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CONTROL AND ELECTRONIC SUBSYSTEMS FOR THE ADVANCED SERVOMANIPULATOR*

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ABSTRACT - The advanced servomanipulator (ASM) represents a new generation of electrically driven force-reflecting manipulator systems designed to be remotely maintainable. This ASM is being developed to perform remote maintenance in a nuclear fuel reprocessing plant where human access is not allowed. The primary function of the manipulator control system is to maintain stable, accurate master/slave operation while providing sensitive force reflection to the operator. The control system is based upon tightly coupled distributed digital microprocessing methods.

The architectural structure of the control system is outlined and is compared to the previously developed Model M-2 control system, and justification for the advances incorporated into the ASM structure are given. The various modes of operation and diagnostics are described, and throughput requirements associated with joint servo-control and counterbalancing are discussed. The fundamental elements of the control system are reviewed, including the processor selection (Motorola MC68000) and the language (FORTH).

The purpose of this document is to review the design decisions and the resulting design selections to serve as a base for future improvements. Four main areas will be covered: (1) system overview, (2) hardware implementation, (3) software partitioning, and (4) remote electronics considerations. Each area will address the specifics of the selected equipment or the functional requirements of the control method.

I. OVERVIEW OF CONTROL SYSTEM

The ASM is one of several subsystems which form the advanced integrated maintenance system (AIMS). The complete AIMS system consists of manipulators, operator interface, transporter, facility coordination computer, and slave-to-transporter interface. Figure 1 shows the relationship between various entities within AIMS. These subsystems are equally important to providing an acceptable total maintenance system. The ASM is the most complicated subsystem from a control viewpoint, and its architecture will greatly influence the other subsystems. This paper emphasizes manipulator control development.

MASTER

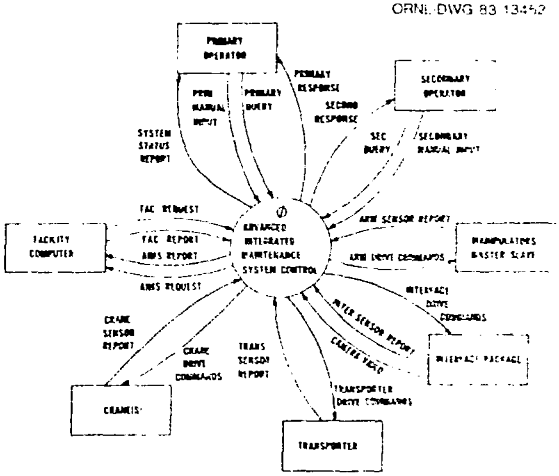

Fig. 1. System-level diagram for the advanced integrated maintenance system (AIMS).

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Figure 2 shows a board-level hardware diagram. The link between the master controller and the slave system is a single serial communication line. By defining the data structure and protocol of this line, development of both systems can proceed in a parallel manner with complete coordination. Note that the major portion of the intelligent electronics remains outside the reprocessing cell for reliability/maintainability purposes. Implicit in the design is analog input and output adequate to handle transporter motions and interface package requirements in addition to manipulator needs. Communication bandwidth is also planned to handle the added data flow for the hoist, cameras, azimuth, and transporter controls.

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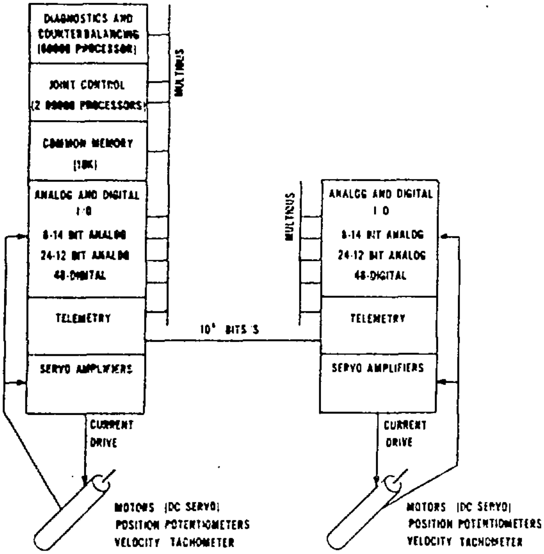

Fig. 2. Overview of hardware system for master/slave electronics.

