Design of a Wireless Control System for a Laboratory Planetary Rover

by

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Submitted to the
Department of Mechanical Engineering
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Abstract

A wireless control system was designed for an experimental test bed Mars rover in the MIT Department of Mechanical Engineering Field and Space Robotics Laboratory. The wireless rover system contains the rover's control and power systems on-board. It is based on a PC/104 computer, uses several different I/O modules, and is powered by nickel cadmium batteries. The system controls 12 motors via pulse width modulation, reads four encoders and six tachometers, and uses a six axis force-torque sensor. The system is designed to be modular and is highly upgradable and expandable.

Thesis Supervisor: Dr. Steven Dubowsky

Professor of Mechanical Engineering

Acknowledgements

First I would like to thank Dr. Steven Dubowsky for giving me the opportunity, trust, and freedom to work on a project of this magnitude. The Field and Space Robotics Laboratory has taught me a great deal and has served as my test ground for taking the knowledge gained in class and applying it to a real problem. I would also like to thank NASA and JPL for their support of my work on this project.

Working in the lab I've had wonderful colleagues who deserve a great deal of thanks, including Robert Burn, Shane Farritor, Herve Hacot, Karl Iagnemma, Peter Jaffe, Alvaro Rodriguez, and Vivek Sujan. Special thanks goes to Hisamitsu Kozono without whom I would still be trying to figure out how to write code for the rover's controller.

Thanks goes to my family for always being curious about my work and to my friends for giving me help when I needed it. Particularly, thanks to Kevin McCormick for teaching me how to make printed circuit boards and to Jascha Franklin-Hodge for helping to get the PC/104 up and running. Finally, I would not have been able to make it through MIT without Christy Canida; thanks goes to her for everything.

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Chapter 1 Introduction

1.1 Motivation

There has been much scientific excitement recently about the possibility of life existing or having existed on Mars. A meteorite found on Antarctica in 1993, dubbed “Allen Hills 84001,” appeared to both be of Martian origin and contain chemical traces which may have been the remains of organic life (McKay, 1996). This discovery renewed interest in the possibility of finding life on Mars to a level not seen since the Viking missions in the late 1970’s. Finding evidence of life on another planet would be a monumental discovery.

What is the best way to explore Mars? Current technology makes a manned mission to Mars largely impractical due to the prohibitive cost and inherent dangers. With current technological limitations, robots provide the most feasible, reliable, and safe way to explore Mars. The overwhelming success of the Sojourner mission in 1997, both technically and in terms of popular support, and the National Aeronautics and Space Association’s (NASA) plan for robotic missions to Mars every two years into the next century show that robots are and will be the paradigm for planetary exploration for some time (Hayati, 1997).

However, much of the technology for robotic exploration of Mars does not yet exist. The Sojourner mission successfully used a rover for some limited exploration, but future robots, be they explorers or workers, will need to work faster, perform a greater number of increasingly difficult tasks, and travel larger distances all with a very high degree of autonomy.

In order to design these newer more advanced robotic systems for planetary exploration, they need to be first modeled and tested on earth. The Field and Space Robotics Laboratory (FSRL) at the Massachusetts Institute of Technology is working on several problems relating to robotic exploration of space. A model Mars rover, based on the Jet Propulsion Laboratory's Light Weight Survivable Rover (LSR shown in Figure 1.1, FSRL version 1 rover shown in Figure 1.1, and FSRL version 2 shown in Figure 1.3) has been designed and built in the FSRL. The FSRL rover has been used to study such things as local path planning, soil tire interaction, and the implementation of a smart traction control scheme using fuzzy logic (Hacot 1998, Burn 1998).

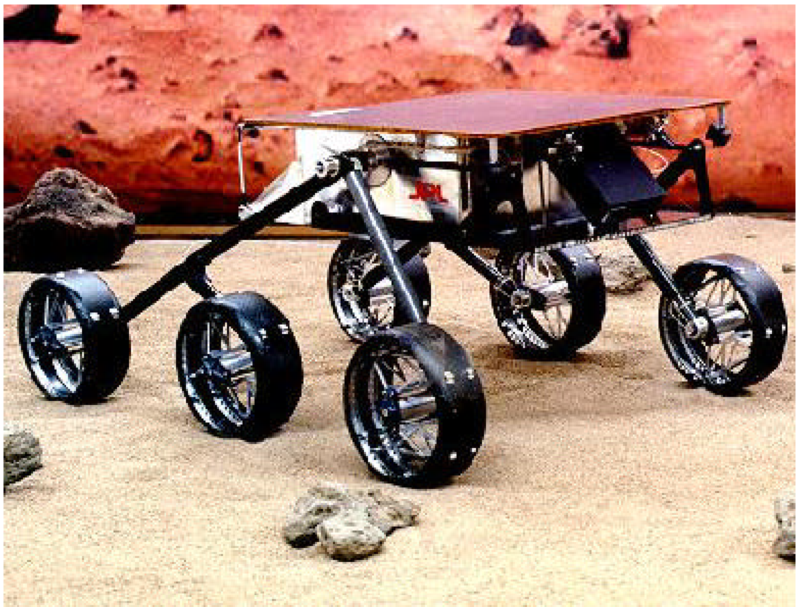

Figure 1.1 JPL's LSR (Schenker, 1997)

Prior to this work, the FSRL rover has undergone two iterations, Mod 1 and Mod 2. The Mod 1 rover was a six wheeled rocker bogie configuration tethered vehicle and is shown in Figure 1.2. Mod 1 contained a small aluminum body and six independently actuated drive wheels controlled by a desktop computer and large set of linear amplifiers.

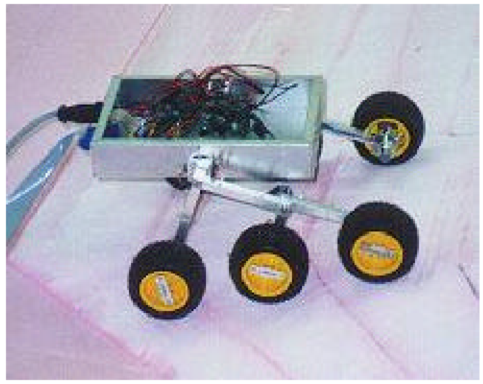

Figure 1.2 Mod 1

The Mod 2 rover built upon Mod 1 by adding a three degree of freedom arm that uses one of two end-effectors, which were designed specifically for the system. Mod 2 was also tethered to the computer for power and control, and contained only very minimal signal conditioning circuitry on board (Burn, 1998).

