FMR is informed in advance as to the configuration of the array and it then only requires one scan to determine the position and orientation of the array. It then indexes through the array one pallet at a time using a priori knowledge of the relative spacing of the pallets in the array.

(4) Move into position in front of the selected pallet.

This position is required to be at an appropriate distance from the selected pallet so that more precise sensor positioning of the fork can be accomplished before tine insertion is attempted. The position is determined from the sensor data collected during the scan step for random pallets. It is an indexed relative position for all but the first pallet in the case of an array.

(5) Determine the entry side of the pallet.

Some pallet types only provide for fork tine entry from two sides rather than all four sides, e.g., 155 mm pallets. Therefore, in the case of randomly oriented pallets of this type it is necessary to determine the proper entry side before proceeding. The strategy here is to use the sensors to determine the long side of the pallet since the two-way entry pallets are not square but have a rectangular base and are entered on the longer side.

(6) Orient the fork to the entry side for fork insertion.

Once the entry side of the pallet is established, the fork must be properly oriented for tine insertion. Sensor feedback is used to get the end-effector centered on the pallet and normal to it. The sensors are then used to determine the precise location of the pallet feet and thus the entry location.

(7) Insert the fork tines.

The fork tines are now inserted under the pallet. Proximity sensors on the tine tips are used to guide this motion.

(8) Lift the pallet and retract.

The pallet is lifted and retracted along the same path as the entry was accomplished. The fork is then tilted back to assure retention of the pallet during transit to the conveyor. There are sensors on the fork to verify that the pallet is still in place.

(9) Move to the conveyor and place the pallet on it.

Since the conveyor is fixed in the FMR work area this move is to a taught location and requires no sensor feedback information.

4. CONTROL SYSTEM ARCHITECTURE AND DESIGN

The basis for autonomous operation of the FMR is a hierarchically structured control system developed at NBS. This control system architecture permits the decomposition of the control system into relatively simple modules with well defined functions. The control system currently consists of four major elements each of which has several sub-elements. The four major elements are: (1) the Real-Time Control System and end-effector-mounted sensor package, developed at and supplied by NBS to MMBA, (2) the FMR Manipulator Controller to be developed by MMBA as an integral element of the FMR manipulator, (3) the Manual Control System, also to be developed by MMBA as an integral element of the FMR manipulator, and (4) the Watchdog Safety System, originally developed at NBS, to be implemented by MMBA. The control system elements, showing their relationships to each other, are diagrammed in Figure 5.

The next section is an overview of the hierarchical control concepts developed at NBS and employed on the FMR project. This is followed by sections briefly describing each of the four major control system elements and their interrelationships.

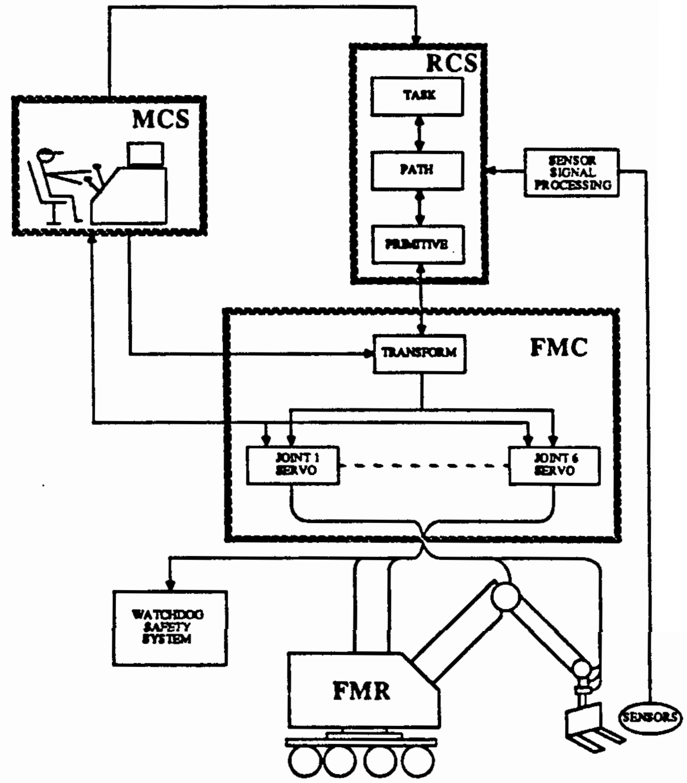


Figure 5. Control system elements.

