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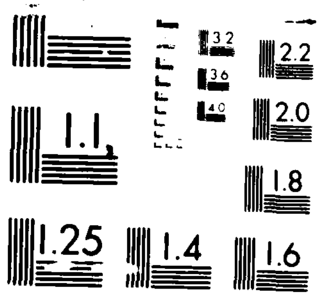

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This study examines the concepts involved in enhancing the operation of the Integrated Smart Artillery Synthesis (ISAS), a robotic ammunition handling system, and defines the technology required to implement it. The proposed system consists primarily of the Electronic Control Unit (ECU) and data bus to process status data and closed loop control parameters and to interface with a central fire control system. Present large data bases would be replaced by real-time information acquisition along with generic closed-loop control routines and automatic switching logic to control ammunition handling and (cont)

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delivery in a rapidly changing environment. The implementation of new sensing methods, such as vision technology, is also investigated.

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INTRODUCTION

Background

In recent years, advances have been made in applying automation or robot technology to artillery vehicles in order to improve combat effectiveness. One aspect of this involves the automated loading and firing of ammunition.

The Integrated Smart Artillery Synthesis (ISAS) vehicle is a testbed that demonstrates these advanced robotic concepts. It is based on an M109A1B 155mm self-propelled howitzer. Among the concepts that it demonstrates is a projectile and charge autoloader system based on a jointed, multiple degree of freedom, turret-mounted robot. Control of this system is presently achieved using a standard Allen-Bradley industrial controller and various sensors.

In order to further improve the reliability of this autoloader, an advanced control system investigation was required. This study was performed to apply existing microprocessor-based electronic control unit (ECU) technology, and to examine innovative solutions to the electronic control of a robotic autoloader in order to determine the configuration of an advanced ECU (AECU). Project objectives are discussed in the following section.

Objective

The original objective of this project was to enhance the operation of the ISAS autoloader robot using an advanced control system that would incorporate component redundancy, automatic moding logic and artificial intelligence, and a variety of sensing methods, including machine vision.

After the project was awarded, Vista Controls was instructed by ARDEC to slightly modify the project objectives. It was desired that the study results be directed to a more generic system. To do this, various mechanical designs would be evaluated, with estimations made of the required new sensor suite, vision system, servo loops and a resulting generic controller.

Scope

This report addresses the requirements and conceptual design of an AECU. Several existing ammunition handling systems were examined, and significant development was done on alternate autoloaders. These systems formed the baseline system and worst case requirements that an AECU would need to control. They also pointed the way to the best types of sensors and advanced control methodologies that could be applied to improve operation.

The AECU itself was then developed, using several approaches incorporating different architectures. The AECU concept that was determined meets the objectives of applying advanced control methods with flexibility to be used with many types of machines.

BASELINE EVALUATION

Present ISAS System

The ISAS system was considered the baseline, both from a mechanical and control system point of view (ref. 1). Each of these aspects are discussed in the following sections.

Mechanical System

The mechanisms associated with the ISAS have been evaluated to provide the number and types of control loops required. The major components of the present ISAS are the robotic loader, sliding-block breech and flick loader tray. Extensive detail development of ISAS improvements has been neglected in favor of research towards generic control system concepts.

The ISAS loader consists of an arm-type jointed robot mounted to an overhead x-y linear positioning platform. The degrees of freedom include overhead x and y (linear, operated by rotary motors and jackscrews), upper azimuth (rotational), upper pitch (rotational), lower pitch (rotational), wrist roll (rotational) and extension (linear). All motions are electro-hydraulically actuated, including the gripper. Figure 1 illustrates the ISAS robot arm and flick loader.

Projectiles and charges are loaded from various positions along the turret ring, and moved into a loader tray at the breech. A multi-lug sliding breech block is used. The loader tray is mounted to the gun mount of the vehicle, and rotates down and out of the way of recoil prior to firing. It includes a flick loader mechanism to seat the projectile in the gun and load the charge into the breech.

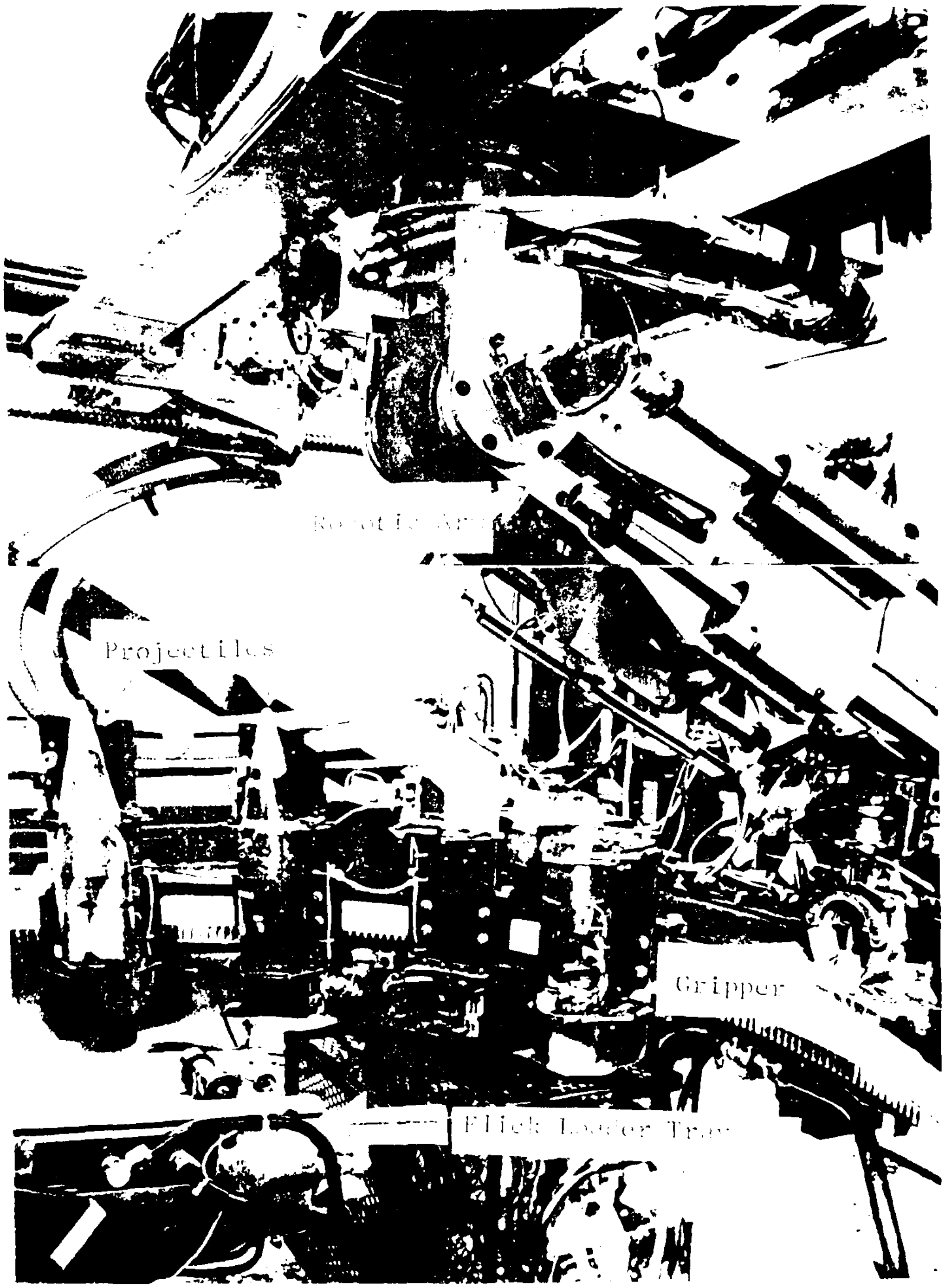


Figure 1. ISAS arm and flick loader

Control System

The present control system consists of an Allen-Bradley controller and peripherals (figure 2) commanding a servo control box, which drives the robot hydraulics (figure 3). The servo loops employ resolver feedback, and use fairly basic compensation, as shown in figure 4. There are 5 flick loader proximity switches fed directly to the FCC, and 6 limit switches and 5 proximity switches that are input direct to the AB controller. As can be seen in figure 2, the AB controller consists of several panels and peripherals, and is primarily configured to industrial type applications. This yields a bulkier, more complicated system than is necessary, and is also not constructed for the shock environment of the M109.

Motion control consists of pre-programmed, point-to-point subroutines in the AB that are called and executed by the fire control computer (FCC).

General Mechanical System

The next step in evaluating a generic control system was to estimate other types of mechanical systems to be controlled. The driving aspects of such devices are examined in the following sections. Overall constraints are set forth, including the man-machine interface, turret constraints, round and charge type and resupply interface. The required sequence of events to perform the autoloading tasks is then detailed. This determines the required combination of motions, geometry, structures and resulting control system to accomplish the task.

Finally, several mechanical autoloader configurations are proposed, and compared on their respective merits and from a controller point of view. The original ISAS robot is also compared. From this, a controller design is generated that will be flexible enough to accommodate these different mechanical systems.

Constraints

Figures 5 and 6 are timing diagrams for future battle scenarios involving field artillery that were presented in the Vista Controls AFAS Requirements Overview white paper (ref. 3). Figure 5 depicts a typical time sequence of events of the existing M109 during engagement in this battle scenario. Alongside the M109 sequence is an expected counterfire scenario for future technology. The time sequence represents present M109 performance rather than that required for an AFAS. This sequence highlights

