

NAVLAB: An Autonomous Navigation Testbed

**Kevin Dowling, Rob Guzikowski, Jim Ladd
Henning Pangels, Jeff Singh, and William Whittaker**

CMU-RI-TR-87-24

**The Robotics Institute
Carnegie Mellon University
Pittsburgh, Pennsylvania 15213**

November 1987

Copyright 1987 Carnegie Mellon University

This research was sponsored by the Defense Advanced Research Project Agency (DARPA) under contract number DACA76-86-C-0019. The views and conclusions in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of DARPA or the US government.

Table of Contents

| | |
|--|-----------|
| 1. Introduction | 1 |
| 2. Controller | 3 |
| 2.1 System Architecture | 3 |
| 2.2 Virtual Vehicle | 4 |
| 2.3 Controller Architecture | 5 |
| 2.3.1 Hardware | 5 |
| 2.3.1.1 Primary Computing | 5 |
| 2.3.1.2 Secondary Computing | 7 |
| 2.3.2 System Software | 7 |
| 2.3.2.1 Interprocessor Communication | 8 |
| 2.3.3 Command Preprocessor | 8 |
| 2.3.4 Pilot | 9 |
| 2.3.5 Sensor/Device Management System | 11 |
| 2.3.5.1 Bitbus System | 11 |
| 2.3.5.2 Fast Sensor Monitoring | 12 |
| 2.4 Motion Control | 12 |
| 2.4.1 Dash Panel Control | 14 |
| 2.4.2 Steering Control | 15 |
| 2.4.3 Drive | 15 |
| 2.5 Sensors/Devices | 16 |
| 2.5.1 Inertial Navigation | 16 |
| 2.5.2 Sensors/Devices on Bitbus Network | 16 |
| 3. Vehicle Shell | 18 |
| 3.1 Exterior Design | 18 |
| 3.2 Interior Design | 18 |
| 3.2.1 Cooling | 20 |
| 4. Locomotion | 22 |
| 4.1 Steering | 22 |
| 4.2 Drive | 22 |
| 4.2.1 Vehicle Engine | 23 |
| 4.2.1.1 Engine RPM Control | 24 |
| 4.2.2 Hydraulic Pump | 24 |
| 4.2.3 Hydraulic Motor | 24 |
| 4.2.4 Transmission | 26 |
| 4.2.5 Reservoir, Heat Exchanger, and Filters | 26 |
| 4.2.6 Hydrostat Sensor and Control System | 26 |
| 5. Electrical System | 29 |
| 5.1 AC Power | 29 |
| 5.1.1 Generators | 29 |
| 5.1.2 Shore Power | 30 |
| 5.1.3 Power Conditioning | 30 |
| 5.2 DC Power | 30 |
| 6. Telemetry | 32 |
| 6.1 High Bandwidth Transmission | 32 |
| 6.2 Low Bandwidth Transmission | 32 |
| 6.3 Cellular Phone | 33 |
| 7. Perceptive Sensing and Computing | 34 |
| 7.1 Video | 34 |
| 7.2 Laser Ranging | 34 |
| 7.3 Pan and Tilt Mechanism | 34 |
| 7.4 Computing Configuration for Sensing | 34 |
| I. Modifications to Vehicle | 36 |

| | |
|--|-----------|
| II. Power Budget | 37 |
| III. Weight and Center of Gravity Budget | 38 |
| IV. Implementation of the Virtual Vehicle Instruction Set | 40 |
| V. References | 44 |

List of Figures

| | |
|---|-----------|
| Figure 2-1: The Hierarchical Layering of a System Architecture for Modeling and Planning | 4 |
| Figure 2-2: Architecture of Controller | 6 |
| Figure 2-3: Hardware Configuration | 7 |
| Figure 2-4: Bitbus Server | 12 |
| Figure 2-5: Motion Actuation | 13 |
| Figure 2-6: Dash Panel Layout | 14 |
| Figure 3-1: Side and Rear View of the Vehicle | 19 |
| Figure 3-2: Interior Layout of Vehicle | 20 |
| Figure 4-1: Steering Adaptation | 22 |
| Figure 4-2: Schematic of Vehicle Drivetrain | 23 |
| Figure 4-3: Mechanism for Engine RPM Control | 24 |
| Figure 4-4: Hydro Drive System | 25 |
| Figure 4-5: Hydrostat Sensor and Control Lines | 27 |
| Figure 5-1: Wiring Schematic for AC Power | 29 |
| Figure 5-2: Wiring Schematic for DC Power | 31 |
| Figure 6-1: Telemetry Configuration of NavLab | 32 |
| Figure 7-1: Pan and Tilt Mechanism | 35 |
| Figure 7-2: Typical Architecture | 35 |

Abstract

The NavLab is a testbed for research in outdoor navigation, image understanding, and the role of human interaction with intelligent systems; it accommodates researchers and all computing onboard. The core of the NavLab is the vehicle controller, a multi-processor computer that controls all locomotion, actuation and physical sensing; it interacts with a computer host and human operator to implement varying degrees of autonomy. The chassis is a modified van with a computer-controllable, hydraulic drivetrain. The NavLab supports a choice of sensing to accommodate many types of navigation research. This technical report details the control computing and physical configuration of the NavLab vehicle.

1. Introduction

The NavLab is a testbed for research in outdoor navigation, image understanding, and the role of human interaction with intelligent systems. A mobile navigation habitat, it accommodates researchers and significant onboard computing. Applications for field navigation vehicles include mapping of hazardous waste sites, off-road haulage, material handling at construction worksites, and exploration of planetary surfaces.

The NavLab is a roadworthy truck modified so that humans or computers can control as occasion demands. Because it is self-contained, it is not subject to telemetry bottlenecks, communication faults or dependence on stationary infrastructure, and can travel to confront navigation problems of interest at any site.

The core of the NavLab is the vehicle controller. In autonomous mode, this multi-processor computer controls all locomotion, actuation and physical sensing. It interacts with a computer host and human operator to implement varying degrees of autonomy. The NavLab controller queues and executes Virtual Vehicle commands originating from a computer or human host. This command set provides high-level motion and control primitives that mask the physical details of the vehicle, and is extensible for control of other mobile systems.

The NavLab configuration consists of a chassis, drivetrain and shell. The chassis is a modified, cut-away van with a computer-controllable, hydraulic drivetrain. Driver's controls allow a human monitor to override automatic control for overland travel, setup and recovery from experimental errors. The shell houses all onboard equipment including computers, controllers, telemetry, and internal sensors. In addition, it provides a working area for operators, allowing research within the confines of the vehicle. Equipment racks, monitors, lighting, air-conditioning, seating and desk space create a mobile environment for research.

Humans can monitor and supervise the NavLab from the operator's console for setup, error recovery and tuning. Interface modes include Virtual Vehicle instructions, joystick motion control, and direct servo motion commands. The console also incorporates several displays to show the current states of both the vehicle and control computer.

The NavLab supports a choice of sensing to accommodate many types of navigation research. Video cameras provide color and intensity images for scene interpretation. NavLab vision experiments use a single camera to analyze road edges through intensity, texture, and color segmentation. A scanning rangefinder sweeps the surroundings with a distance-measuring laser that provides useful three-dimensional information about the geometry and reflectivity of the environment. Laser experiments navigate through geometric features like trees and buildings. Taken together, data of color, intensity, range and reflectance provide a rich basis for building natural scene descriptions. Sensor information from several sources can be fused to achieve more robust perception. A blackboard architecture integrates the distributed processes that sense, map, plan and drive.

The NavLab represents continuing evolution in the design of navigation vehicles. Fully self-contained, it is a milestone in mobile robotics.

This technical report details the control computing and physical configuration of the NavLab vehicle. Information on other aspects of the NavLab, including perception, modelling, planning and blackboard

architectures, can be found in articles listed in Appendix V.

2. Controller

The NavLab controller parses and implements a Virtual Vehicle instruction set. The controller is implemented as a loosely coupled parallel processor. Commands are received via a serial link from Host computers or an onboard console. Five axes of motion are controlled: drive, steering, pan and tilt motions for the cameras, and a pan motion for a laser ranging device. Status of devices onboard is monitored by a sensor subsystem that constantly polls processors dedicated to groups of sensors via a high-speed serial bus. Status information is displayed on the console inside the vehicle and is available to the Host computer via queries.

2.1 System Architecture

The control computing for the NavLab is based on the hierarchy shown in Figure 2-1, a system architecture for robot modeling and planning associated with autonomous task execution in unstructured and dynamic environments. The NavLab controller is tantamount to the lowest level of the architecture. The need for an interface protocol between the control computing and the higher level computing forges the virtual system, which allows the low-level control computing to mask the physical implementation details from the higher level computing. This is accomplished through command primitives that define the interface. Using the virtual system, many of the high-level modeling and planning functions can port across a number of different physical systems that can be controlled with the same command primitives. Only the lowest level control computing must deal with the physical differences of the system.

Complex systems usually defy any attempts at mathematical modeling techniques, which makes control parameters impossible to even estimate. A set of pseudo constants, tunable from an operator's console, adjust the parameters and gains. The NavLab maintains these constants in file structures that remain on disk for power-up initialization. The system always starts up with default values established from the most recent tuning of the system.

The control computing accepts commands from a host or human operator who can intervene at various levels of control to insure safe operation during experiments. The assumption during development is that the higher levels of computing will not succeed in all situations. The control computing thus provides a graceful transition between computer and human control when failures occur. The hooks for human inputs are also useful for setup and recovery during experiments.

The sensors monitored by control computing reflect the state and ability of the system to respond to commands issued by the cognitive planning layers. The values of the observed parameters have fixed maximum limits that are characterized by the physical system. These limits, however, are not static and can move inward during certain operating conditions. Physical parameters such as heat and pressure can diminish NavLab's mechanical ability to respond to commands. The parameter limits are dynamically adjustable by the controller to protect the NavLab. When controlling with a powerful physical plant like the NavLab, erroneous plans and commands have significant impact. The control computer should never execute commands blindly, so mechanisms are needed for validating and rejecting commands, with advisories communicated to the source of commands.

Control computing, the lowest of the three levels within the autonomous mobile system architecture, interacts with the physical system. The design criteria set forth for the NavLab low-level controller include an open-ended architecture, a virtual system interface and multiple command streams.

are inexact. Errors are compensated for by dynamically planning arcs to reach subgoal points along the path.

To facilitate synchronization, all drive and steering commands are initiated at the transitions between arcs. The capability is provided to make changes to vehicle motion (e.g., curvature of the arc, vehicle velocity) on the fly. Arcs (specified as [arclength, radius of curvature]) can be queued for sequential implementation.

The Virtual Vehicle and Host interact as follows:

- The Host issues a new arc command before the arc in execution is completed.
- If an immediate condition is specified, the old arc is discarded and the new arc is accepted immediately. Otherwise, the new arc is initiated at the end of the arc being executed.
- When a new arc is initiated, vehicle position is reported to the Host for use in calculating future path plans.
- The Host incorporates the reported position in planning the next arc, thereby compensating for deviations from the desired path.

The Virtual Vehicle instruction set and details of interfacing can be found in Appendix IV.

2.3 Controller Architecture

The NavLab controller is a powerful and flexible multi-processor system. A functional block diagram of the controller is shown in Figure 2-2. A Pilot module, responsible for management and operation of the key peripherals and I/O devices in the system, maintains direct control of all physical action and motion. The Pilot is also responsible for system startup and synchronization and acts as the hub in a star configuration for inter-processor communication. A Command Preprocessor manages I/O between the controller and devices that communicate with it. The Sensor Manager controls a network of 8-bit micro-controllers distributed throughout the vehicle to provide points of intelligent analog and digital I/O. Accommodations are made for an Advisor to set limits on physical motion parameters based on the perceived condition of the mechanical systems of the vehicle. The Advisor incorporates a bump detection subsystem that signals the Pilot if immediate action is necessary.

Each module in the system contains its own operating environment for independent/parallel operation. The operating environments are subsets of those used for system development. Code for each module is down-loadable to permit easy modification to the system.

2.3.1 Hardware

The NavLab controller is designed as a two-tiered multi-processor system. The first tier is responsible for the primary computing, control I/O and motion control. It is comprised of 4 Intel 28612 processor boards residing in a common Multibus backplane. The second tier performs remote data acquisition and control of devices located around the vehicle using a serial network of 8-bit micro-controllers. The Sensor Management System in the first tier is the interface between the two tiers.

2.3.1.1 Primary Computing

Processors in the first tier take advantage of the multiple bus structure of the system to increase processing throughput. Each processor contains a local bus with enough memory resources to support its own execution environment. Processors have bus master capabilities to access and control I/O

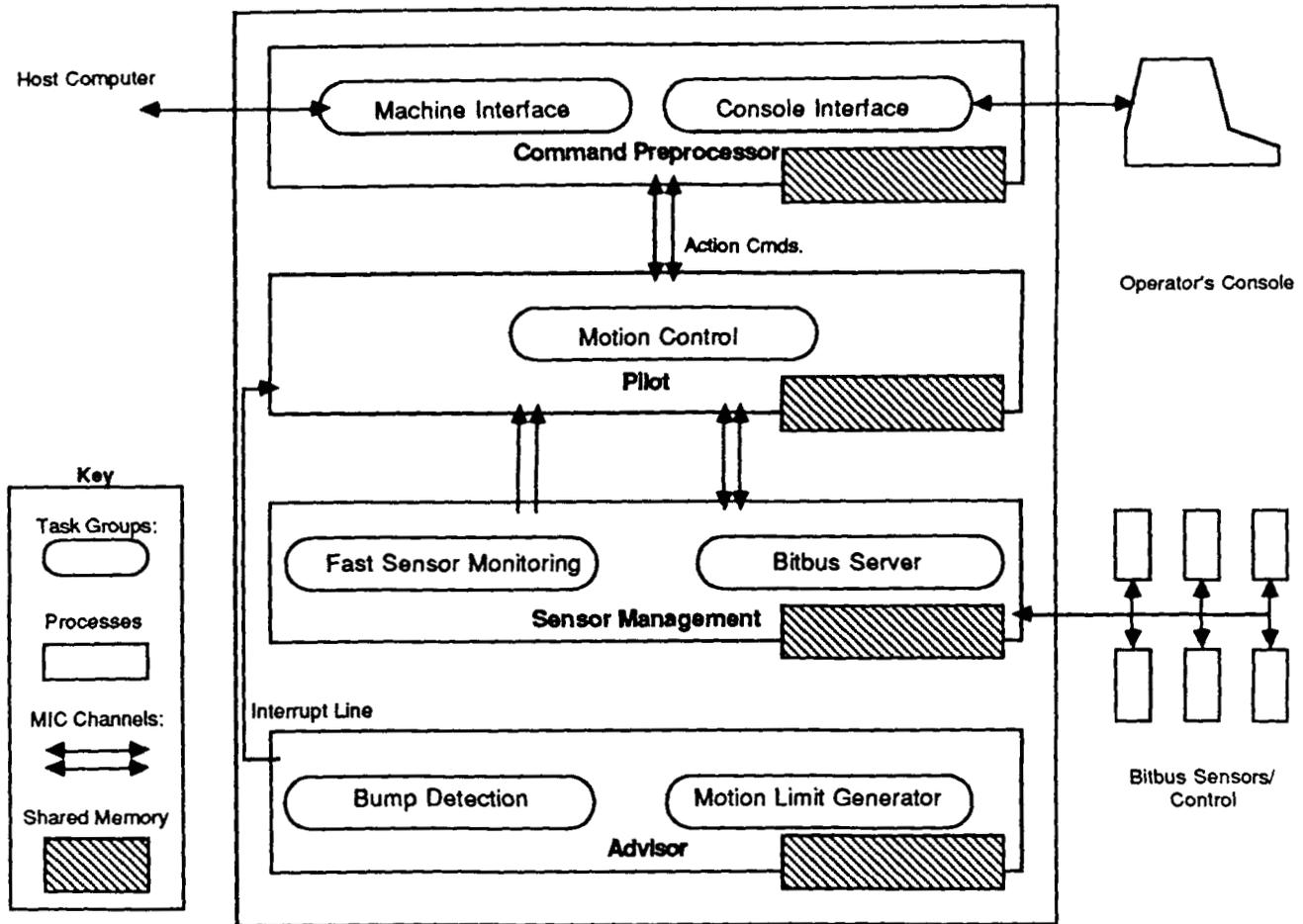


Figure 2-2: Architecture of Controller

boards and shared memory spaces. Critical memory and I/O locations are controlled using a semaphore system while bus contention is arbitrated in hardware. Interrupt lines in the Multibus backplane tie the processors together for inter-processor communications.