In using Mod 2 for research, the tether proved to be a major drawback of the system. The tether puts an absolute maximum range on Mod 2's position and prevents it from making any sharp turns or backing up without human intervention. The tether also drags on the ground and imparts forces on the rover, changing its dynamics. Hence a wireless solution is required.

Without a tether the FSRL rover would not only be more conducive to research, but the computer simulations and the actual performance of the vehicle would display a greater degree of correlation. Modeling the forces from the tether is very difficult, and an experiment typically endeavors to eliminate the forces from the tether altogether. The

Mod 2 tether was thick, and in fact several meters of the tether was equivalent in mass to the rover itself.

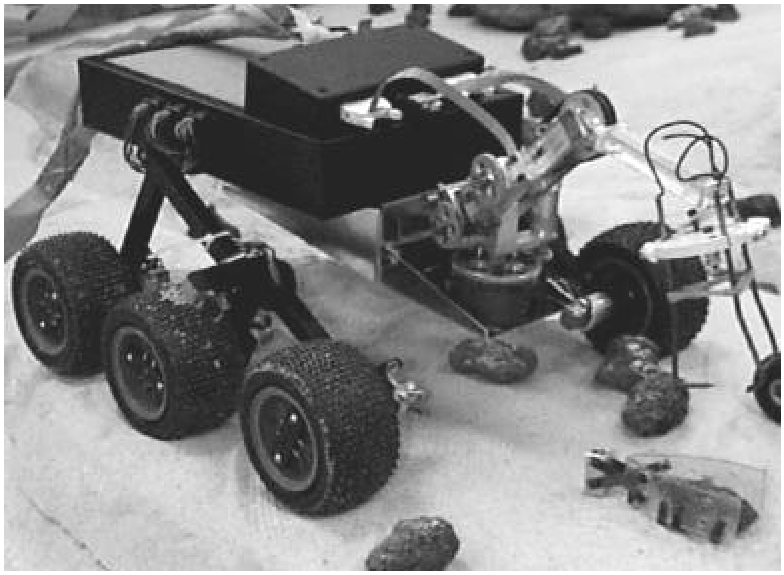

Figure 1.3 FSRL Mod 2 rover (Burn, 1998)

A wireless rover also allows for experiments that are more compatible with those being performed with different planetary exploration test beds (Volpe, 1996, Schenker, 1997). Without wires it is possible to take the FSRL rover out of the lab for rough terrain testing.

Another drawback of the Mod 2 rover was the limited number of channels. The tether to the lab computer could only power the drive wheels or the arm. Both systems could not be used simultaneously.

A tetherless system is generally more suited to the studies desired by the FSRL. Moving base manipulator control, soil tire interaction, and local path planning are all more appropriately studied on a wireless system than on the tethered Mod 2 rover.

1.2 Approach

The Mod 3 Wireless Rover System (WRS) was designed given various constraints and functional requirements which will be described in detail in Chapter 2. A goal of the design was to maintain compatibility with the Eldercare Personal Aid for Mobility and Monitoring (PAMM) project within the FSRL, which is very similar in scope and hardware the to WRS (Kozono, 1998). The PAMM project is a device designed to assist the elderly on several levels, ranging from complete guidance and navigation to use as a simple walking aid. Keeping the two projects compatible was desirable for a number of reasons. The development of drivers and low level control need only be done once, and the hardware itself could be shared.

Working within the constraints described later and towards the goal of the compatibility, the approach was to determine the range of available and suitable components and weigh their costs and benefits. Selection charts, which quantify and compare the various attributes of a certain system, were used extensively.

1.3 Summary of Results

Table 1.1 shows the quantitative results of the Wireless Rover System (WRS) and Figure 1.4 shows a picture of the WRS. Figure 1.5 shows a block diagram of the desired subsystems and interaction for the WRS.

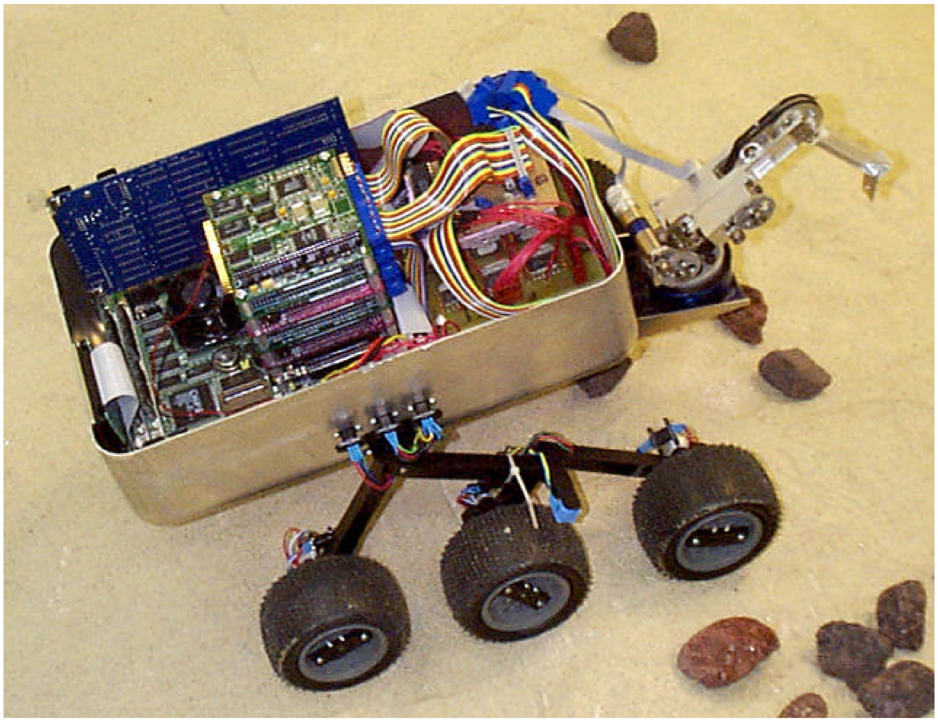

Figure 1.4 The Wireless rover system

Table 1.1 Quantitative results and desired values of the WRS

Metric	**Obtained result**	**Desired value**
Speed	78 mm/s	80 mm/s
Angular speed	1.75 rad/s	Unspecified
Mass	5.98 kg	< 6.1 kg
Power consumption	25 watts	low power
Sampling frequency	93 Hz	100 Hz
Battery time before recharge	31 minutes	≥ 30 minutes
PWM motor control capacity	12	≥ 9
Number of encoders read	4	≥ 3
Wireless communication range	3 m	Large enough for use in FSRL Mars yard
Wireless communication data rate	9600 baud	High level planning control
Processor	486 DX2 66MHz, 1 MFLOPS	At least 500,000 FLOPS
RAM	32 MB	Unspecified
Hard drive capacity	1.4 GB	Unspecified
Cost	$5868.8	< $10,000

This thesis is divided into six chapters and twelve appendices. Chapter 2 discusses the definitions of the system's functional requirements and the selections of components. Chapter 3 describes components in the system and their interconnections. Chapter 4 explains the software used in testing the control system of the WRS. Chapter 5 gives notes on using and expanding the WRS, and chapter 6 presents conclusions and future work. The appendices give specific details about various aspects of the system.

