

**Integration of Advanced Teleoperation Technologies
for Control of Space Robots**

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ABSTRACT

Teleoperated robots require one or more humans to control actuators, mechanisms, and other robot equipment given feedback from onboard sensors. To accomplish this task, the human or humans require some form of control station. Desirable features of such a control station include operation by a single human, comfort, and natural human interfaces (visual, audio, motion, tactile, etc.). These interfaces should work to maximize performance of the human/robot system by streamlining the link between human brain and robot equipment.

This paper describes development of a control station testbed with the characteristics described above. Initially, this testbed will be used to control two teleoperated robots. Features of the robots include anthropomorphic mechanisms, slaving to the testbed, and delivery of sensory feedback to the testbed. The testbed will make use of technologies such as helmet mounted displays, voice recognition, and exoskeleton masters. It will allow for integration and testing of emerging telepresence technologies along with techniques for coping with control link time delays.

Systems developed from this testbed could be applied to ground control of space based robots. During man-tended operations, the Space Station Freedom may benefit from ground control of IVA or

EVA robots with science or maintenance tasks. Planetary exploration may also find advanced teleoperation systems to be very useful.

1.0 INTRODUCTION

Remotely controlled robots may be successfully applied in hazardous environments such as high radiation zones, deep sea locations, earth orbit, and extra-terrestrial sites. Three dominant control modes are teleoperation, supervised autonomy, and shared control¹. Teleoperation is characterized by direct human-in-the-loop manual control and small time delays (< 1 sec.). In supervised autonomy, commands are generated by the operator and sent to the robot control system for execution. Shared control makes use of both teleoperation inputs and an autonomous robot control system. In each of these modes, a human operator is involved and must interact with some form of computer based control station.

Figure 1.1 illustrates a spectrum of technologies which may be used in a remote robot control station. At one end are conventional technologies such as hand controllers, 2-D video, keyboards, and computer monitors. The other end is labeled as telepresence technologies and includes force reflective exoskeletons, stereo (3-D) video, voice recognition, and synthetic speech.

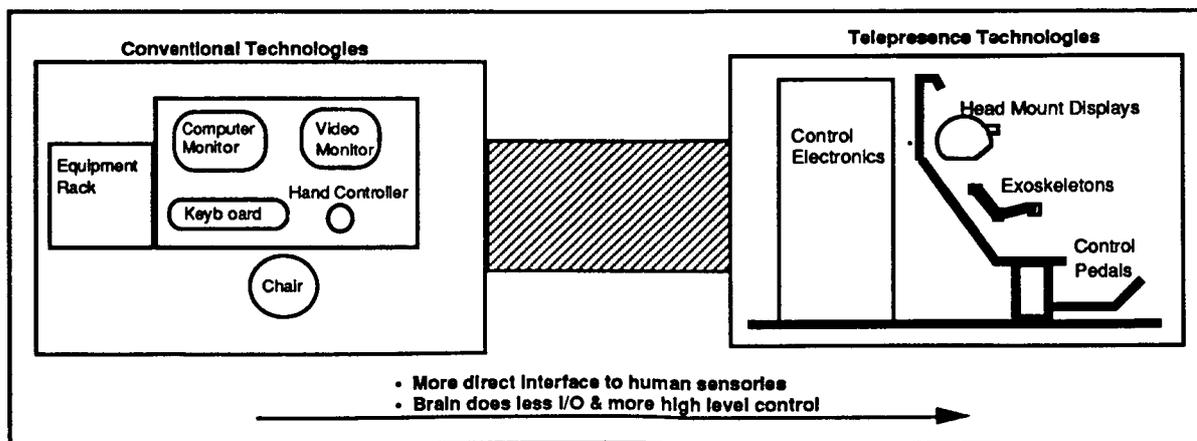


Figure 1.1 - Remote Robot Control Technology Spectrum

Telepresence can be defined as the sense of being physically present with object(s) at a remote site³. Telepresence technologies attempt to immerse a human operator in the remote environment with actuator control and sensory feedback devices which closely interface to the human central nervous system. Robots at the remote site are designed with anthropomorphic actuators and sensory devices, such as stereo camera pairs and tactile sensors.

Telepresence technologies offer interfaces to the human sensory system which are more direct than those of the conventional technologies defined. This frees the brain from many unnatural input/output conversion tasks, allowing more concentration on higher level control and process oriented tasks. The result is a more intuitive way of controlling remote robots.

Major challenges facing telepresence technologies include working with time delays, increasing video resolution and field of view, and provision of adequate force/torque and haptic feedback.