Each processor is identically configured with 256 K local ROM, 512 K local RAM, and a 256 K window to the Multibus. The ROMs on the I/O processors only contain operating system software and a download facility to allow loading of applications. The multiple bus structure permits a total system memory of 2.5 MB even though only 1 MB is addressable from each processor.

The controller also contains intelligent slave boards for I/O expansion and servo motor control. These boards may be accessed by any bus master. Often, access is restricted to a specific processor to avoid contention problems.

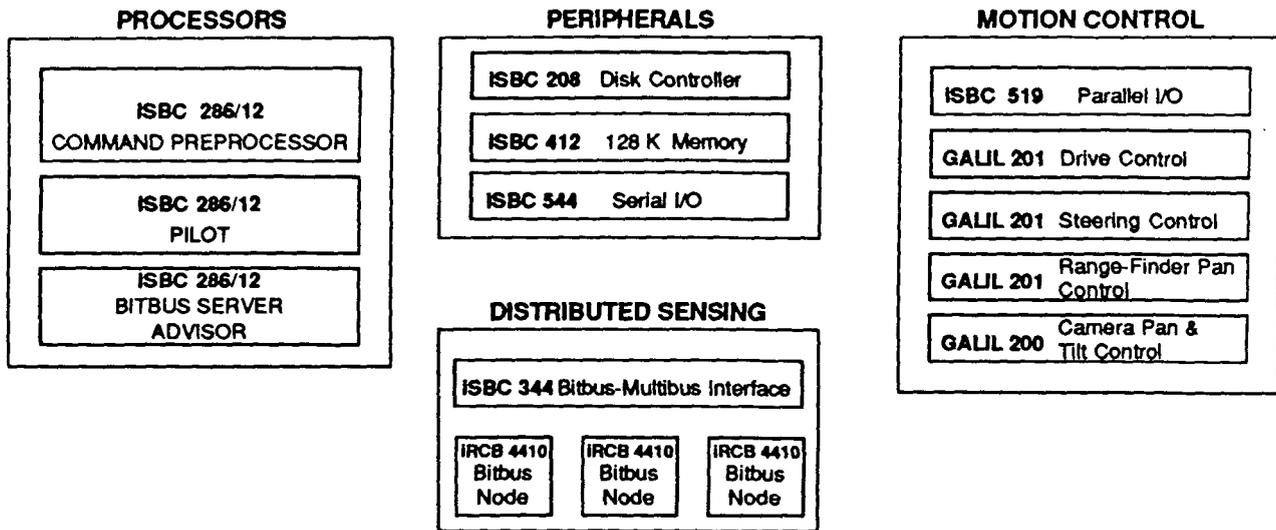


Figure 2-3: Hardware Configuration

2.3.1.2 Secondary Computing

The second computing tier physically distributes sensing and control of devices around the vehicle by using nodes that consist of 8-bit microcontrollers communicating over a high-speed serial bus using a message protocol called Bitbus. The network is controlled by a Master node that either continually polls other nodes to read analog and digital inputs or continuously commands them with reference values. The communication overhead makes Bitbus suitable to tasks that require high-level control and slow data acquisition. The serial bus network is extensible to support up to 250 nodes. Further implementation details of Bitbus can be found in Section 2.3.5.1.

2.3.2 System Software

System software for the controller is based on the iRMX 86 real-time operating system. iRMX is configurable to customize operating environments for each processor in the system. These operating environments are resident in ROM local to each board and are booted from reset. iRMX 86 provides objects to support an event-driven, multi-tasking environment.

A facility to down-load object code was developed for building and testing multiprocessor systems. A single processor accesses the mass storage device containing object code files for downloading. This processor, like a system server, loads object code into shared memory and signals the appropriate target board when a valid record is available. The other processors contain consumer jobs to copy records from shared memory to their local memory. On signal from the server processor, a consumer job releases the server CPU to allow the local Operating System to start the jobs from the newly loaded code. Once the application software is running, the consumer load job lies idle and waits for a signal from the server processor to reset and begin the load sequence again. This flexible load facility is a valuable tool for building and testing multiprocessor systems.

2.3.2.1 Interprocessor Communication

Processors communicate using shared memory in two different ways. Common variables are accessed by multiple processors to share state information (scratch pad communication). Messages can also be written to specific memory locations on other processor boards and the receiving board is signaled by an interrupt. This method is often used by one board to direct processing on another board.

Scratch Pad Communication

This method is a simple solution to sharing a large amount of data between modules. Processes that acquire data (status of devices, vehicle orientation, speed, etc.) post this information to the scratch pad area instead of sending the data to all modules that need them. Most shared variables are independent of each other; hence contention problems are limited to access of the individual memory locations to read or write. Dependent variables (ones that must be accessed as a group) require a software semaphore to provide mutual exclusion. An indivisible test and set instruction provided by PL/M-86 was used to create the semaphore system.

Module for Interprocessor Communications

The Module for Interprocessor Communication (MIC) was developed to support flexible pipelined communications between tasks running on separate processor boards. MIC provides the applications programmer with a simple set of procedure calls from which a task can queue messages containing a board and task destination. MIC handles the transfer of these messages between boards.

MIC is implemented as a star architecture. All messages are sent through a central node to limit the number of required interrupt lines. This scheme is well suited to the NavLab controller because most interprocessor communications are to a central node (the Pilot).

MIC was built using tools provided by iRMX including inter-task communication, dynamic memory allocation, and FIFO queues. MIC runs as an interrupt-driven task. It responds to signal interrupts to determine the destination of a received message and then sends it to the appropriate task. iRMX system calls permit asynchronous message transfers between tasks.

MIC was designed to be compact (5 K), fast, and capable. MIC is able to dynamically allocate message segments to meet the load of interprocessor communication traffic that varies from processor to processor. This prevents wasting memory and time required by the system programmer to tune buffer sizes for individual boards. When application code is modified to change message traffic, MIC can adjust to use only the necessary memory resources.

2.3.3 Command Preprocessor

The Command Preprocessor front-ends I/O originating from two sources: the driving Host computer (Host) and the operator's console (Console). At the lowest level, it drives the physical data links supporting these command streams. In the NavLab controller, RS232C serial channels are controlled. At the next level, it validates data integrity of Host-originated Virtual Vehicle Interface (VVI) command packets by checking format correctness, parameter count, and packet size. At the highest level it checks parameter values against established limits. The Command Preprocessor has the ability to reject commands exceeding the current operating limits, but the Pilot has final authority on command acceptance. Query commands issued by the Host are handled directly by the Command Preprocessor without Pilot involvement.

The Command Preprocessor communicates primarily with the Pilot module. The other modules are indirectly accessed through value lookups in the Scratch Pad. All commands involving action, such as motion commands or control commands to a device managed by the Bitbus Sensor/Control Network, are first sent through the Pilot to update its knowledge of the vehicle state affected by the controller.

The Command Preprocessor contains two separate subprocesses to service the Host and Console concurrently. The Host Interface is responsible for maintaining communications between the controller and the Host. The Console Interface interprets commands from the operator console keyboard. The Console is given priority over the Host so that it is possible for the operator to override Host commands. Commands are received as ASCII packets. The Host sends only numeric data; each command is given an opcode. The Console allows the operator to enter commands as simple mnemonics.

Communication errors are trapped by syntactic data validation. The Command Preprocessor takes two different actions based on the type of command it receives. For motion commands, the arguments are validated based on the allowable ranges of vehicle motions posted in shared memory by the Advisor. If all the arguments are acceptable, the command is passed on to the Pilot. An acknowledge message is then sent, signaling that the command was accepted and will be executed. If for any reason the command is found to be invalid, a disacknowledge message along with an explanation for rejection is sent to the command initiator.

The Command Preprocessor processes query commands (e.g., heading, position). The requests are satisfied by accessing the shared memory region where the information is updated constantly. This method makes it unnecessary to interrupt other processes. The data is formatted and shipped to the requestor.

The Command Preprocessor also maintains the display on the operator console onboard the NavLab. The screen is divided into three parts:

1. Display -- A window displays vehicle data. The operator can select between 5 different displays:
 - Sensor data shown in graphical form (vertical bars).
 - Sensor data shown in alphanumeric form.
 - Status of switches controlled by the controller shown in alphanumeric form.
 - Command packets between controller and the Host.
 - A help screen that explains how the operator can control the vehicle by using the Virtual Vehicle instruction set.
2. Command line -- Allows the operator to:
 - Enter Virtual Vehicle commands.
 - Enter software joystick commands.
 - Turn on/off switches controlled by the Bitbus network.
3. Information area -- A window is reserved for special messages that may be sent by any process in the controller.

2.3.4 Pilot

The Pilot's main function is controlling or initiating all physical action and motion control. The Pilot also plays the central role in inter-processor communications by acting as the hub in a star configuration. All commands altering the state of the vehicle are filtered through the Pilot, eliminating contention and state ambiguity problems potential to systems altered by multiple independent processes. For the generalized

case, the Pilot module would occupy several processor boards and handle manipulation as well as locomotor control.

The Pilot is composed of a hierarchy of concurrent processes (tasks), each of which is dedicated to maintaining a specific subset of state variables and initiating all actions affecting those variables. At the lowest level, each axis of motion has an individual driver process associated with it that formats motor-controller specific command strings, performs I/O exchanges with the motor-controller board, and maintains the current values of all pertinent variables for that axis in local memory. The axis drivers at this level have no notion of the physical configuration of the overall system. Coordination of motions is handled by higher-level processes.

Action requests can be submitted to the Pilot by the Command Preprocessor at any time. On receipt of such a request, the Pilot returns an acknowledge/disacknowledge message to the Command Preprocessor indicating whether it can execute the command. If the received command can be executed, it is decoded and forwarded to the appropriate subprocess for handling. Depending on the type of action requested, this process may then

- direct motions (via the appropriate axis drivers)
- read or set parallel I/O lines (for example, to select a different transmission gear)
- update the values of some state variables.

Because individual processes each have a specific run-time priority, critical commands (e.g., "STOP") always obtain control of the CPU, even if a lower-priority command is still in progress. Also, because task scheduling is event-driven rather than time-shared, high-priority processes always run uninterrupted, i.e., in constant time.

A special set of tasks within the Pilot maintains and processes a queue of arcs specifying a path for the vehicle. These arcs are executed continuously and a position report is issued to the Command Preprocessor on completion of each arc. Velocity and acceleration parameters can be updated at any time during execution of an arc; in addition, one value for each of these variables may be queued to go into effect with the beginning of the *next* arc execution.

The Pilot has the final responsibility for command acceptance or rejection, command queue management, and implementing established equations to achieve requested arc trajectories. Implementation details of the vehicle are masked by the Pilot.

The NavLab incorporates braking as well as forward and reverse propulsion in a single, bi-directional hydrostatic drive. For the generalized vehicle case, the Pilot would coordinate brake/throttle control to achieve velocity and position objectives. At the servo level, motion is controlled by motion control boards commanded by the Pilot. Emergency stop conditions are signaled to the Pilot by a critical interrupt line controlled by a planned Health Preservation module with bump detection facilities. On assertion of this line, the Pilot is responsible for graceful shutdown, leaving the vehicle ready for recovery actions issued from the operator's console. Because only the Pilot controls the motion, it is always aware of the current motion state.

Finally, a few background processes perform such functions as maintaining the system clock and calculating position coordinates based on sensor measurements.

2.3.5 Sensor/Device Management System

Apart from the five main axes of motion, there are numerous sensors that must be monitored and devices that must be activated. The Sensor/Device Management System manages two classes of sensors. The first class is characterized by sensors and devices that need not be monitored/controlled frequently. For example, a sensor might be dedicated to monitoring hydraulic fluid temperature; while this information is important, it is not essential that it be updated more frequently than once in several seconds. Another class of sensors is that group of devices that must be monitored frequently. An example is a process that must analyze data from inertial devices and post these results in shared memory several times a second.

2.3.5.1 Bitbus System

The Bitbus System is a highly flexible and expandable data acquisition and control system. By taking advantage of the Bitbus distributed control architecture, the Distributed System supports analog status sensors and digital I/O channels using microcontrollers distributed on a serial network. Nodes on this network transfer data to the Bitbus Server module using the Bitbus message passing protocol. The Bitbus nodes are programmable to meet a wide range of sensor and control configurations. Data returned to the Bitbus server are conditioned and scaled at the Bitbus node, reducing computational requirements of the Bitbus server.