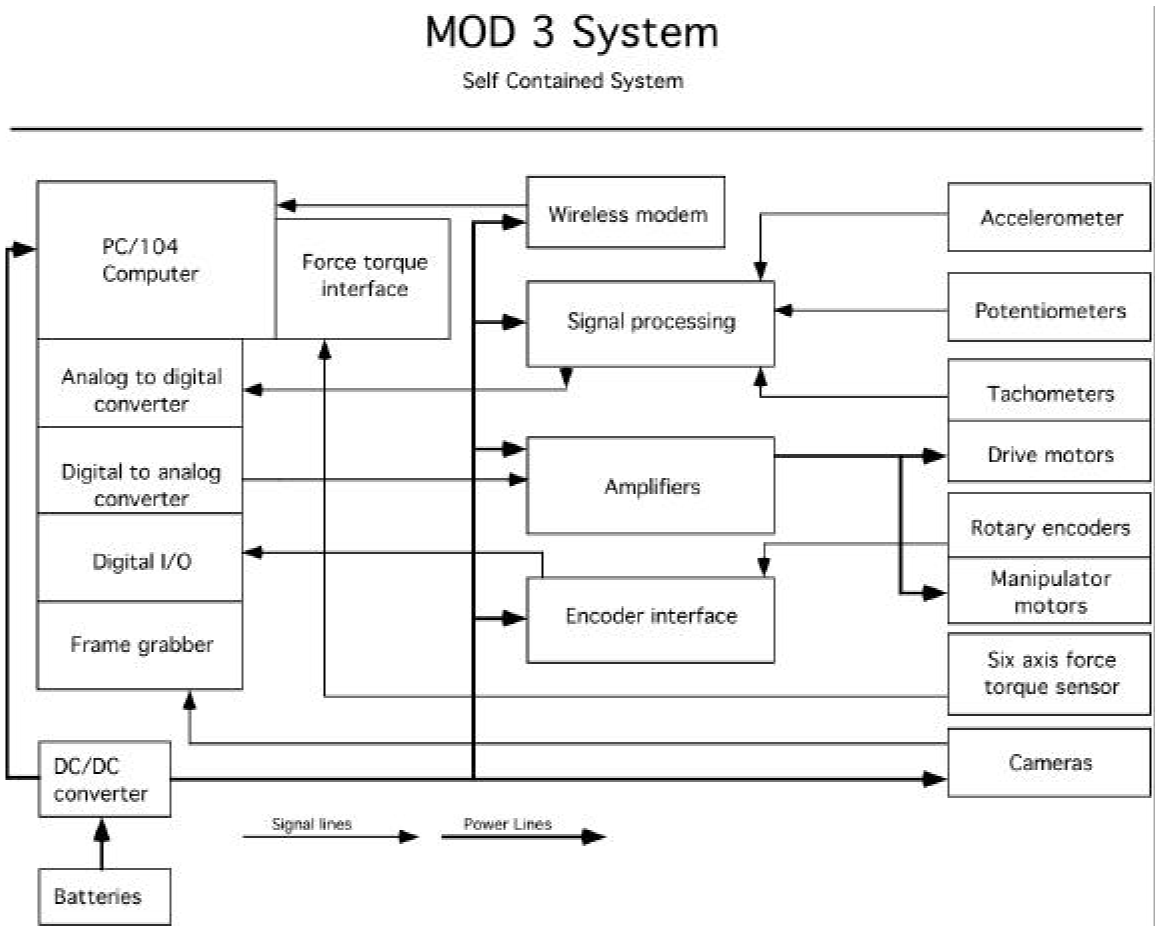

Figure 1.5 Block diagram of the initial Mod 3 design

Chapter 2   System Conceptual Design

The conceptual design of the wireless rover system endeavored to examine all of the available alternatives and meet the functional requirements with the best selection. The requirements of the wireless rover system are given in Section 2.1, and the alternatives and selection are presented together in Section 2.2.

2.1   Requirements

The functional requirements were defined by determining what the system needs to meet the ultimate goal of operating without a tether. In order to make a robotic system wireless, aspects such as size, weight, power consumption, and functionality need to be addressed. Coupling component selection with the constraints of limited time, budget, and manpower lead to the functional requirements. Table 2.1 shows the functional requirements.

Table 2.1 Functional Requirements of Mod 3, wireless rover system.

Functional Requirement	Design Parameter
Use Mod 2 rover	Control and power systems must fit in a 350mm x 200mm x 180mm volume, with mass less than 6.1 kg
Budget	Cost <$10,000
Control 12 motors	12 channels of D/A converters, suitable amplifiers, enough A/D and digital I/O channels to read tachometers and encoders
Interface with force torque sensor	PC or VME computer platform
Computational power	Processor equivalent to at least 486 with math co-processor
Communication	Wirelessly communicate with another computer for high level planning control
30 minute wireless runtime	Low power draw

The requirements of the system involve such metrics as functionality, size, mass, power consumption, cost, computational power, and freedom for later expansion. The primary functional requirement of the system was to operate without a tether using the Mod 2 iteration of the FSRL rover (Burn 1998, Hacot 1998). From this initial requirement stem a set of budgetary and time requirements and several other functional requirements which are best divided into two categories, mechanical and electrical. Each of these types of requirements are discussed separately.

2.1.1 Budgetary and Time Requirements

The wireless system must be designed and built within a limited time span and budget. The budget of the project including the Mod 2 system, is approximately $10,000, and it needs to be completed in a time span of roughly four months.

To satisfy the logistical requirements, much of the WRS utilizes commercially available off the shelf parts (COTS). Not enough time exists to design and build entirely custom parts for the WRS. Although interfacing commercial parts is quick, they tend to be more costly than custom built solutions, ignoring labor costs. Meeting the budgetary and time requirements necessitated finding a balance.

2.1.2 Mechanical Requirements

The mechanical requirements dictate things such as the size and weight of the system. The mass of the electronics must be less than 2.6 kg keeping the mass of the complete rover under 6.1 kg. The electronics must also be contained within a volume able to fit on the Mod 2 chassis.