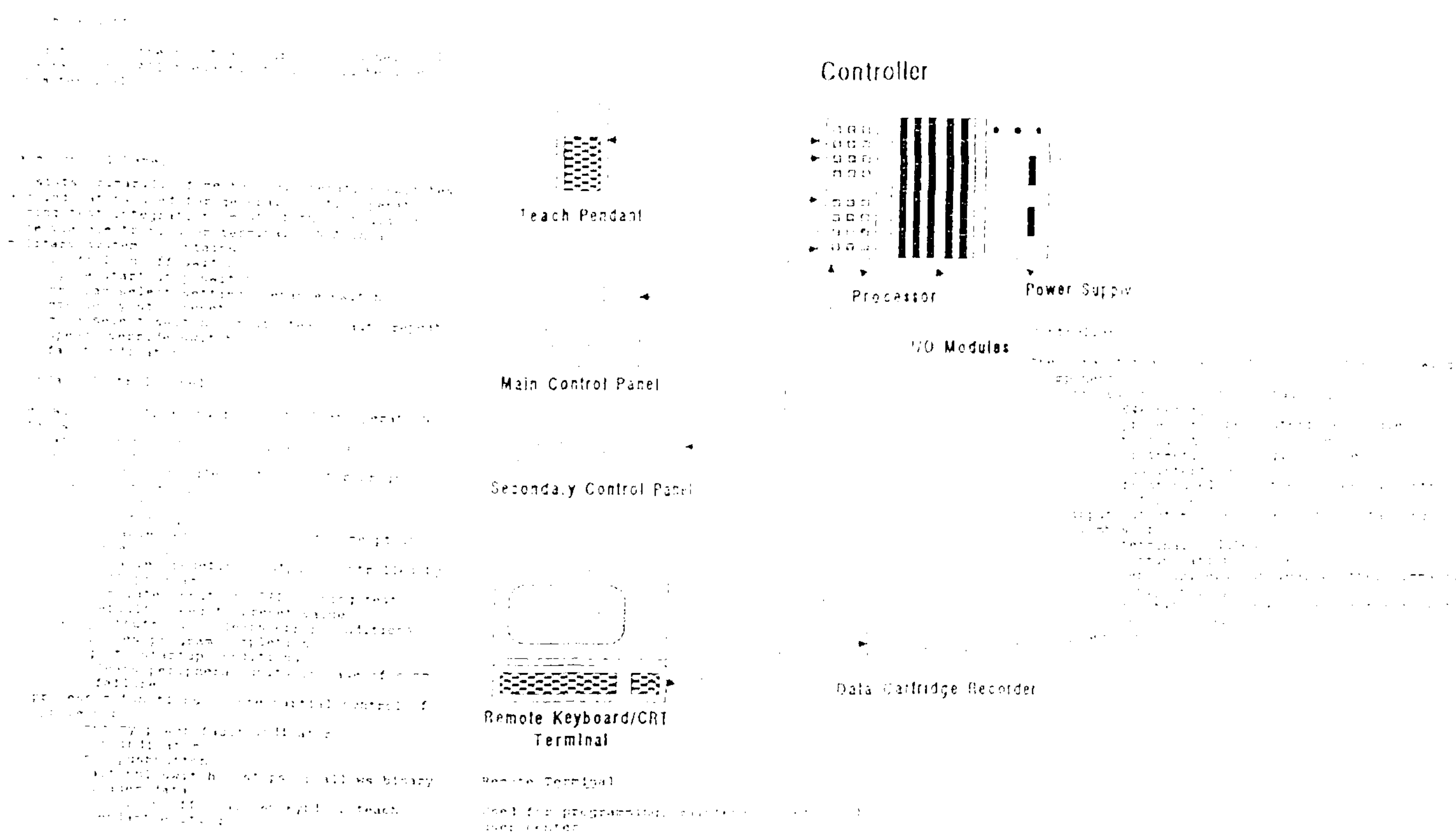


Figure 2. Allen-Bradley control system

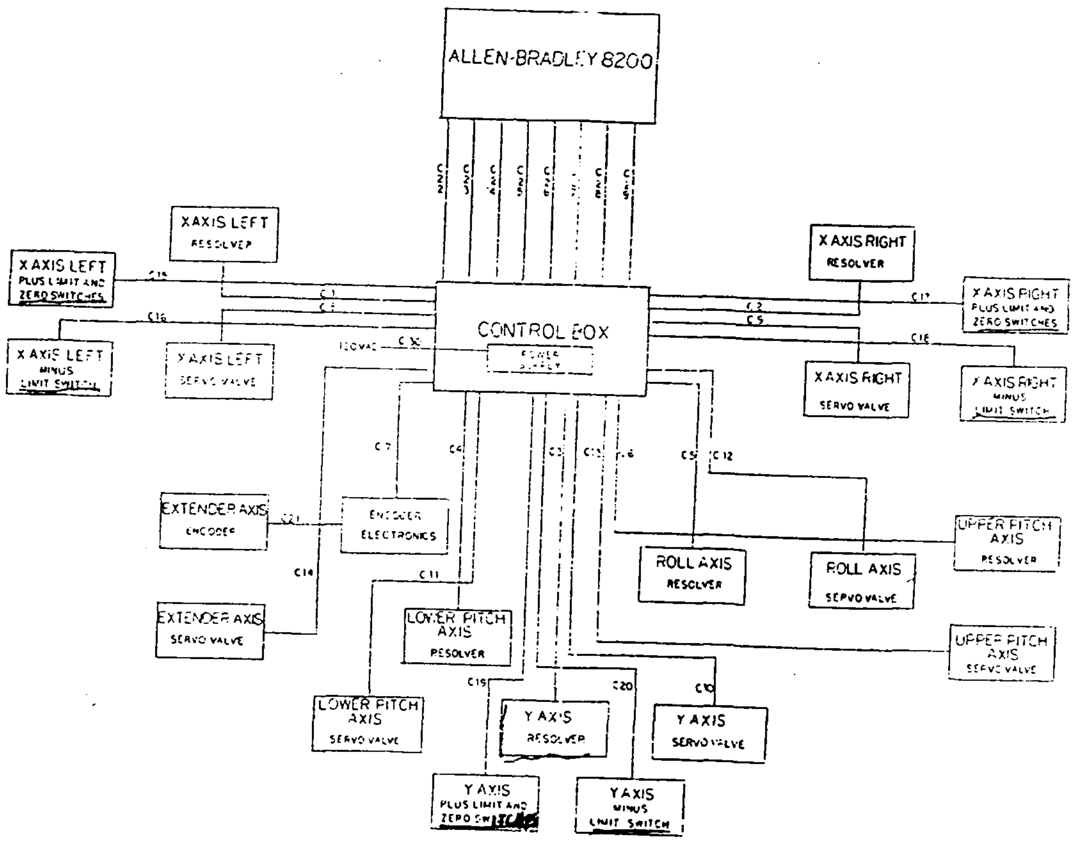


Figure 3. Servo loop block diagram

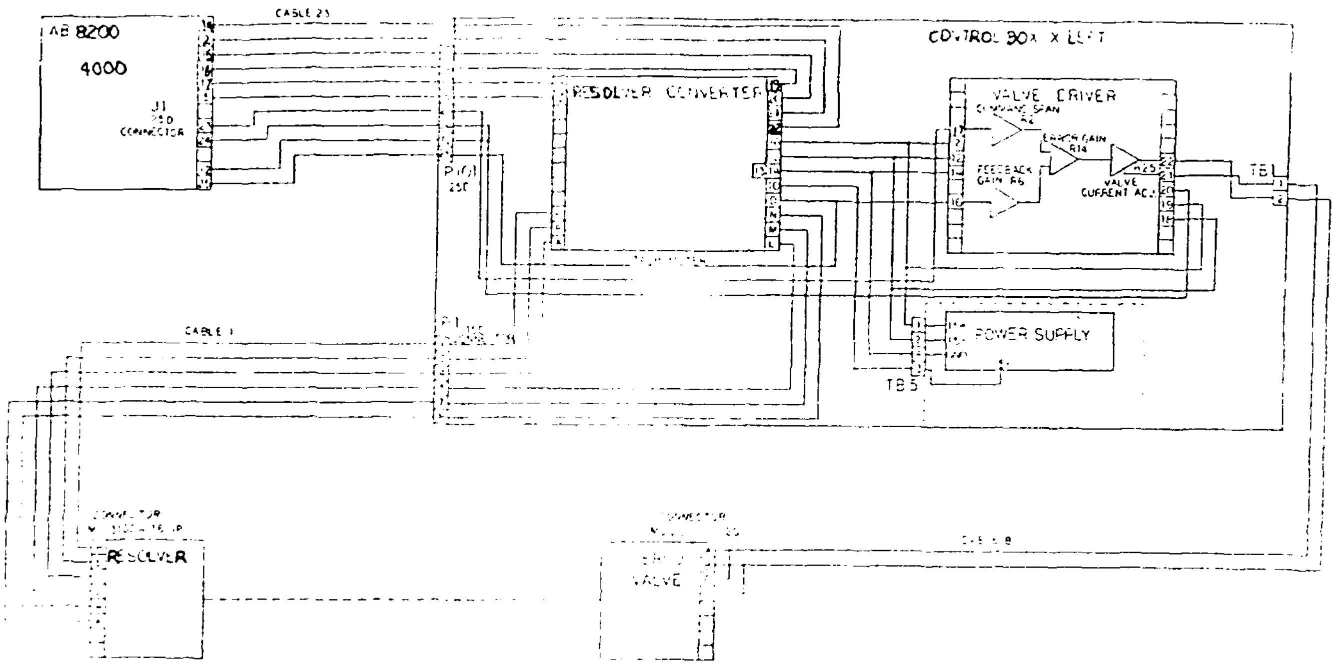


Figure 4. ISAS servo loop

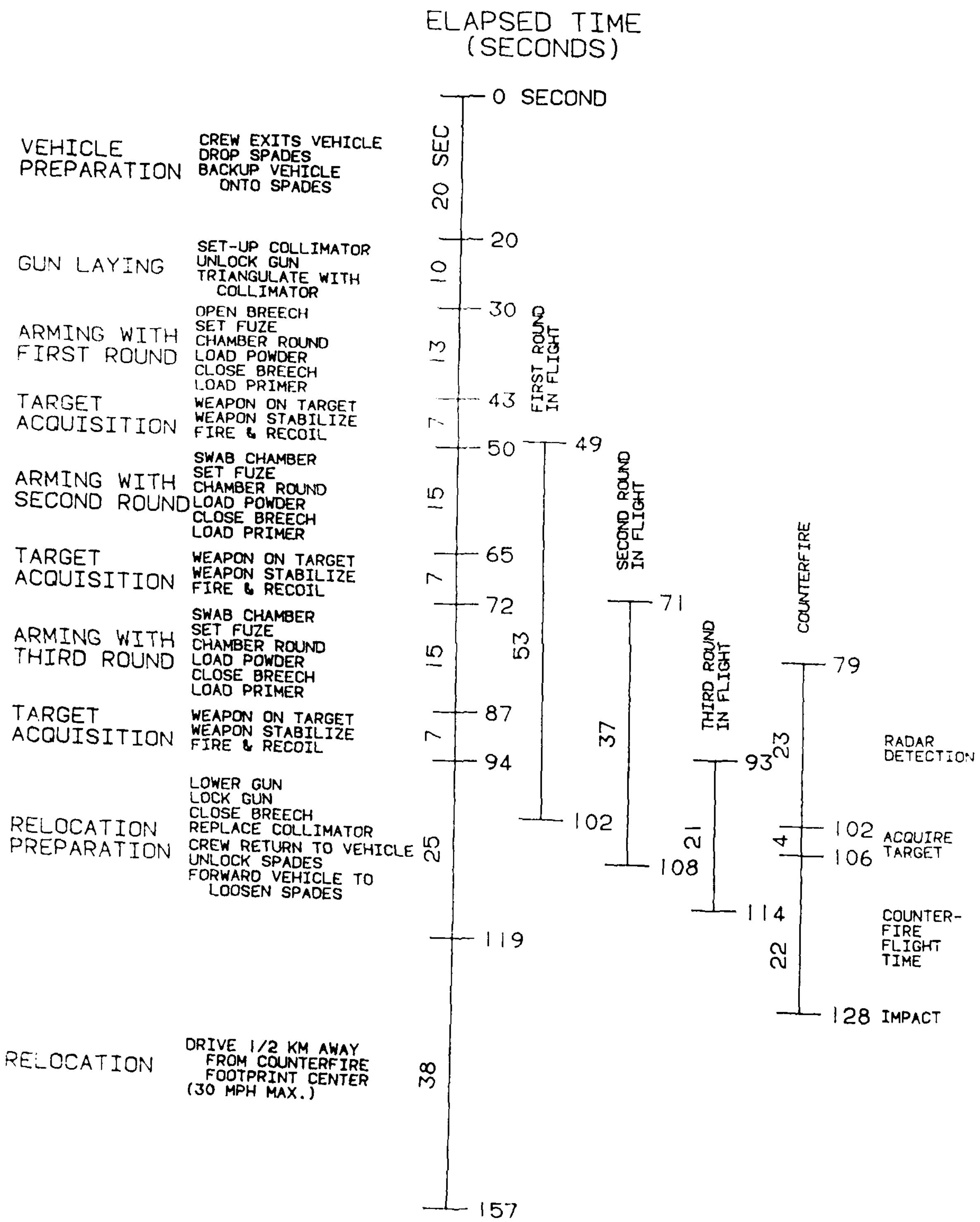


Figure 5. Time sequence of M109 scenario

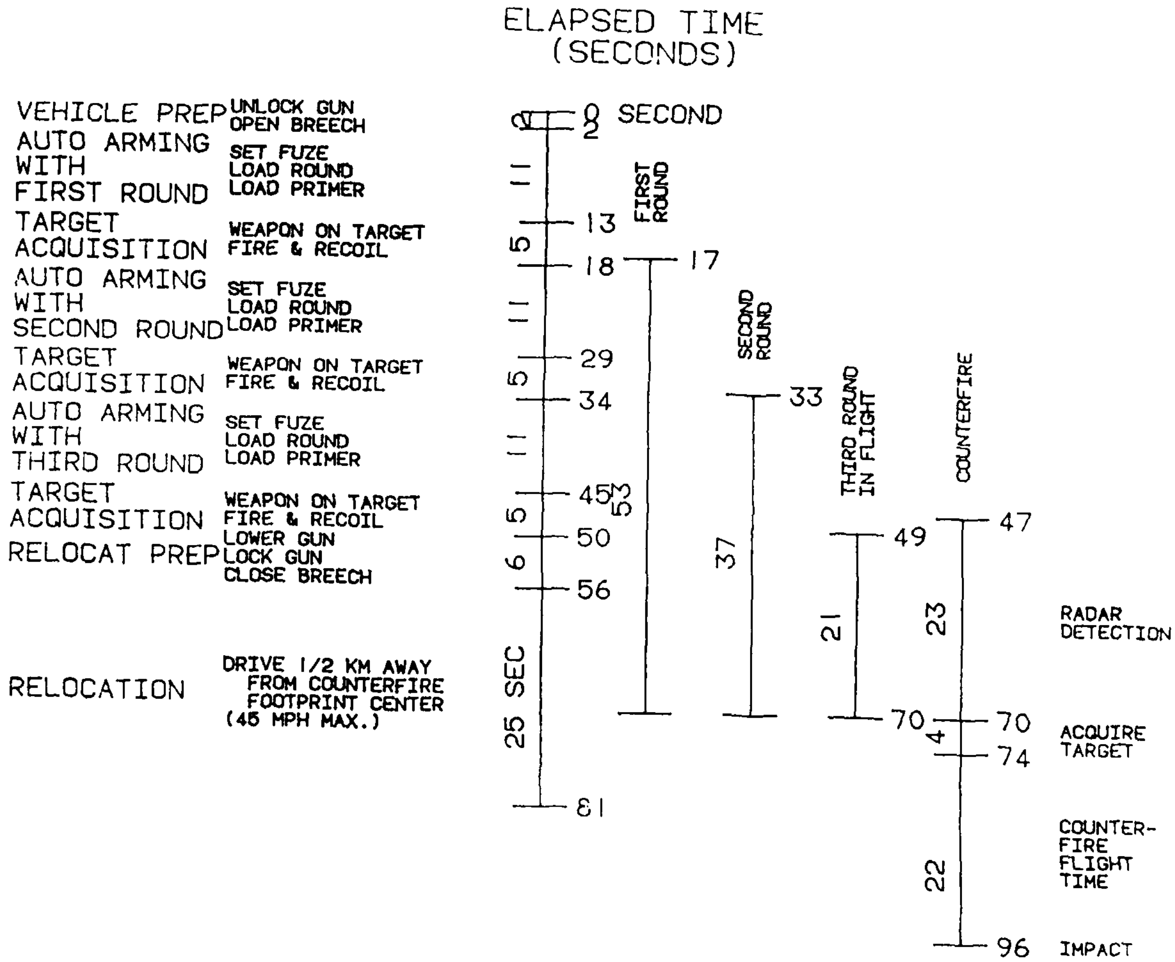


Figure 6. Time sequence of AFAS scenario

where major improvements for an artillery system are required and where deficiency of current systems are most apparent.

In the time sequence, during firing of a three-round burst, enemy counterfire impacts at the 128 second mark, before the self-propelled howitzer has the opportunity to move. The time sequence for a two-round burst is 22 seconds less than the three-round burst. The time saved allows the vehicle to be out of the one kilometer diameter counterfire footprint in 135 seconds, still not quick enough to match the counterfire impact at 128 seconds. Therefore, with the present system, the only safe alternative is to fire one round and immediately relocate. Time elapsed is now reduced to 113 seconds. As a result, there is a margin of 15 seconds between leaving the one kilometer diameter counterfire footprint and the time of counterfire impact.

The present artillery system may increase survivability by limiting firing to a one-round burst before moving. The increased survivability comes at a sacrifice in lethality due to an overall firing rate of only one shot per 115 seconds, an average of .5 shots per minute (spm). The time sequence may be separated into three major portions:

1) responsiveness, covering vehicle preparation and gun laying,

2) firing rate, which includes arming of the gun and target acquisition, and

3) mobility, covering relocation preparation and the actual relocation.

Of the three, mobility is the driving factor for increased survivability, while elapsed time reductions in the combination of all three increases lethality by raising the overall firing rate.

Figure 6 depicts a time sequence of an AFAS with all the improvements as suggested in the following sections. As compared to the original time sequence for the existing M109, the 50 seconds required for vehicle preparation and gun laying are totally eliminated. Arming of the first round is at 11 seconds rather than 13 seconds. Target acquisition time is at five seconds per round, shortened by two seconds as compared to the original system. Arming and loading of each successive round is reduced to 11 seconds from the original 15 seconds. Relocation preparation is shortened by 19 seconds to a final time requirement of six seconds. This scenario shows the AFAS can fire a three-round burst and exit the counter fire footprint in 81 seconds and still have 15 seconds of margin from counterfire attack.

The overall firing rate for the AFAS is at 2.2 spm; this rate is 4.5 times the overall firing rate of the existing M109 in a future battle scenario. The incorporation of the subsystems will also decrease crew size. Since the requirement for a loader, a crew member to monitor the collimator, and a crew member to dispose of the unused powder has been eliminated by the subsystems, a total minimum crew size of three is required, consisting of a commander, driver, and gunner.

The following constraints have been chosen as representative of the requirements and challenges associated with the Howitzer Improvement Program (HIP) and the Advanced Field Artillery System (AFAS) (refs. 2 and 3). The individual merits can be argued, however the main objective is to establish the controller interface, computation and throughput requirements.

Three-Man Crew - A three-man crew would consist of a commander, gunner and driver. This allows for two men in the turret to be able to manually load the Copperhead missile, although failure rates for the autoloader system should be low enough that general manual operations are not required. A three-man crew capability was also demonstrated by the Human Engineering Labs (HEL) testbed.

Load On Move - Loading on the move is not a requirement, since analysis has shown that it does not contribute significantly to improved firing rates, and would compromise system safety or cost.

Shoot On Move - Shooting on the move does not appear to be easily achievable in the near future, and is not a requirement. Analysis shows that shooting rapidly and then moving is enough to avoid enemy counterfire at this time.

HIP Configured Chassis - Any autoloading system must be adaptable to the chassis and turret systems tested in the HIP. Minor modifications to turret may be required. This will allow the integration of an autoloader system into the overall advanced 155mm self-propelled vehicle (SPV) with a minimum of conflict.

Standard Rotary Breech - A standard interrupted-thread rotary breech block has been assumed, since all planned HIP configurations are presently slated to use this. A servo system may be used to replace the standard mechanical release. If a sliding multilug breech is used, the impacts to the control system would be minimal, and involve only modifications to the input/output (I/O) sections of the controller.

Auto Primer Mechanism - This mechanism would be more or less autonomous. Controller functions would consist mainly of monitoring the amount of primers.

Unicharge - Propellant is assumed to be unicharge. Other types of propellant would significantly affect the mechanical system, and thus the number of channels and signals to monitor and control.

Positive Ram - A positive projectile rammer, such as a strongback chain is assumed.

Manual Backup - Manual backup modes will be provided for. System redundancy will be such that these modes will rarely be encountered, and will function at degraded rates of fire.

Magazine - A magazine-based projectile and charge storage system is envisioned. The overall autoloading task is much simplified if this is done.

Automatic Fuzing System - It is assumed that a generic controller will need to handle this system. The only other alternative is to pre-fuze the projectiles before the autoloader gets to them, either in the resupply vehicle or manually in the 155mm SPV.

Sequence of Events

The individual sequence of events associated with firing were obtained from reference 4, and are outlined in table 1. There are 6 men involved in the firing process - the chief of section, cannoneers 1 through 4, and the driver. The #1 cannoneer performs the actual loading of rounds into the gun. Cannoneers 2-4 and the driver fuze projectiles, prepare charges and transport these to the #1 cannoneer. The chief of section inspects all components of the round prior to loading into the gun.

From these actions, the motions and functions required for the mechanical robot and control system to perform during firing are determined. The capability to select and fuze projectiles, and select powder is needed, either by a magazine-based bustle system to move the round components to central locations, or by robotic arms to access the components, or by a combination of these methods. The use of unicharge simplifies the powder preparation greatly.

Table 1 : Standard 155mm Crew Operations

Chief	Gunner	#1 Cannoneer	#2 Cannoneer	#3 Cannoneer	#4 Cannoneer	Driver
	Sets Barrel			Inspects, cleans projectile	Prepares propellant	Helps #4
			Fuzes projectile, sets fuze, verifies	Holds projectile upright		
Checks all components of round prior to loading		Puts projectile into tray, rams it into breech, stores ram		Carries fuzed projectile to #1		
		Loads Charge into breech			Gets rid of extra powder	Carries propellant to #1
		Closes breech Inserts primer Closes primer block Attaches lanyard Fires round Swabs and inspects chamber	R E P E A T S	O P E R A T I O N S	A S	N E C E S S A R Y

The actual loading is performed by either a dedicated mechanism or a jointed-type robot. Subsystems to operate the breech, load and eject the primers, and fire the gun are required. A vision system will perform the inspection and verification tasks.

Proposed Mechanical Systems

In addition to the ISAS robot, there are several types of mechanical systems that would perform the required tasks. Each method that we examined of course involved compromises in one form or another. The purpose of this section is not to come up with the best mechanical system and do detailed development of it, but rather to put forth the various configurations and evaluate the types of control that each would need. In this way, a generic control system could be designed to be adaptable to whatever system is used in future experiments, and in the HIP.