The primary responsibility of the Bitbus server is to acquire and move sensor data to shared memory locations recognized by other modules in the controller. When the Pilot sends an action command request, the server must format messages to control any devices supported by a Bitbus node. In support of these functions, the server must also handle node initialization, self-monitoring, and fault recovery for the Bitbus network. The chief advantage of using a Bitbus network is the modular expandability and flexibility that is inherent to the Bitbus architecture. Complex inter-processor message passing facilities are included in the architecture, relieving the programmer of much responsibility.

In simple systems with limited I/O points, the Distributed System could be replaced with a single board computer equipped with the appropriate I/O expansion modules. An effort should be made to keep I/O operations local to the processor to avoid consuming bus bandwidth. With either implementation scenario, the update rates of shared variables should be adjustable to control the bus access frequency of the Distributed System for tuning purposes.

The Bitbus network provides a distributed control structure to service the first class of sensors. A list of sensors and devices on this network can be found in Section 2.5.2.

The Bitbus network is based on a master (Bitbus server) and slave (Bitbus nodes) concept (Figure 2-4). Nodes provide the connection between the sensors/devices and the central Bitbus Server. Because each node operates independently, fast data acquisition can be achieved by distributing the work load among many nodes. Nodes can also be programmed to perform control tasks by reacting immediately to critical conditions as they arise.

The Bitbus Server, one process on the Sensor Management Module, initializes the network and monitors status. Because the nodes cannot initiate communications, the Server must continuously poll each node for output data. When the Server receives a message from a node, it posts the relevant information in shared memory for reference by other processes. When some high-level process needs to control a Bitbus node, a message is sent to the Server. This message is then broadcast on the network where it is

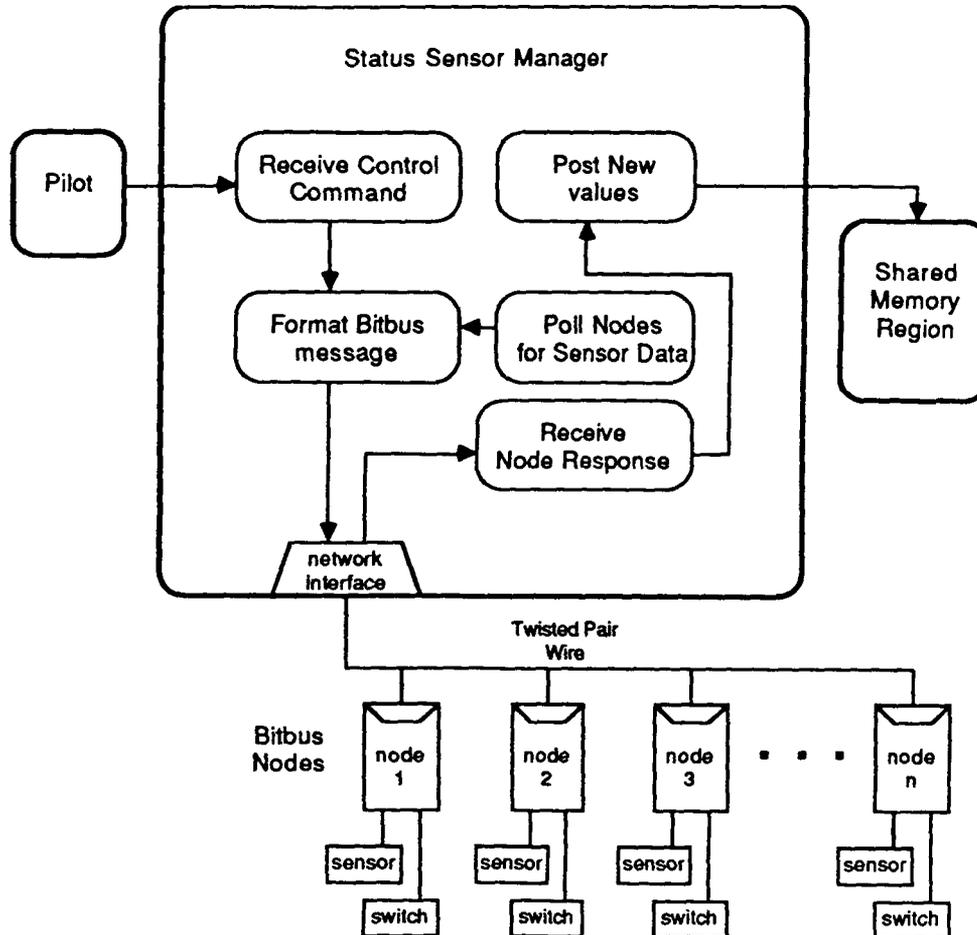


Figure 2-4: Bitbus Server

trapped and processed by the addressed node.

2.3.5.2 Fast Sensor Monitoring

The Sensor Management system also maintains processes to monitor those devices that must be serviced at a high frequency. At present, the only such device envisioned is an Inertial Navigation System anticipated to report position and orientation data about 10 times/sec. The incoming data is parsed and posted in shared memory. Other devices that need to be monitored constantly can be added to the controller simply by allocating a process to them. This method is preferable to the Bitbus method when data must be accessed frequently and must be made available to the entire system quickly.

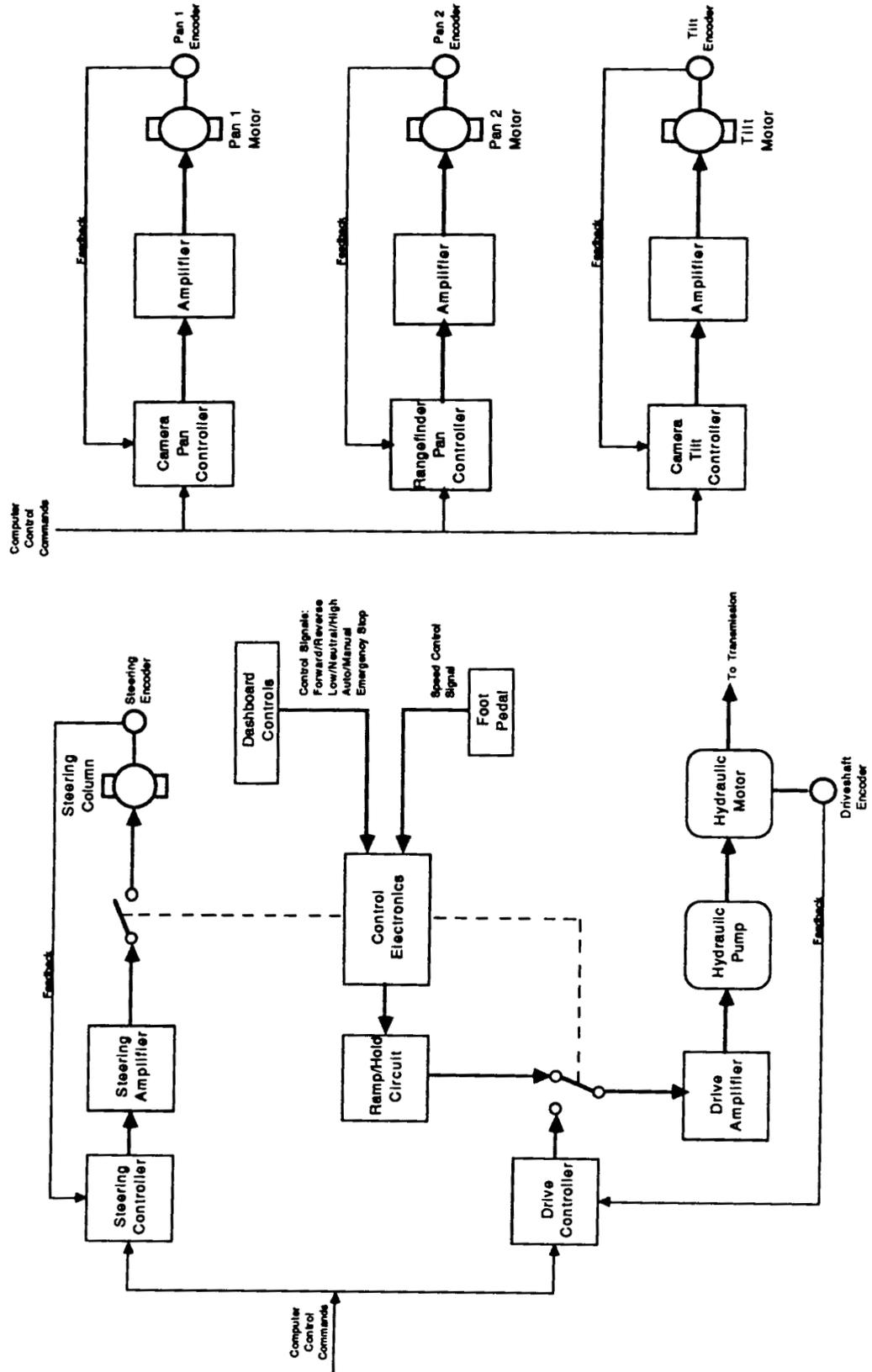
2.4 Motion Control

Of the 5 axes of motion, only drive and steering can be controlled both manually and automatically. The other three motions of pan and tilt are only used in automatic operation. Figure 2-5 (a) shows the configuration during manual operation. All axes of motion on the NavLab are physically controlled by Galil DMC-200 series motor controllers. These controllers were chosen for:

- Multibus compatibility
- multiple modes of control (position, velocity, torque)

Drive/Steering Control

Sensor Motion Control



(a)

(b)

Figure 2-5: Motion Actuation

- coordinated motion of two or more axes (DMC-200 only)
- programmable acceleration and slew rates
- status, position, and error reporting.

A digital phase lead control law with adjustable gain, pole and zero provides a stable closed-loop system for a wide range of plant dynamics. The motor controllers communicate with the Pilot subsystem through Multibus I/O ports for data as well as handshake exchange.

Single axis Galil DMC-201 controllers are used for steering, drive, and laser-ranging pan motions, while a DMC-200 two-axis unit is used for the camera pan and tilt (Figure 2-5 [b]). Each controller is software-calibrated at power-up to match the dynamics of the controlled axis. Thus, motor controller boards can be interchanged simply by selection of appropriate I/O addresses via jumpers.

2.4.1 Dash Panel Control

The vehicle operates manually to simplify transport to and from test sites. Manual operation doesn't require any computing or generator power. The electronic components active during manual operation are powered by the NavLab's 12 V system.

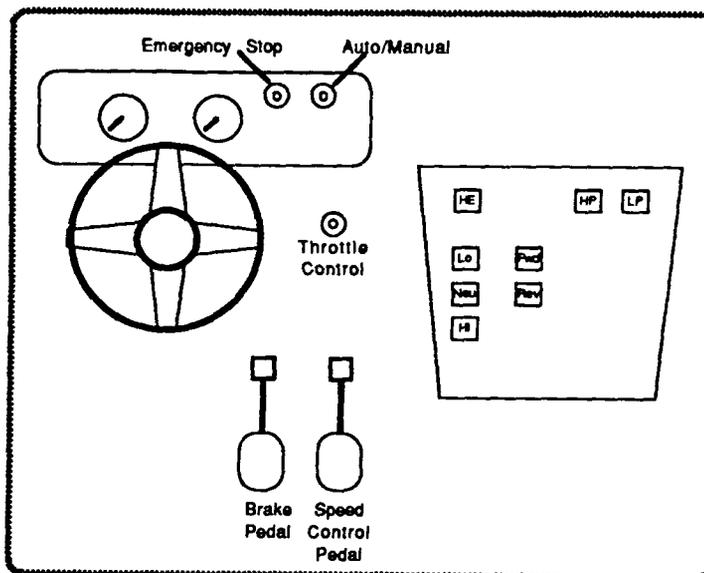


Figure 2-6: Dash Panel Layout

A human interface is incorporated for safe and easy use by drivers of standard automobiles. Figure 2-6 shows illuminated pushbutton controls mounted within reach of the driver.

- **High, Neutral, & Low:** allow the operator to choose gears. Because switching directly from one gear to another produces an unsafe lurching of the vehicle, a hardware logic function allows switching only by first selecting Neutral.
- **Forward, Reverse:** select the direction in which the vehicle moves.
- **Auto/Manual:** a pull-push switch that switches between manual and automatic control.
- **Emergency Stop:** disables autonomous locomotion and brings the vehicle to a rapid, controlled stop. Servo-lock of steering is disabled; steering is returned to manual control.
- **Brake Pedal:** as in commercial cruise control systems, a light touch of the brake pedal brings

the vehicle back under manual control.

- **Speed Control Pedal:** activates a 20K ohm potentiometer to produce a voltage proportional to the angle of deflection of the pedal.
- **Throttle Control:** this dial sets the vehicle engine RPM as detailed in Section 4.2.1.1.
- **HE:** this switch turns on/off the heat exchanger fan for the hydraulic system.
- **HP, LP:** These lamps are lit when the dirty oil filters in the high and low pressure hydraulic systems indicate an alarm.

By default, when the vehicle is powered up, it is put into manual mode, neutral gear, and forward direction. It is necessary to provide the ability to override the autonomous mode in a fast but controlled manner if an emergency develops. To ensure reliable operation, manual override is a hardwired electronic circuit with sealed electromagnetic relays instead of sequential logic gates. This design proved to be immune to the noise and power fluctuations common to automotive electrical systems. Because this circuitry is essential to vehicle locomotion, it is powered by the vehicle 12 V system rather than the generator.

An electronic ramp/hold circuit in series with the foot pedal provides adjustable limits on acceleration and deceleration and ensures that abrupt movements of the foot pedal do not cause the vehicle to lurch. This feature was included both for safety and ease of driving. A second ramp/hold unit ensures a smooth deceleration in case of an emergency stop.

2.4.2 Steering Control

The steering control system consists of a computer-controlled DC servo motor linked to the steering column by a toothed belt. A single axis motor controller (DMC-201) uses feedback from an optical 1200-line incremental encoder mounted directly on the motor shaft to maintain tight position control over the steering wheel. A servo-amplifier converts the $\pm 10V$ control signal from the motor controller to drive the DC motor with up to 11 amps of continuous current. At maximum speed, the steering mechanism can be moved between its two extreme positions in 2 seconds.

Feedback is obtained from an encoder on the motor shaft that is mated to the steering wheel, which is always turned a specified amount. Differences between intended and achieved radius occur due to linkage non-linearities and factors such as friction between the road and the wheels, grade of the road, vehicle speed, and speed with which the steering wheel is turned.

Limit switches on the steering linkage are hardwired inputs to the controller board and provide both a safety stop to protect the steering mechanism and a reference point for roughly calibrating the steering control system to a known position on power-up or system reset.