2.0 PROJECT OVERVIEW

2.1 Objectives

The primary project objective is to develop a teleoperator control station testbed which makes use of telepresence technologies. This testbed is referred to as the Teleoperated Robot Interface Platform (TRIP) and should provide teleoperation capabilities for two JSC development robots. One robot is the Dexterous Anthropomorphic Robotic Testbed (DART)⁴. DART is a dual-arm, dual-hand robot with a camera platform which provides stereo video. It will be able to operate under human control augmented by on board intelligence for use in development of IVA and EVA robotic systems. The second, AERCAM, is a prototype mobile camera platform capable of teleoperation. Initially, this prototype will be flown on an air bearing floor at JSC.

In a more general sense, TRIP will be used as a testbed for emerging telepresence technologies, such as head mounted displays, exoskeletons, and programming systems. In addition, TRIP will allow testing of proposed solutions to the problems induced by control link time delays. Systems developed with the TRIP testbed should support future operations on board the Space Station Freedom, including the possibility of ground control using shared control techniques.

2.2 Goals & Constraints

TRIP development goals include flexibility, ease of use, and growth paths. A flexible system will support the testbed objectives through maximum use of standard hardware and software interfaces, a modular approach to system design, and the use of software for most calibration tasks. The system

should also allow for ease of development and use by minimizing and simplifying the software learning curves. Ease of use will support tight schedules and minimal manpower. A system designed with growth paths will foster an evolutionary development by protecting both hardware and software investments. Design for growth seeks to avoid obsolescence by choosing established software tools with supported growth paths and by avoiding hardware with closed or unsupported architectures.

Development constraints consist of cost and system performance. Design must be sensitive to costs by maximizing system capability given current year funding. Basic system level results should not depend on large amounts of future funding. Basic performance requirements, such as data rates and connectivity, must also be satisfied. Optimization of performance variables at the expense of system flexibility will be avoided unless required.

2.3 Facilities & Support

TRIP is under development in the Dexterous Robotics Lab of JSC's Automation & Robotics Division. The two target robots are also under development in division labs. To date, all primary design and development work has been conducted in-house by JSC civil service staff members. Only a limited amount of contractor support has been available or used.

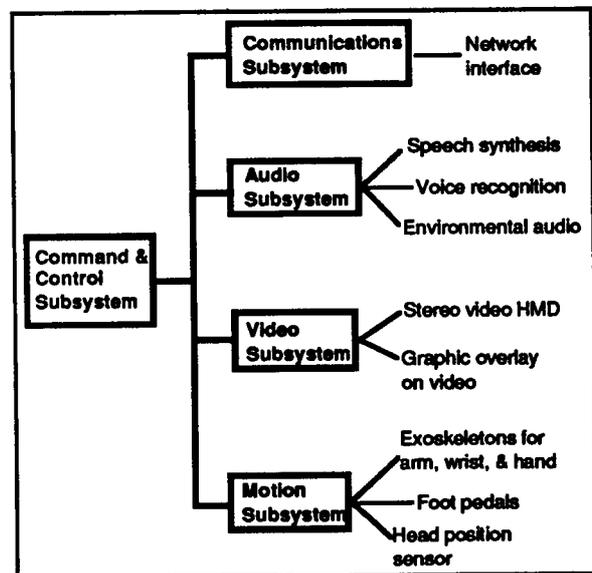


Figure 3.1.1 - TRIP Subsystems and Technologies

3.0 SYSTEM DESCRIPTION

3.1 Organization

TRIP is the integration of assorted telepresence technologies as illustrated in figure 3.1.1. These include exoskeletons for the operators hand, wrist

and arm joints, a head mounted display for viewing stereo video and graphics, speech synthesis and voice recognition systems, and a network interface for passing data to/from a remote robot. These systems should work in concert to provide intuitive control of a remote robot by one human operator. TRIP is organized into five subsystems, each consisting of hardware and associated software.

3.2 Hardware Architecture

The hardware architecture is shown in figure 3.2.1. Selections were driven primarily by the flexibility goal along with the availability and cost of both software and special purpose boards (video, audio, etc.). Hardware cost and growth path trends were also considered.