All of the control and power systems need to fit inside a volume of nearly 0.01 m^3, which is a design parameter set by the central frame size of the Mod 2 rover, shown in Figure 2.1. The six wheels of the rover are mounted directly to the gearhead shafts of the drive motors, which sets the maximum weight of the rover. The loads on each gearhead are limited to 20N, 8mm from the mounting face (Figure 2.2). Assuming a steady state, kinematically stable condition of three of the six wheels supporting the entire mass, the maximum mass of the complete wireless rover system is 6.1 kg.

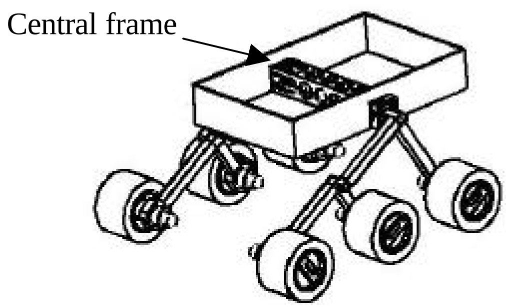

Figure 2.1 Mod 1 Rover showing central frame. (Burn, 1998)

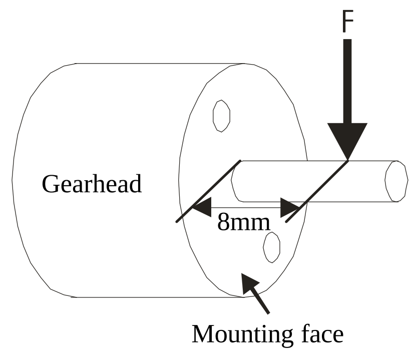

Figure 2.2 Force on the drive motor gearhead shaft.

2.1.3 Electrical Requirements

The electrical requirements comprise such things as control voltages and currents of the drive motors, sensory inputs, power, and computational speed. The electrical requirements are drawn largely from the necessary functions of the WRS: control of several motors, reading data from a number of sources, and processing all the information in real time.

The processor must be computationally powerful enough to control the wireless system in real time. A typical scenario might include sampling the various sensors at a frequency of 100 Hz, implementing a classic or innovative scheme for control of the several motors, communicating via wireless modem with a host computer, and planning a path based on information determined visually or otherwise. The base requirement to achieve this level of computation can be found be assuming a set operations which need to be computed per unit time and comparing this with the operations per second of a processor. Assume a proportional integral control scheme of the type,

$$error = desired - actual\,, \tag{1}$$

$$command = K_p error[n] + K_i error[n-1]\,, \tag{2}$$

where n is the sample number and K_p and K_i are constant gains. Calculating the command signal will require 8 floating point operations, where addition is defined as one floating point operation and multiplication is three floating point operations (Sujan, 1998). Assume that every cycle a command signal is calculated for six motors, which leads to 48 floating point operations per cycle. A cycle time of 0.1 milliseconds is reasonable for so few calculations which leads to 480,000 floating point operations per second (FLOPS)[1]. A 486 DX/2 33Mhz is rated at approximately 500,000 FLOPS and is thus the minimum computational requirement (Dongarra, 1994).

The WRS needs at least 12 digital to analog converters (D/A’s). The Mod 2 rover has 9 DC motors, 6 for the drive wheels and 3 for the arm. However, the control system should control at least 12 motors, allowing either the arm to be expanded into a 6 degree of freedom manipulator or for motors to be used in a manipulated vision system. Controlling 12 motors sets a requirement for 12 channels of D/A’s.

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[1] Only the command signal is calculated every 0.1 milliseconds. Communications, sampling sensors not associated with the command signal, and other functions would be sampled or calculated at a much slower frequency, in this case approximately 100 Hz.

The WRS needs at least 6 differential and 7 single ended analog to digital converters (A/D's). The wireless rover system has several analog sensors. The six drive motors have integral tachometers which each require a differential input. There are four potentiometers that are used to measure the angles of the bogies and the rockers with respect to the body and require four single ended inputs. A three axis accelerometer is used to measure the rover's position with respect to a gravity vector, which needs three single ended inputs; one for each orthogonal direction. The minimum number of A/D channels must be at least 6 differential and 7 single ended channels.

In addition to analog feedback, the wireless rover system needs to read information from encoders. The system needs to be able to read data from at least 3 encoders simultaneously and be expandable. Only the three joints of the manipulator have encoders, but in future versions all the motors may use encoders.

A specific force torque base sensor (discussed in Section 3.5.1) is to be used in the WRS system. The sensor is placed under the base of the arm and uses a receiver board to decouple and process the force and torque signals. The receiver is available only in ISA or VME bus formats, so the computer platform of the rover must have either a VME or ISA bus.

The system must be able to run completely wireless for a minimum of 30 minutes. This requirement coupled with the maximum mass of the wireless system, implying a maximum battery mass, sets the limiting power draw of the system.

2.2 Alternatives and Selection

The alternatives for the wireless rover system are all coupled in some fashion. The number of possible combinations of alternatives is too large to effectively describe all of them in any detail, so the alternatives at each step in the design are depicted followed by a discussion of the final selection made. The discussion begins with the selection at the highest level in the design, the computing architecture.

2.2.1 Computing structure

The computing alternatives are shown as a flow chart in Figure 2.3. From the VME or ISA bus and volume requirements, three general types of computing architectures emerge: a VME based back plane, PC/104 embedded computer, or a PC based back plane. All three can be purchased as fully featured computers packaged into single board configurations and are typically used in industrial, factory floor, and field applications (i.e. vending machines, computer controlled mills and lathes, military computers). No desktop type computers are considered because they do not meet the size requirement.