2.4.3 Drive

A single axis motor controller services the drive system. The voltage (-10V to 10V) produced by the motor controller is converted to a current signal (-100mA to 100mA) by an amplifier that directly operates a hydraulic servo valve to set the speed of the hydraulic motor. Acceleration of the vehicle is limited by a ramp/hold circuit, mentioned in Section 2.4.1, in effect providing a low pass filter to the input signal. An optical 300-line incremental encoder mounted on the hydraulic motor shaft provides feedback to the motor controller. Because the transmission is downstream of the hydraulic motor (i.e., between the motor and the driveshaft), the encoder pulses must be interpreted differently for high and low gears.

2.5 Sensors/Devices

At present, the controller features for handling sensors are not fully implemented. Two fronts of expansion are proposed for the near future. An Inertial Navigation System will be incorporated to provide continuous position and orientation information. A Bitbus network will be used to monitor and control devices distributed around the vehicle.

2.5.1 Inertial Navigation

An Inertial Navigation System (INS) to be deployed on the NavLab will receive distance data as input and will provide position and inclination data along the axes specified as output. The INS detects initial heading on its own and provides updates of position and heading.

The following information will be obtained from the INS:

1. True heading of the vehicle -- 0.5 degree resolution.
2. Rate of change of heading -- 0.5 degs/sec resolution.
3. X, Y, Z position in cm -- 10 cm resolution. This will allow movement on a 100 km² grid.
4. Roll and pitch inclination -- 0.5 degree resolution.

Performance criteria include:

- Dead Reckoning Capability: Speeds along the direction of travel of up to 60 km/hour; turning speeds (change of orientation) of up to 40 degrees/sec.
- Accuracy: Maximum long track error: 1% of distance traveled. Maximum cross track error: 0.1 degree/hour.
- Updates: Must be able to handle the accuracy requirements above with updates coming only once an hour or once in 5km.
- Necessity of Stopping: Must not need more than 5 minutes for the vehicle to be completely stationary on power-up or on recalibration.

At present a device that uses three mechanical gyroscopes and requires an odometer input is being considered. A second device being considered is a strap-down system that uses ring laser gyroscopes. This is much more accurate than the first and does not require odometer input.

2.5.2 Sensors/Devices on Bitbus Network

The following is a list of sensors and devices that are monitored and controlled by the Bitbus network. Scan cycle time indicates the period at which each of the sensors is monitored. Temperature units are degrees centigrade. Pressure units are pounds/sq. inch.

| Sensor | Scan Cycle | Minimum | Maximum |
|-----------------------------|------------|---------|----------|
| Thermocouples | | | |
| Engine Oil | 30 sec | 0 deg | 175 deg |
| Engine Coolant | 30 sec | 0 deg | 150 deg |
| NavLab Cabin | 30 sec | -10 deg | 40 deg |
| NavLab External | 30 sec | -10 deg | 40 deg |
| Hydraulic Reservoir | 30 sec | 0 degs | 100 degs |
| Pressure Transducers | | | |
| Engine Oil | 10 sec | 0 psi | 60 psi |
| Hi-pressure System (input) | 10 sec | 0 psi | 3000 psi |
| Hi-pressure System (output) | 10 sec | 0 psi | 3000 psi |

Voltages & Currents

| | | | |
|---------------------|--------|-------|------|
| Battery Voltage | 30 sec | 0 V | 15 V |
| RPM | 2 sec | 0 V | 5 V |
| GAS Level | 60 sec | 0 V | 5 V |
| Low Level Reservoir | 60 sec | 0 V | 5 V |
| Swash Plate Angle | 1 sec | -10 V | 10 V |

Switch Settings

| | |
|-------------------------|-------|
| Transmission Gear State | 1 sec |
| Generators (2) | 1 sec |
| Heat Exchanger | 1 sec |

3. Vehicle Shell

NavLab's foundation is a 1985 General Motors Vandura cutaway chassis chosen as a commercial base to simplify development. As acquired, the vehicle consisted of a chassis, a drivetrain and a cab. A custom shell was constructed to house the onboard AC power generation, power distribution, control and computing equipment. Space for operators is provided, allowing research activity within the confines of the vehicle. The original configuration also included a 350 ci V-8, cruise control, an automatic transmission, dual rear wheels, power steering, power brakes and a 33 gal fuel tank.

3.1 Exterior Design

The shell was custom-built with particular attention paid to strength requirements, anticipating needs for extensibility. The roof and cab support air-conditioning, antennas, sensors, and working personnel. The floor of the shell supports about 2000 kg. The shell is dimensioned so that researchers can stand inside; five equipment racks are housed side by side along one side of the vehicle. Figure 3-1 shows a rear and side view of the vehicle.

The shell is made entirely of steel. Heavy gauge was used on the front and back walls while lighter gauges were used along the side walls and roof. A metallic blue paint protects the entire shell. There are compartments for the generators and power-related equipment. Louvered metal doors provide outside access; there is no access to these compartments from inside the vehicle to keep fumes from entering the shell.

A wiring port in the floor behind the driver's seat allows wiring from the underside to enter the vehicle. Another access vent in the shell above the passenger compartment enables wiring from cameras and range sensors to enter the vehicle.

3.2 Interior Design

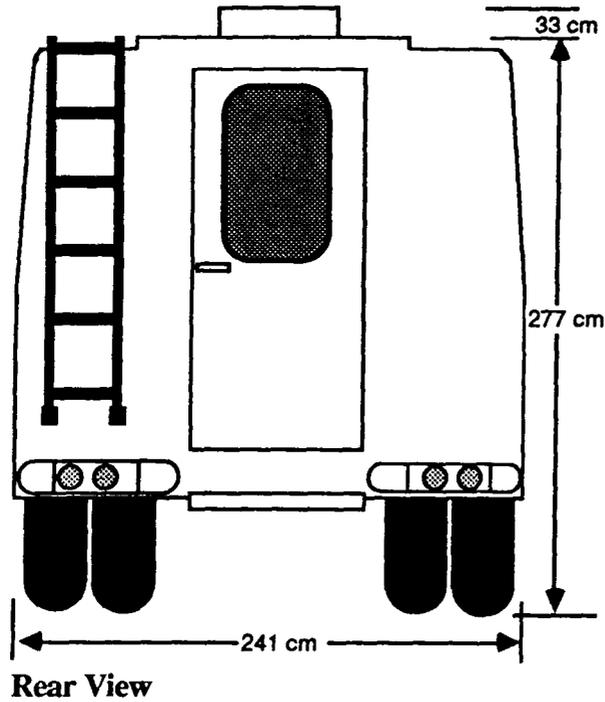
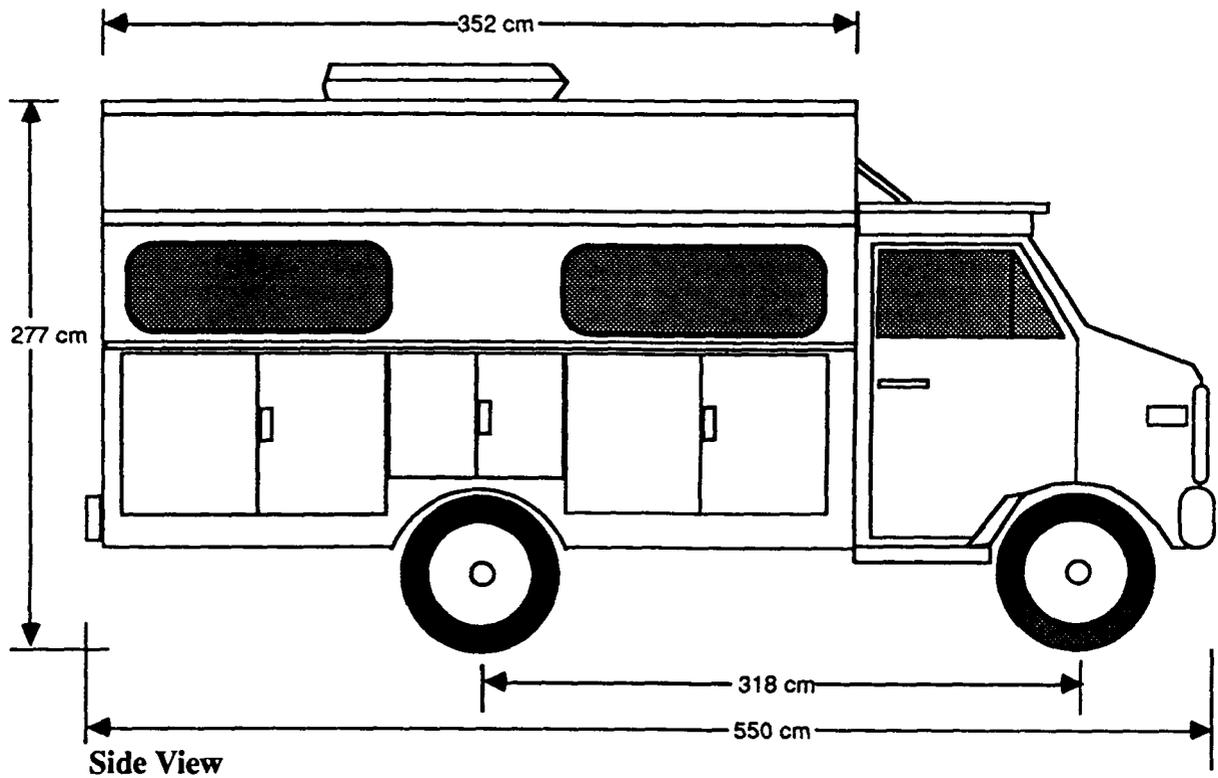
Figure 3-2 shows a topdown view of the NavLab. The cab has two seats, one for a driver and one for a passenger. A console located between the two seats allows the operator to control and monitor the transmission. A research area behind the cab contains computing, sensing, and control equipment, as well as space for two researchers.

Five equipment racks are located on the left side. A desk area extending the length of the research area is located opposite the racks across the aisle. Three video monitors mounted above the desk area can swivel to a desired viewing position.

Along the rear edge of the desktop an outlet strip provides power for the various terminals and test equipment. Bolt-down inserts with elastic straps prevent computer equipment from sliding on the desktop when the vehicle is moving.

Cabling between devices passes through cable trays mounted close to the ceiling. The tray design securely holds video and communication cables but allows for easy removal or addition. Track-mounted lights above the desk area provide independently aimed illumination.

In addition to the two seats in the cab, a swivel seat, centered in the desk area, is mounted on the wall of a generator compartment. Extra removable seats can be mounted in the aisle for more researchers.



General Navlab Specs

Total Weight: 5449kg
 Minimum Turning Radius: 750 cm
 Center of Gravity: (112cm, 244cm)
 (x,y,) with rear corner on the driver's side as the origin.

Figure 3-1: Side and Rear View of the Vehicle

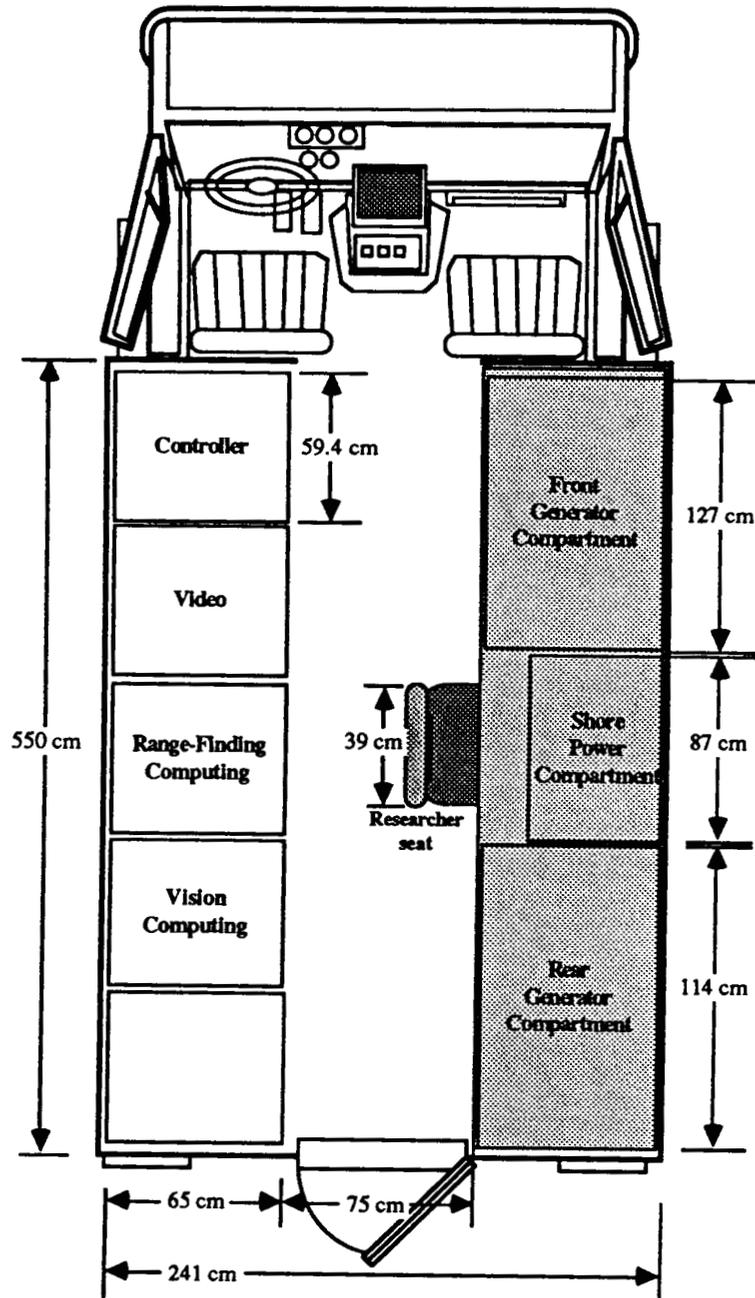


Figure 3-2: Interior Layout of Vehicle

3.2.1 Cooling

The heat generated by power conditioning, lighting, and electronics would damage some of the experimental computing. Thus in addition to the air conditioning provided on the van, a standard roof-mounted recreational vehicle air conditioner provides cooling.

Fiber insulation between the shell and interior panels also provides protection from the heat. Insulation inside and outside the shell helps control interior climate. Underfloor insulation keeps heat from the hydrostats and exhaust from entering the interior. Flat sheets of fiberglass covered with thin gauge aluminum are inserted in floor areas between frame members. High temperature silicon-based insulation covered with heavy gauge aluminum foil covers exhaust pipes.