4.1. Hierarchical Control Concepts

A hierarchical control system, such as the one shown in Figure 6, is partitioned vertically into levels of control. The basic command and control structure is a tree, configured such that each computational module has a single superior, and one or more subordinate modules. The top module is where the highest level decisions are made and the longest planning horizon exists. Goals and plans generated at this highest level are transmitted as commands to the next lower level, where they are decomposed into sequences of subgoals. In general, the decisions and corresponding decompositions at each level take into account: (a) commands from the level above, (b) processed sensory feedback information, and (c) status reports from the next lower control level.

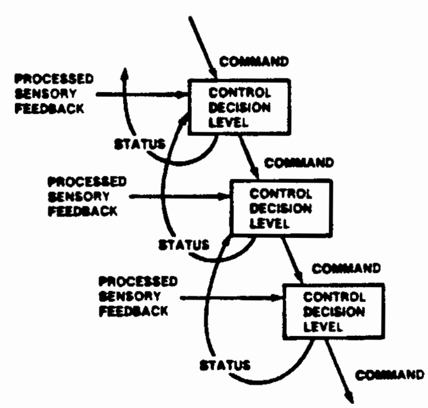


Figure 6. Hierarchical control structure.

Each hierarchical level of the system is capable of performing certain functions. The commands executed at a lower level are the result of task decomposition at the next higher level. That is, a higher level task is decomposed into "n" simpler lower level tasks and consequently, the lower level must run "n" times faster than the next higher level viewed on a commands per unit time basis. While the lower level may be executing commands at a higher rate than its superior level, the superior level generally requires more processing time to make its decisions because it is operating on a more complex task. This situation creates much of the rationale for the hierarchical structure of the system and also provides guidelines for the assignment of functions to the appropriate levels.

The application programming of the higher levels of control is more task specific than that of the lower levels. The higher levels require more specific data about the objects being manipulated and may depend upon specialized sensors and highly processed sensor information to make the required control decisions. However, an important aspect of this is that control of the system becomes robot-independent above a certain hierarchical level. That is, the higher levels deal with the state of the "world" and the objects in it and not with the physical parameters of the specific robotic manipulator.

The lowest control levels perform the more device specific control functions dealing with smooth, stable motion control. These control levels run at high update rates and can be thought of as the inner loops in a classical nested loop control structure. Typical low level functions are: individual joint level servo control, coordinate transformations and the calculation of smooth trajectories. The lower levels might also include more task specific capabilities such as implementations of sophisticated adaptive control techniques or model reference control algorithms.

This hierarchical control structure serves as an overall guideline for the architecture and partitioning of a sensory interactive robot control system such as the FMR. The Robot Systems Division at NBS has been working on the design and implementation of this control structure for several years and continues to perform research in this area. It is intended that one of the primary products of this research be a standardizable set of data interfaces and protocols between the various modules and levels of the system so that robots, controllers and sensory systems from different sources can be plugged together much like stereo components are today. This would allow systems to be configured for specific applications at lower cost and with much greater flexibility.

These principles as applied to the FMR provide the system with a logical functional partitioning with well defined interfaces between its elements. This structure has several strong advantages for the FMR as a research and development project. It: (a) facilitates the simple integration of subsystems developed by different groups or organizations, (b) allows the incremental building and/or evolution of the system, and (c) provides for upward compatibility as technology advances.