Trunnion Mounted - One proposed method involves pivoting the transfer mechanism at the gun trunnions. A magazine is used for the projectiles and charges, and one is used for the fuzes. A general mechanical layout for this system is shown in figure 7.

General operation consists of moving a projectile from the magazine into the transfer unit, then fuzing the projectile. The transfer unit then rotates and moves to the breech and loads the projectile. The unicharge is then loaded similarly. This configuration is relatively simple mechanically, and allows personnel to be stationed in the turret. A timing diagram for this system is shown in figure 8.

Roof Mounted - An example roof mounted system is illustrated in figures 9 and 10. There are several combinations of linear and rotary actuators that could be used to achieve the required geometrical motions, which are very similar to the trunnion mounted system. The concept shown uses one linear motion, three rotary motions and two links. A cantilevered arm is shown in order to accommodate a standard rotary breech, however a parallel arm configuration with a sliding block breech would be preferable . The fuze and round magazines are identical to the trunnion mounted system.

FMC Concept - The FMC proposed system (ref. 5) is shown in figure 11. It uses rotating magazines and a trunnion mounted transfer unit. This system involves significantly less degrees of freedom and sensors, that an

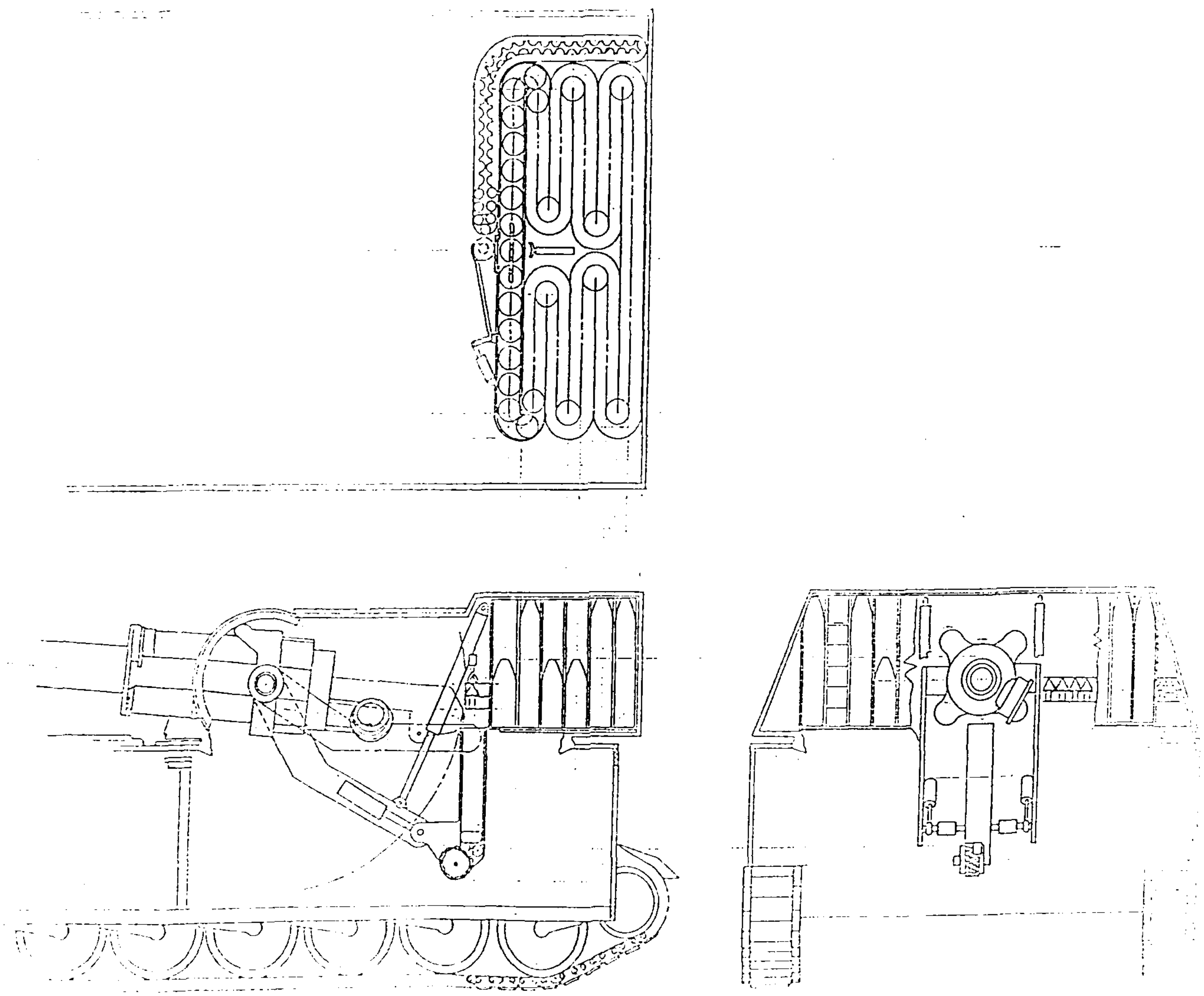


Figure 7. Trunnion-mounted mechanical system

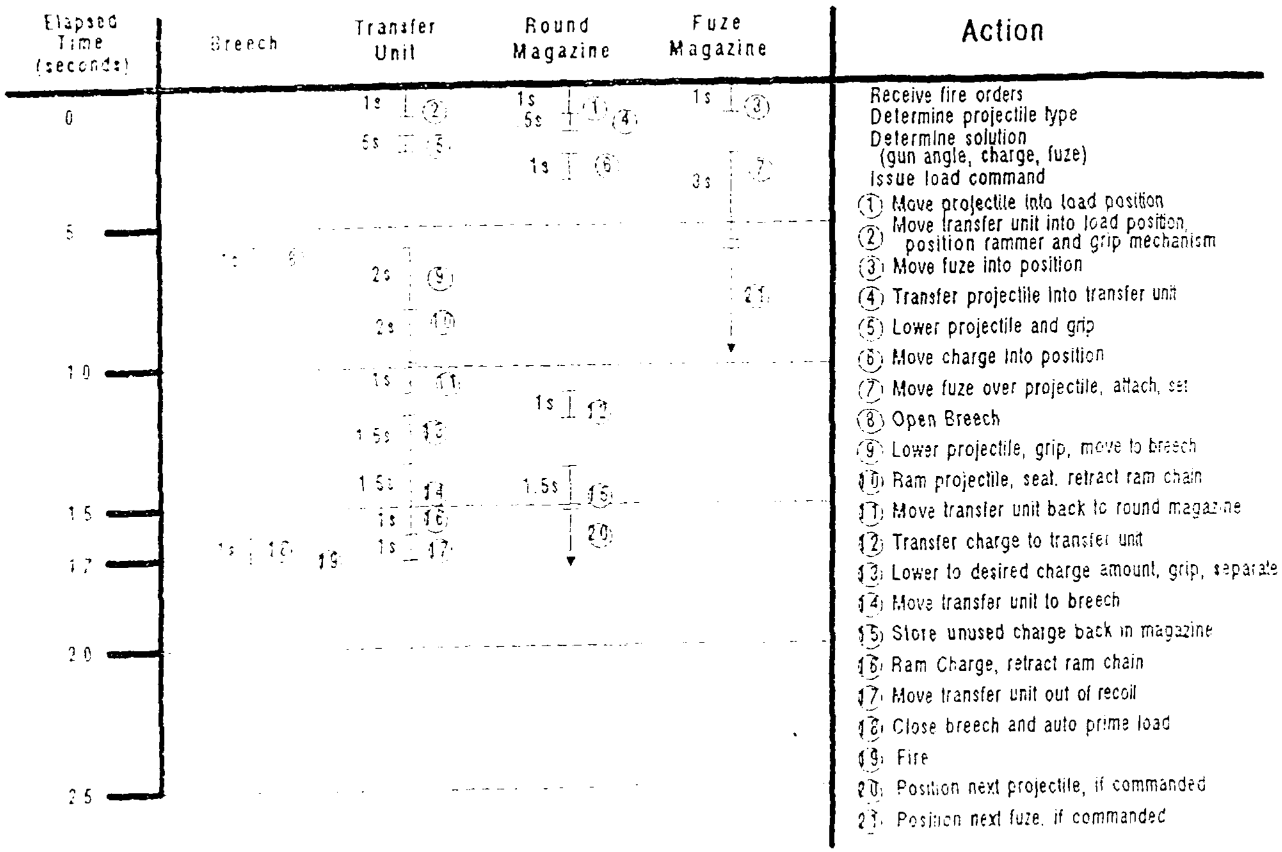


Figure 8. Trunnion-mounted system timing diagram

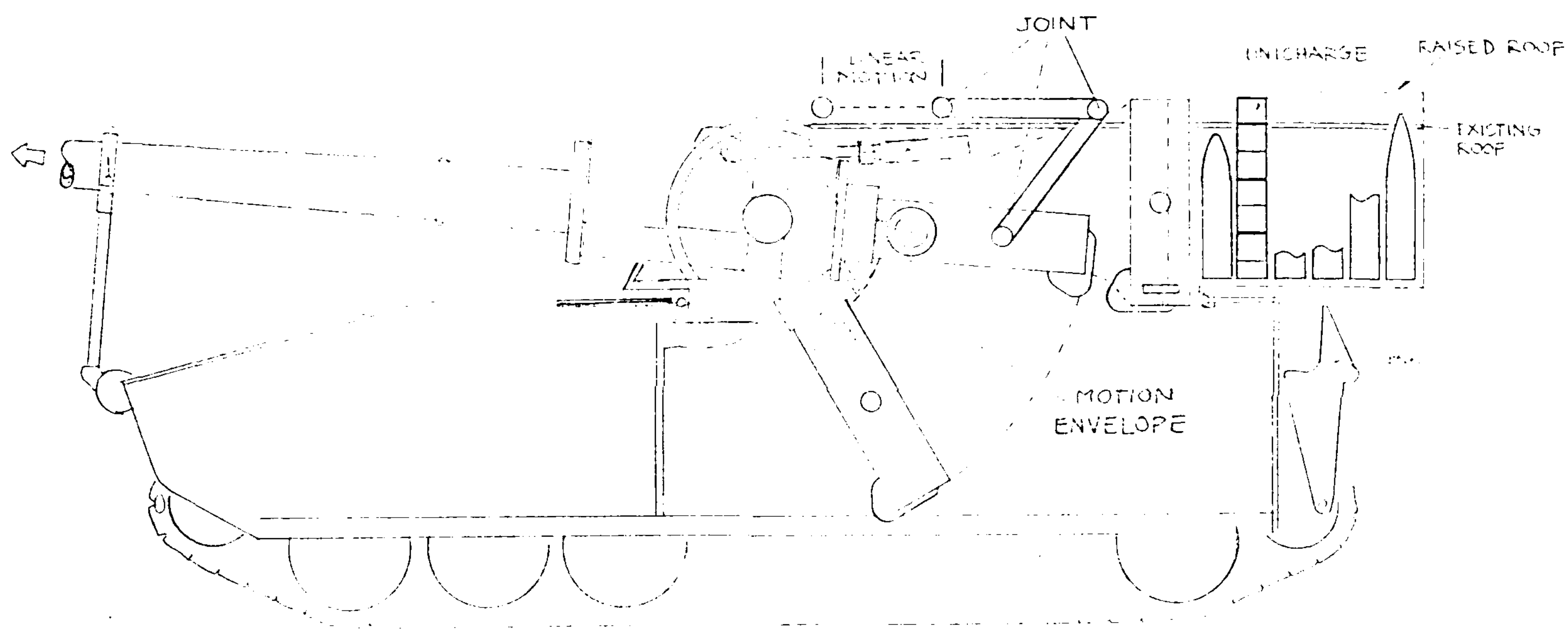


Figure 9. Roof-mounted mechanical system, side view

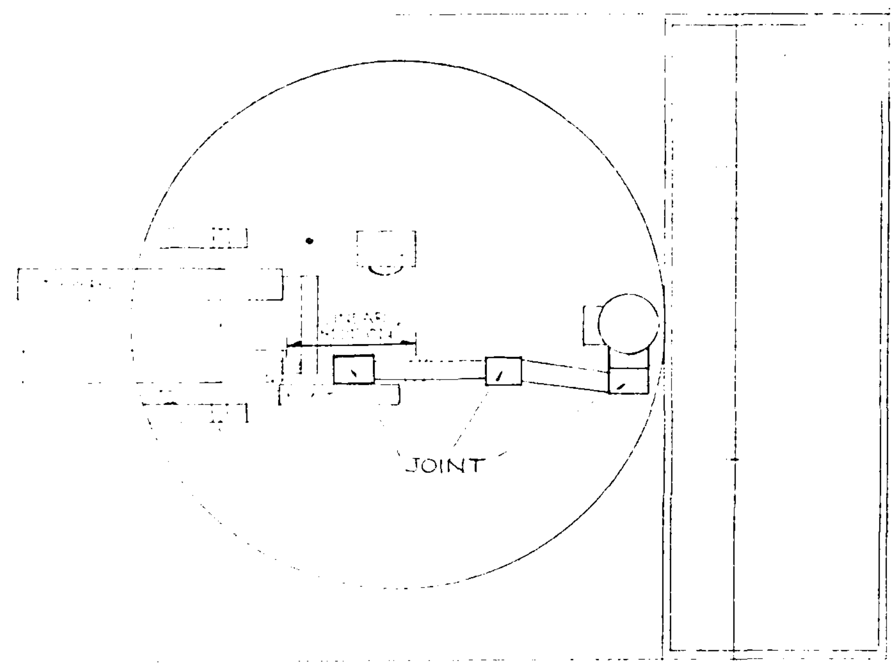


Figure 10. Root-mounted mechanical system, top view

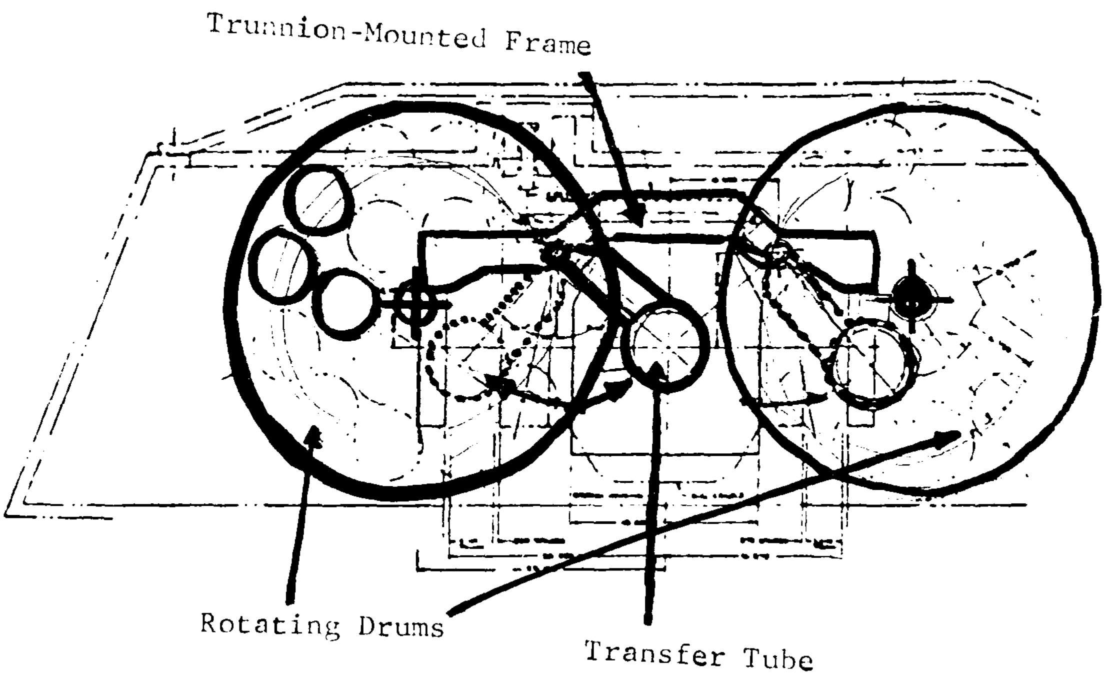


Figure 11. FMC autoloader concept

AECU would have to accommodate, than the roof or trunnion mounted systems.