4. Locomotion

Steering and drive motions coordinate to drive the NavLab through planned trajectories. Both axes of motion are controlled by analog signals issued by the controller while in automatic mode or through manual controls.

4.1 Steering

Figure 4-1 shows a front and side view of the NavLab steering mechanism.

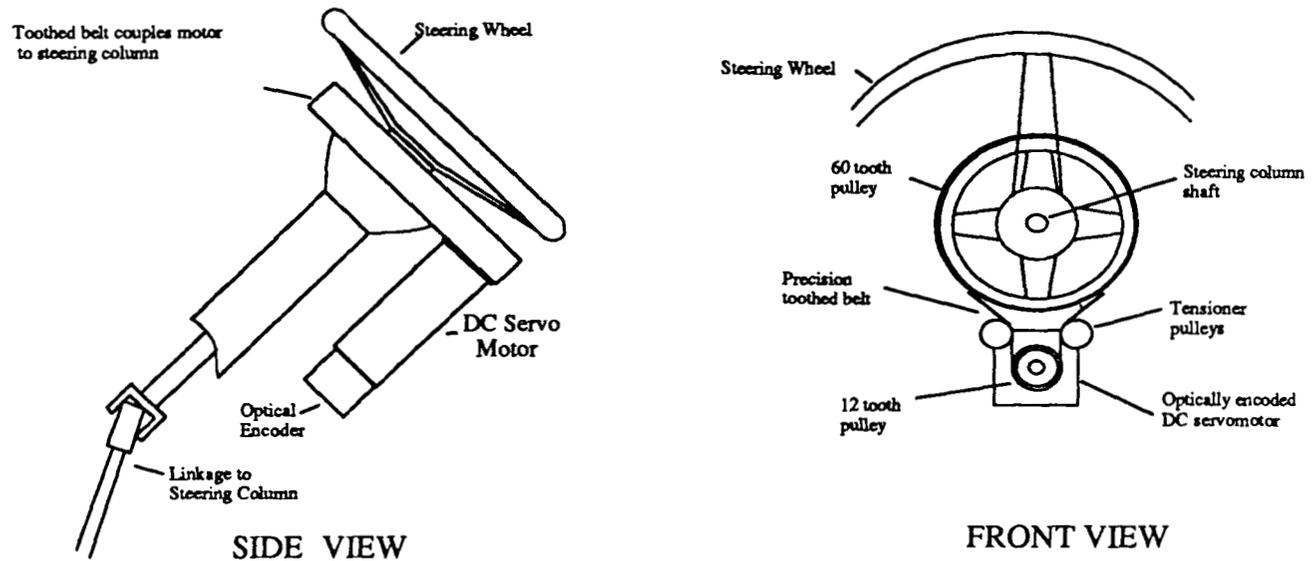


Figure 4-1: Steering Adaptation

The original linkage and steering column are driven by a DC servomotor mounted below the steering column. The motor is connected to the steering column shaft via a precision toothed belt; two toothed pulleys provide a gear reduction of 5 to 1. This configuration provides high enough torque to turn the steering shaft but low enough for the operator to overpower the steering motor in an emergency. A special hub ties all the steering elements together and a safety enclosure houses the moving parts. Limit switches at the extremes of steering travel prevent command error from damaging the system.

4.2 Drive

A hydraulic pump and motor combination comprises NavLab drive. This hydrostatic combination was selected because it provides precise control of position, speed and acceleration. Hydrostatic equipment also has a long history of smooth control and finely adjustable response.

Drive power comes from the main vehicle engine. Engine RPM is limited by a governor to prevent overdriving the attached hydraulic pump. Pump output is controlled by an analog signal.¹ The

¹This signal originates from either a foot pedal that replaces the standard gas pedal or a drive controller, depending on whether the vehicle is in manual or automatic mode.

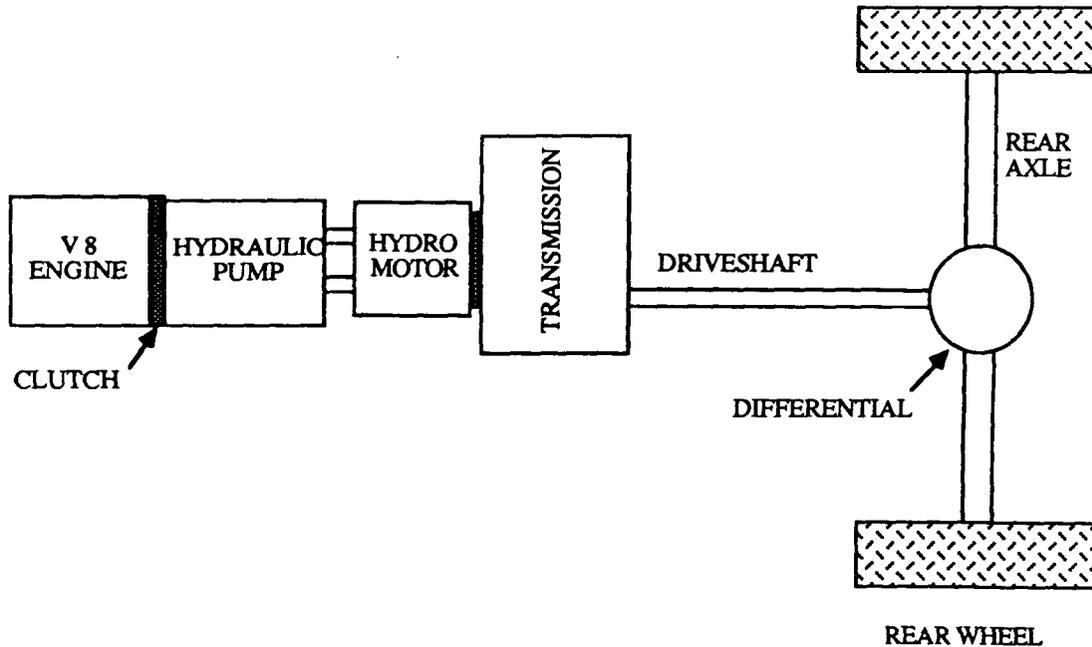


Figure 4-2: Schematic of Vehicle Drivetrain

displacement of the pump (proportional to the signal from the footpedal) determines the speed at which the hydraulic motor moves. The motor in turn powers a two-speed transmission which operates at either a 4:1 (low gear) or 1:1 (high gear) ratio, turning the driveshaft connected to the vehicle differential. Figure 4-2 shows a schematic of the drivetrain.

The configuration described above makes control of vehicle motion simpler than if the vehicle transmission and brakes had to be controlled to produce desired velocity. The standard braking system is intact but is only used in case of emergency because the analog signal to the hydraulic pump controls both accelerations and decelerations.

4.2.1 Vehicle Engine

The standard 350 ci V-8 engine is the main source of driving power. The following modifications were made:

- An electrically actuated clutch was installed to couple the vehicle engine to the hydraulic pump. The clutch is disengaged to isolate it from the engine when the engine is being started.
- The alternator was upgraded to a 120 amp dual output unit to satisfy the additional requirements of the two-battery, 12 volt system onboard.
- One stock emission control air pump was substituted by a hydraulic power takeoff unit. It is driven from the crankshaft end and shares a stock V-belt with the power steering pump.
- An engine oil cooler was installed to reduce oil deterioration caused by the constant high engine temperature.

4.2.1.1 Engine RPM Control

An engine RPM control keeps the vehicle engine running at a determined range of RPM irrespective of grade and speed. A magnetic pickup on the output shaft of the engine provides feedback to a specialized controller that maintains a constant RPM by moving an actuator linked to the engine carburetor. Figure 4-2 shows a schematic of the mechanism.

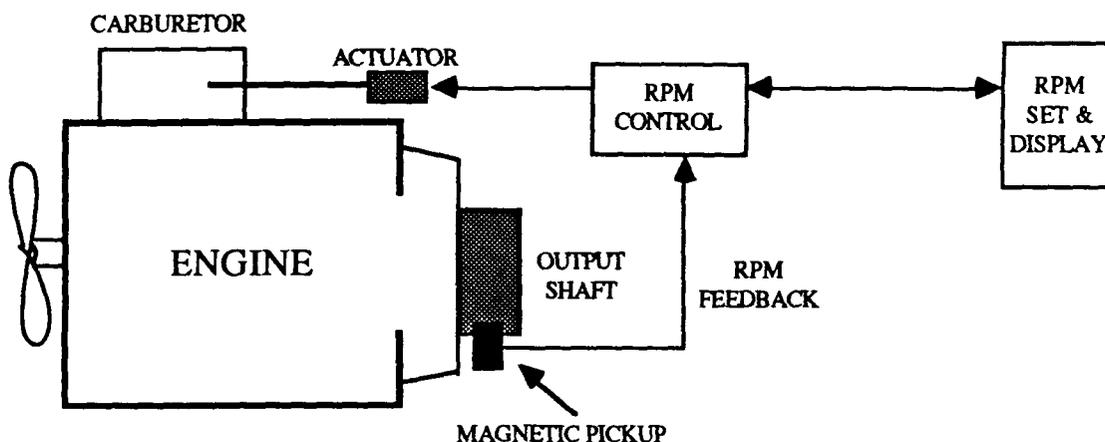


Figure 4-3: Mechanism for Engine RPM Control

4.2.2 Hydraulic Pump

The output of the engine drives a hydraulic pump through a flexible coupling. The pump is suspended from a frame crossmember with rubber shock mounts to allow movement with the engine.

The pump, a Sunstrand axial piston pump, is equipped with an electronic displacement control valve that alters the angle of an internal swashplate between 0 and 18 degrees, depending on an input signal that varies from -10 to 10 V. Negative voltages cause the pump to turn in the reverse direction. At 0 volts the pump has a holding torque to keep the vehicle stationary. At 10 V the displacement is maximum, corresponding to maximum driving speed.

Hydraulic fluid is supplied to the pump from the reservoir by an integral charge pump to replace the fluid pumped to the motor while an equal amount of surplus hot oil is drained from the pump case and passed through the main heat exchanger.

4.2.3 Hydraulic Motor

Hydraulic power from the pump is transmitted to a matching fixed displacement motor attached directly to the transmission. High-pressure flexible hose couples the motor and pump. Because the motor is a fixed displacement type, it always turns the same amount for every unit volume of fluid pumped in, resulting in an RPM of the motor that is directly proportional to the input signal of the pump.

A 10 micron filter cleans the return leg of the high pressure system. An additional crossmember supports

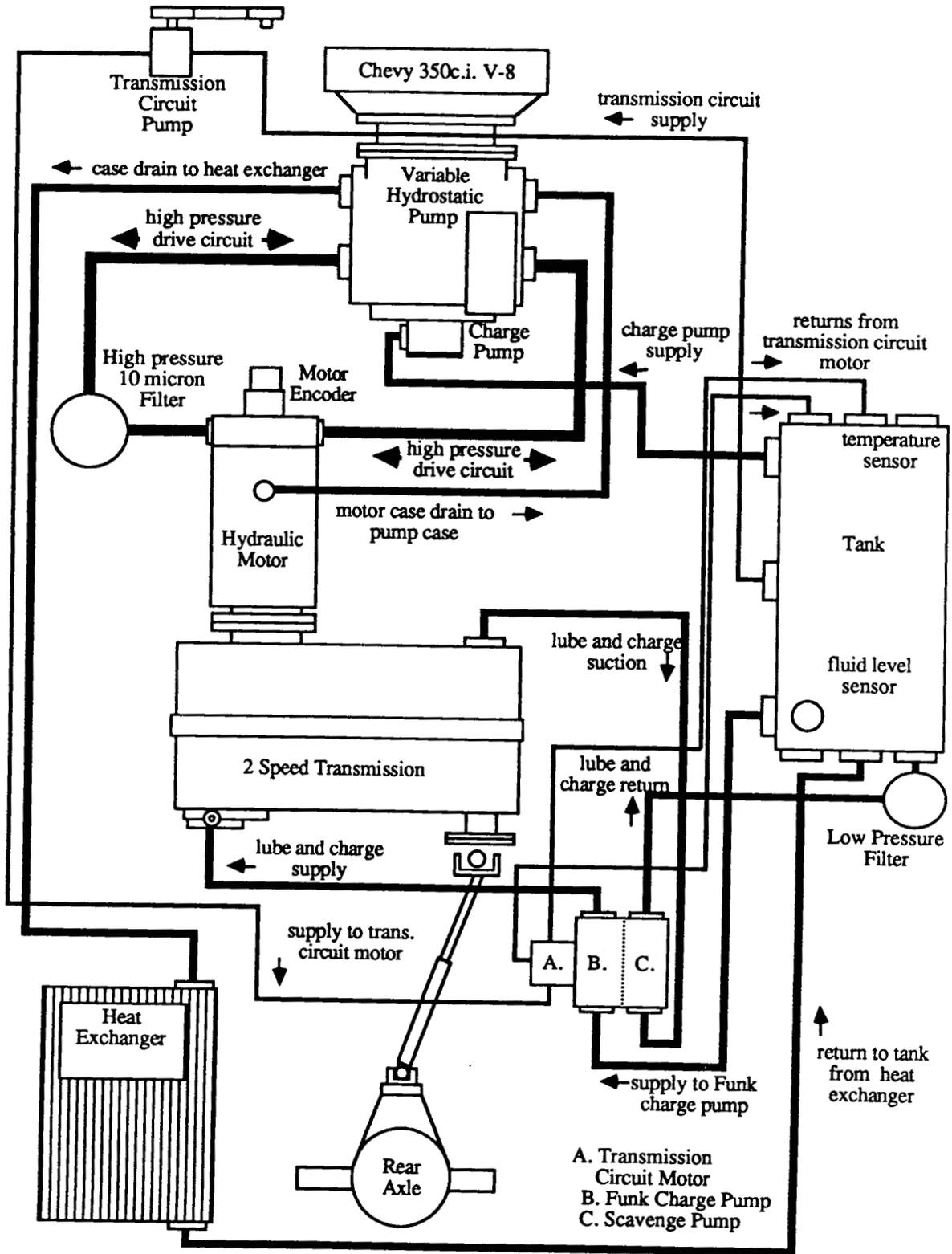


Figure 4-4: Hydro Drive System

the hydrostatic motor. The motor unit has an SAE standard shaft mounted to a mating flange on the driveshaft's forward universal joint yoke.