The ASM control system performs many functions. Its major tasks are as follows:

1. force-reflecting master/slave manipulation,
2. status and self-diagnostic routines,
3. electronic counterbalancing calculations,
4. robotic operations,
5. end effector world coordinate location, and
6. multi-modal operation including indexing, brake operation, force reflection changing, and status reporting.

The use of digital controls allows easy transfer from one mode to the next. The use of tightly coupled systems with on-bus direct memory access boards eliminates communication overload and assures adequate bandwidth for loop closure.

Figure 3 illustrates the subsystem level pertinent to ASM control. Note that this diagram is an expansion of a portion of Fig. 1. Boxes are hardware items, lines are data paths, and each circle represents a software package which must be developed. The common memory is divided into a real-time input data base, a real-time command output data base, and the mode of operation. These three data areas provide all of the information necessary for

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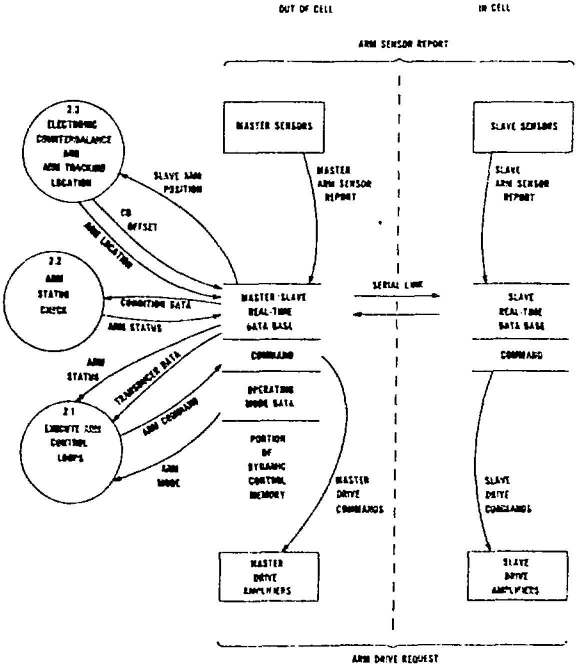

Fig. 3. Diagram of master/slave activity partitioning.

normal operating conditions. More detail on their contents will be presented in the software implemention section of this paper.

II. HARDWARE IMPLEMENTATION

Refer to Fig. 2 for the general layout of the control electronics. All required control electronics for the master/slave implementation are contained within the arm racks, which allows the electronic components to be remote from the arms so that a shielded enclosure can protect them from radiation damage. Only the motor, sensors, and cabling are directly exposed to the environment. Figure 4 illustrates the selected motor configuration including sensor system and amplifier drive. This section will review the items selected, mention alternatives, and state areas for future hardware improvements.

Building upon lessons learned from the development of Central Research Laboratory (CRL) Model M-2 and improvements in the digital hardware available, an updated hardware control philosophy was taken. Central-ized arm control was pursued rather than distributing control of each joint function to a separate microprocessor. Communication bandwidth limitation on the Model M-2 system resulted in reduced flexibility in specialized applications (especially robotic implementation). However, a tightly coupled communication system should ease implementation of future control functions; it also allows direct data logging of system parameters, as all data resides directly on the bus.

From the time of its conception, the ASM control system was intended to be constructed from off-the-shelf components. To do so meant that the selected bus must not only provide for our communication needs, but also that significant hardware items be available for the bus. The consensus choice was therefore the IEEE 796 bus due to the variety of compatible hardware available for it. The IEEE 796 (or multibus, as it is commonly called) provides a universal standard for communication and pinout which is supported by several manufacturers.

A digital control system relies on peripheral equipment to communicate with the analog world. One desirable feature of the multibus system is the diversity and high quality of available peripheral items for interfacing to the real world. The selected components are listed in Table 1.