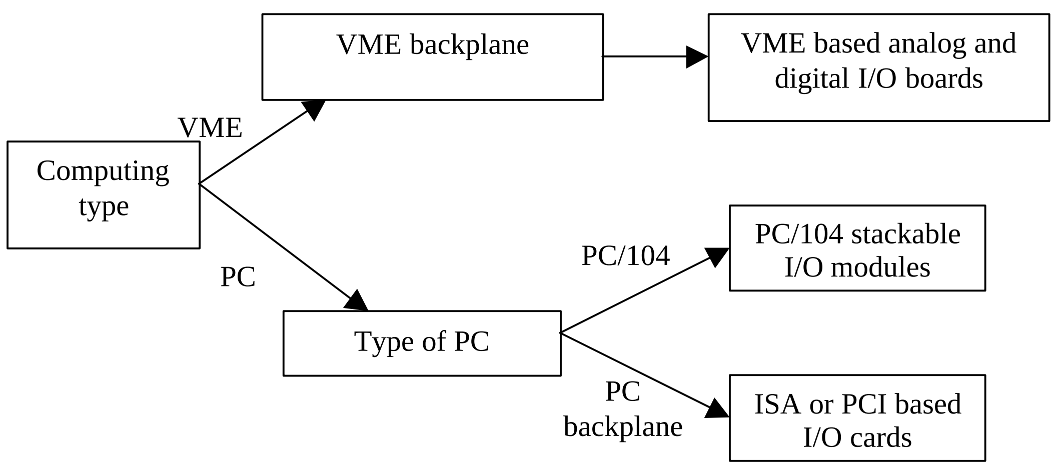


Figure 2.3 Flow chart of WRS computing architecture alternatives

The selection of a PC/104 as the computing platform was made based on power, cost, and ease of use constraints; a weighted selection chart is shown in Table 2.2. Both the VME and PC backplanes are generally used for stationary applications and so are not designed for low power consumption. On the other hand, not only is the PC/104 configuration intended for low power consumption, but the stackable modules themselves are also designed for low power (see Appendix C for a full description of the PC/104 standard). The cost of each of the different computers is comparable, including the backplane or mother boards and other baseline boards or hardware, with VME costing approximately 1.5 times the PC.

VME bus is well suited for multiple processors and asynchronous computing. For the proposed amount of computing necessary in the WRS system, only one processor is needed. Additionally, VME bus computers typically use a real-time operating system, such as Vxworks, which is costly and difficult to learn, making a VME based computer an impractical choice.

A PC/104 computer is a favorable selection because it easily runs Windows and is compatible within the FSRL. Due to the commonality of Windows, technical support is readily available and the operating system is well understood within the FSRL. The PAMM project (discussed in Section 1.2) uses a PC/104 based computer, so compatibility between the two systems is preserved by the choice of a PC/104.

Another factor in the decision for the use of PC/104 based computers comes from the Jet Propulsion Laboratory. The Exploration Technology rover, called FIDO (Field Integrated Design and Operations), is based on a PC/104. The PC/104 architecture is considered the next generation of computing for planetary exploration robotics (Iagnemma, 1998).

Although the PC/104 stackable bus and ISA bus are compatible, physically connecting an ISA bus card, such as the force torque receiver board, to the PC/104 header is not possible. Fortunately this represents only a slight problem, and either a PC/104 motherboard which includes an ISA slot or an ISA to PC/104 connector is required.

Table 2.2 Computing platform selection

Computing Architecture Selection							
Criteria		Platforms					
		PC back plate (Baseline)		**VME System**		**PC/104**	
	Weight (%)	Score (1-5)	Weighted	Score (1-5)	Weighted	Score (1-5)	Weighted
Motherboard or back plate							
Cost including OS	10	3	0.3	1	0.1	3	0.3
Power consumption	15	3	0.45	2	0.3	4	0.6
Ease of use	20	3	0.6	2	0.4	3	0.6
Modules							
Size	15	3	0.45	2	0.3	5	0.75
Power consumption	15	3	0.45	2	0.3	4	0.6
Cost	10	3	0.3	3	0.3	2	0.2
Ease of use	15	3	0.45	2	0.3	3	0.45
Totals	100		**3**		**2**		**3.5**

2.2.2 Modules

This section discusses the alternatives for the PC/104 modules needed to fulfill the functional requirements of the wireless rover system. A plethora of modules are available in the PC/104 format, so nearly all of the computer interface or control requirements can be met by some sort of commercially available product. However, nearly every function required by the WRS can also be met by a custom board designed and built in the lab.

There are advantages and drawbacks associated with both solutions. The advantages of using COTS PC/104 modules are the absence of design or debugging phases and readily available technical support. However, PC/104 modules tend to be expensive and although modules exist which address every required function of the WRS, the range of functions of an individual module is limited. Such a limited range then requires a large number of individual modules.

Custom modules have the advantage of being able to meet simple requirements, such as reading encoders and pulse width modulation (PWM) amplification of motors, with ease and to the exact needs of the system. Additionally, for simple functions custom built boards tend to be less expensive, both in terms of cost of components and man hours, than COTS solutions. Custom boards are limited functionally only by the skill of the designer, but there is little or no technical support.

A selection chart is shown in Table 2.3, where a score of 5 means very well suited to a custom board, 1 is not suited at all, and a score of 3 means it makes little difference. The modules with relatively high scores were selected to be custom built. The decision of selecting modules that were to be custom made was based on the ease of making the boards as compared to the cost savings and increased specificity to the system. A/D and D/A converters are difficult to design and build, especially because of noise constraints (the noise on a 16 bit A/D converter reading a 5 volt signal must be less than $\approx 76\mu V$ for the last bit to have any meaning). A digital input/output module (DI/O) is not difficult to design, but they are priced low enough (approximately $150) that it is not worth the time to build one. Motion control modules can be very expensive, and typically have more functionality then the WRS needs. Custom amplifiers can meet the exact specifications for little above the cost of individual components. The price of a PC/104 encoder module is much higher than its utility in the WRS, and a custom solution is reasonably simple and very inexpensive. The power supply is close to the baseline since a set of individual DC/DC converters costs less than a single package, but a single package takes up much less space and has a higher efficiency.

Table 2.3 Custom or COTS PC/104 module selection chart

COTS or Custom PC/104 Modules selection chart									
		Functions							
		Baseline		**A/D**		**D/A**		**Power Supply (DC/DC)**	
Criteria	Weight (%)	Score (1-5)	Weighted Score	Score (1-5)	Weighted	Score (1-5)	Weighted	Score (1-5)	Weighted
Ease of design	25	3	0.75	1	0.25	1	0.25	2	0.5
Ease of construction	15	3	0.45	3	0.45	3	0.45	3	0.45
System's need for specific function	20	3	0.6	3	0.6	3	0.6	4	0.8
Price ratio (COTS/custom)	20	3	0.6	2	0.4	2	0.4	2	0.4
Debugging	20	3	0.6	2	0.4	2	0.4	3	0.6
Totals	100		**3**		**2.1**		**2.1**		**2.75**
		Functions							
		Encoder interface		**Amplifiers**		**Digital I/O**			
Criteria	Weight (%)	Score (1-5)	Weighted	Score (1-5)	Weighted	Score (1-5)	Weighted		
Ease of design	25	4	1	3	0.75	2	0.5		
Ease of construction	15	5	0.75	3	0.45	3	0.45		
System's need for specific function	20	4	0.8	5	1	1	0.2		
Price ratio (COTS/custom)	20	5	1	4	0.8	1	0.2		
Debugging	20	4	0.8	2	0.4	3	0.6		
Totals	100		**4.35**		**3.4**		**1.95**		

Diamond System Inc. A/D and D/A converters and DI/O's were chosen to maintain compatibility with PAMM. This selection allows knowledge, software, and hardware to be shared between the two projects, reducing development time for both projects.