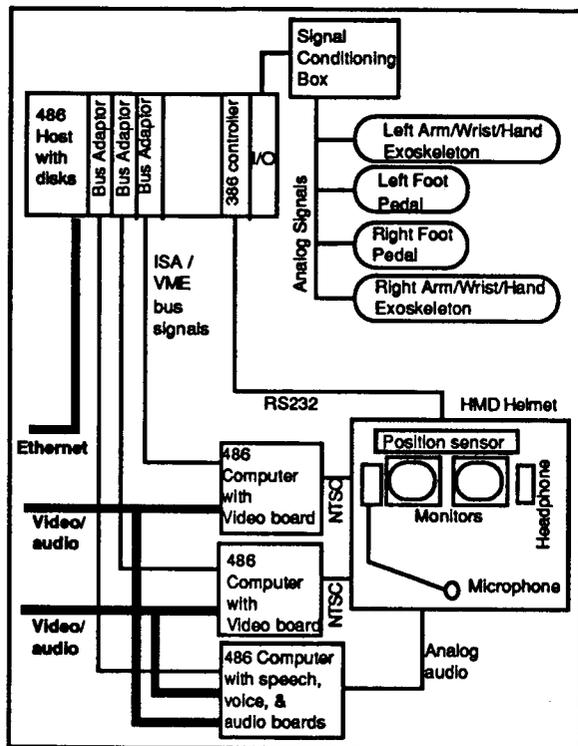


Figure 3.2.1 - Hardware Architecture

The hardware architecture consists of exoskeletons, a head mounted display, a chair platform with control pedals, i486 & i386 microprocessors in ISA & VME buses, and assorted I/O, audio, and video boards. A single family of processors was selected to minimize software learning curves and keep costs relatively low. The ISA bus offers reasonable performance and a myriad of low cost, special purpose I/O boards to choose from. The VMEbus offers an industry standard with high bandwidth performance, extreme flexibility, and a large number of I/O and processor boards. Selections of boards for both buses were based on a balance of cost, flexibility, and performance. Software driver libraries were also considered in the board selections as this represents

a potentially labor intensive set of development tasks.

Exoskeletons are attached to a body harness and gloves which the operator wears. An analog signal conditioning box provides power to the exoskeletons and filters the signals produced by potentiometers and hall effect sensors. These signals are then read by an analog to digital (A/D) converter board in the VMEbus. An embedded i386 computer processes raw data from the A/D board and makes the results available on the VMEbus.

The head mounted display (HMD) consists of monitors, optics, a position sensor, headphones, and a microphone. The position sensor reports roll, pitch, and yaw to an embedded i386 computer via an RS-232 link from its own processor based control box. Two i486 based computers deliver video with text or graphics overlay to the monitors. The headphones are driven by a third i486 computer which handles speech synthesis and other audio feedback functions. This computer also handles voice recognition tasks, making use of the microphone. All three computers use ISA to VME bus adaptors to communicate with the VMEbus. Video and audio signals from a remote robot are currently transmitted through dedicated channels.

A chair platform includes control pedals and a transmitter for the HMD position sensor. Potentiometers in the pedals are powered and read by the same hardware used with the exoskeletons. Signals are also processed by the embedded i386 computer and results are available on the VMEbus. The HMD position sensor transmitter has its own power supply and processor based control box.

An i486 embedded in the VMEbus serves as the command and control computer of TRIP. Through the VMEbus, this computer can communicate with all subsystems and coordinate their interactions. In addition, this computer handles all data communications with remote robots through an ethernet network board and a single dedicated cable.

3.3 Software Architecture

Figure 3.3.1 displays the current high level software architecture. Software modules are shown in round-edge rectangles, and hardware is represented in square-edge rectangles.

The software architecture consists of control and configuration tasks, command routers, command handlers, bus data exchange drivers, RS-232 interface drivers, and TCP/IP network interface drivers.

The control and configuration tasks reside on an embedded i486 computer in the VMEbus. These allow the operator to calibrate subsystems and define subsystem interaction rules. Control tasks

coordinate the interactions between various subsystems.

Command routers serve two functions. First, process data from input devices to produce specific subsystem commands. Second, route these commands to the appropriate subsystem message areas. Command routers are used with the voice recognition system and all motion input devices.

Command handlers accept commands or messages from command routers and execute the commands or answer messages. Command handlers are used with output systems such as video and graphic overlays, speech synthesis, and environmental audio.

Bus data exchange drivers allow commands and messages to be physically exchanged between the ISA buses and the VMEbus. Both embedded and external computers use these drivers

Drivers for the RS-232 ports are used by the embedded i386 computer to communicate with the HMD position sensor controller. Commands can be sent to the controller and raw orientation data is read. This raw data is also parsed and made available to bus data exchange drivers.

Network access is provided by interface drivers using the TCP/IP protocols. These are used by the communication subsystem to transmit commands to or receive messages from a remote robot. They are also used to handle commands from TRIP subsystems and route commands from the robot to appropriate handlers.