Chrysler Concept - This system is illustrated in figure 12, and uses a full rotating breech with a simplified transfer unit (ref. 6). Again, there are no large differences in the number or types of control channels involved. The control system concept is discussed in the following sections.

Control System Concept

Based on the ISAS, the conceptual autoloaders, and those proposed by FMC and Chrysler, a control system and AECU configuration is set forth. The AECU itself will include expandable slots to incorporate additional input/output (I/O) cards, an improved microprocessor, and simplified and ruggedized packaging. User interface will be done via a cathode ray tube (CRT) terminal. Other interfaces will include the vision system, servo driver box and fire control computer (FCC) or gunner's station. This conceptual layout is shown in figure 13.

The control loops themselves will be accomplished with multiple digital processors, rather than individual analog servo cards. This is the best method to increase adaptability to various mechanical systems and to incorporate advanced modern control methods. Details of the various aspects of this concept are discussed in the Sensors, Stability and Control, and AECU Sections.

STRUCTURAL AND MECHANICAL DESIGN

The intent of this part of the study was originally to develop the details of the AECU packaging, and to do mounting structure analysis for the control components. Since both the ISAS robot and M109 test bed are expected to change significantly, it was decided to direct more of this effort toward development of overall baseline mechanical autoloading systems. This would allow an AECU to be designed that could accommodate what we believe would be an optimum autoloader, as well as other candidate systems. This further establishes the limits (computational power, I/O, etc.) that a generic AECU should be capable of handling.

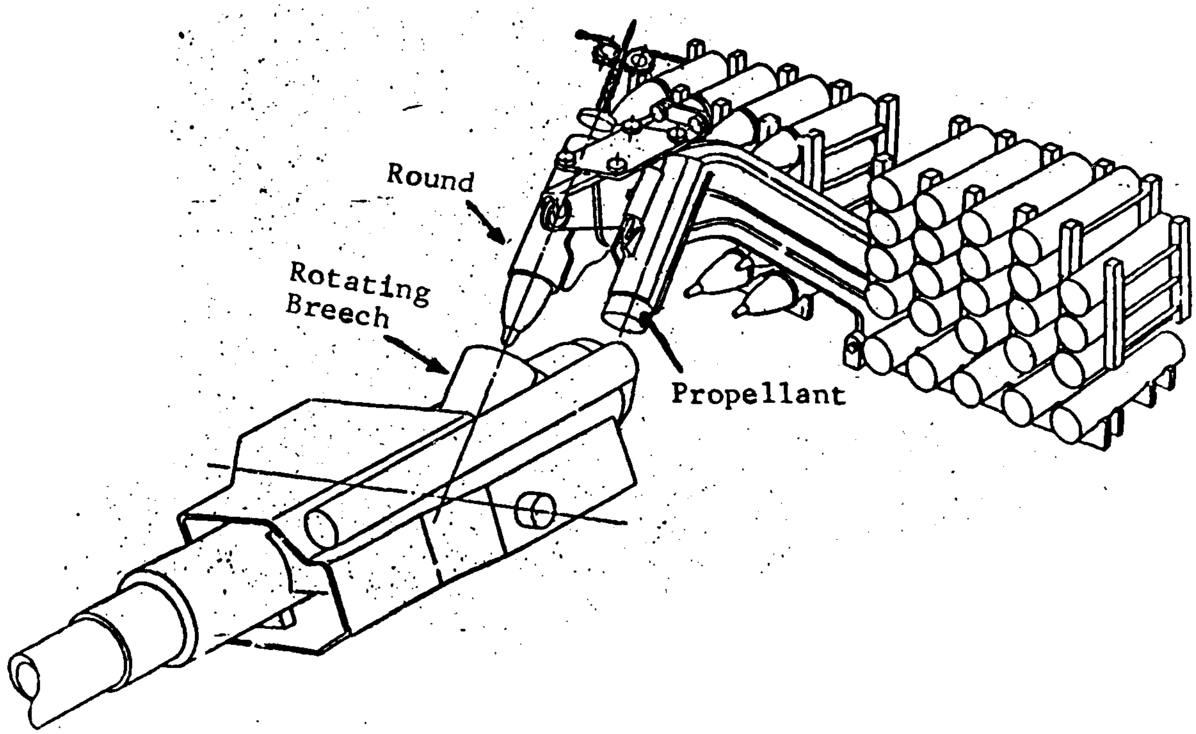


Figure 12. Chrysler autoloader concept

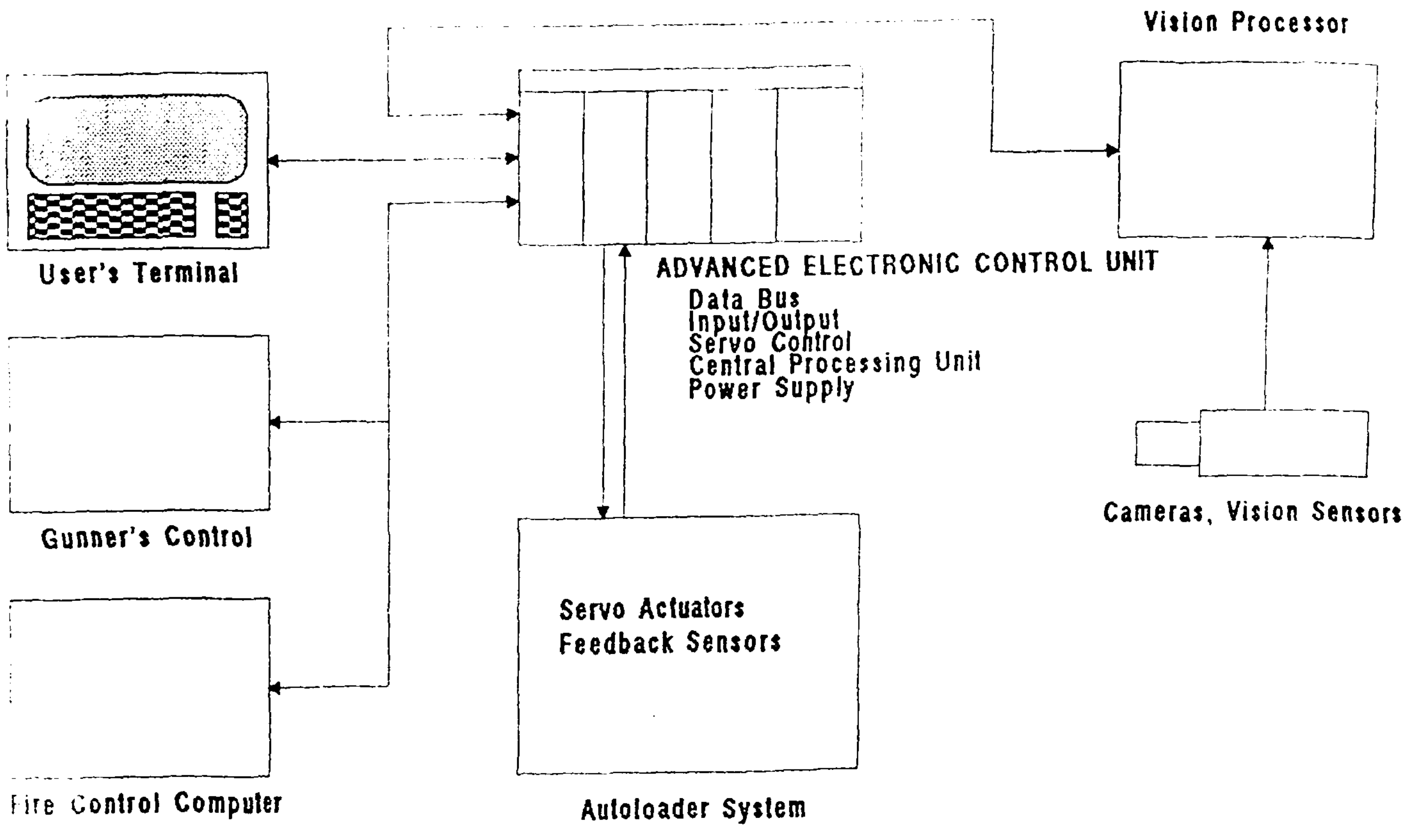


Figure 13. Advanced control system concept

Geometrical Solutions

The first step taken in estimating mechanical configurations was to review the required motions of the projectiles and charges from storage to the breech. A standard M109 gun was assumed (vs. the re-mounted ISAS gun tube), which fixes the breech location within a certain range with respect to the turret. The storage options were then evaluated, along with transfer unit geometries and mechanizations.

Ammunition Storage

Figures 14 through 17 illustrate some configurations that were reviewed. The ISAS configuration was developed to a point where projectiles and charges were stored around the perimeter of the turret, both vertically and horizontally (figure 1). Another configuration, presented at the Artillery Industry Day (Reference 2), used chassis projectile storage and a full-width turret bustle for charges and some projectiles (figures 14 and 15). Both of these concepts would require a flexible, multi-jointed robotic arm to perform autoloading, and would preclude personnel in the turret.

Turret-based projectile and charge storage methods include FMC and Chrysler concepts (figures 11 and 12) and alternate conceptual locations for magazines (figures 16 and 17). Any candidate system should allow vertical storage of the white phosphorous projectiles and manual loading of the M712 Copperhead. While affected by each particular implementation, the turret-based systems are generally more amenable to dedicated mechanical loaders as opposed to flexible robotic arms, and allow personnel in the turret.

For purposes of this study, we assumed vertical storage of projectiles and charges in a chain-ladder type magazine bustle located at the rear of the turret, as shown in figure 5. This addresses the white phosphorous and copperhead requirements, and the transfer unit would allow two operators in the turret during firing.

Transfer Unit

There are several mechanical configurations that can achieve the geometrical motion requirements. For the assumed magazine and breech configuration, both the trunnion and roof mounted systems have the required motion range. This range of motions needed of the transfer unit, along with the two configurations that we examined and outlined, are shown in figures 7, 9 and 10. Although the motions for each system could be produced by various

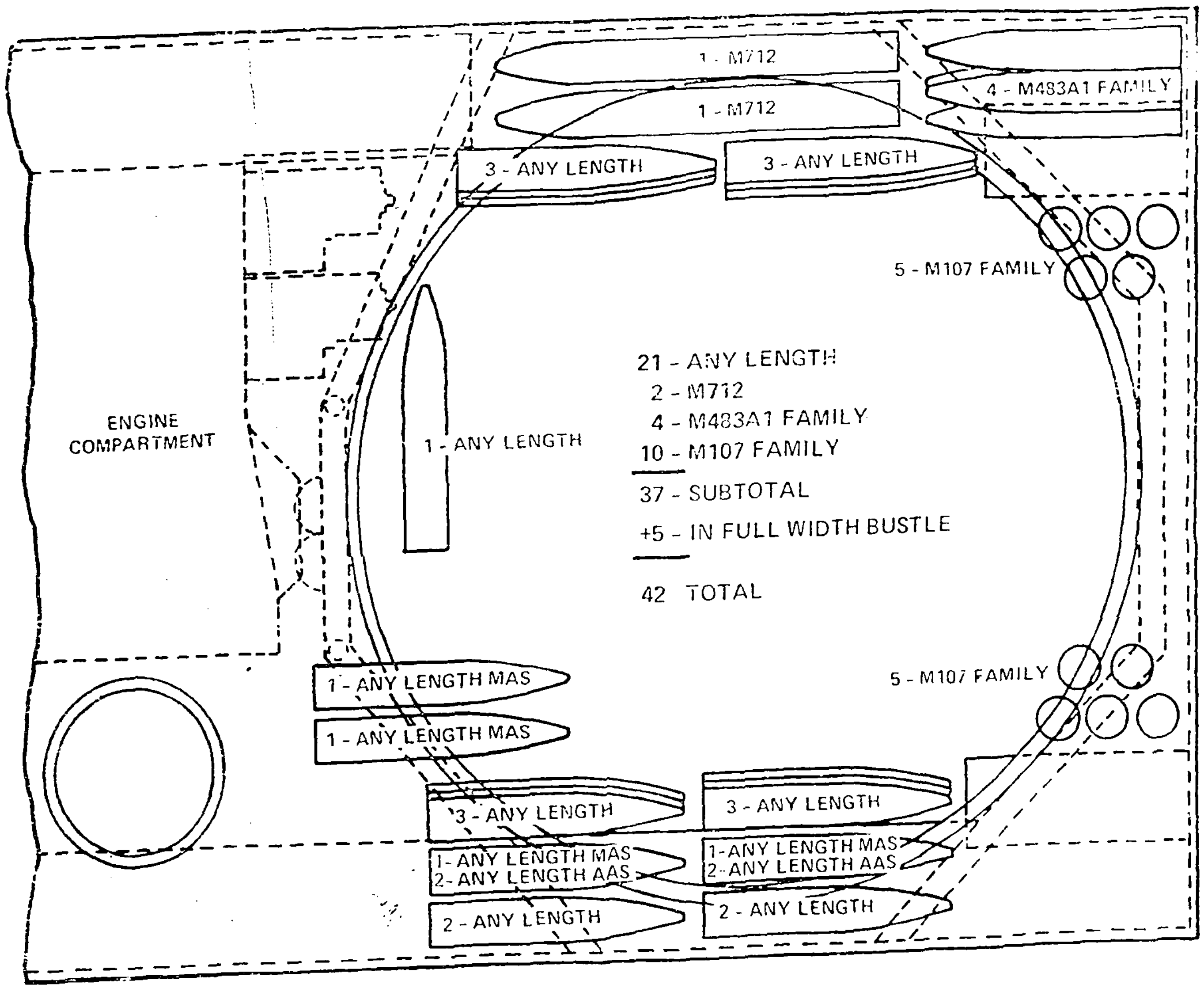
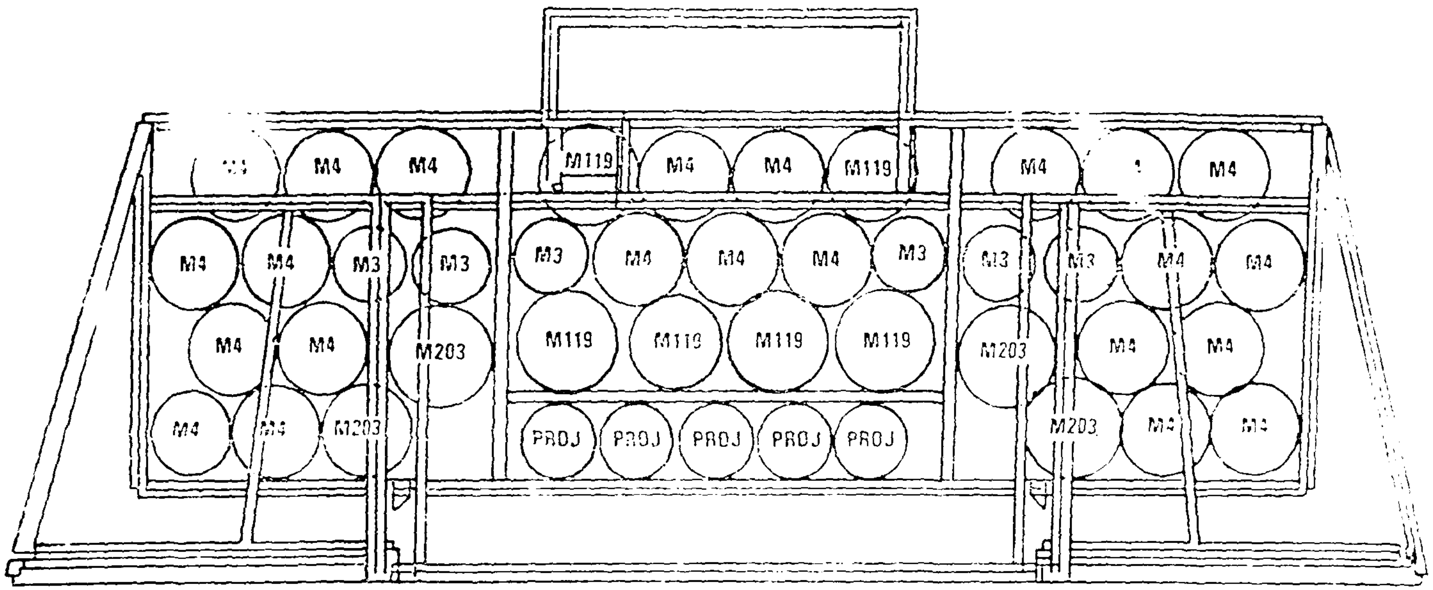