4.2. Real-Time Control System

One product of the research and development work of the Robot Systems Division has been the development and implementation of a general purpose robot control system called the Real-Time Control System (RCS). It is a multi-processor system which provides the user with a rich programming environment for implementing real-time sensory interactive robotic applications. The current version of the RCS is built with 8086-based single-board computers in a Multibus backplane and is based on the Forth language and operating system.

4.2.1 RCS Hierarchical Structure

The RCS is hierarchically structured as previously described and may have different numbers of control levels depending on the application. For the FMR application, the RCS is divided into three hierarchical levels called (from the top down) Task, Path and Primitive (see Figure 5). These levels of control are basically independent of the particular robot or manipulator. Therefore the RCS can readily be transported to different robots.

The Task level accepts commands from the operator in terms of object manipulations. The primary command implemented for the FMR application is a TRANSFER command. This command instructs the FMR to transfer a single pallet or an array of pallets from a source location (e.g., incoming truck bed or working platform) to a destination location (e.g., the outgoing conveyor system). The Task level decomposes the TRANSFER command into a series of steps or motions called PATHS. The PATHS resulting from a typical TRANSFER command are as follows: (1) move to the vicinity of a pallet, (2) approach the pallet and pick it up, (3) depart from the pallet pickup point, (4) move to the approach position of the destination location, (5) approach the destination location and release the pallet, and (6) depart from the release location and move to a safe location. These steps are formatted as PATH commands and are passed, individually, down to the Path level for execution.

The Path level decomposes these high level PATHS into a series of intermediate "goal poses". (A goal pose is defined as the desired location of the end-effector in space specified in all six degrees of freedom.) These goal poses are called Path Points (ppt's). In the FMR application many of these Path Points are not absolute but are determined using feedback from the end-effector-mounted sensors. Once determined, the desired Path Points are formatted as GO-TO <Path Point> commands and passed, individually, down to the Primitive level for execution.

The Primitive level decomposes the path to the Path Point goal pose into a series of intermediate poses which produce a smooth motion trajectory. These poses are then passed down to the FMR Manipulator Controller described in Section 4.3.

4.2.2. RCS Programming

The software architecture of the FMR RCS controller is logically divided in two halves -- the control portion consisting of the control levels mentioned previously (TASK, PATH and PRIM) and the data portion. This approach creates the ideal structure for a data-driven control system where functional tasks are described via data files executable by the control system.

The data portion of the RCS is managed by a robot programming language called RSL for Robot Sensor Language. RSL is the interface which allows the applications programmer to edit and compile a program executable by the robot. The program typically requires the robot to perform several steps. Each step calls upon the RCS controller to execute a specific function. Thus, the program can be thought of as a series of function calls.

The intention of an RSL robot program is to guide each control level through the decomposition of a high level command such as the TRANSFER command discussed previously. Therefore, portions of the robot program are implemented at each level of the hierarchy. RSL also gives the programmer the capability for defining robot locations, transforms, objects and other types of data structures necessary for further specification of a robot task. The next sections will describe how the FMR is programmed.

4.2.2.1. The TRANSFER Command

The input command to the TASK level for transferring a pallet is called TRANSFER. The TASK level searches the data files for the Paths which describe how to transfer the pallet. The search for the appropriate Paths in the data files is keyed by parameters of the TRANSFER command which specify the objects to transfer (pallet or array of pallets), their source location and their destination location. The applications programmer is responsible for defining each Path required for the transfer of the pallets. Note that Paths can be shared by each pallet in an array or by other TRANSFER commands.

4.2.2.2. Path Points

Each Path consists of a sequence of Path Points which further decompose the task. For the FMR application, a set of Path Point commands were developed which utilize the sensor data to perform the necessary operations to transfer a pallet. Three of these commands are Range, Edge and Equate. The Range command performs translational positioning of the fork using ranging sensor data. The Edge command scans an area of the work volume searching for the edges of pallets. The Equate command performs rotational positioning of the fork until the range reading of two sensors are equal.