Table 1. Analog and digital capabilities in each arm of the ASM control system

Component	Number per arm	Function
14-bit analog	8	Arm position (8)
12-bit analog in	32	Arm velocity (8) Arm current (8) Camera position Transporter positioner
12-bit analog out	12	Arm drive (8) Transporter drive (4)
Digital input/ output	48	Brakes (8) Temperature (8) Amplifier fault (8) Power amplifiers (12) Cameras/lights (expandable)

The processor choice was easily reduced to two units, the INTEL 8086 and the Motorola 68000. Both processors are 16-bit machines which support 32-bit operation and therefore would have adequate accuracy for our application. The INTEL unit had the advantage of an available math coprocessor (Motorola's is expected in late 1983), but for memory access the INTEL unit used an unwieldly 20-bit address word which was slow to implement. The Motorola 68000 system was chosen because of these factors.

A multiboard set from Data Translation was selected for analog and digital input/output. A special stand-alone routine for the system has been implemented in-house to allow easy operation by synchronizing the sample with the communication link, thereby always providing the latest possible data. To transmit data between master and slave buses requires a high-speed data link. A multibus compatible serial communication system is used for this purpose. It provides a one-megabaud data rate and a simple command structure for operation.

In order to reduce components and cable count, motor temperature is not directly measured. The history of current usage will be used with a heat transfer model to approximate the motor temperature and protect its components. Judicious safety factors will be used to assure a conservative temperature estimate.

Pulse width modulated amplifiers which accept a voltage signal in the range of ±10 V and develop a current proportional to the voltage are used as servo drives. The pulse width modulated frequency of 20 kHz is above the audible level and provides a small signal bandwidth of 6 kHz. These amplifiers will be packaged eight per system in a fan-cooled, 19-in. rack-mountable enclosure. The power rating of each is 1000 W, with a standby power of less than 5 W. Diagnostic indications of excess temperature and short circuit (over current) will be provided. A voltage output proportional to the current will be available to the control system. Basic subcomponents of this system are being analyzed for radiation susceptibility. Alternate components and/or fabrication techniques will be determined for future hot applications.

A unique low-inertia basket armature motor was developed for the ASM. Its geometry offers excellent heat transfer with low friction and inertia, which optimizes its torque-to-friction ratio, and its large torque-to-inertia ratio promises to yield very good response. The motor also has large brushes for prolonged operation and is fitted with high temperature insulation for reliable operation.

Only two measurements per axis are required for servo loop closure: position and velocity. Potentiometers are being used for position sensing because of their simplicity, hardenability, absolute indication, and high level signal output. Care has been taken to design the system so that noise will be minimized. For instance, shielded leads are used throughout to reduce noise pickup from motor drives. A 14-bit position resolution is used.

A tachometer is being included in the ASM motor package for velocity determination. Derived velocity from filtered position signals may ultimately be used in order to simplify the motor package and wiring by eliminating some parts. This derivation has been performed successfully on the servomotor test stand. A 12-bit resolution is used for velocity determination.

Current information is used to determine loading conditions and allow torque control by the servo system. Twelve-bit resolution is used for current input. The current signal is generated by the servo-amplifier system in the ±5-V range and is input through the analog-to-digital input board.

III. SOFTWARE IMPLEMENTATION

The development of a digital control system for a servomanipulator requires attention to the real-time aspects of communication and loop closure rate. The control design frequency of 100 Hz was chosen to be an order of magnitude greater than the estimated mechanical natural frequency of 10 to 15 Hz.[1] With backlash and friction nonlinearities, it is important that satisfactory computational power be provided for algorithms to compensate for these effects. Our philosophy was to base our system on a powerful processor (the Motorola MC 68000) and supported bus structure (multibus) which would allow expansion of processing power at a later date if necessary. The advantage of choosing a multibus compatible system is the variety of products available for enhancement of the system's capabilities (input/output, array processing, etc.). This will allow flexible expandibility of the ASM system to meet future demands.

Figure 3 gives an overview of the software packages required to operate a minimum master/slave implementation. Primary software efforts include:

1. Joint control--provide stable, responsive force-reflecting manipulator control.
2. Counterbalance calculation--determine deadweight offset torques.
3. Communication coordination--provide system sequencing and control data flow.
4. Data input/output--provide stand-alone operation of input/output devices.
5. Command interface--provide for future addition of man-machine interface.
6. Status--model motor loading for overheating and monitor amplifiers for proper operation.