4.2.4 Transmission

The Funk transmission, an electrically shifted two-speed gear box installed between the hydraulic motor and the driveshaft, is bolted to a reinforced frame member. It is mechanically coupled to the motor on the input side and to the driveshaft on the output side. The transmission provides a ratio of 3.950:1 in low gear and 1.0441:1 in high gear. Low gear supports low-speed experimentation (0-20 km/h); high gear (0-40 km/h) transports the vehicle along public roads in manual mode. The gear is selected electronically by applying a voltage to one of two solenoids on the transmission; if neither solenoid is activated, the transmission is in neutral gear. It is necessary to shift into neutral when changing from one gear to another.

A flow-through lubrication and charge system was added to the transmission to circulate hydraulic fluid. The fluid is returned to the reservoir through a low-pressure filter.

4.2.5 Reservoir, Heat Exchanger, and Filters

A reservoir holds about 80 liters of hydraulic fluid. Because seals and bearing surfaces are sensitive to temperature and contamination of the hydraulic fluid, oil returned to the reservoir must be allowed enough time to de-aerate and cool. Heat is removed by passing oil from the pump case drain through a heat exchanger. Cooled oil is directed back to the reservoir. Dirt in the oil is filtered at two points: in the return leg of the high-pressure system and between the transmission and the reservoir.

A series of valves assist in the cooling and circulation of working fluid. A shuttle valve and a low pressure bleed-off valve act together to allow a small portion of the working fluid to circulate through the oil cooler and reservoir. A make-up pump replenishes the fluid that is removed via a bleed-off valve.

The reservoir is equipped with a thermistor and a level gauge to relay tank status to the vehicle controller.

4.2.6 Hydrostat Sensor and Control System

Figure 4-5 shows the sensing and control system associated with the hydraulic drive system. All the components are located on the underside of the vehicle so all lines enter the vehicle through a wiring port in the floor behind the driver's seat.

Control lines include:

1. Hydrostatic pump displacement: This line controls the swash plate angle in the pump regulating the displacement of hydraulic fluid to the motor.
2. Gear selection: This line controls the gear (high or low) of the transmission.
3. Heat exchanger fan control: This line controls the on/off state of a fan that cools the hydraulic fluid.

Sensors include:

1. Dirty filter sensors: one dirty filter sensor is installed in each of the high- and low-pressure legs of the hydraulic system. These sensors trigger an alarm when they become clogged.
2. Pressure transducers: These read system pressure at input and output of the hydraulic motor.

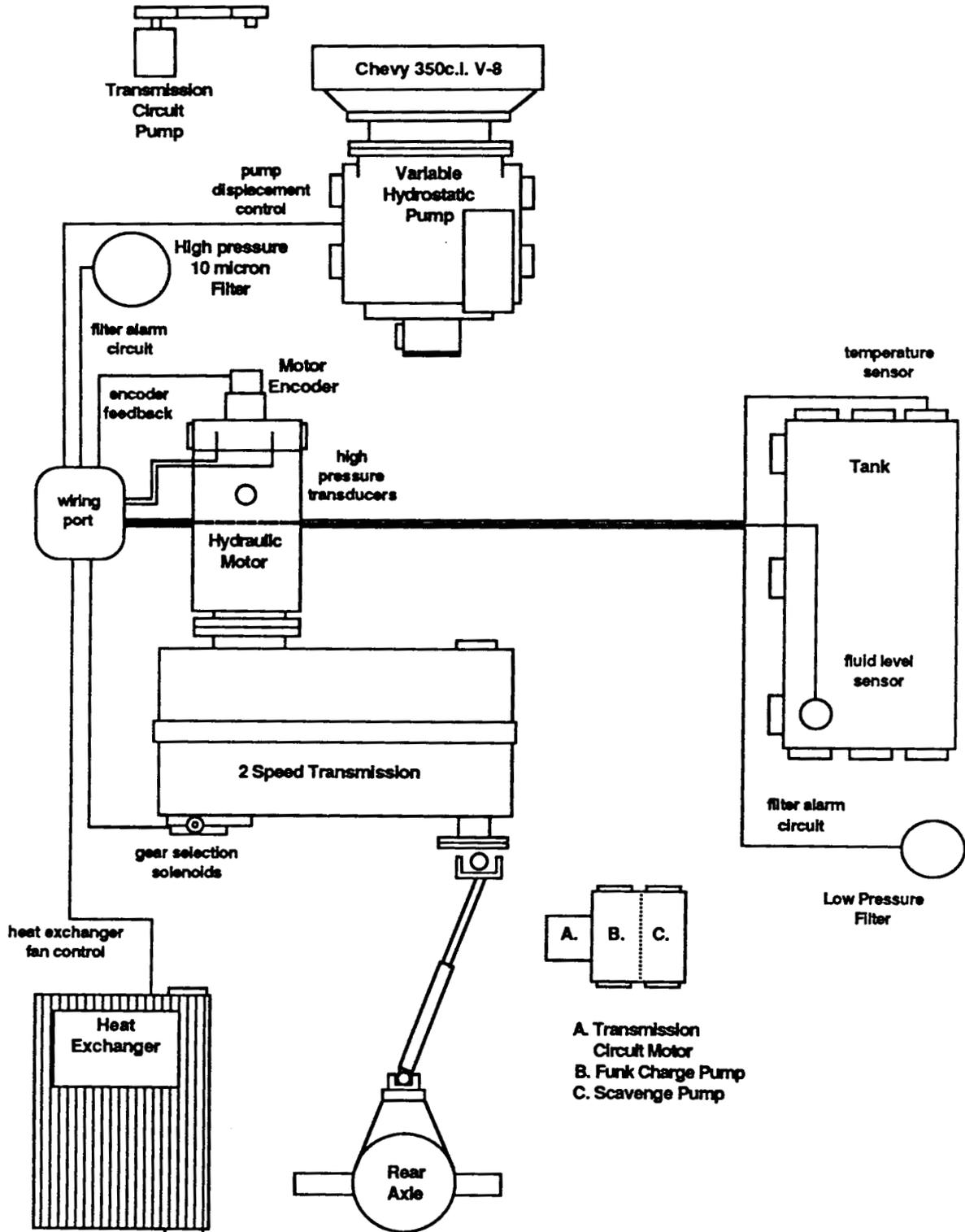


Figure 4-5: Hydrostat Sensor and Control Lines

3. Reservoir sensors: These measure fluid level and temperature of hydraulic fluid in the reservoir.
4. Motor encoder feedback: An optical encoder mounted on the shaft of the hydraulic motor provides feedback to the drive controller.
5. Steering limit switches: Limit switches are installed on the steering mechanism to signal an alarm if the wheels are cranked beyond acceptable limits.

5. Electrical System

All the electrical power needed by the NavLab is available onboard the vehicle. Electrical power can, however, be brought in from a shore power plug while the vehicle is in a fixed location. Power is distributed such that the generators are not needed to drive the NavLab manually.

5.1 AC Power

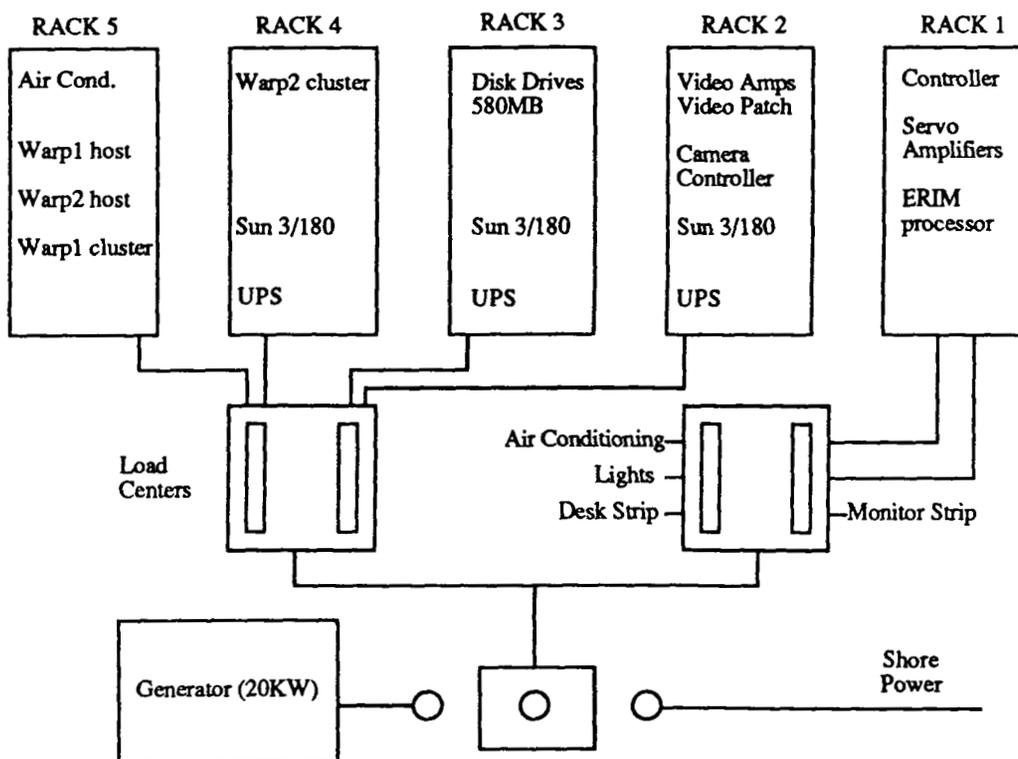


Figure 5-1: Wiring Schematic for AC Power

Figure 5-1 shows a schematic of the AC power system onboard the NavLab.

5.1.1 Generators

The generator supplies 100 VAC power to the variety of devices on the NavLab. The generator resides in a compartment accessible only from the outside of the vehicle, insuring the separation of noxious fumes from the interior.

Two compartments house an engine that is hydraulically coupled to a hydraulic generator unit in the forward compartment. This arrangement allows a single source of power up to 20 KW. Fuel to supply the engine comes from the vehicle fuel lines and the electrical power to start the generator is supplied by the vehicle 12 VDC system. The unit can be stopped and started by a panel switch.

5.1.2 Shore Power

The NavLab can plug into power from a building when stationary, alleviating constant generator operation. An extension cord from a nearby power outlet (220 VAC 50A) mates to a 220 VAC single-phase plug mounted in the outside center compartment.

5.1.3 Power Conditioning

Because variations in load and temperature affect generator power output, the power from the generators must be conditioned to protect sensitive machinery from spikes and brown-outs. This is done by passing power through Uninterruptable Power Supplies (UPS). These devices not only condition the power from the generators but also provide full-load backup for up to 15 minutes, even if the generators or shore power are shut down, allowing a graceful system shutdown if power fails. Three UPS devices provide a total of 6KW of conditioned power, which will more than suffice for a complete configuration of computing equipment. The lights, air conditioner, video monitors, and servo-amplifiers do not receive conditioned power because they are much less prone to fluctuations in generator output.

5.2 DC Power

Because many of the devices onboard use DC power, the standard vehicle 12 V system was extended by adding an extra battery and replacing the alternator with a dual output 120 amp unit that charges both batteries.

Figure 5-2 shows a wiring schematic for the DC power system. The original battery powers:

1. Vehicle ignition -- starting power for the engine;
2. Dash panel -- all switches on the dash panel;
3. Interior lights -- overhead lights in the research area;
4. Control electronics -- the input voltage to two power supplies. One converts the 12 V into -12 V and the other converts 12 V to 5 V. Each power supply has a limit of 3 amps.

The second battery provides:

1. starting power for the generators;
2. power for generator compartment lights;
3. power to run the hydraulic fluid cooler fan.

An additional 28V power supply is mounted in the equipment racks. This takes an input from the 110 AC system and produces up to 30 amps of current, most of which is used by an ERIM laser scanner. The inertial navigation device will operate on the same power supply.

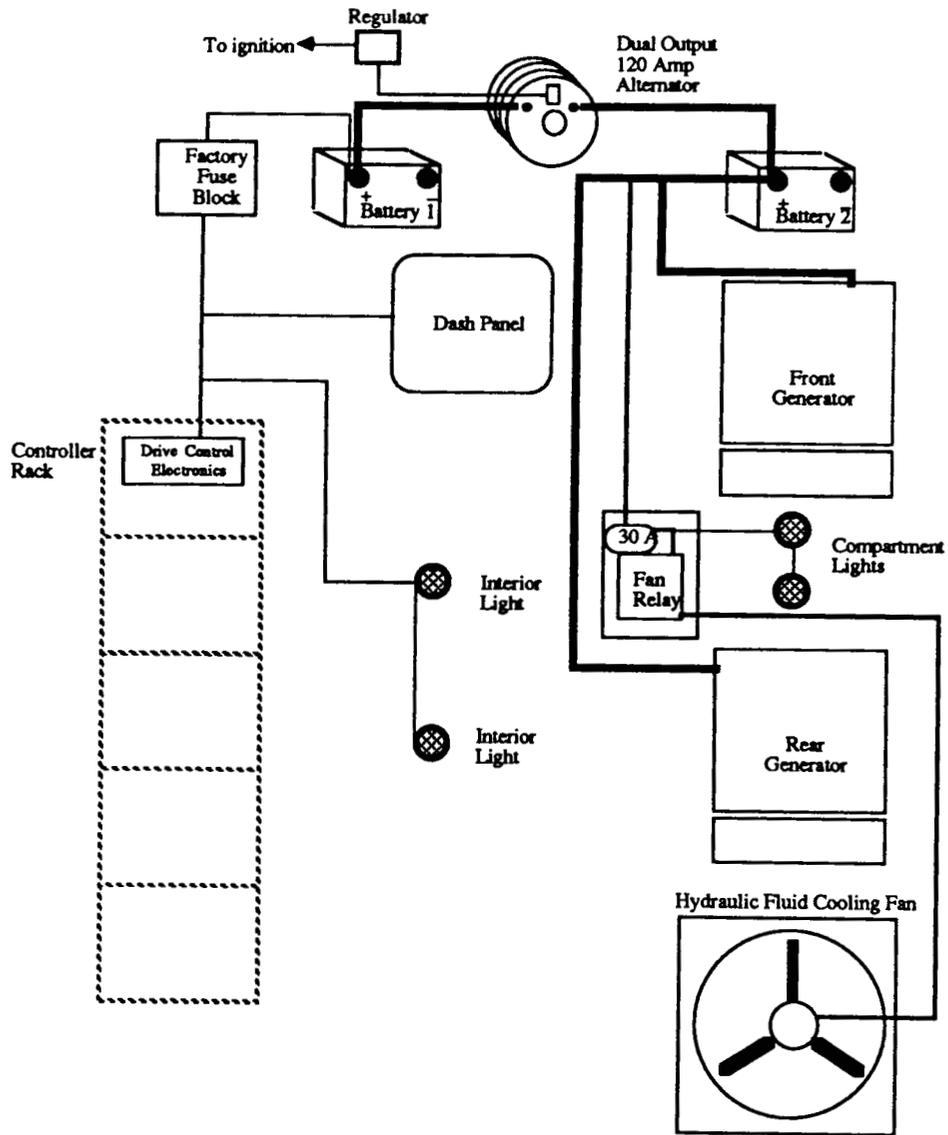


Figure 5-2: Wiring Schematic for DC Power

6. Telemetry

Telemetry to the vehicle was thought to be useful where environmental sensitivity, location, or size of computing equipment precludes installation onboard the NavLab. This feature has not yet found use in practice. NavLab telemetry provides control and monitoring from a remote site, allowing stationary computers to be used in navigation experiments.