Figure 14. Ammunition layout, projectiles



12 - M3A1 PROPELLING CHARGES
23 - M4A2 PROPELLING CHARGES
6 - M119 PROPELLING CHARGES
4 - M203 PROPELLING CHARGES
45 - PROPELLING CHARGES BASED ON ONE POTENITAL MIX
5 - PROJECTILES, CONVENTIONAL LONG OR SHORT WHEEL BASE

Figure 15. Ammunition layout, charges

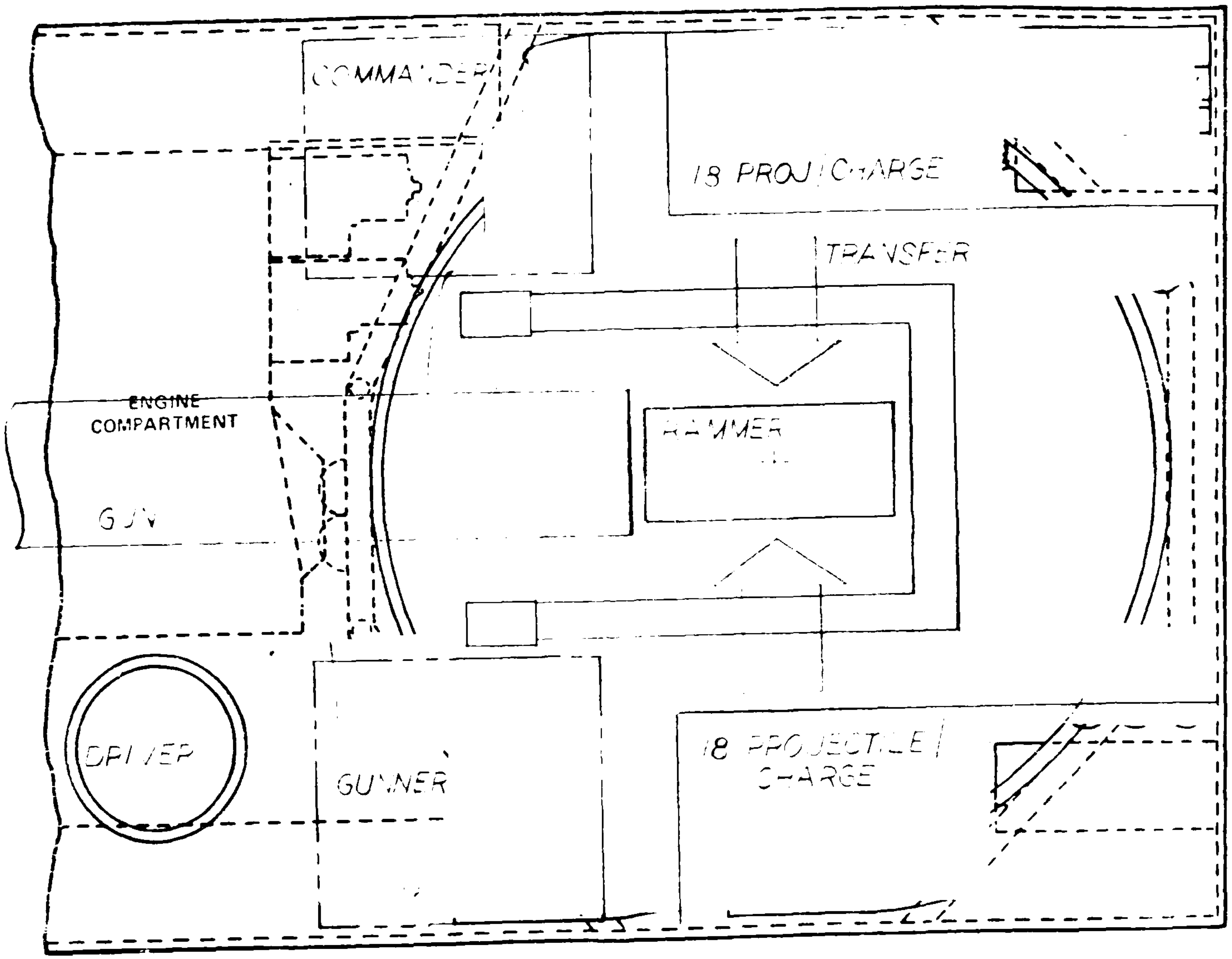


Figure 16. Ammunition layout, rear cab

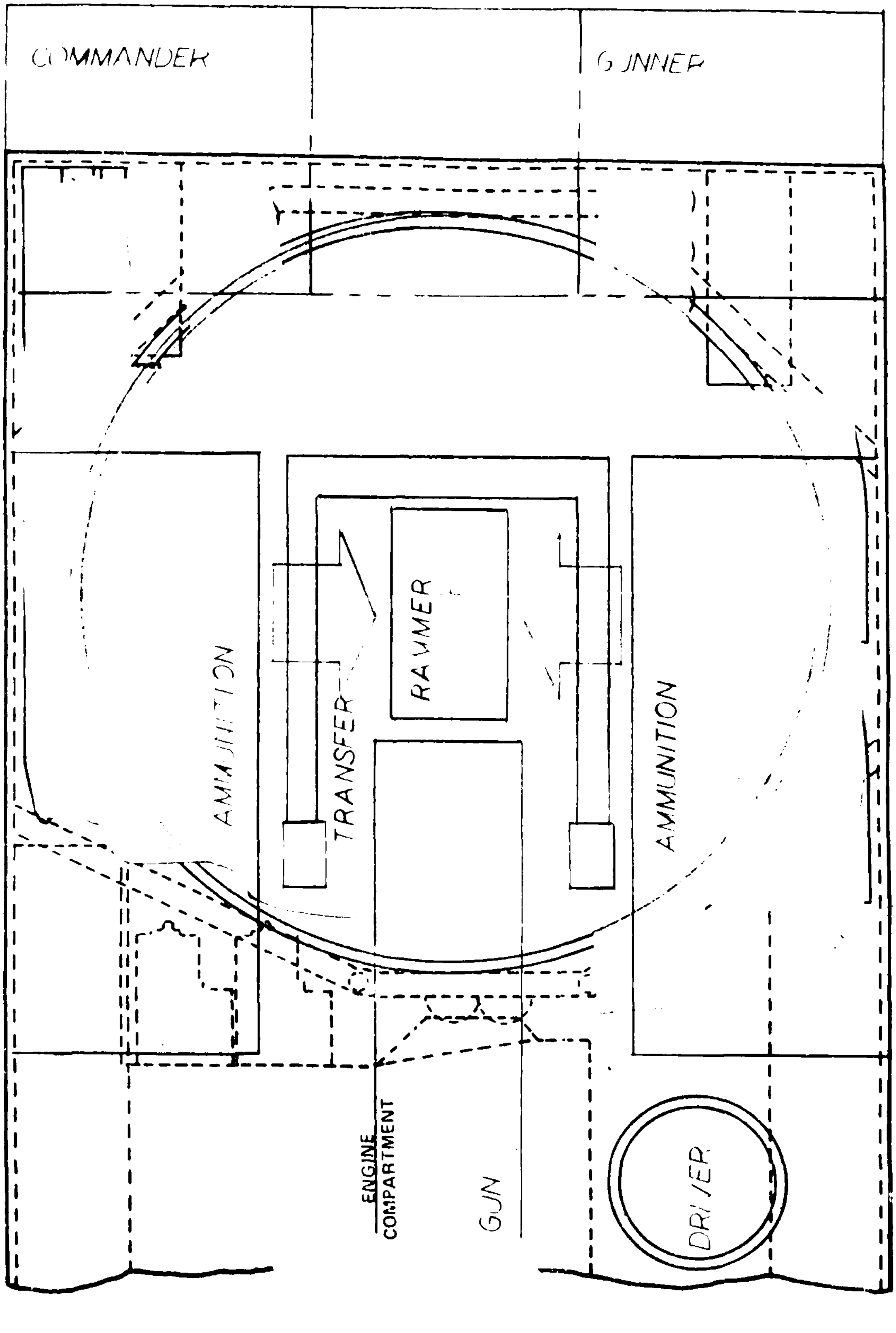


Figure 17. Ammunition layout, front cab

combinations of linear and rotary actuators, the total number of channels for the transfer unit does not exceed 8, with 1 more for the rammer.

The transfer units associated with the FMC and Chrysler systems (figures 11 and 12) involve different geometrical motions due to the differences in magazine and breech design. These systems are more limited than those we proposed, and involve less servo channels for control. The FMC system requires only 4 channels for the transfer unit, with an additional 5 associated with the drums and ramming operations. The Chrysler system needs about 4 channels for the transfer unit, with an additional 6 for the breech, rammers and magazine.

General Enclosure Form Factor

The investigation of various tanks and mobile artillery, including the M1-E1 and M-109, indicated that there is no standard form factor for the enclosure and packaging of the electronics being used at this time. Since increased vehicle electronics (vetronics), including the proposed controller, communication equipment, etc., are being incorporated into modern tanks and field artillery, some sort of standard vetronics bay is required. Such a bay would be similar to the avionics bays in modern aircraft.

The recommended choice for this vetronics bay is the Airinc ATR short form factor. This is a standardized bay that can accommodate advanced electronics on standard card shapes, as those proposed for the Army LHX family of helicopters, resulting in commonality of components and logistical benefits. This packaging method also allows for future electronics expansion.

SENSORS

The purpose of this section is to evaluate the types of sensors that may be implemented to control a given autoloading system. The existing ISAS sensors are considered the baseline. These establish a set of minimum requirements for the controller I/O and servo loops. Different types of sensors that could be applied to ISAS, or any other mechanical system, are also examined.

Requirements

Sensor types fall under two general categories: motion or servo control and verification. Motion control sensors are required in the feedback loops that control the robot motions, as well as the magazine and other subsystem motions. Verification sensors are implemented to provide the inputs that will allow the microprocessor to essentially duplicate the human operator decision-making process. Functions will include projectile, fuze and charge identification and selection, system status determination, and safety observations. These subjects are detailed in the following sections.

Existing Sensors

A diagram showing the existing ISAS sensors is shown in figure 3. The transfer robot uses 6 angular encoders and 1 linear encoder. There are 6 limit switches associated with the x-y gantry mechanism. The flick loader incorporates 5 proximity switches, whose signals are fed directly to the FCC. There is a shot sensor proximity switch mounted in the gun. The breech block uses 4 proximity switches tied to the breech controller and FCC.

All the servo loops are single redundant. The existing system does not incorporate the subsystems, such as the magazine bustle, fuze mechanism and auto primer system, that are included for the estimation of required additional sensors.

Additional Sensors

The existing ISAS set of sensors probably represents the minimum that a generic controller would need to accommodate. Additional numbers and types of sensors are required for redundancy, improved dynamic response, and mechanical systems with more control loops. The maximum estimated number and types of sensors will be addressed in order to design an AECU of sufficient capacity. These issues are discussed below.

Alternate Mechanical System Motion Sensors

The basic motion sensing requirements of an alternate mechanical system are similar to the ISAS, differing primarily in the number of degrees of freedom that require control. The control loops evaluated here include those in the transfer unit, loading mechanism, magazine, auto fuze mechanism, and auto primer, since a generic AECU will have to accommodate these systems. The expected worst case with respect to I/O and servo channel capacity is for a system similar to the roof or trunnion-mounted system. A control and feedback diagram for this system is shown in figure 18.

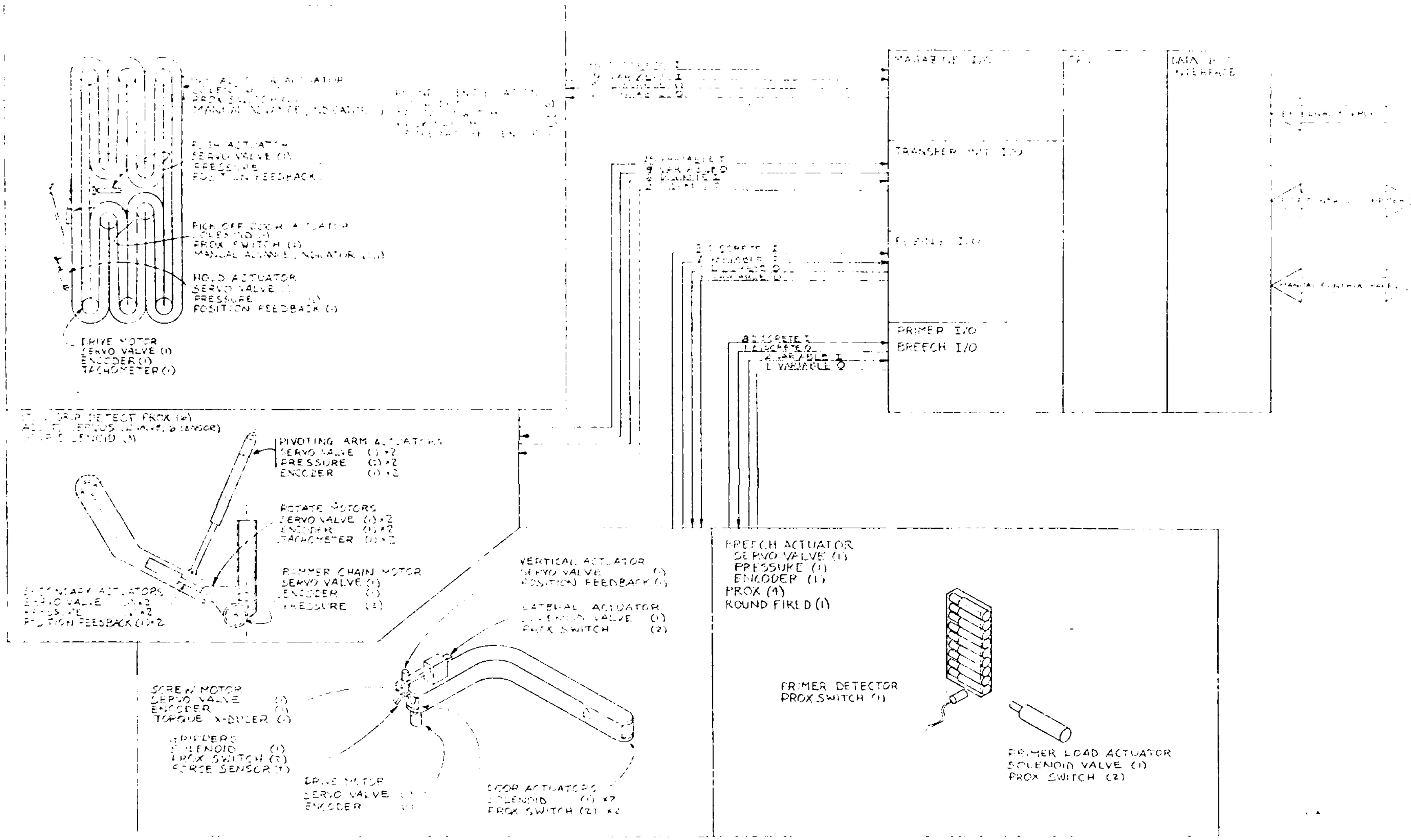


Figure 18. AFCF control and feedback diagram

The transfer unit itself will use 25 feedbacks for the servo loops. These include pressure transducers, encoders, tachometers and force sensors. The magazine will have 3 servo channels using 9 feedbacks. The autofuzing mechanism will require 3 servo channels with 7 feedbacks, while the breech may require 1 servo channel with 2 feedbacks.

The capacity for handling several channels of force sensing must be provided for. These sensors will be used to measure grip forces associated with ammunition handling, and seating forces of projectile ramming. This will not pose a problem, since the digital control loops will be easily programmable to deal with force feedback, as will the command software and logic.

Improved Dynamic Response

Higher bandwidth in a servo system results in faster, more precise response, with less overshoot and oscillations. Servo systems with certain mechanical configurations can be improved dynamically by several methods. One is to use higher derivative sensors in the loop closures for increased gain and higher crossover frequency. These include rate sensors and accelerometers mounted on mechanical members, and delta pressure transducers installed in hydraulic actuators.

Verification

Verification involves using sensors to check the system for correct, safe operations. A standard sensor used for this is the proximity sensor. In the complex operation of loading and firing rounds, many mechanical functions must be done in harmony for the system to function. Proximity switches will be the primary method to ensure that commanded motions have been completed.