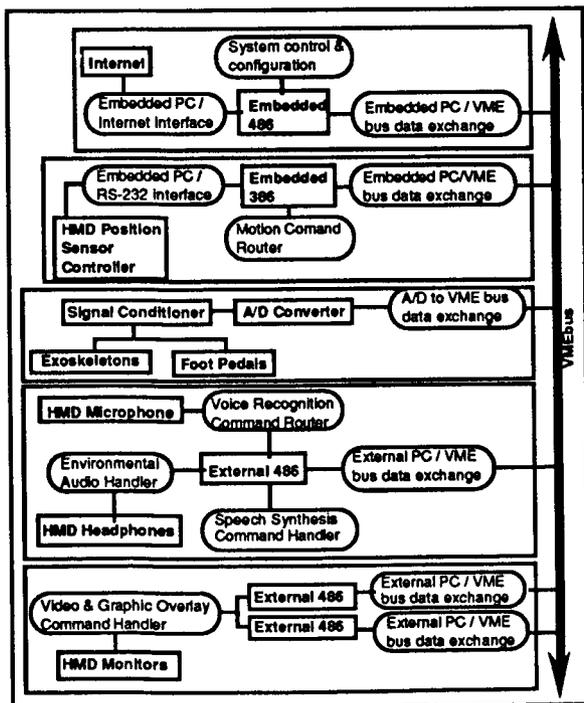


Figure 3.3.1 - Software Architecture

3.4 Software Tools

Current software tools comprise two operating systems and three compilers. Windows 3.1 and iRMX are the operating systems and they support development with Visual Basic, Borland C++, and iRMX C.

Windows 3.1 provides cooperative, event driven multitasking with an easy to use graphical human interface. A large number of board level drivers directly support this operating system and development with its standard user interface. Windows 3.1 also provides a growth path to a 32 bit preemptive multitasking/multiprocessing environment with Windows NT. Windows NT will be backward compatible with 3.1 and will use the same graphical interface standards. It should be available at the end of 1992.

iRMX provides 32 bit mode operation of the Intel microprocessors and real time task scheduling for low level, time critical tasks. A unique feature of this operating system is its ability to run Windows as a task and communicate between the two operating systems. This enables the best of two worlds: 32 bit hard real time tasking and an easy to use standard interface.

Visual Basic (VB) is an object oriented visual development environment for the Windows operating system. Objects can send or receive messages, and events can be used to trigger user developed code or operating system calls. The syntax is similar to that of Basic, but the code structure and object orientation endow it with many features found in C++. The visual development environment lends itself to very rapid prototyping of code and almost effortless user interface development. VB does not support some of the low level capabilities found in C or C++, but Dynamic Link Library (DLL) functions written in C or C++ may easily be called. Operating system functions may also be called directly from VB. Dynamic Data Exchange (DDE), a client/server intertask communication protocol, is also supported and easy to use.

Borland C++ is an object oriented C development environment which supports development for the Windows operating system. Specific to this project, it allows the development of low level DLL functions which may be called from VB code. Borland supplies an efficient code development environment with extensive debugging support. The object orientation promotes development of complete code modules which are easy to reuse and build upon.

iRMX C is a compiler and assorted tools for developing C code task modules which run in the iRMX real time operating system. These modules will accommodate time critical, low level functions as required by the TRIP. These functions may

communicate with Windows hosted code to report system status, alarms, or data needs.

3.5 Floor Layout

A planform view of TRIP hardware is displayed in figure 3.5.1. Shown are the chair platform, a 19 inch equipment rack, and two development work sites. An adjustable chair is mounted to the platform and serves as the operator work site. Pedals, exoskeletons, and the HMD are all connected from the chair platform to equipment in the 19 inch rack. The rack contains all TRIP computers along with audio and video ancillary equipment. Two development work sites each incorporate a keyboard, mouse, and two SVGA monitors. One work site supports development on VMEbus subsystems which include command and control, communication, and motion. The other work site supports development on the audio and video subsystems.

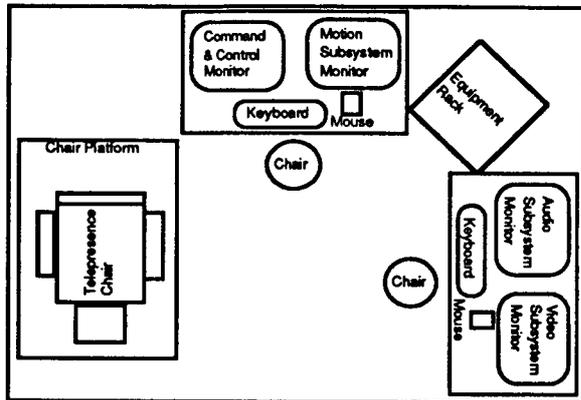


Figure 3.5.1 - Floor Layout

4.0 SUBSYSTEM DETAILS

4.1 Motion Subsystem

The motion subsystem generates commands to control position or rate of all articulated members on a remote robot. Robot members include arms, hands, torso's, camera platforms, and mobile bases. The operator controls these using a combination of exoskeletons, foot pedals, and position sensors. Force reflection and tactile feedback for the operator are planned as growth paths in the arm and hand exoskeletons of this subsystem.