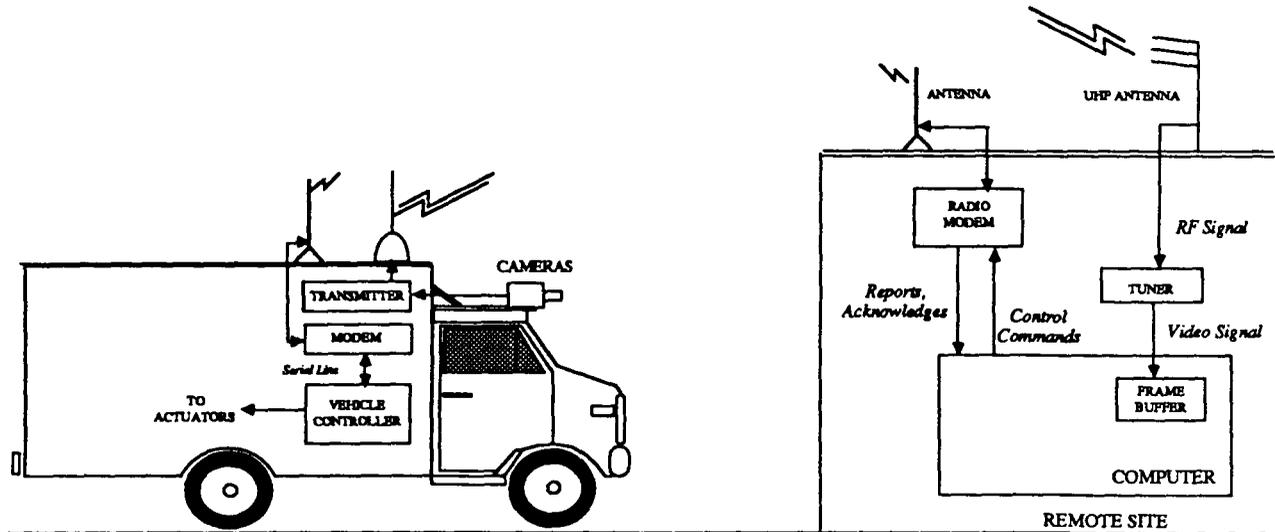


Figure 6-1: Telemetry Configuration of NavLab

The scenario in Figure 6-1 shows the closed loop set-up of a vehicle experiment where computing might be distributed offboard. The camera outputs a video signal that is broadcast over a UHF frequency and picked up by an antenna and receiver located on the Carnegie Mellon campus. The receiver provides the video signal to a frame buffer within the computer that processes the image. The signal is digitized and then analyzed. Commands to the vehicle are sent over a serial line to a wireless modem. A radio modem on the vehicle picks up this signal and feeds it to the controller.

6.1 High Bandwidth Transmission

An experimental radio license obtained from the FCC covers several broadcast frequencies. The license covers 2 UHF television channels, a full duplex radio link, and a 2 MHz microwave link.

The video signal is transmitted on the video transmitter while range data are transmitted over an aural sideband of one UHF channel. Because transmission rates can be as high as 56 K baud, the other aural sidebands not currently in use could serve several other data transmission needs.

6.2 Low Bandwidth Transmission

Two sets of 1200 baud radio modems are used for simple, low-bandwidth digital communication. These devices provide a transparent RS-232 connection between computers and facilitate sending commands to and from an offboard machine and the NavLab controller.

6.3 Cellular Phone

Separation of vehicle from stationary base facilities involves not only communication over distance for the machines but also for humans. For this reason, a cellular phone using existing mobile communications networks within the city has been installed.

7. Perceptive Sensing and Computing

A variety of sensors can be mounted on the NavLab depending on the type of research being conducted. Vision, laser ranging, and sonar ranging are the most popular sensing modes. More details of sensors and computing can be found in articles listed in Appendix V.

7.1 Video

Cameras provide a standard RS-170 video image to the frame buffer. Vision processing transforms this image into a scene description to support navigation.

Typically, a single camera mounted in the front of the vehicle provides a wide-angle view of the scene. Some vision algorithms, however, call for a stereo pair of cameras. Broadcast-quality cameras that provide red-green-blue color signals are used. Remote control units allow control over camera functions like gain, color balance, and iris size. Presently, camera focus and zoom must be controlled manually.

7.2 Laser Ranging

Laser ranging is useful in areas where vision algorithms fail -- in detecting depth discontinuities in scenes where the edges are not obvious and in those scenes that have uneven lighting because of shadows. Whereas the camera is a passive instrument, the laser rangefinder is an active device that emits a beam in a raster fashion and captures the reflection to provide two types of information -- distance and reflectance. The data are then analyzed to provide a scene description. Laser ranging provides a direct 3-D description of the scene while vision requires more expensive computation to extract this information. Range readings are particularly useful because they are not affected by ambient light.

The current laser ranging device, manufactured by ERIM, provides a 256x64x8 bit depth map. The scanner output is processed by a Motorola M68000 processor and sent to a Sun computer dedicated to ranging.

7.3 Pan and Tilt Mechanism

Vision and ranging sensors can be mounted in various configurations. Most configurations call for two independent pan motions -- one for the laser scanner and another for the cameras. Tilt is needed for both the laser scanner and cameras.

Pan and tilt design reflects a need to accurately position sensors over a large viewing range. Less than 4 seconds is required to view 180 degrees.

Cameras are mounted on rigid 5 cm diameter aluminum poles 2 meters long mounted horizontally through a worm drive gearset with a hollow bore. The gearset provides a 50:1 ratio and is driven by a DC brushed servo motor. An 800 line encoder provides feedback for the tilt motion.

7.4 Computing Configuration for Sensing

Figure 7-2 shows configuration of computing for simple, perceptive sensing. Much more complex setups are common. Each sensor commonly requires its own workstation or specialized processor. Another computer runs the blackboard system that integrates perception, modeling, and planning.

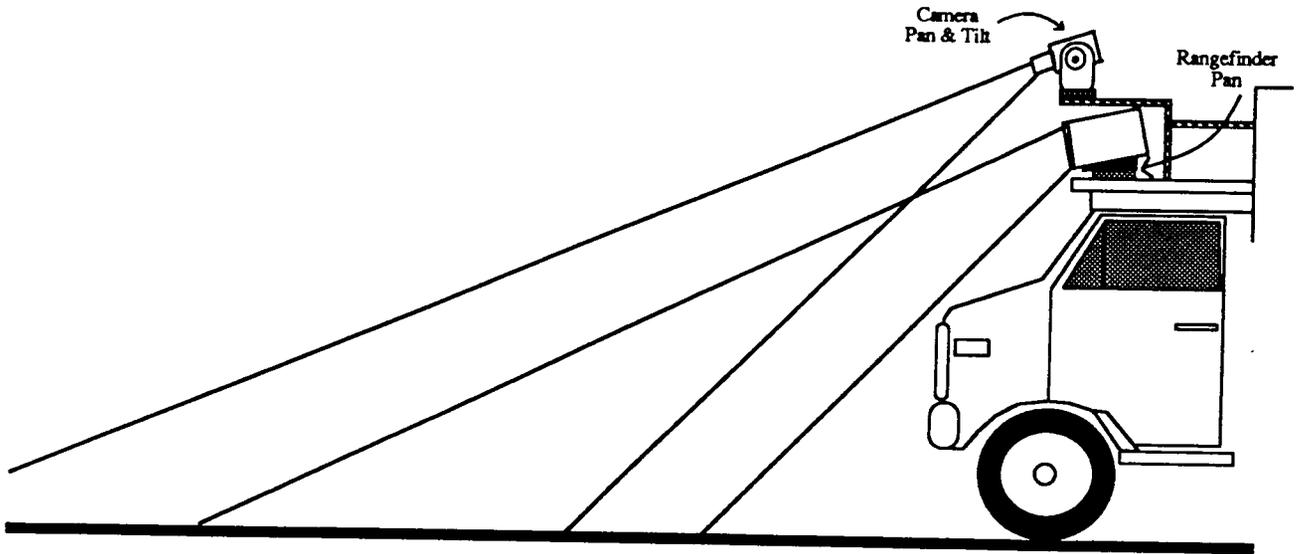


Figure 7-1: Pan and Tilt Mechanism

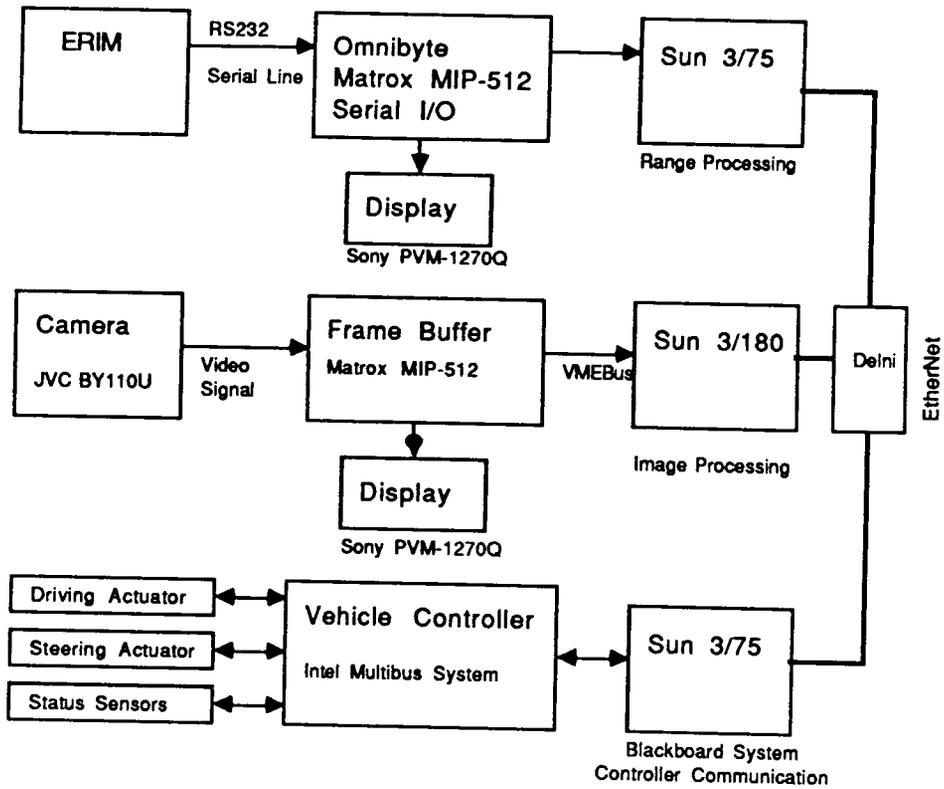


Figure 7-2: Typical Architecture

I. Modifications to Vehicle

The chassis was originally rated for 10,000 lbs. gross vehicle weight. The final vehicle weight was established as 12,000 lbs., thus necessitating a more robust suspension. In order to achieve the necessary load rating the front coil springs were upgraded and two extra leaves were added to the rear springs, increasing the gross vehicle weight by 2400 lbs. Heavy duty gas/oil shock absorbers were installed to minimize a slight tendency to pitch due to the extra weight. In addition, the original equipment tires were exchanged for Goodyear radials with a higher load and all-weather rating.

Modifications to the frame were minimized to preserve strength and stiffness. However, in order to mount some of the larger hydrostatic components alterations had to be made. The main forward crossbeam, transmission rear support beam and surrounding floor were completely removed. The crossbeam was replaced by a box section which bridges the hydrostatic pump. A channel section was added as support for the pump and also provides additional frame strength.

II. Power Budget

NavLab AC power requirements have risen steadily since the first integration to accommodate the WARP computing system, air conditioning, and uninterruptible power supplies (UPS). Power is currently provided by a 20.0 kW generator. The power budget is as follows:

| <u>CIRCUIT</u> | <u>PEAK AMP DRAW</u> | <u>PEAK WATTAGE</u> | <u>FUSE</u> |
|--------------------------------|----------------------|---------------------|-------------|
| <u>Main No. 1</u> | <u>90</u> | <u>10,000</u> | <u>100</u> |
| Coleman Air Conditioner | 17.5 | 1,930 | 20 |
| Lights (4 / 100 w) | 3.6 | 400 | 5 |
| Monitor Strip (5 / 80 w) | 3.6 | 400 | 5 |
| PMI Amplifier | 18.2 | 2,000 | 20 |
| Desk Strip (10 / 60 w) | 5.5 | 600 | 10 |
| Sola UPS (600 w output) | 7.0 | 750 | 10 |
| Intel Controller Computer | 11.4 | 1,250 | * |
| Behlman UPS (2000 w output) | 27.0 | 3,000 | 40 |
| Sun Vision Host Computer | 12.0 | 1,320 | * |
| Disk Drives | 6.3 | 700 | * |
| Development Circuit | 15.0 | 1,650 | 20 |
| <u>Main No. 2</u> | <u>90</u> | <u>10,000</u> | <u>100</u> |
| McLean Midwest Air Conditioner | 14.0 | 1,540 | 20 |
| Behlman UPS (2000 w output) | 27.0 | 3,000 | 40 |
| Sun WARP Host Computer | 12.0 | 1,320 | * |
| Disk Drives | 6.3 | 700 | * |
| VME WARP Control Cage | 9.0 | 1,000 | * |
| Behlman UPS (2000 w output) | 27.0 | 3,000 | 40 |
| WARP Power | 16.4 | 1,800 | * |
| Video | 4.5 | 500 | 5 |
| Erim Laser Scanner | 2.7 | 300 | 5 |
| Development Circuit | 15.0 | 1,650 | 20 |

III. Weight and Center of Gravity Budget

Location in (x,y) is given with left (driver's side) rear corner as the origin. Positive y is toward the cab, positive x toward the passenger side. The shell is 241cm wide (x) and 343cm long (y).