Optical color sensors and prox. switches will be used to detect round presence and type during loading and unloading from the magazine. An example system, shown in figure 19, uses prox. switches to detect round height and optical sensors to detect color bands. Unicharge cartridges can be detected by the color sensors. This will allow the AECU to keep track of projectiles and charges, which is necessary for automatic operations.

Redundancy

System redundancy can be accomplished in several ways. The basic method is to duplicate all failure-prone mechanisms and sensors. Simple duplication would require

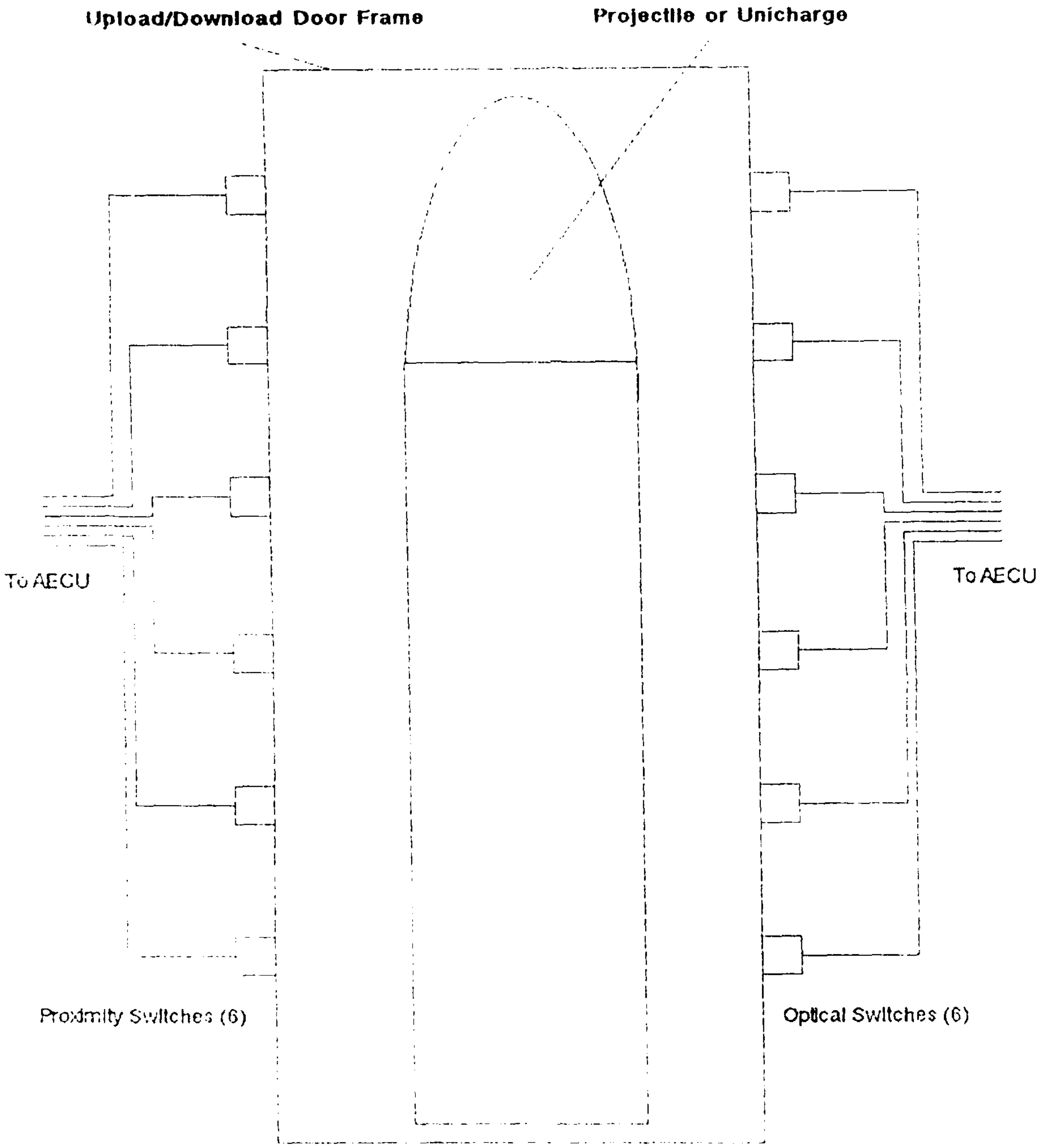


Figure 19. Round identification method

doubling such items as the prox switches and optical detectors.

An alternative redundancy scheme is to use a vision system to determine the system state. This has the added advantage of dissimilar redundancy, or checking the same parameters by different methods.

Final Configuration

The final sensor suite will not be detailed to great lengths, since any particular mechanism will have different sensor requirements. However, certain areas of sensor usage have been identified as common to most autoloading systems. Also, the proposed controller card designs are such that any combination of the recommended sensors can be implemented as necessary. The sensor types are outlined in the following sections.

Position

Resolvers and encoders are standard devices used for mechanical joints and the magazine. These feedback signals can be fed through a derivative computation to simulate a rate feedback. Position feedback from an ultrasonic ranger may be desirable for certain specific applications, and can be accommodated by the AECU.

Rate

Tachometers are expected to be used for items such as the rammer, magazine, and autofuzer to provide direct rate feedback. These are mostly used for speed control applications.

Acceleration

Higher derivative acceleration terms can be measured using small accelerometers attached to key parts of the mechanical structure. They are most useful when trying to achieve high-rate, high-bandwidth system response, which is an expected characteristic of an advanced autoloader. They can also be used to compensate for undesirable structural dynamics and resonances.

Also providing acceleration feedback will be pressure transducers on the electrohydraulic actuators. This provides a dynamic feedback equivalent to acceleration, and can be further used as a steady-state force control feedback parameter. This is necessary for good static robot performance in an acceleration (i.e. gravity) field, when carrying heavy loads, and in the robotic mating or contact of different hydraulic actuator components with stationary surfaces.

Force

Force sensors, such as load cells and strain gauge devices, are expected to be used in controlling projectile seating forces and grips, in addition to those aspects described in the previous paragraph.

Discretes

Proximity switches have been demonstrated to be the most reliable devices, as compared to mechanical limit switches, in providing presence/absence information on mechanical components. These are used extensively in the present ISAS and M1-E1 TTB autoloader, and are relatively inexpensive.

Vision

A Vision system interface capability is recommended for the AECU. At this time, it will be primarily used in providing redundancy for the position feedbacks, and in safety management.

The position redundancy consists of primarily the discrete proximity switches, and in some cases the encoder/resolver position signals. Algorithms to detect presence/absence by vision are very easy to implement. These algorithms are also applied to detecting human presence within the operating envelope of the autoloader. More complex position computations are possible given an appropriate vision system and algorithms.

Camera systems such as the Fairchild CCD/CAM 5000 are extremely small, rugged and versatile, and can be configured so that multiple cameras cam be located, and each used by 1 processor during different phases of the autoloader sequence.

STABILITY AND CONTROL REQUIREMENT

A generic AECU will have to accommodate command structures, servo control loops and discrete control loops for a variety of mechanical systems. The autoloader systems that we examined range from mechanized automation (Chrysler, FMC) that involve a minimum of servo control and programmability to a highly flexible robotic system (ISAS) requiring significant servo loops and computation for path control. The factors influencing the stability and control aspects of the AECU are discussed in the following sections.

Servo Loops

Three of the foundation issues involved in servo control design are the physical system to be controlled, the desired control parameters or states and their responses, and the available sensed parameters or states. For this specific AECU, the physical systems are not known. We will assume the transfer unit to be some hydraulically-based mechanism, with the associated subsystems (magazine, autofuze) also hydraulic.

The main desired control states are the position of the transfer unit, magazine, fuzer and breech. Also to be controlled are various forces associated with safe general hydraulic operation, fuzing, projectile seating and grip force. The available feedback sensors are discussed in the Sensors Section.

The use of digital, microprocessor-based control loops will allow the application of many modern controls techniques, including state space, multi-input, multi-output, and optimal methods.

The servo loops will have sufficient speed to obtain control bandwidths to 100 hz. This implies digital timing of at least 500 hz.

Command and Control

The command and control functions are programmed into the AECU firmware. This will consist of programs to perform the required autoloading tasks. The main routines will use logic and subroutines to drive the servo loops with the correct timing, rates and displacements. This methodology allows iterative user development through a PC-type terminal.

The software will be designed to allow the use of advanced control techniques in the command loops. Standard single-axis command structures will be replaced by matrix operations that will optimize the path control and favorably impact stability, as judged by the cross-coupling, speed and overshoot criteria.

REDUNDANCY

Requirements

Based on the initial overall system assumptions, the redundancy requirements for an autoloader were evaluated. The first failure level involves sensor failure. Failures of this nature can be compensated for by using multiple sensors to measure the same parameter, and by using a vision system to provide dissimilar redundancy. The AECU executive processor will provide the redundancy management logic and weighting, coordinating measured sensor values with reasonable values and with the vision system.

The second level involves individual mechanical component failures, such as electro-hydraulic servovalves. A correctly designed autoloader using multiple actuators and motors for the transfer units, magazine, rammer and autofuzer can compensate for this. A single failure can be detected directly or empirically by the AECU, with command changes to the remaining functional component compensating at reduced overall rates.

In the case of total electrical or hydraulic failure, a manual backup capability is required. This takes the form of hand cranks on items such as the transfer unit, magazine, rammer and breech. Also appropriate will be moving the transfer unit out of the way, such as against the roof or floor, to permit manual loading. A fully robotic howitzer could not of course tolerate such a failure, and would need redundant electrical and hydraulic subsystems. Unlike the previous two failure modes, this type of failure cannot be dealt with in the AECU or control system, and is solely a function of correct mechanical design.

Failure Modes and Effects Analysis

A detailed FMEA was not performed due to the lack of a specifically defined autoloader or robot, such as the ISAS or second generation FMC device.

AECU DESIGN

Introduction

The design of an Advanced Electronic Control Unit (AECU) required the investigation of several new processors and high level languages. Further, a study was made of the best architecture for the dedicated control task of a 155-mm autoloader. Some of the conclusions came from the work done by Vista Controls on the M1 Tank autoloader system in which a multi-processor system was used to control the magazine and the transfer unit. Analog position and force loops were used to provide position control and load limiting. This configuration works well but is somewhat restricted with respect to changing gains dynamically and performing kinematic calculations in real time. The multiple processor architecture shown in figure 20 represents our current approach to the autoloader control system. There are several ways of interfacing the various processors with the main control processor. One is memory mapping using DMA, the other is using the standard input/output calls. For reasons of speed, the DMA memory mapped method is chosen for this application. The hardware architecture for the AECU that we recommend is shown in figure 20. Although shown as a bus -structured, multi-processor system, we are actually using a shared memory technique which allows the control loop processors to communicate with the executive processor through a DMA path.

An alternate hardware architecture is shown in figure 21, and uses an analog control loop closure. The reasons for the all-digital approach are discussed in the Analog vs. Digital section.

Central Processor Card

A MIL STD 1750 processor was chosen for the executive CPU because of the directive to standardize on the 1750 for future military weapon systems, and because this processor is being used in a number of current aerospace applications with good success. Vista Controls has found the support for the 1750 devices growing daily. The speeds of the devices are also increasing rapidly, as significant R&D is being applied to their development. The MD-281 and the F-1750 appear to the best candidates for this application. They can easily meet the throughput requirements and support the frame-driven structure needed by the autoloading system.

Memory Card

Memory for the executive processor shares two roles; one as program memory for the executive processor and one as shared memory for I/O communication with the control processors.

A 1553B communication I/O attached to the main or executive bus will be used to communicate with the fire control computer to receive commands and send status of the loader system to the fire control computer. This card is

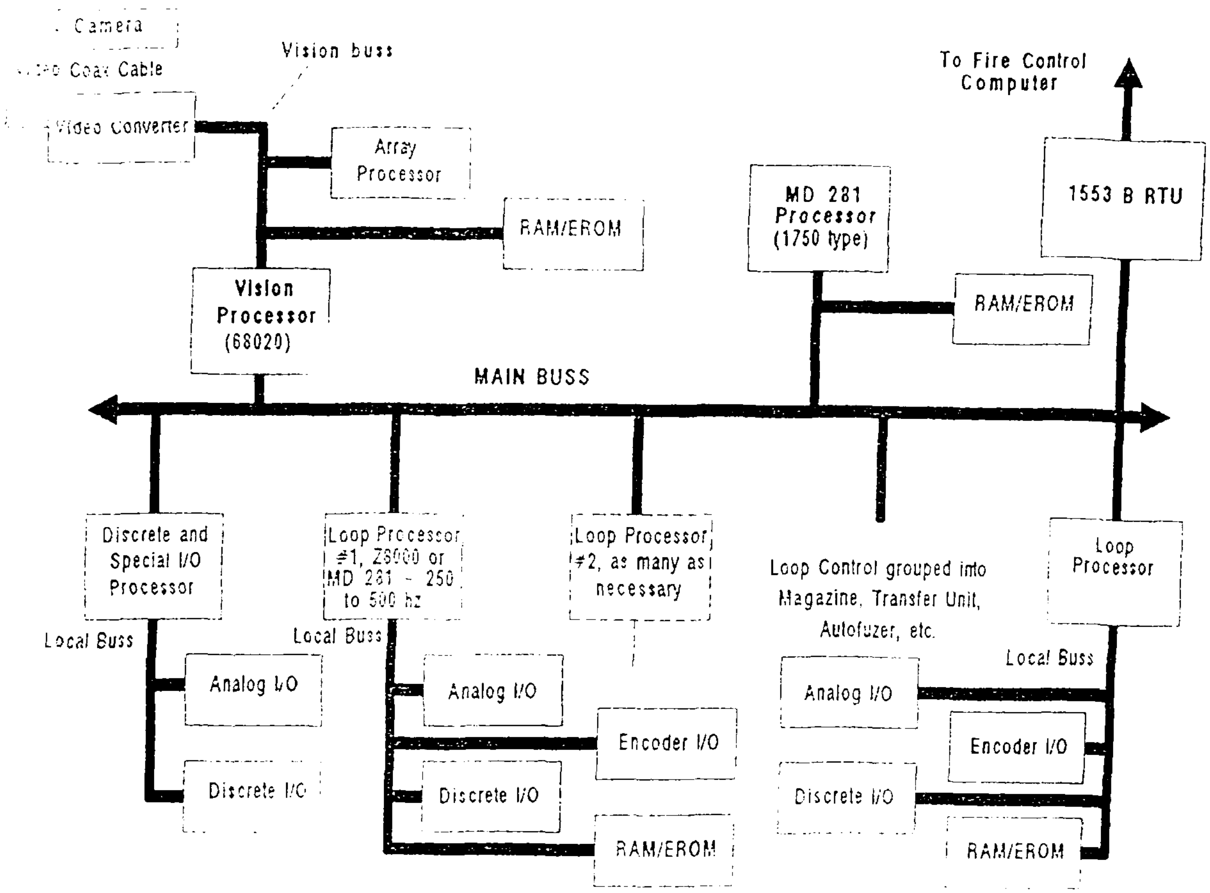


Figure 20. Baseline AECU

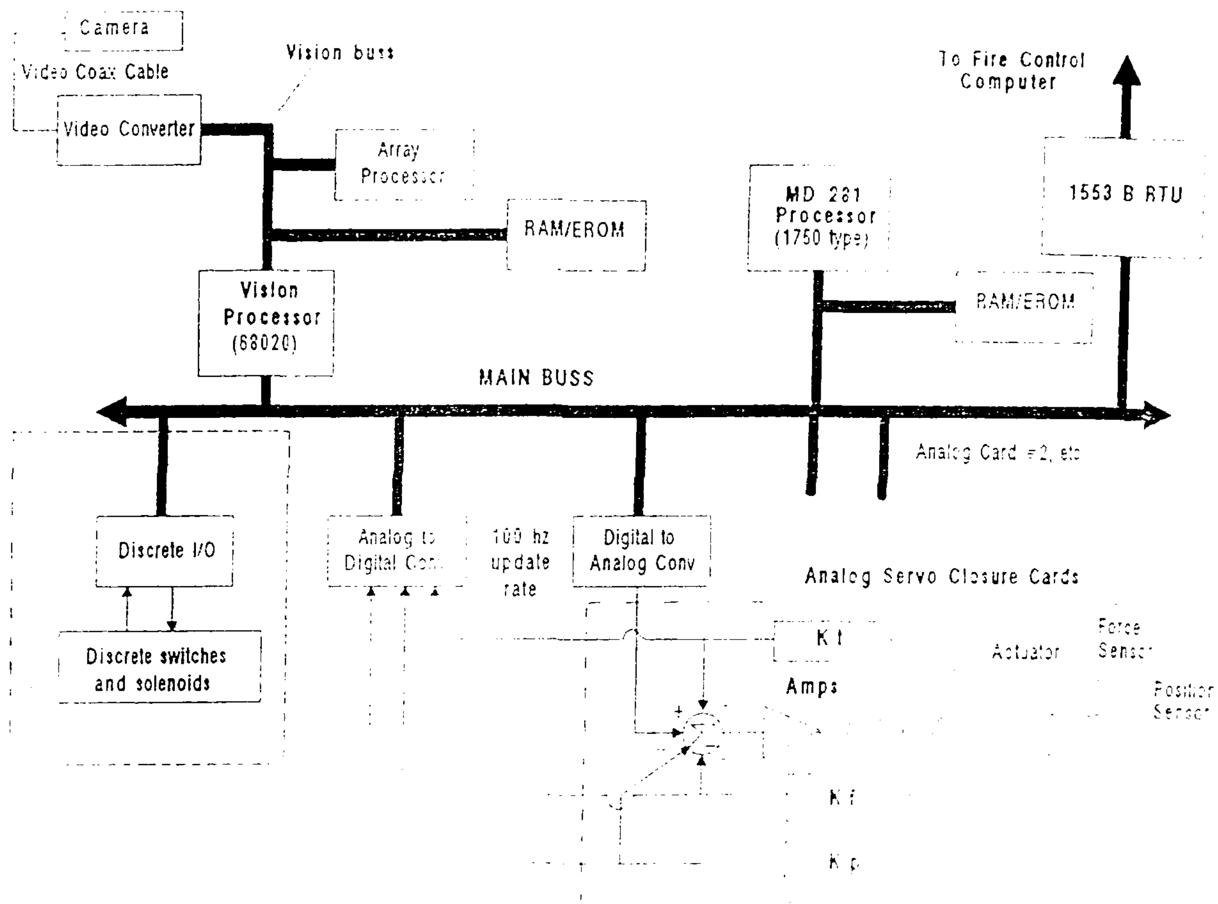


Figure 21. Alternate AECU configuration

well developed and has little development risk. Data bandwidth is more than sufficient for the loader communications requirements.