For example, in leveling the fork tines with respect to the truck bed, the Equate command is used. Equate takes as its arguments two ranging sensors and attempts to balance their range readings. For instance, a roll motion about the tool X axis (see Figure 7) can be controlled using range sensors 3 and 4 (see Figure 3). The output of Equate is the goal pose of the fork which will yield the balanced range readings.

The range sensors are integrated into the control system at the PATH level for the purpose of generating goal poses which are passed to the PRIM level for further decomposition. While the PRIM level is performing its task, the PATH level continues to monitor the sensors in a closed loop fashion to ensure that the goal pose is always accurate. Whenever a new set of range values is available from the sensors, a new goal pose is calculated and passed to the PRIM level.

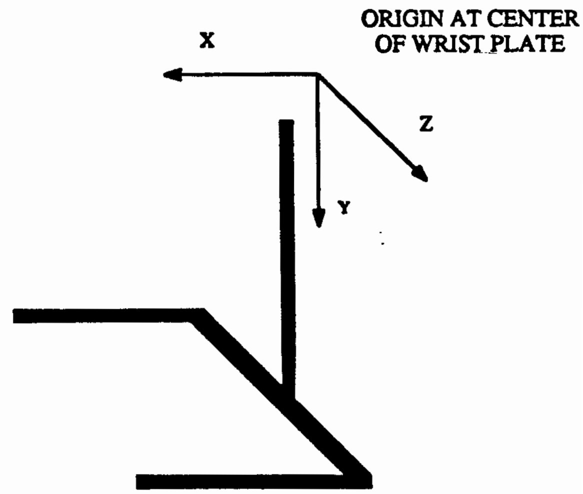


Figure 7. Tool coordinate frame.

4.2.2.3. Example of a Pallet Acquisition

A simplistic program describing how a pallet is to be acquired can be formulated using the Range, Edge and Equate commands. Figure 8 shows the sequence of steps required to align the fork with the pallet. In Figure 8(a), the fork is being moved in a search for the edge of the pallet using the Edge command. Figure 8(b) shows the fork aligned with the edge of the pallet and executing a Range command to position the fork a selected distance from the pallet. Figure 8(c) shows the Range command completed and the fork rotating using an Equate command to align with the face of the pallet. Figure 8(d) shows the fork aligned with the pallet, ready for insertion of the tines.

4.3. FMR Manipulator Controller

Below the Primitive level, in the FMR Manipulator Controller (FMC), are the two lowest levels of control (see Figure 5). The top level, the Transform level, performs the transformation from cartesian space into joint space. The lowest level, the Servo level, performs individual joint servo control. The performance of each of these functions requires "knowledge" of the physical configuration and capabilities of the manipulator and, therefore, falls logically into the FMC as opposed to the RCS.

The Transform level accepts commands from the Primitive level in terms of goal points in either "World" or "Tool" cartesian coordinates. The origin of the World coordinate system is placed at the base of the robot and the Tool coordinate system is placed at the FMR wrist plate (see Figure 7). The Transform level then performs computations incorporating parametric information about the FMR such as link lengths and joint angle limitations to transform cartesian coordinate end-effector poses into the appropriate individual joint positions necessary to achieve these desired poses (i.e., the inverse kinematic transform).

The Servo level accepts desired joint positions from the Transform level and performs the appropriate control law computations at each joint.