2.2.3 Batteries

To meet the functional requirement of operating without a tether for a minimum of 30 minutes, the WRS needs to carry its own power source. For the size, budget, and proposed use of the WRS, batteries are the logical choice. Four types of batteries are considered and organized in a selection chart shown in Table 2.4.

Table 2.4 Battery selection chart

Battery Selection Chart							
Criteria	Weight (%)	Battery type					
		Baseline		**NiCad**		**Nickel Metal Hydride**	
		Score (1-5)	Weighted	Score (1-5)	Weighted	Score (1-5)	Weighted
Energy density	17	3	0.51	3	0.51	3	0.51
Cost	15	3	0.45	4	0.6	2	0.3
Rechargable	10	3	0.3	5	0.5	4	0.4
Weight	18	3	0.54	3	0.54	4	0.72
Current sourcing	25	3	0.75	4	1	4	1
Compatibility	15	3	0.45	5	0.75	2	0.3
Totals	**100**		**3**		**3.9**		**3.23**
Criteria	Weight (%)	Battery type					
		Alkaline		**Lead Acid**		**Lithium Ion**	
		Score (1-5)	Weighted	Score (1-5)	Weighted	Score	Weighted
Energy density	17	5	0.85	2	0.34	4	0.68
Cost	15	2	0.3	2	0.3	2	0.3
Rechargable	10	1	0.1	5	0.5	3	0.3
Weight	18	4	0.72	2	0.36	4	0.72
Current sourcing	25	2	0.5	5	1.25	2	0.5
Compatibility	15	3	0.45	2	0.3	2	0.3
Totals	**100**		**2.92**		**3.05**		**2.8**

Nickel cadmium (NiCad) batteries are selected based on the requirements of low weight, energy capacity of 45kJ or greater, and high current sourcing. An additional factor in the selection is that PAMM uses NiCad batteries and once again, compatibility between the two projects is desirable.

The characterists of the batteries considered for use in the WRS are shown in Table 2.5. Nickel metal hydride batteries have a greater energy density than NiCad and can source equivalent current. Nickel metal hydride, however, are more expensive and require a special charger. Alkaline batteries have a very high energy density, but their current sourcing is quite poor. A set of 12 AA size alkaline batteries connected in series cannot source enough current to start the WRS. Lead acid batteries can source a great deal of current, but typically have a low energy density and volumetric efficiency.

Table 2.5 Battery characteristics, all considered are AA type cells except for sealed lead acid. (Dan, P. 1998)

Characteristic	Types of batteries				
	Sealed lead acid	Nickel Cadmium	Nickel Metal Hydride	Lithium Ion	Alkaline Manganese Dioxide (standard alkaline)
Average operating voltage per cell	2	1.2	1.25	3.6	1.5
Energy density (Wh/Kg)	35	45	55	100	160
Volumetric efficiency (Wh/liter)	85	150	180	225	400
Cost ($/Wh)	0.25 – 0.50	0.75 – 1.5	1.5 – 3.0	2.5 – 3.5	0.2 – 0.5
Memory effect	No	Yes	No	No	N/A
Self discharge rate (%/month)	5 – 10	25	20 – 25	8	0.1
Temperature range (°C)	0 to 50	-10 to 50	-10 to 50	-10 to 50	-20 to 55
Maximum continuous current drain (A)	> 50	> 5	> 4	1	1
Maximum pulse current drain	> 100	> 10	> 10	2	2
Environmental Concerns	Yes	Yes	No	No	Yes
Rechargeable	Yes	Yes	Yes	Yes	No

Chapter 3 Design of the Wireless Rover System

This chapter presents the design of Mod 3, the wireless rover system (WRS). Each section discusses a subsystem of the WRS, giving pertinent details such as the manufacturer, characteristics, and functionality.

3.1 Controller

This section describes the computer controller of the WRS, including the PC/104 based computer, I/O modules, and data storage.

3.1.1 PC/104 motherboard

The PC/104 motherboard is a PCM-4890 single board 486 computer with PC/104 bus and a single ISA slot. It accepts CPUs in the range of 80486SX to 5x86 133 MHz and supports up to 64 MB of RAM. It has an integrated video controller for both standard and LCD displays.

One of the most attractive features of the motherboard is its size. At 203mm by 146 mm with a functional depth of 40 mm (measured at the RAM), the motherboard is smaller than a 5 ¼in disk drive. It operates on a single power supply of 5 volts at 2 amps. A schematic diagram of the motherboard is shown in Figure 3.1.