These six basic packages will be supplied with the initial system.

At the control level, operational speed is a critical element of language choice. Ease of implementation and adaptability for change are also key elements for a successful development language. FORTH is the language chosen because its attributes are strong in these areas. Optimized FORTH executes at rates which approach the speed of assembly language routines,[2] but FORTH development efforts proceed more quickly due to its on-line debugging characteristics and structured nature. Our initial interest in FORTH came from conversations with the National Bureau of Standards (NBS) robotics development personnel, who have used FORTH for several years to develop complex robot control systems.[3] After several months of FORTH experience during this project, we have been extremely impressed with its flexibility and capabilities.

The primary function of the joint control software is to provide stable, responsive, force-reflecting master/slave operation. The block diagram in Fig. 4 shows the basic structure of the digital control loops. Position and velocity differences between master and slave are combined to determine the torque command to the motors. These torque commands are equal and opposite in a 1:1 force reflection mode, thereby providing a realistic sense of feel to the operator.

Additional control calculations have been included to improve response and sensitivity because the significant inertia and friction associated with a fully gear-driven system requires the additional compensation techniques. Friction compensation, inertia compensation, and software limit stops are provided to enhance performance. Adjustable force ratio factors and current limits allow these parameters to be varied to meet task needs. Electronic counterbalancing provides offset torques to the slave to counteract manipulator deadweight.

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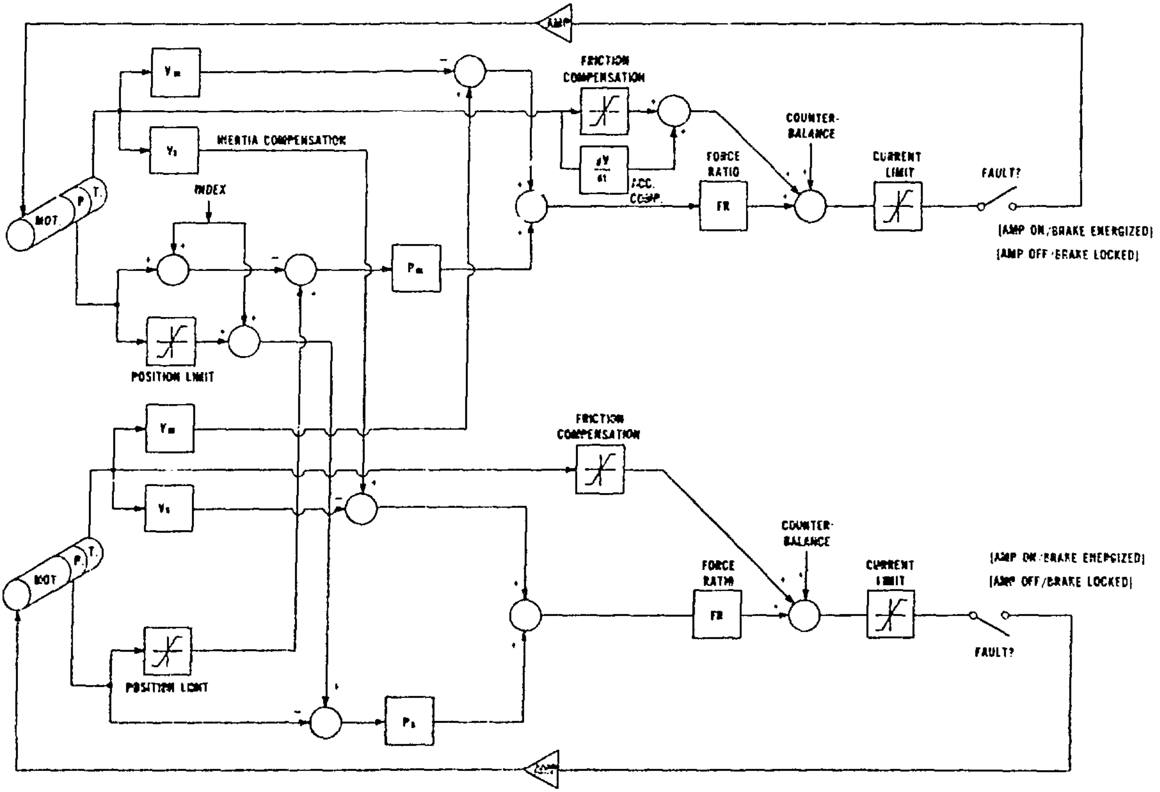

Fig. 4. Block diagram of the joint servo control configuration.