Current components of this subsystem are detailed in figure 4.1.1. It consists of an embedded i386 computer, an HMD position sensor, an A/D board with a signal conditioning box, exoskeleton arm and hand masters, and foot pedals.

An embedded i386 based computer from the Radisys Corporation is used for subsystem processing and control. It runs at a clock speed of 25 MHz, contains 8 MB of DRAM, a keyboard controller, serial ports, and an ISA compatible private bus which supports a

40 MB hard disk and a super VGA controller board. It boots with a PC/AT compatible BIOS ROM and supports a number of operating systems. Radisys also supplies low level functions which allow direct access to all VMEbus memory spaces. These functions are compatible with TRIP software tools.

A Logitech 6D Mouse is used to sense the HMD position and orientation. It makes use of an ultrasonic transmitter and receiver triangles to determine location in Cartesian space (x, y, z) and orientation (roll, pitch, yaw) as Euler angles or quaternions. Also included is a dedicated control processor which communicates with the host processor via RS-232. Advantages of ultrasonics over magnetic sensors include reduced lag times and no interference from metal structures. A disadvantage is that the full range (0-360 degrees) of Euler angles is not supported, although TRIP does not require the full range for HMD tracking.

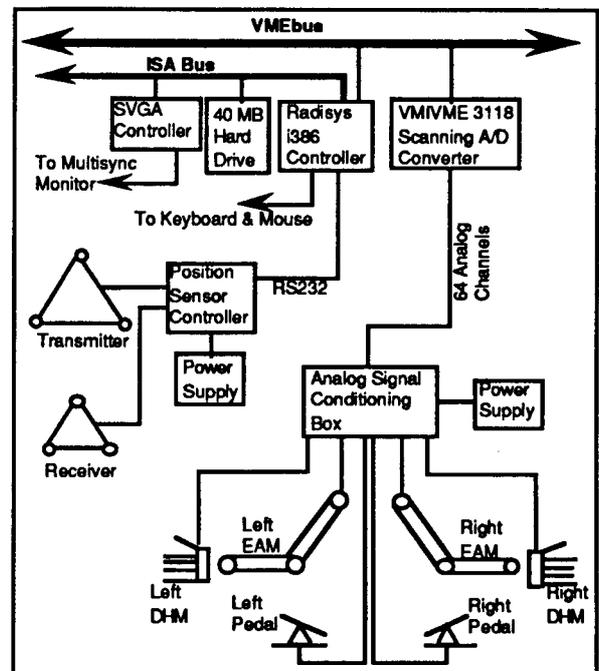


Figure 4.1.1 - Motion Subsystem Block Diagram

A VMIVME 3118 scanning A/D board is used in conjunction with a signal conditioning board developed in-house to support 64 differential channels. The A/D board interfaces to the VMEbus via control registers and a dual ported RAM data buffer. The signal conditioning board is housed in a separate box with a dedicated power supply. The board low pass filters (10 Hz) each channel and buffers the signal lines to the A/D board. It also supplies power to sensors on the exoskeletons and foot pedals.

Two exoskeleton arm masters (EAM) and two dexterous hand masters (DHM) from Exos, Inc. are

utilized in TRIP. The EAM provides precise measurements of human shoulder and elbow joint angles. Potentiometers are currently used to sense the angles. The DHM uses hall effect sensors to measure joint angles of the human hand. A GripMaster (GM) is integrated into each DHM to measure wrist motion. Development continues to be funded by NASA with future objectives including the addition of sensory feedback in all areas. The current TRIP design will be capable of integrating these planned improvements.

Foot pedals can be used to control robot torso and/or mobile base motion. In both cases, potentiometers are used to sense ankle joint angles which provide rate and directional control of robot motors. These pedals are attached to the chair platform.

Software tasks running on the i386 read and process raw data from each of the input devices. One task reads a data buffer on the A/D board and processes for joint angle or rate commands. Processing includes some simple (i.e. boxcar) noise filtering and any required coordinate transforms. The A/D board continuously scans all active channels and updates the entire data buffer at about 800 Hz. A second task on the i386 reads and parses data from an RS-232 port to determine roll, pitch, and yaw of the HMD. This port communicates with the position sensor controller which continuously updates position readings at about 50 Hz. A third task on i386 accepts processed data from the other tasks and routes it to the appropriate command handlers (i.e., communication, graphic overlay, etc.) using bus data exchange drivers.