Video I/O Card

The Video I/O interface card provides for the high-speed interface of the video processor to the executive processor. Signals reflecting the loader state and the intrusion state are available every 10 millseconds at this bus interface. Several of the time-critical flags will be passed by the shared memory to the control processors. The video processor, actually a forth engine, is a set of special purpose VLSI that has been developed on a number of aerospace applications.

Control Loop Processor Card

The control loop processors are identical to the executive processor cards and are interchangeable. This commonality provides for a significant reduction in maintenance cost and logistics. RAM and EROM are integral part of the CPU card and have access times in the 60 nanosecond region. The control processors connect to the control I/O through a local high-speed bus . The CPU is running at 25 MHz and is using the clock to generate the 2.5 millisecond interrupts. The control processor configuration is shown in figure 20.

Input/Output Card

The analog and discrete input/outputs are designed to interface with the particular mechanical loader configuration that is used. In the case of the 155-mm autoloader, Vista Controls has looked at a number of different mechanical configurations and has designed a relatively universal I/O card to interface with many different hardware configurations. The basic actuation block is shown in figure 22. Comparisons of the mechanical configurations studied are illustrated by figures 23-26. It is interesting to note that for most of the systems the I/O requirements are very similar. Therefore it is possible to design the I/O cards to service each degree of freedom. This design makes the AECU very flexible (i.e., add an I/O card for each degree of freedom).