Other operational modes include indexing, deadman, brakes, and robotic capabilities. These modes are accomplished with the same control loop by varying the input parameters. These routines are presently implemented on two boards with a loop closure rate of 100 Hz, while a third single-board computer performs diagnostics and counterbalance calculations.

The master bus has a common memory board mapped for optimum efficiency of the input/output. This memory is addressable by all master processors and allows interprocessor communication. No processor-to-processor communication is necessary because all critical parameters are available in the common block. This distribution of activities is similar to the hierarchical control schemes used by NBS for positioning robot controls.

Diagnostics are provided to protect the system from damage and to inform the operator of system conditions. The following primary states are monitored or modeled:

1. Amplifier temperature--thermal/switch digital
2. Amplifier short circuit--digital
3. Motor temperature--modeled analog

Other diagnostic functions planned for the software implementation include the following:

1. Link data fidelity
2. Link timeout
3. Individual processor timeouts

Special start-up software will be required to synchronize motor/encoder systems with counterbalance routines, allow motor interchange, and assure the continuity of all sensor circuits. Other routines will be developed as necessitated by operating demands.

The ability to store and retrieve data on requested parameters at various intervals is also available. This will be useful in the optimization of control gain selection. Graphic output capabilities are planned for the man-machine interface.

IV. REMOTE ELECTRONICS

The performance improvements provided by servomanipulators are expected to significantly broaden the range of performable remote maintenance tasks and to enhance the general ability to deal with unexpected events.[4,5] The increased dexterity provided through force reflection and human-compatible dynamic response results in greater mechanical and electrical complexities in the remote slave system as compared to less dexterous concepts. Simply speaking, as the sophistication of the manipulator/transporter system increases, the number of measurements, control outputs, and interconnecting conductors increases proportionally. It is estimated that each backdrivable servo-controlled axis of motion requires 8 to 12 power and signal conductors. For a single mobile work maintenance system, a minimum of 14 manipulator axes, 4 transporter axes, 2 hoist axes, 12 camera axes, and 3 video channels will be required for an integrated package that can transverse a reprocessing cell. In the next-generation reprocessing facility, these cells may be as large as 200 m long by 12 m wide by 25 m high.[6] Because the system must move about the large work area freely, the large number of conductors presents a severe cable handling problem. Cable management systems have been used successfully in the past, but not in these proportions.[5,7]

The magnitude of the potential cable handling problem, as well as related shielding penetration and power transmission requirements, motivated the analysis of alternative concepts. It was noted very early that the utilization of in-cell electronics could dramatically reduce the number of electrical conductors which would have to transverse the remote environment and the out-of-cell area. For example, in-cell signal conditioning and multiplexing can be used to condense video and control wiring. In addition, only line-power cabling is required if the servo power amplifiers and power supplies are moved to the radioactive side. The feasibility of this concept hinges upon the integrity of the protection that can be provided to attenuate the radiological and chemical characteristics of the reprocessing environment or mitigate their consequences.

The only known alternate to remote electronics is standard cable management concepts modified to meet the increased requirements. In this approach, one would likely use cable materials with maximum accumulated dose capabilities and handling mechanisms such as articulated laydown trays. The bridge and carriage movements required by the large cell volume would necessitate long lengths of large cable bundles which, in turn, would require extensive cable flexing during operation. In this regard, two remote operations concerns are apparent: (1) the cable insulation and sheathing materials generally embrittle with exposure such that failures caused by flexing certainly would be possible, and (2) remote cable replacement, a bridge-level task, would represent a very difficult task. Because of the complexity and uncertainty of the cabling approach it was decided to further investigate remote electronics.

There are three fundamental factors associated with engineering a protective remote electronics enclosure: (1) radiation tolerance/protection, (2) thermal management, and (3) remote diagnosis and repair.