4.2 Video Subsystem

A video subsystem handles all live video signals along with any computer generated graphics. Video is supplied by camera pairs on the remote robot which are designed to provide stereo video to the human eyes. Computer generated graphics and/or text may be calibrated to the video and overlaid to provide visual feedback, simulation results, or task tools to the operator.

Figure 4.2.1 is a diagram showing half of the video subsystem. Each half feeds one of the operators eyes, and both halves are identical. Components include a helmet with HMD's, a video scan converter, a frame grabber and video compression board, an SVGA graphics board, an i486 based ISA bus computer, and ISA to VMEbus adaptor boards.

A head mounted display helmet from Virtual Research is currently in house. It incorporates headphones, the Logitech 6-D Mouse receiver triangle, two color LCD displays (360 x 240 pixels), and wide angle optics from Leep Systems. The helmet is designed for comfort is extremely easy to don and doff. The Leep Systems optics have become an industry standard and can provide a field-of-view in excess of 100°. Currently available LCD displays do not have

the resolution required to support the detailed video or graphics ultimately desired in TRIP. In response, work is progressing in-house to develop higher resolution black and white HMD's which make use of wide angle optics and flat panel CRT's. Other concepts for increased resolution and color are under consideration.

The Genie scan converter from Jovian will accept 60 Hz non-interlaced RGB signals (i.e. VGA at 640 x 480) as input and produce a 30 Hz interlaced NTSC signal as output. Monitors in most head mounted displays currently require an NTSC signal. In addition, the scan converter provides a gain adjustment and flicker filtering. Without the flicker filtering, certain horizontal lines appear to flicker and may contribute excessively to operator fatigue.

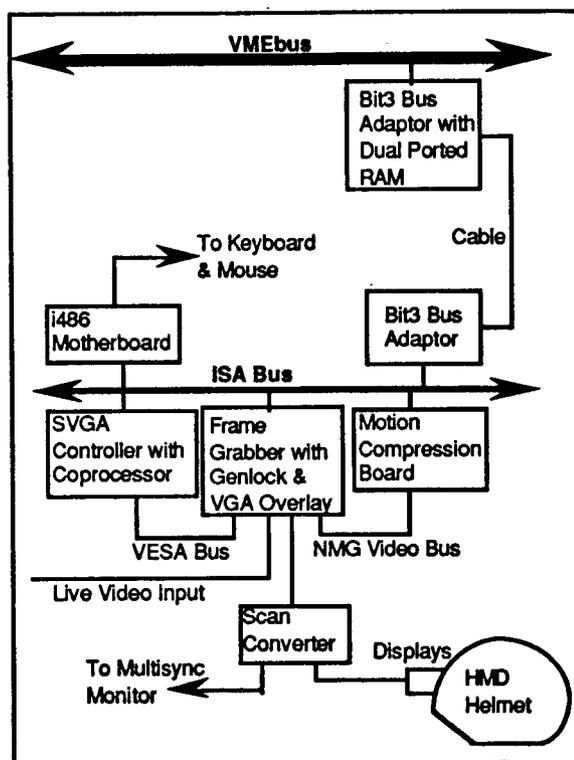


Figure 4.2.1 - Video Subsystem Block Diagram

The frame grabber and video compression boards are supplied by New Media Graphics and both include low level software drivers which are compatible with TRIP software tools. The frame grabber digitizes and scan converts live video from external cameras, allowing software manipulation of the images. In addition, this board will genlock and overlay (via graphics color keying) VGA signals using a dedicated video (VESA) bus. The video compression board enables compression and decompression of full motion (30 Hz) video using a C-Cube CL550 JPEG chip. It supports storage, playback, and network transmission of video signals using a private video bus with the frame grabber.

An Orchid Fahrenheit 1280⁰ graphics accelerator was selected as the VGA board. It provides complete Super VGA functionality and makes use of a dedicated on-board processor to support graphics intensive applications. Low level drivers are included for the Windows operating system.

Two i486 based computers are used for subsystem control functions and as graphics engines. Each runs at a clock speed of 33 MHz, contains 8 MB of DRAM, a keyboard controller, serial ports, and an ISA bus which supports a 210 MB hard disk and subsystem video boards. They boot with a PC/AT compatible BIOS ROM and support all TRIP operating systems.