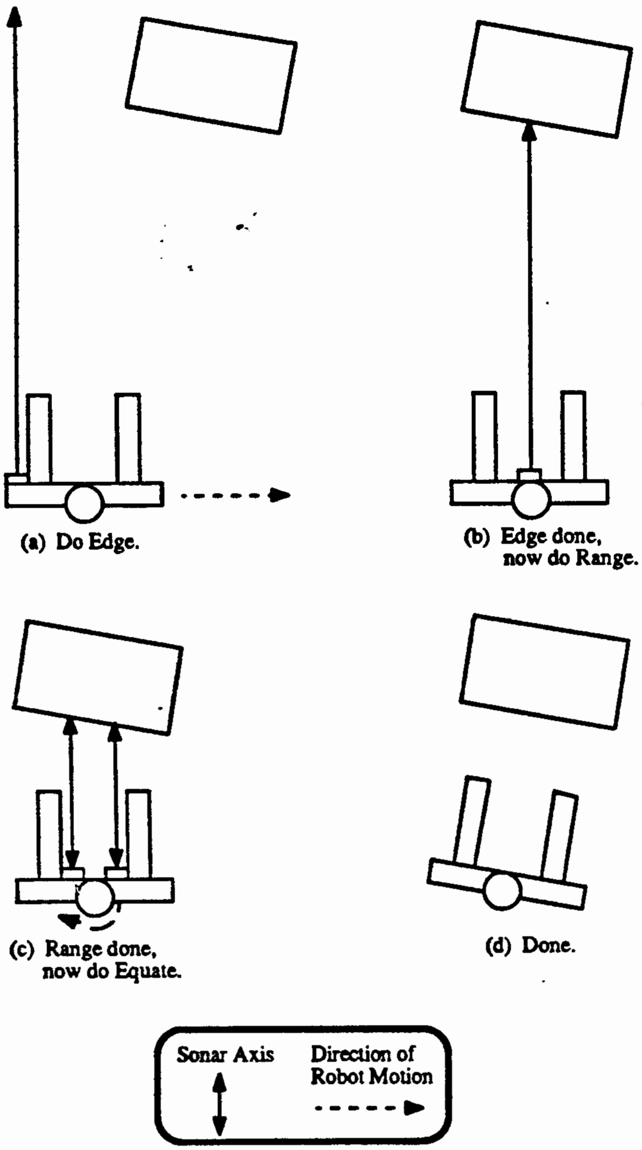


Figure 8. Example of pallet acquisition sequence.

4.4. Control Summary

In summary, it is the function of the control levels implemented in the RCS to close the high level sensor loops that relate to the state of the world surrounding the FMR and the objects to be manipulated. It is the function of the control levels in the FMC to provide smooth stable motion of the manipulator arm, as directed by commands passed down from the RCS.

It is not within the scope of this paper to explore the internal workings of the RCS or the MCS in further detail. This information is available in the references [4, 5] or by contacting the author(s).

4.5. Operator Interface

The FMR is to be operable by one person in two primary operational modes. These modes are: (1) robotic and (2) teleoperated.

In the robotic mode, the operator will input commands to the RCS (such as the previously described TRANSFER command), along with the required command parameters. These parameters tell the RCS what type of pallet, or pallets, are to be moved, their location (e.g., truck bed, working platform #1, etc.) and where they are to be moved. Once the operator has properly commanded the system, it is to function automatically on a repetitive basis without operator intervention.

The teleoperated mode will give direct control of the manipulator motion to the operator. The operator's teleoperation workstation will be physically located on the FMR (see Figure 9). [NOTE: During initial development and testing, there will be a remote operator's workstation with a complete set of controls. MMBA is evaluating the feasibility of having both on-chassis and remote operator's workstations for the final FMR system.] The operator, via joystick, will be allowed control of the robot in Joint, World, and Tool coordinate frames. In terms of the previously described control structure, this means that the operator, by selecting world or tool transformation mode, effectively replaces the Primitive level and inputs command directly to the Transform level. By selecting the Joint mode, he operates at the lowest level and thus, replaces the Transform level. This gives him the capability to move each joint individually (see Figure 5).

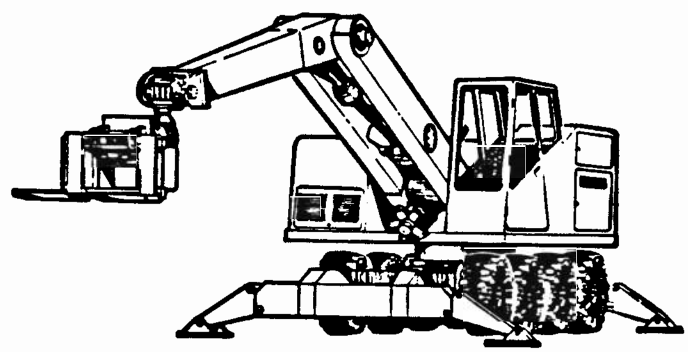


Figure 9. FMR preliminary design configuration.