| <u>Item:</u> | <u>Location (cm, cm)</u> | <u>Weight (kg)</u> |
|---------------------------------------|--------------------------|--------------------|
| Driver | 63, 368 | 79.4 |
| Passenger | 152, 368 | 79.4 |
| Empty Rack & 10kg hardware | 51, 34 | 81.6 |
| | 51, 103 | 81.6 |
| | 51, 171 | 81.6 |
| | 51, 240 | 81.6 |
| | 51, 309 | 81.6 |
| Signal Wiring | | 22.7 |
| Power Wiring | | 45.4 |
| Insulation | | 13.6 |
| <u>Passenger side</u> | | |
| Generator | 203, 58 | 117.9 |
| | 203, 285 | 117.9 |
| Air Conditioner | 117, 200 | 52.2 |
| Power Conditioner | 224, 171 | 100.7 |
| Breaker Panel | 201, 8 | 18.1 |
| Table Top | 201, 171 | 31.8 |
| Monitor Shelf | 216, 170 | 2.3 |
| Sony Monitors | 208, 279 | 14.1 |
| | 208, 165 | 14.1 |
| Seat | 132, 157 | 18.1 |
| Operator | 132, 157 | 68.0 |
| Terminals | | |
| Sun | 201, 216 | 27.2 |
| Wyse | 201, 102 | 6.8 |
| Marlite | | |
| back wall | 122, 0 | 9.5 |
| left | 0, 171 | 26.3 |
| right | 241, 171 | 11.8 |
| front | 122, 343 | 5.0 |
| Gas Tank | 135, 97 | 119.7 |
| Shore Power Switch | 198, 135 | 18.1 |
| | 198, 183 | 18.1 |
| Shore Power Plug | 198, 152 | 2.3 |
| Track Lights | 185, 178 | 4.5 |
| <u>Hydraulic Equipment:</u> | | |
| Funk | 109, 287 | 124.7 |
| Reservoir | 201, 272 | 136.0 |
| Sunstrand Pump | 122, 373 | 132.9 |
| Sunstrand Motor | 89, 330 | 74.4 |
| Pall Filter | 51, 333 | 11.3 |
| Dowty Tandem Pump & Charge Pump Motor | 135, 203 | 5.9 |
| Heat Exchanger & Fan | 53, 51 | 24.9 |

| | | |
|-----------------------|-------------------|-------------|
| <u>Rack 1:</u> | | |
| | UPS | 54.4 |
| | 2 Amplifiers, | |
| | 1 Transformer, | |
| | 3 Power Supplies | 52.2 |
| | Intel Chassis | 24.9 |
| | Patch Panel & | |
| | Control Circuitry | 9.1 |
| | Tables | <u>11.3</u> |
| Total | 42,287 | 152.0 |
| <u>Rack 2:</u> | | |
| | Video | 22.7 |
| | ERIM Power Supply | <u>24.0</u> |
| Total | 42,226 | 46.7 |
| <u>Rack 3:</u> | | |
| | Sun | 68.0 |
| | UPS | <u>54.4</u> |
| Total | 42,165 | 122.5 |
| <u>Rack 4:</u> | | |
| | Sun | <u>68.0</u> |
| Total | 42,104 | 68.0 |
| <u>Rack 5:</u> | | |
| | Empty | |
| Total | 42, 43 | 0.0 |
| <u>Pan & Tilt</u> | | |
| | 2 1135 Motors | 8.9 |
| | 2 Turntables | 26.3 |
| | 1 Tilt Gearing | 22.7 |
| | 1 Aluminum Rod | 4.5 |
| | 2 JVC's | 5.0 |
| | ERIM | 34.0 |
| | PMI motor | 4.5 |
| | 56 C Coupling | 4.5 |
| | Bracketing | |
| | lower mount | 18.1 |
| | upper mount | <u>45.4</u> |
| Total | 121,447 | 174.0 |
| <u>Shell</u> | <u>121,171</u> | <u>1153</u> |
| <u>Van Body</u> | | |
| | front axle | 101,427 |
| | rear axle | 101,109 |
| | | 1120 |
| | | 649 |

Overall:

Center of Gravity: 112,244

Weight Total: 5449kg

IV. Implementation of the Virtual Vehicle Instruction Set

Protocol

A simple high-level handshaking protocol has been designed for RS-232 communication between the Virtual Vehicle and any host computer issuing commands to the vehicle. It provides a means of exchanging commands and status information with a reasonable level of reliability and optional error recovery. The motivation for this is that errors in communication should be detected and acted upon without interfering with normal operations of host or Virtual Vehicle. By adhering more or less strictly to the protocol, the relative importance and subsequent computational overhead of error-free communication can be chosen at will and may be varied dynamically.

Messages between Virtual Vehicle and host are of the following form:

```
<length><packet ID><opcode>[<argument 1>/../<argument n>/]<CR>
```

The individual fields of a packet are defined as follows:

| | |
|--------------------------|--|
| <length> | 2 characters wide. Contains the total number of ASCII characters in the packet, including the length field itself. Length is represented in decimal, so messages are limited to 99 characters. |
| <packet ID> | 3 characters wide. Unique identifier to be used as reference to the packet in subsequent protocol transactions. Can be any combination of printable ASCII characters (20H - 7FH), although numeric values (30H through 39H) will be used most frequently. See description below for usage and purpose of this field. |
| <opcode> | 2 characters wide. Represents, in decimal, the numeric index of the command to be acted upon by the Virtual Vehicle. This implies a range of 0 through 99 for possible opcodes. |
| <arguments> | Zero or more numeric arguments, of variable width. Arguments are terminated by a slash ("/"). Leading zeroes are allowed. All arguments must be integer values. |
| <CR> | Carriage Return (0DH) character indicates end-of-packet. Must follow immediately after the last argument-terminating slash, or after the opcode in the case of zero arguments. The <CR> is NOT considered part of the packet, so it is not included in the <length> field. |

The following rules define the handshake between two devices. They should be followed closely to achieve maximum communication reliability. However, as is indicated in the appropriate paragraphs, error checking is done at the discretion of the receiving device.

- For every packet to be sent, the sending device generates a unique 3-character packet ID code. This can be done, for example, by incrementally numbering packets or by encoding the current system time. Random generation of codes is discouraged, since this theoretically allows duplicate packet ID's. Using the full range of 96 symbols in each of the 3 character positions yields a range of 884,736 unique ID codes, which is in excess of the anticipated number of messages exchanged during a typical mission of the Virtual Vehicle.
- Packets are prefixed with the length of the packet and terminated by the end-of-packet character <CR>. The receiving device should check the actual length of the received packet against the <length> field to ensure integrity of each packet.
- Each packet received may be further validated by ensuring that
 - the opcode is valid,
 - the number of arguments is correct for the given opcode, and
 - the arguments are within allowable limits. These limits may change dynamically as a

function of, for example, vehicle speed or road conditions.

- If none of the above error conditions are detected, the receiving device returns an ACK message to the sender, indicating that the message was received correctly and the appropriate action, if any, is being performed. The ACK message uses the *same* packet ID as that of the message being acknowledged.
- In case of an error, the receiving device must return a NAK message to the sender to indicate that the packet was rejected and no command is being executed. As its only argument, the NAK message contains an error code indicating the reason for rejecting the packet. A NAK message also has the same packet ID code as the message in question.
- Upon receiving a NAK as reply to a message, a device has the option of retransmitting the offending message (with new packet ID), logging the error, ignoring it, or taking any other action that might be appropriate. By the same token, while expecting a NAK or ACK in response to a transmitted message, a device may choose to time out, wait forever, or take other appropriate action. These conventions provide for very flexible operation that allows critical system operations to continue even in case of protocol errors. In dealing with these situations, the Virtual Vehicle will adhere to the following conventions:
 - NAK or ACK messages are *always* generated and sent in response to data messages received by the VVI. At this point, handshake for the current message is considered complete; i.e., no further action is *expected*.
 - Unexpected NAK or ACK messages (i.e., those referring to an unknown or previously acknowledged packet ID) are ignored. However, the error *is* logged and/or announced at the VV system console.
 - If a NAK is received as response to a message originated by the VV, the message may or may not be retransmitted repeatedly (with a new packet ID), depending on the type of message and reason for rejection.
 - If neither NAK nor ACK is received by the VV within a certain timeout period (configurable parameter, typically on the order of seconds), the error condition is logged and/or announced at the VV system console. After this, the VV still expects a response to the packet in question, but no further action is taken and subsequent messages are treated as if no error had occurred.

Commands issued by Host/Console

| Mnemonic | Opcode | Meaning | Arguments |
|----------|--------|----------------------|---|
| NAK | 00 | Negative Acknowledge | cc/ cc= 00 : Packet length error 01 : Num. of Args error 02 : Not ready for cmd 03 : Illegal Opcode 1X : X'th argument below current minimum limit (1 < X < 9) 2X = X'th argument above current maximum limit (1 < X < 9) |
| ACK | 01 | Acknowledge | |
| ABO | 02 | Abort Motion | |
| STO | 03 | Stop/Suspend Motion | |
| STA | 04 | Startup | |
| TRA | 05 | Travel | l/r/i/ l : arc length r : radius of curv. i : 1 = immediate |

| | | | |
|-----|----|----------------------|--|
| CHP | 06 | Change Position | x/y/h/ x : Δ x pos. y : Δ y pos. h : Δ heading |
| STM | 11 | Set time to zero | |
| SVL | 12 | Set Velocity | v/i/ v : velocity i : 1 = immediate |
| SAC | 13 | Set Acceleration | a/i/ a : acceleration i : 1 = immediate |
| SP1 | 14 | Set Pan 1 | p/ p : pan angle |
| ST1 | 15 | Set Tilt 1 | t/ t : tilt angle |
| SP2 | 16 | Set Pan 2 | p/ p : pan angle |
| ST1 | 17 | Set Tilt 2 | t/ t : tilt angle |
| SSR | 18 | Set Steering Rate | s/ s : steering rate (0-99 %) |
| INF | 21 | Get Vehicle Info | |
| POS | 22 | Get position | |
| TIM | 23 | Get Vehicle Time | |
| VEL | 24 | Get Vehicle Velocity | |
| ACC | 25 | Get Vehicle Acc. | |
| PN1 | 26 | Get Pan Angle 1 | |
| TL1 | 27 | Get Tilt Angle 1 | |
| PN2 | 28 | Get Pan Angle 2 | |
| TL1 | 29 | Get Tilt Angle 2 | |
| STR | 30 | Get Steering Rate | |
| ROL | 31 | Get Roll | |
| RLR | 32 | Get Roll Rate | |
| PIT | 33 | Get Pitch | |
| PTR | 34 | Get Pitch Rate | |
| HDR | 35 | Get Heading Rate | |
| REP | 36 | Get Status | d/ d : device number |

Responses from Virtual Vehicle

| Mnemonic | Opcode | Meaning | Arguments |
|----------|--------|----------------------|---|
| NAK | 00 | Negative Acknowledge | cc/ cc= 00 : Packet length error 01 : Num. of Args error 02 : Not ready for cmd 03 : Illegal Opcode 1X : X'th argument below current minimum limit (1 < X < 9) 2X = X'th argument above current maximum limit (1 < X < 9) |
| ACK | 01 | Acknowledge | |
| RVI | 51 | Vehicle Info | l/w/h/g/m/x/y/s/ |

| | | | |
|-----|----|------------------|--|
| | | | l : length |
| | | | w : width |
| | | | h : height |
| | | | g : weight |
| | | | m : minimum turning radius |
| | | | x : X of C.G |
| | | | y : Y of C.G |
| | | | s : 0 = wheel steer |
| | | | 1 = skid steer |
| RVP | 52 | Vehicle position | x/y/h/t/ x : x position y : y position h : heading t : time |
| RVT | 53 | Vehicle Time | t/ |
| RVV | 54 | Vehicle Vel. | v/t/ |
| RVA | 55 | Vehicle Acc. | a/t/ |
| RP1 | 56 | Pan angle 1 | p/t/ |
| RT1 | 57 | Tilt Angle 1 | t/t/ |
| RP2 | 58 | Pan angle 2 | p/t/ |
| RT2 | 59 | Tilt Angle 2 | t/t/ |
| RSR | 60 | Steering Rate | s/t/ |
| RRL | 61 | Roll | r/t/ |
| RRR | 62 | Roll Rate | r/t/ |
| RPT | 63 | Pitch | p/t/ |
| RPR | 64 | Pitch Rate | p/t/ |
| RHR | 65 | Heading Rate | h/t/ |
| RST | 66 | Report Status | d/s/t/ d : device number s : status code |
| ADN | 80 | Arcdone | id/x/y/h/t/ id : arc ID code x,y : Pos. at end of arc h : heading at end of arc t : time at end of arc |

Note: All distance units are cm, time units are msec, velocity units are cm/s, acceleration units are cm/s² and angle units are half degrees. Weight units are kilograms.

V. References

- Goto, Y. and A. Stentz. "The CMU System for Mobile Robot Navigation," in *IEEE International Conference on Robotics and Automation*, 1987.
- Hebert, M. and T Kanade. "Outdoor Scene Analysis Using Range Data," in *IEEE International Conference on Robotics and Automation*, 1986.
- Kanade, T., C. Thorpe, and W. Whittaker. "Autonomous Land Vehicle Project at CMU," in *ACM Computer Conference*, February 1986.
- Kanade, T. and C. Thorpe. *CMU Strategic Computing Vision Project Report: 1984 - 1985*, Technical Report, The Robotics Institute, Carnegie Mellon University, 1985.
- Krogh, B. and C. Thorpe. "Integrated Path Planning and Dynamic Steering Control for Autonomous Vehicles," in *IEEE International Conference on Robotics and Automation*, 1986.
- Shafer, S., A Stentz, and C. Thorpe. "An Architecture for Sensor Fusion in a Mobile Robot," in *IEEE International Conference on Robotics and Automation*, 1986.
- Thorpe, C. *1986 Year End Report for Road Following at Carnegie Mellon*, Technical Report, The Robotics Institute, Carnegie Mellon University, 1986.
- Wallace, R., A. Stentz, C. Thorpe, C. Moravec, W. Whittaker, and T. Kanade. "First Results in Robot Road-Following," in *International Joint Conference on Artificial Intelligence*, 1985.
- Wallace, R., K. Matsuzaki, Y. Goto, J. Crisman, J. Webb, and T. Kanade. "Progress in Robot Road-Following," in *IEEE International Conference on Robotics and Automation*, 1986.