Bus adaptors are supplied by Bit3 Corporation and provide a high bandwidth link between the VMEbus and ISA bus. Boards in each bus are linked with a shielded, multiconductor cable. The VMEbus board contains 2 MB of dual ported RAM which maps into the memory space of both buses.

This subsystem accepts commands and messages from the VMEbus through the bus adaptors. Software tasks running on the i486 computers are used to control the display of live video and to generate desired graphics or text overlays. Graphics can include wireframe models driven by simulations and text may include voice menu selections or data from the remote robot. The video, graphics, and/or text are merged in the frame grabber and fed to the scan converter. This converter produces a filtered 30 Hz interlaced NTSC signal which the HMD directly accepts and displays to the operator. Future HMD's with higher resolutions may directly accept the 60 Hz non-interlaced RGB signals, allowing scan converters to be bypassed.

4.3 Audio Subsystem

Speech synthesis, environmental audio, and voice recognition are all part of the audio subsystem. Speech synthesis provides TRIP an additional path for relaying data or messages to the operator. Environmental audio can be used to supply cues or feedback on the remote environment. This can take the form of actual environmental sounds (where possible) and/or computer generated sounds which cue the operator. Voice recognition essentially replaces the keyboard as an operator input device and is required when the operator is wearing exoskeletons.

Figure 4.3.1 diagrams the audio subsystem. Components include helmet mounted headphones and microphone, a voice recognition system board, a speech synthesis board, an audio mixing system with an interface board, an i486 based ISA bus computer, and ISA to VMEbus adaptor boards.

The headphones and a microphone are part of the helmet assembly. Headphones are driven by an audio

mixing system and the microphone supplies audio signals to a voice recognition system.

The voice recognition system was developed by Speech Systems Incorporated. It provides continuous speech recognition which is speaker independent and includes a large vocabulary dictionary (about 40,000 words) which can be amended by the developer. A unique combination of speech encoding, acoustic frame compression, and linguistic decoding is used to support large, variable duration segments.

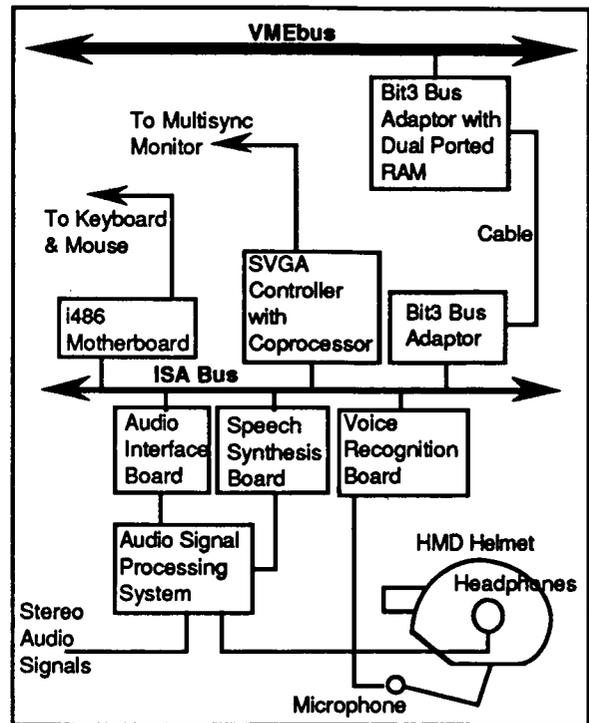


Figure 4.3.1 - Audio Subsystem Block Diagram

Speech synthesis is provided by the DoubleTalk PC board and drivers from RC Systems. The board uses its own 10 MHz, 16 bit microprocessor and supports multiple speech technologies such as text-to-speech, LPC, PCM, ADPCM, and CVSD. The analog output can directly drive headphones or be directed through a mixing system.

Audio switching, mixing, and signal processing is accommodated with a CDPC multimedia system by Media Vision. The system is based on the electronics of their Pro AudioSpectrum 16 and includes multiple audio input and output signal options. Signal processing includes digital filtering, tone control, bass enhancement, and signal equalization. The analog mixer supports volume control of each source, fade in/out, and audio panning. The system includes an ISA bus interface board and low level drivers which are compatible with TRIP software tools.

An i486 based computer is used for subsystem processing and control. It runs at a clock speed of 33 MHz, contains 8 MB of DRAM, a keyboard controller, serial ports, and an ISA bus which supports a 210 MB hard disk and subsystem audio boards. It boots with a PC/AT compatible BIOS ROM and supports all TRIP operating systems.

A Bit3 bus adaptor provides a high bandwidth link between the VMEbus and this subsystem. Boards in each bus are linked with a shielded, multiconductor cable. The VMEbus board contains 2 MB of dual ported RAM which maps into the memory space of both buses.