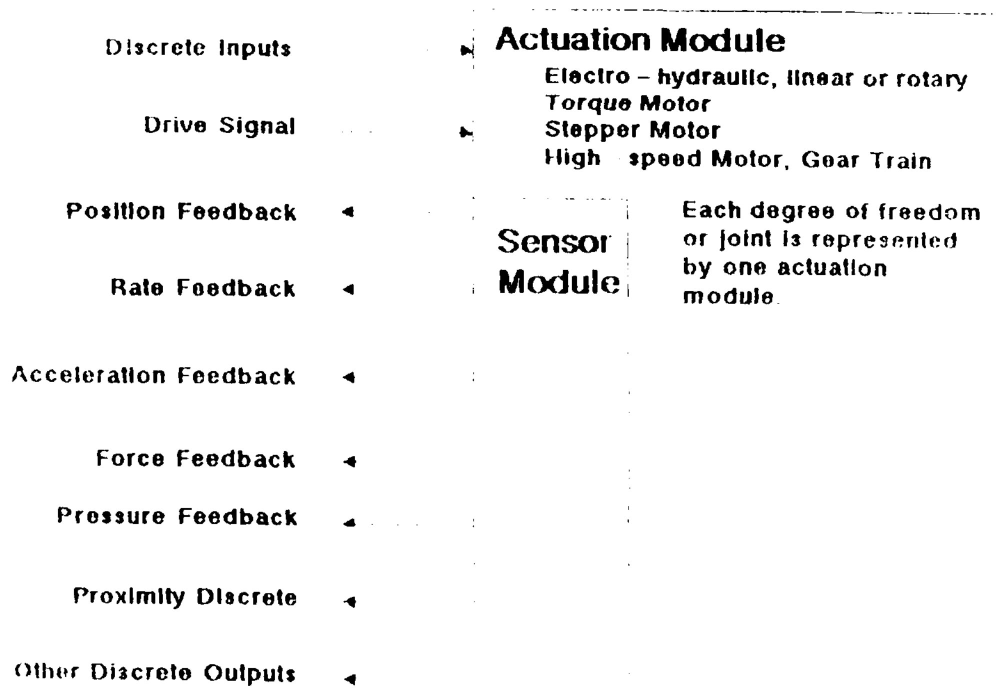


Figure 22. Actuator/sensor representation

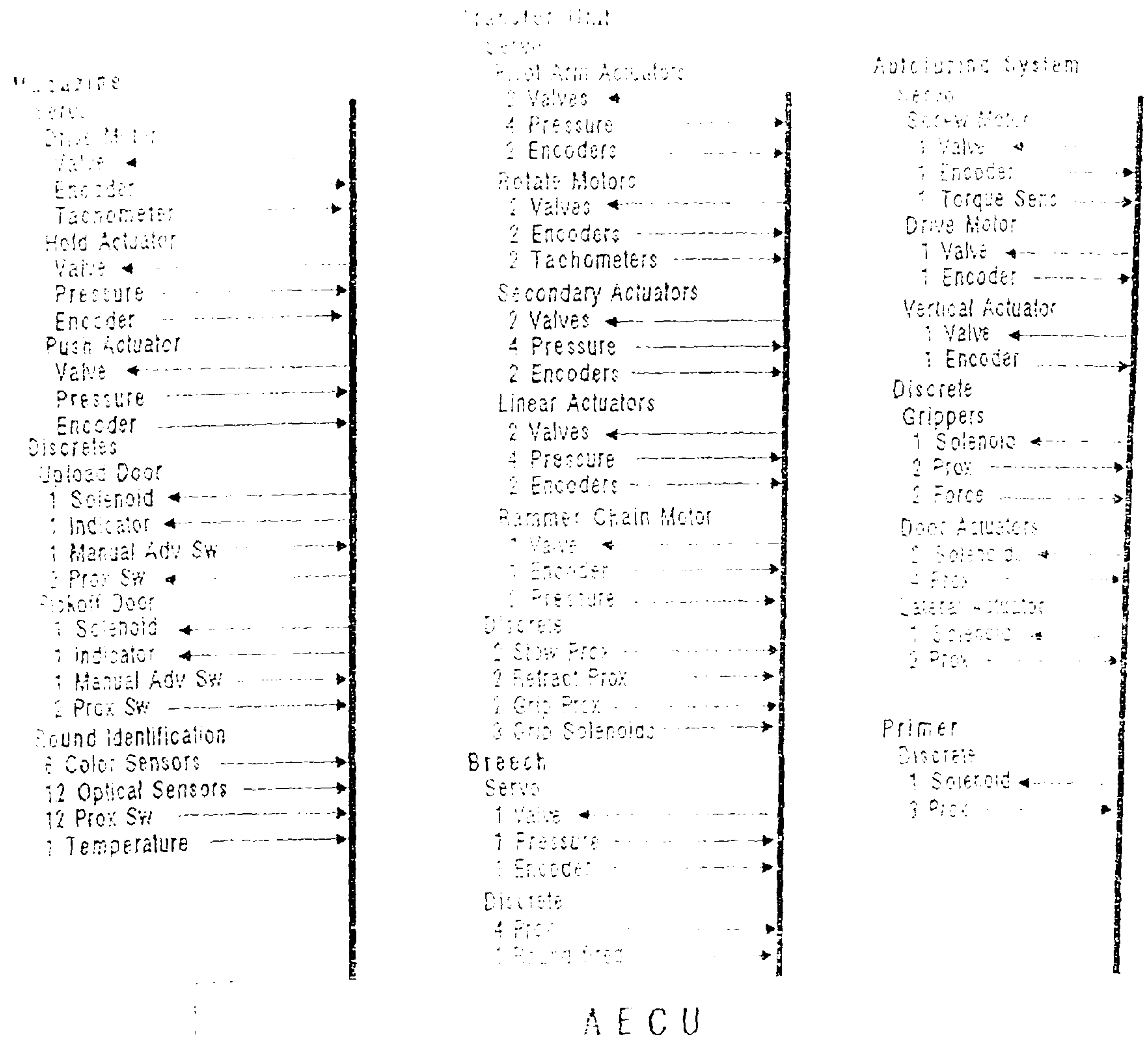


Figure [illegible]. Trunnion-mounted system control requirements

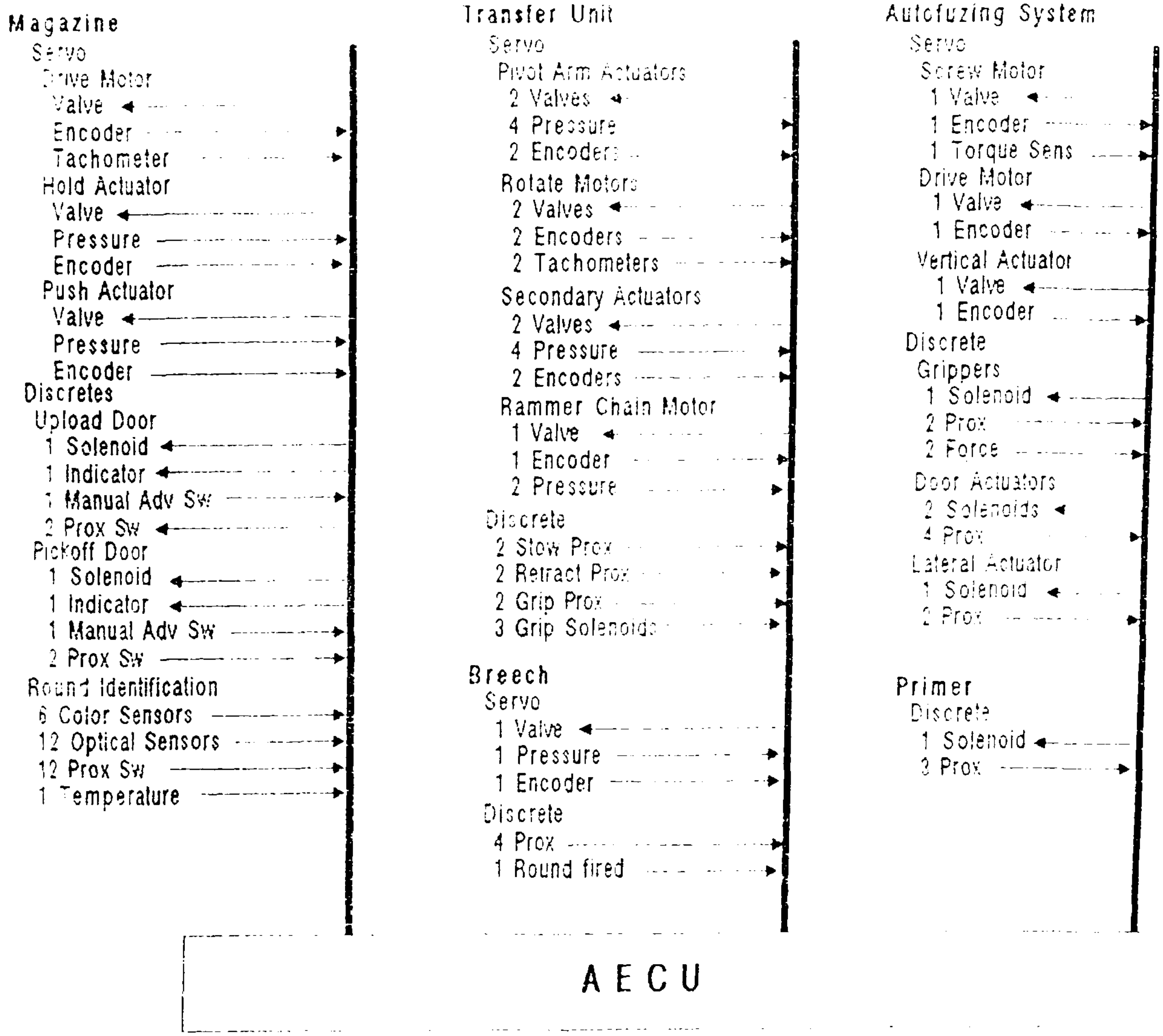


Figure 24. Roof-mounted system control requirements

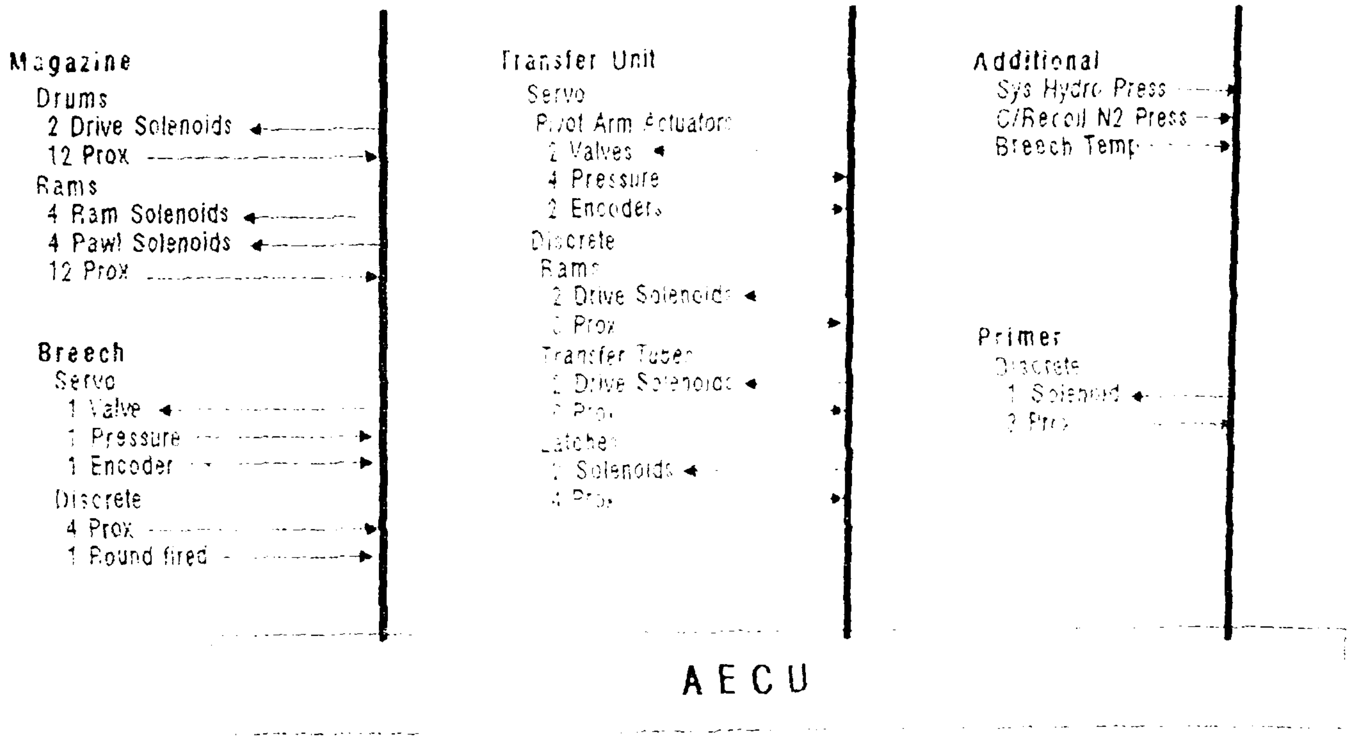


Figure 25. FMC system control requirements

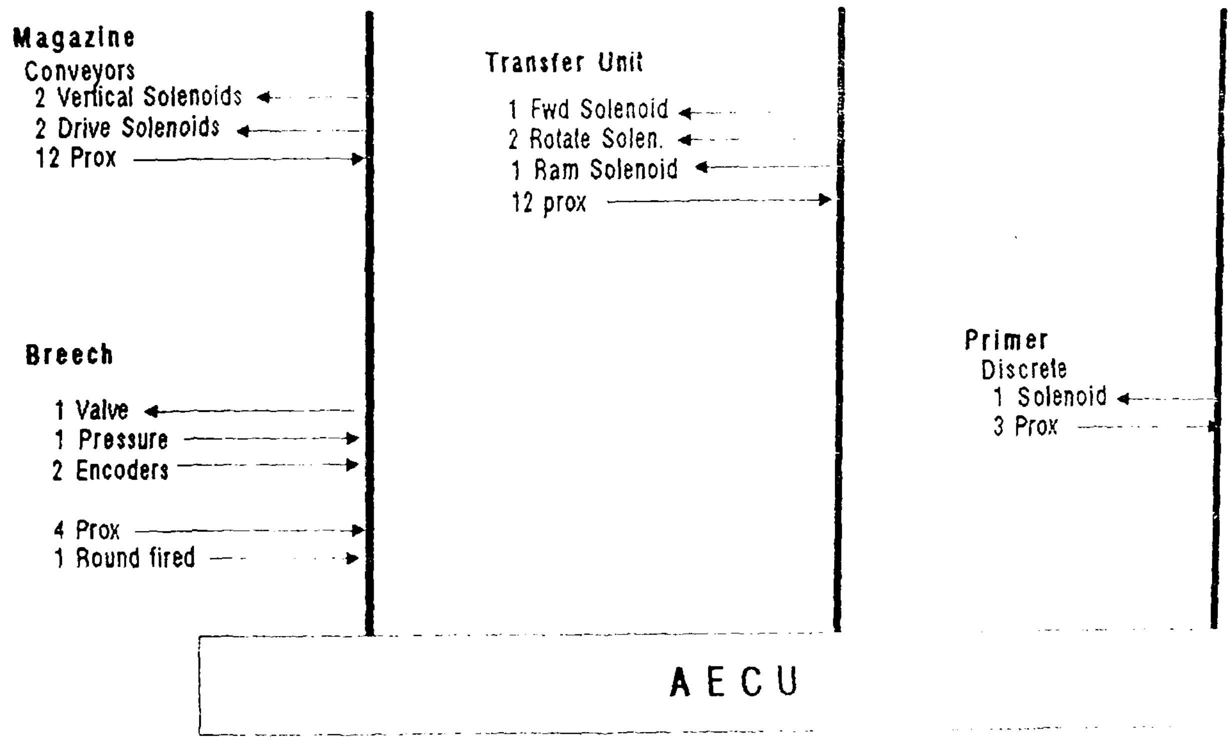


Figure 26. Chrysler control system requirements

Processor selection

A number of processors were considered for the loader task, as shown in table 2. Vista Controls recently performed the same trade study for the AH-64A helicopter for McDonnell Douglas Helicopter Co. The basic conclusions are that most of the commercial processors are not maintained long enough to support a military program, and that most are not sufficiently radiation hardened to survive a mild level of radiation. The 1750 series of processors has a clear edge in this review. There are several situations that the 1750 series does not handle well; in particular, bit manipulation is relatively poor in time efficiency. The DOD mandate of using 1750 in new design is also a good reason for choosing this processor. Because of the mandate, a significant amount of support software is becoming available to the developer. The complier efficiencies are also becoming much better, and are producing very compact code. Although ADA-based compliers have not shown good efficiency in control law code in the past, our recent use of these has shown a factor of three improvement. Projections indicate that ADA 1750 object code should be equal to C code within the year.

Analog versus Digital

The trade between a analog inner control loop and a digital control loop has been the subject of many studies. Our experience has shown that the hardware is now available to do digital loop closure. With the high speed I/O, control loop rates of 500 updates/sec are achievable. This allows structural notch filters to be implemented out to 50 Hz, and control system bandpasses on the order of 20 Hz. This is more than sufficient for the autoloader task. The advantages of being able to dynamically adjust the loop parameters for changing kinematic relations far out weight the small amount of added software complexity. The digital inner loop closure also allows the point-by-point shaping of the rate and acceleration of the loader.

Packaging

The packaging of the AECU cards is in the process of being defined. A form factor similar to the proposed LHX helicopter standard should be used to minimize inventory requirements.
This is approximately a six inch by eight inch form factor. The PC cards would be a four-layer configuration with ground and power planes. The backplane would be a nine-layer board with a ground plane.

Application Areas	Processor
16-bit	65C816/65C802 8096 783XX 68200 ADP F-1750 MD 281 Magic 5 8086/8088/80186/80188 80286
32-bit	80386 34010 VL 86C010 ARM IMS T212,T414 Z8000/Z80000 68000 Series 32000 WE32 Family CLIPPER
32-bit bipolar and CMOS	8X305,8X400 2900,29C00,29G00 29300/400,29C300 74AS8XX/74AS88XX
16- and 32-bit DSPs	mPD7720A 320 DSP Family MB8764 ADSP 2100 PCB 5010/11 DSP 56000 77230 DSP32
Special-Architecture DSPs	7281 A100 DSP

Table 2: Processors Considered for AECU

Language Selection

ADA has been tentatively selected as the language with some assembly code in the inner loop control tc achieve the necessary speed. In any case, all of the PDL would be in ADA. C and Jovial would be the backup languages if the expected compiler efficiency of ADA is not achieved.

Software Structure

The major functions and structure of the software implementation for the AECU are presented in figures 27 and 28. This software performs all the computations, logic, and signal management functions required for the AECU operation.

Executive Processing

The software structure is divided into the main or executive processor and the control processor structure. The executive processor preforms the following functions :

- startup and shutdown
- Interrupt processing
- executive
- frame synchronization
- foreground scheduling
- middle ground scheduling
- background scheduling

This structure is illusrated in figure 27.

Control Loop Processing

Control loop processing performs similar tasks to the executive processor, but is running on a 2.5 millisecond clock. Its basic task is to perform the inner and outer control law computations, plus set up the logic for each of the degrees of freedom. This software structure is shown in figure 28.

I/O Processing

The I/O processing takes the signals from each of the sensors and makes them available to the control law computation. The control processor also looks at the shared memory for discrete and command update and places information about the control processor status there for the executive processor to use.

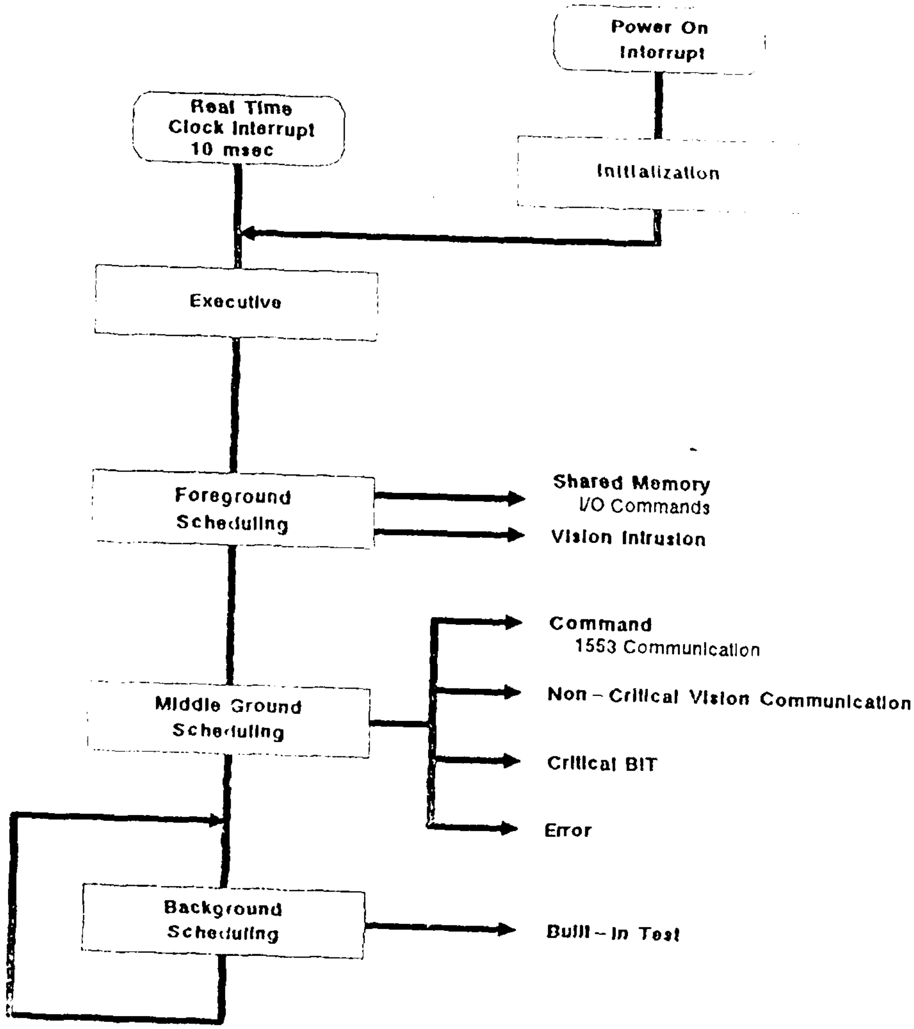


Figure 27. Executive processor software structure

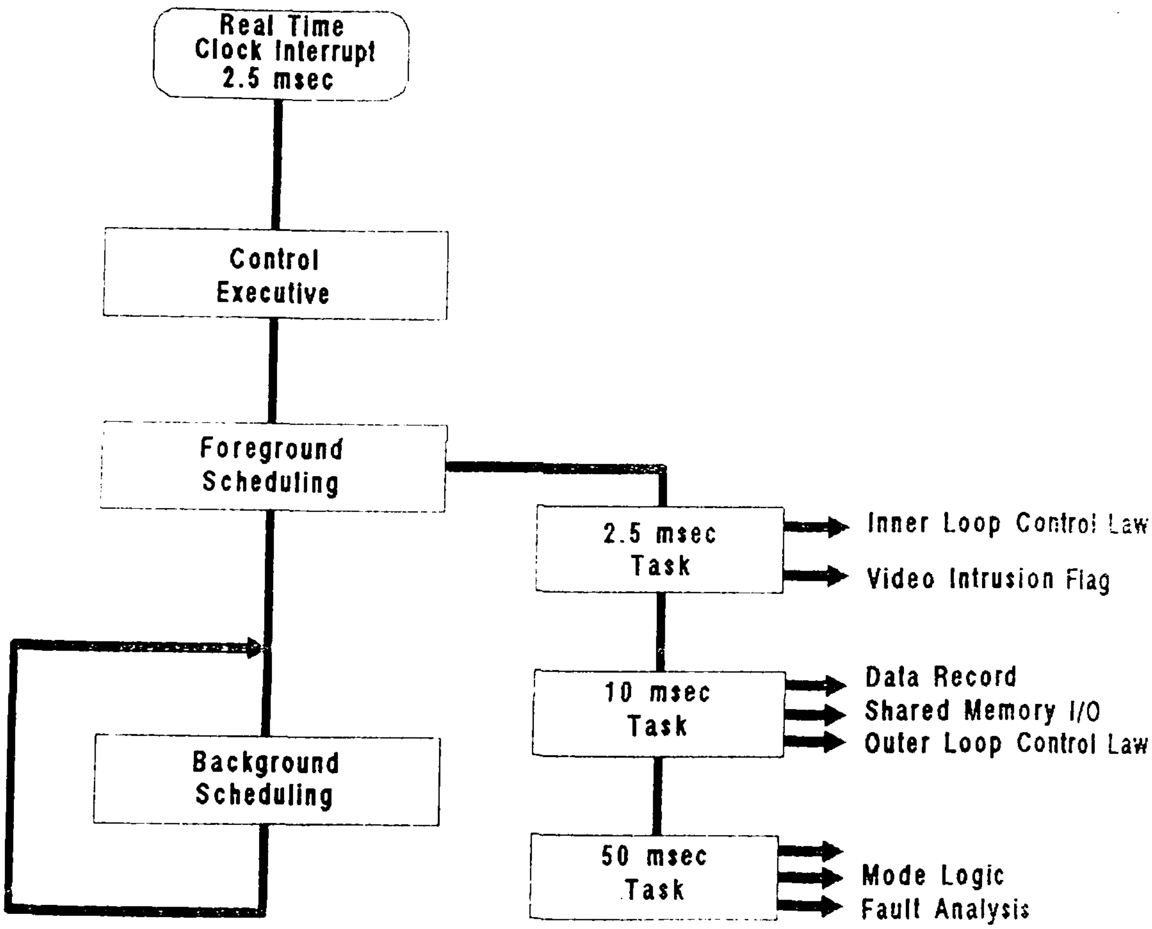


Figure 28. Control processor software structure

Control Laws

The control laws can be broken into several segments; the first is the inner loop closure, and the second the outer loop closure. The design of the control laws follow the optimal control method of least acceleration control to satisfy the position and rate requirements. This method generally assures smooth operation and consistent positional accuracy. The derivation of these laws are done in the Z domain so as to eliminate the analog phase of the program.

CONCLUSIONS

1. A single generic Advanced Electronic Control Unit can be designed and built to control a variety of military laboratory and combat autoloaders and robots. Current processor technology makes an all-digital command and control package possible, allowing for tailoring of both command sequences and logic associated with different autoloaders, and of the different dynamic requirements of the control loops. Using digital cards will also allow the implementation of state space and other modern control techniques.

2. The mechanical configurations studied to perform the autoloading task were found to have similar requirements as far as sensors and actuation, allowing a generic controller as that proposed to be effectively used, with a minimum of compromises, in conjunction with different mechanical and robotic systems.

3. The controller can be modularized so that only the required electronic cards for a given mechanical system need be implemented. This modularity includes electronic commonality with other Army systems, notably the LHX family of helicopters.

4. Vision technology is shown to provide operational benefits, including safety and dissimilar sensor redundancy. The controller is designed to interface with such a system.

RECOMMENDATIONS

There are several aspects of a Phase II Advanced Electronic Control Unit development project that should be pursued. These are briefly outlined below. A more detailed presentation of each of these aspects is given in the Phase II proposal, submitted to ARDEC under separate cover.

1. Vista Controls feels that the most effective way to prove the generic controller concept is to refurbish the existing ISAS robotic autoloader system and build a prototype generic controller to demonstrate the advantages of the all-digital approach. The ISAS robot is ideal for this purpose on several accounts, including:

a. It is already built and has been extensively tested.

b. The overall system (robot, flick loader tray, and breech) makes use of all the types of control loops expected on future howitzer autoloaders.

c. It is already configured for the autoloader process, as opposed to a laboratory, industrial-type robot.

Several basic areas for modification would be explored. The mechanical components and sensors would be modified to provide improved dynamic performance. Redundant sensors would be incorporated, and logic would be programmed to provide degraded modes of operation and improve the failure tolerance.

With this modified ISAS as the baseline mechanical system, the AECU would be built and integrated into the system. Improved digital high-bandwidth servo control would be incorporated and demonstrated to speed up the autoloader response time. The programmability and human interface aspects would be demonstrated. A vision system would be installed to demonstrate the safety and sensor redundancy benefits.

2. As a more advanced option, Vista Controls would build a prototype transfer unit, magazine and autofuzer in addition to the generic controller to demonstrate operation, including the use of advanced control concepts. This mechanical system would be based on the results presented in this study.

We feel that significant advantages would be gained by this approach. The generic controller concept would be demonstrated identically as proposed in Item 1 above. In addition, advanced autoloader concepts would be proved. Vista Controls feels that these concepts fit in directly with the HIP and AFAS present and future requirements, as outlined in this study and in the AFAS Requirements Overview paper (ref. 3).

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