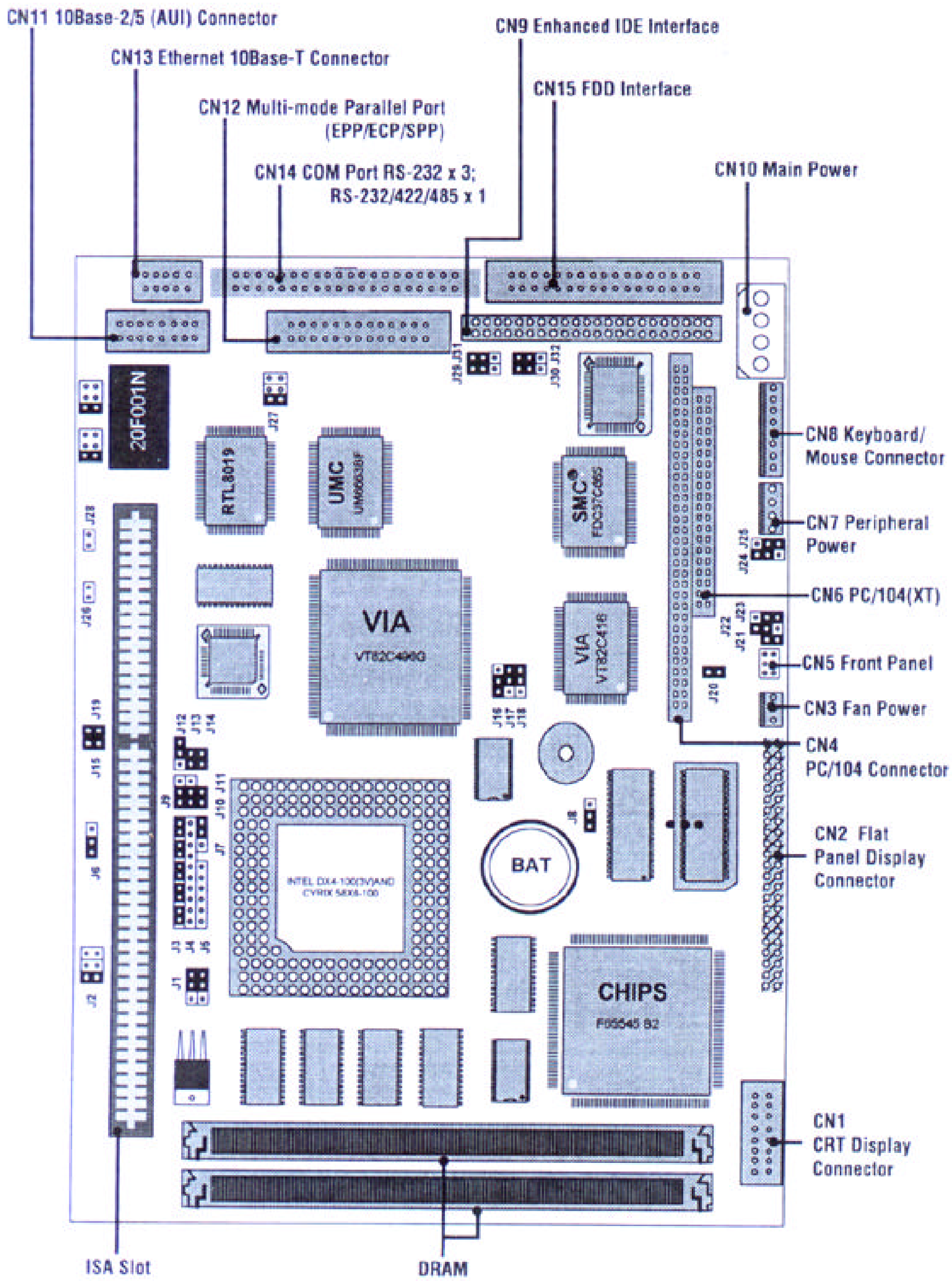


Figure 3.1 Schematic view of the PCM-4890 PC/104 Motherboard (*PCM-4890 User's Manual*. Taiwan, 1996.)

The motherboard is mounted in the back half of the rover body to offset the weight of the arm. The motherboard is held above the rover chassis by aluminum standoffs, with the PC/104 bus centered over the central chassis, which can be seen in Figure 3.2.

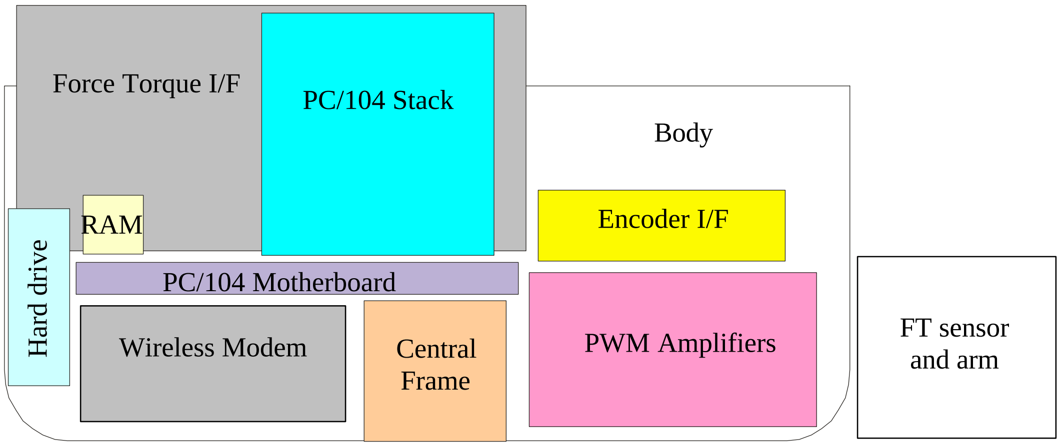


Figure 3.2 Side view of WRS component locations in rover body

3.1.2 I/O Modules

As discussed in Section 2.2.2, the I/O modules are Diamond Systems Inc. PC/104 analog A/D, D/A, and DI/O modules. The WRS has 2 Diamond Systems DMM-16 modules, one Ruby-MM, and one Garnet module. The total number of used and free I/O channels is shown in Table 3.1.

Table 3.1 Number of I/O channels

Total number of I/O channels				
Board	Differential A/D	Single ended A/D	D/A	DI/O
DMM-16 (x2)	8	16	8	8 in 8 out
Ruby-MM			8	24
Garnet				48
Totals	8	16	16	80
Total used	6	7	9	34
Free	2	9	7	46

The A/D conveters read the sensors of the system. The A/D's on the DMM-16 are 16 bit bipolar conveters. All of the A/D converters on a single board must be either single ended or differential. The differential inputs are used to read the tachometers, while the single ended inputs measure the outputs of the potentiometers on the rocker and bogie angles and the output of the accelerometer. Differential converters are actually two A/D converters. One converter reads the "negative" input of the signal while the other reads the "positive" input. The value at the negative is then subtracted from the positive to find the value of the input. Single ended A/D converters are a single converter referenced against ground. Differential A/D converters are better suited for signals with high noise ratios.

The 9 D/A channels are used to drive the inputs of the pulse width modulation (PWM) amplifiers, discussed in Section 3.3. One channel is used for each amplifier for a total of 9 controlled motors. The D/A's on both the DMM-16 and Ruby modules are 12 bit bipolar converters.

The DI/O channels are used both for the amplifiers and for the encoder interface, discussed in Section 3.4. Each amplifier channel requires two digital lines for direction and brake information. The encoder interface requires a data bus of 8 bits and a control bus of 8 bits for reading the three encoders.

3.1.3 Hard drive

A 1.4 GB laptop hard drive provides data storage on the WRS. The laptop hard drive has a small size (76mm x 100mm x 13mm), mass (150 g), and power consumption (3.5 W at startup, < 1 W during power saving) and is resistant to shocks and vibration, making it ideal for use in the WRS. It requires 5 volts at 0.7 amps, which is supplied by the motherboard through the connecting IDE cable.