The audio subsystem exchanges commands and messages with the VMEbus through its bus adaptor. Software tasks running on the i486 computer handle commands for speech synthesis and environmental audio functions. Synthetic speech and environmental audio signals are processed and mixed by the CDPC system, then fed to headphones in the helmet. The operators voice is picked up by the microphone and fed to the voice recognition system for interpretation. Resulting commands are routed to the message areas of appropriate subsystems.

4.4 Communication Subsystem

The communication subsystem provides full duplex data transfers between TRIP and the remote robot using an ethernet based network. Data can represent commands, sensory information, event messages, or requests for information.

Hardware for this subsystem is shown in figure 4.4.1. It basically consists of an embedded i486 computer from Radisys and an ethernet communications board.

The i486 runs at a clock speed of 33 MHz, contains 8 MB of DRAM, a keyboard controller, serial ports, and an ISA compatible private bus which supports a 210 MB hard disk and a super VGA controller board. It is operationally similar to the i386 controller of the motion subsystem and uses the same low level drivers for VMEbus memory accesses.

The ethernet board is Western Digital (8003EB) compatible and uses commonly available packet drivers. It also supports both thin and thick ethernet cables along with TCP/IP socket libraries.

Software tasks running on the i486 computer serve three functions: (1) transfer data packets to and from the remote robot, (2) parse data packets and route information to other TRIP subsystems, and (3) handle commands from TRIP subsystems and build data packets. The data packets consists of structures which organize messages, commands, and information into a form which TRIP and the remote robot can both understand and easily parse. Future plans include incorporation of TelRIP software developed at Rice University. TelRIP (TeleRobotic

Interconnection Protocol) is a layer built on top of TCP/IP with characteristics specific to teleoperation of robots. Other software tasks running on the i486 route messages to other TRIP subsystems.

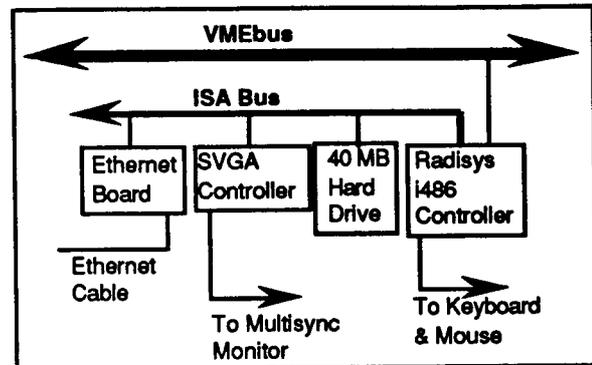


Figure 4.4.1 - Communication & Command/Control Subsystem Block Diagram

4.5 Command & Control Subsystem

The command and control subsystem coordinates interactions of all subsystems with one another. It also serves as the focal point for system configuration and subsystem calibration efforts.

This subsystem primarily consists of software, but shares the embedded i486 used by the communication subsystem shown in figure 4.4.1.

Software running on the i486 computer provides system level arbitration of subsystem task and data interactions. These interactions may be defined in terms of the active communication paths between subsystems and the messages or commands understood on those paths. In addition, each of the other subsystems may be calibrated or adjusted from here to correspond to systems on the remote robot. Examples of this include mapping of exoskeleton joints to robot joints, definition of joint limits, activation of video targeting functions, and selection of environmental audio convolution methods.

5.0 CLOSURE

The project described in this paper is primarily a system integration effort. Architectures and approaches discussed are driven by a combination of operational needs, available technologies, and flexibility to incorporate projected technologies. Design goals included ease of use, configurational flexibility, and the inclusion of growth paths. These goals were constrained by cost and performance limits.

5.1 Current Status

All the basic hardware elements of TRIP are currently being integrated. Software tasks are either in the

detailed design or implementation phase of development. The DART anthropomorphic target robot is currently in the implementation phase and will be interfaced to TRIP by the end of this year. The AERCAM free-flying target robot is in the detailed design phase of development.

5.2 Future Work

Future work will address the implementation and testing of newly developed subsystem and programming technologies. Examples in the video area include higher resolution black & white monitors, direct VGA interfaces with wide angle optics, and computational graphics models as in reference 14. Motion control examples include the addition of force/torque reflection, haptic feedback, and teleprogramming concepts as described in reference 25. TRIP will also make use of 3-D acoustics research and signal processing techniques, such as those of reference 19. Robot communications will be enhanced through updated versions of TelRIP20,21 software. Finally, an icon or block diagram based visual environment will be used for system configuration and subsystem calibrations.

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