4.6. Safety System

The FMR is to be equipped with an auxiliary safety computer system which incorporates, as a minimum, all of the features of the NBS Watchdog Safety System (WSS) [6]. As shown in Figure 5, the WSS is independent of the other FMR controls. It is physically isolated from the FMC and RCS and can override both of these systems and stop the FMR if necessary.

The WSS monitors various system parameters and checks the status of both the FMC and RCS. In particular, the WSS monitors manipulator velocities and accelerations, location of the manipulator (to prevent intrusion into forbidden volumes), and operating parameters (various temperatures, pressures and speeds).

If an error condition is detected by the WSS, it can execute either a pause (manipulator remains powered) or an emergency shutdown. After a pause, the FMR is able to resume the task it was executing from the point at which it was halted without reinitializing the system. In the event

of emergency shutdown, or anything which causes the manipulator to lose power, the FMR is equipped with brakes on the actuators so that the load is not dropped and the manipulator cannot sag.

5. PHASED RESEARCH AND DEVELOPMENT APPROACH

Prior to the selection of MMBA as the primary contractor for designing and fabricating the FMR, NBS had been conducting research on the development of the end-effector sensor package and the integration of this package with the RCS. This research went through several stages involving bench-top testing, preliminary testing on a PUMA 760 robot, and full-system testing and integration on a Unimate 4000 robot {‡}.

5.1. Sensor Selection/Testing

Sensor selection was based on an evaluation of commercially available ranging and proximity sensor systems. These included acoustic, fiber optic, infrared, inductive, laser-based, photoelectric, and 3-D vision type sensors. Parameters such as operating range, resolution, accuracy, reliability, ruggedness, dependence upon environmental conditions, size, and cost were examined. Based on these evaluations, acoustic sensors were chosen for ranging measurements and fiber optic-based optical sensors for proximity detection.

The acoustic sensors are pulse/echo type ultrasonic transceivers. In operation, the sensor transmits an ultrasonic pulse which travels out and is reflected from any objects in its path. When the pulse is transmitted, a clock is started and allowed to run until an echo is received and detected by the sensor. The time it takes the pulse to travel from the sensor to the object and back to the sensor is proportional to the range, or distance between the sensor and the object. The particular sensor being used is manufactured by Polaroid Corporation {‡}. The operational characteristics are as follows:

Sensing Range: 0.9 to 35 ft. (0.27 to 10.7 m)

Resolution: ≈ ±0.25 in. (±0.64 cm)

Frequency: 50 kHz

Beam Angle: ±10°

Operating Temperature: 32 to 140° F (0 to 60° C)

Mode: duplex (transmit and receive)

In the NBS system, the drive electronics are modified to increase the pulse transmission rate (to speed up the feedback and thus, improve the servoing capability) to approximately 24 pulses per second. Since the time for an echo to return is shortened because another pulse is ready to be transmitted sooner, this reduces the maximum sensing range to approximately 10 ft. (3.0 m).

The optical proximity sensor consists of a pulsed infrared emitter and detector with separate fiber optic probes for each. In operation, the emitter continuously transmits the pulsed infrared signal from the transmit fiber optic probe. The detector continuously monitors the receive fiber optic probe for any reflected signal. Any signal above the adjustable threshold indicates that an object is in front of the sensor within a distance corresponding to the threshold. The particular sensor being used is a FIBERLENS manufactured by Scientific Technology Incorporated {‡}. The operational characteristics are as follows:

Sensing Range: up to 12 in. (up to 30.5 cm)

Frequency: pulsed infrared

Beam Angle: ±10° (lens dependent)

Operating Temperature: up to 158° F (up to 70° C)

Mode: continuous,separate transmitter and receiver

In the NBS system, the gain is adjusted so that the effective sensing range is 4 in. (10.2 cm).