The control subsystems discussed earlier in this paper were studied in detail with respect to the remote electronics concept. The manipulator control subsystems incorporate low-power analog and digital circuitry for signal processing, control, and communications. Power supplies and servo-amplifiers use both low-power and high-power devices. Working designs for all necessary functions were developed using commercially available modules, components, and integrated circuits. These designs were then evaluated at the device or component level relative to radiation hardenability based on accepted practices,[8] estimates of the radiation spectra and dose rates and manufacturers' data. This analysis[9] showed that for most electronic modules (excluding digital data acquisition) with minor circuit revisions, correct component substitution (generally CMOS devices for NMOS), and selected fabrication and insulation materials, 1-MR total integrated dose capability should be realizable. The dose rates anticipated in the most active portions of the facility are expected to be in the range of 10^4 to 10^5 R/h, with limited exposure at 10^6 R/h. As a result, local shielding is necessary to achieve practical operating intervals. Detailed radiation shielding analyses are now being performed to quantify the shielding weight versus operating life tradeoff. A preliminary analysis indicated that about two tons of depleted-uranium shielding would provide two to five years of operation for an enclosure large enough to house the manipulator-based maintenance system components. At this time, local shielding of bridge- or carriage-mounted electronics enclosures to achieve reasonable operating life is considered feasible. Development activities will continue.

The remote electronics enclosure must also include thermal management provisions and isolation from nitric acid vapors. High-power components such as the servo-amplifiers will dissipate considerable thermal energy, especially under load, as a result of conversion inefficiencies. Transfer of the total electronics heat load from the sealed enclosure to the cell environment is a critical factor in preserving the high reliability expected from solid-state electronics. Conceptual designs are presently being studied with the hope that passive heat transfer techniques will suffice. Strong nitric acid is a prevalent chemical in the reprocessing system (especially in fuel dissolution), and various scenarios predict cell atmospheric concentrations in the range of 10 to 50 ppm. The ramifications of the corrosive effects of this acid vapor on remote electronics are not fully understood. It appears that several levels of protection are possible, depending on the severity of the problem. Options include sealing the enclosure, using inert materials and coatings, and encapsulating the entire module.

The final issue affecting the feasibility of remote electronics is remote maintainability, which is essential since scheduled replacement will be required by the exposure-limited operating life of the various electronic modules. Because of the bulk shielding required, it will be necessary to mount the remote electronics enclosure on the heavy-load-bearing bridge and/or the trolley members of the transporter. Maintenance tasks at this elevation are not desirable, but they are not impossible. Concepts which address remote maintenance requirements are also presently under development.

Regarding remote operation and diagnosis of the in-cell electronics subsystems during normal operations, the electronics are being designed such that no on-board adjustments will be necessary inside the cell, and gain parameter adjustments will be made through remote control set-up provisions. Various on-line diagnostic routines to assist remote failure analysis are being incorporated in the design development.

It appears that the concept of remote electronics is a quite feasible approach to reducing the cabling complexity associated with force-reflecting servomanipulators in reprocessing cells. In fact, at this time no major technical barriers to this new concept are known. Major development activities are under way to complete the design and demonstration of the concept.

IV. CONTINUING EFFORTS

The ASM control effort represents the foundation on which the advanced integrated maintenance system (AIMS) will be developed. With this in mind, all efforts have been directed toward a flexible and expandable basic system upon which to build. Expansion to control transporters, cameras, lights, and tools should be straightforward. Interfaces to a control station and facility computer are also provided for. Our greatest challenge is providing reliable control electronics for the anticipated environment.

Augmentation of operator capabilities for improved efficiency has long been a goal of the Remote Control Engineering Group. The use of digital controls allows experimentation in this area. Special features planned for the ASM include the following:

1. teach/playback capability
2. automatic end-effector tracking by cameras
3. planar motion constraints for slave operation
4. automatic tool changing
5. self-diagnostic start-up testing
6. supervisory control for repetitive tasks
7. facility mapping and obstacle avoidance

These control system features and the remote maintainability aspects of the ASM will provide an exceptional maintenance system for the harsh environment of fuel reprocessing.

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