5.2. Commercial Robot-Based Testbed

Integration and testing was conducted in three distinct phases. First, tests were done in the lab to verify the ability of the sensors to satisfactorily perform the required measurements on actual pallets. Following this, the sensors were mounted on a light-weight mock-up of the end-effector to check operation while being moved around and positioned by a robot. This mock-up was mounted on a PUMA 760 robot, which was equipped with an NBS RCS. This second phase also permitted the sensors to be integrated with the RCS and the acquisition algorithms to be developed and tested. Because of payload limitations of the mock-up, no pallets were transferred.

The final phase of this developmental work was to install the sensors on a full-size end-effector mounted on a Unimate 4000 robot, which is also equipped with an NBS RCS. Although this is not the final end-effector to be used on the FMR, it permitted the approximate geometry of the end-effector to be simulated for evaluation of various sensor mounting configurations and of the acquisition algorithms. Although the payload of the 4000 is much larger than the 760, it is still well below the weight of the actual pallets. As a solution, light-weight, full-scale simulated pallets weighing approximately 50 lbs. (22.7 kg) were fabricated. Use of these pallets permitted full testing of the integrated sensor package with the RCS.

6. PROJECT STATUS

The FMR is scheduled to be completed in 24 months (May 1988), with a full-scale demonstration 6 months later (November 1988). Since May 1986 when the contract was awarded, MMBA has been working on the preliminary analysis and design of the FMR. Figure 9 shows the preliminary design developed by MMBA. NBS is concluding development and testing of the full sensor package on the Unimate 4000 robot. Delivery of this sensor package and an RCS to MMBA is scheduled for November 1986. Additional sensor types and configurations are also being examined so that alternatives can be suggested to MMBA if necessary. Besides this work, NBS and MMBA are working together to specify the interfaces between the various controllers. The specification of these interfaces is extremely important in terms of simplifying the integration of the various subsystems and of optimizing system performance.

ACKNOWLEDGEMENTS

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FOOTNOTES

§ This paper was prepared by United States Government employees as part of their official duties and is therefore a work of the U. S. Government not subject to copyright.

‡ Commercial equipment is identified in this paper in order to adequately describe the systems under development. In no case does such identification imply recommendation by the National Bureau of Standards, nor does it imply that this equipment was necessarily the best for the purpose.

REFERENCES

[1] Shoemaker, C. M., Field Applications for Robotic Material Handling Systems: A Human Engineering Laboratory Perspective, Proceedings of the 1984 Conference on Intelligent Systems and Machines, April 24-25, 1984, Rochester, Michigan.

[2] Anon., Field Materiel Handling Robot Test Bed, Solicitation No. DAAA15-85-R-0007, Procurement Directorate Edgewood, Aberdeen Proving Ground, Maryland.

[3] Stephens, J. A., and Camden, R. S., Battlefield Robotic Ammunition Supply System, Proceedings of the 1984 Conference on Intelligent Systems and Machines, April 24-25, 1984, Rochester, Michigan.

[4] Barbera, A. J., Fitzgerald, M. L., Albus, J. S., and Haynes, L. S., RCS: The NBS Real-Time Control System, Proceedings of the Robots 8 Conference and Exposition, Volume 2, Future Considerations, June 4-7, 1984, Detroit, Michigan.

[5] Leake, S. A., and Kilmer, R. D. (Editors), Real-Time Control System -- User's Reference Manual, to be published in 1986.

[6] Kilmer, R. D., McCain, H. G., Juberts, M., and Legowik, S. A., Watchdog Safety Computer Design and Implementation, Proceedings of the Robots 8 Conference and Exposition, Volume 2, Future Considerations, June 4-7, 1984, Detroit, Michigan.