3.1.4 Communication

The WRS has a National Semiconductor AirShare Wireless modem for communication. The modems communicate at 9600 baud through serial connections, though the full bandwidth is not utilized due to the abundance of radio frequency interference in the lab. The command modem first sends a predetermined test packet of information. If the modem on the WRS receives this test properly it looks for a command immediately following. If the test packet is incorrectly received the serial port is reset and the test packet is resent (Sujan 1998). Only simple, high order commands need to be sent to the WRS, as all of the low level control can be performed on board.

The modem on the WRS requires a power supply of 6 – 9 volts. Since this is out of the range of the voltages supplied by the HE-104 (Section 3.2) a 9 volt battery powers the modem. The voltage to the modem could also be supplied by a 9 volt voltage regulator. The range of the modems is 3 meters and is dependent on the number and type of objects directly between the modems.

3.2 Power Supply

The power supply for the WRS is a Tri-M Engineering Systems HE-104. The HE-104 is a PC/104 stackable DC/DC converter, which provides power directly to the PC/104 bus. The HE-104 takes any voltage in the range of 6 to 40 volts as an input and outputs 5, 12, and –12 volts on the appropriate location on the computer bus. 5 and 12 volts are standard, while the –12 volts is an option required for the force torque receiver board discussed in Section 3.5.1. The HE-104 has an efficiency near 95% and can provide the WRS with 50 watts of continuous filtered power. The HE-104 is also very tolerant of shocks and vibration.

The HE-104 draws power from NiCad batteries. The batteries are C size cells, six of which are arranged into a package. The packages are sold as Makita hand drill batteries (see Figure 3.3). There are two packages of batteries, which are connected in series. Each package is rated at 7.2 volts and has a capacity of 1700 mAh, although typically the batteries charge to 8.3 volts per pack.

Figure 3.3 NiCad battery pack

3.3 Pulse Width Modulation Amplifiers

Motor control on the WRS is accomplished through PWM amplifiers. Although PWM amps are slightly more complicated in both hardware and control, they are much more power efficient than linear amplifiers. A PWM amp operates by very quickly switching the current or voltage to a load between on and off states. The power supplied to the load is determined by the duty cycle of the switching waveform, as shown in Figure 3.4 and Figure 3.5. Provided that the dynamics of the load are slower than the frequency of switching, the load sees the time average.

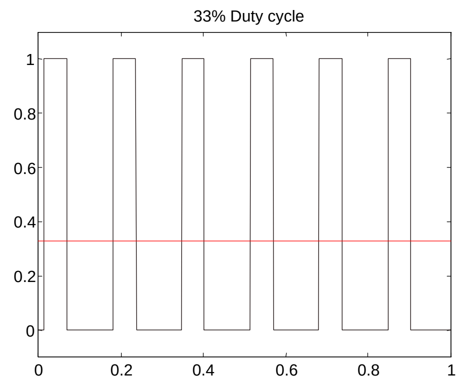


Figure 3.4 33% Duty cycle PWM control signal, average shown as dashed line

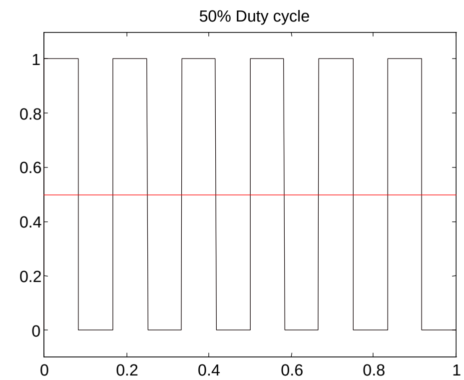


Figure 3.5 50% Duty cycle PWM control signal, average shown as dashed line

To accomplish PWM amplification National Semiconductor LMD18200 power switching ICs are used (full details are given in Appendix A). The switching frequency is approximately 87 kHz, which is tuned to the WRS's motors. The duty cycle is voltage controlled by setting the threshold of monostable oscillators driven by an astable oscillator. One output of the D/A's (discussed in Section 3.1.2) controls the threshold voltage and thus the duty cycle of the amplifiers.

The PWM amplifier circuits are mounted on printed circuit boards. A picture of the printed board before adding the components is shown in Figure 3.6 and a picture of one of the boards after adding components is shown in Figure 3.7. Printed circuit boards are suited for this application because at least two exact copies are required for the WRS. Additionally, the high reliability and wide copper traces for larger current capacity is desirable.

The circuit boards were fabricated through a chemical etching process. Using a standard laser printer, the circuit trace (shown in Appendix A) was printed onto water-soluble paper. The toner on this paper was transferred by heating to a composite copper and insulating material board. The remains of the paper were then washed away, leaving only the toner in the pattern of the circuit trace. Ferric chloride was used to bring the exposed copper into solution and remove it from the board. The remaining toner was washed off, leaving only the copper circuit traces.

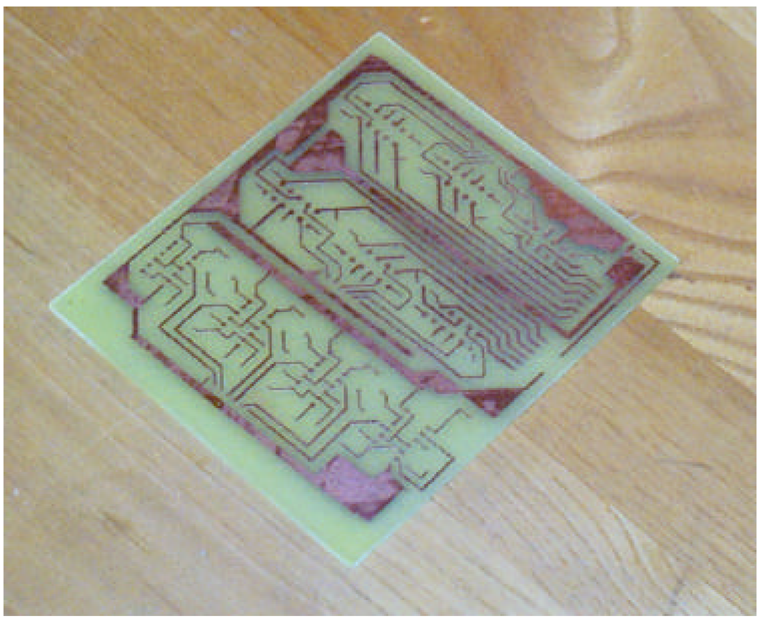


Figure 3.6 PWM circuit board before addition of components

Due to the low current draw of the motors, current control is impractical. The LMD18200 and related power switching chips have current sensing circuitry which can act as a form of feedback. However, because the chips are suited for driving loads at 2-3 amps continuously, the gains of the current sensing are typically several hundred micro amps per amp output (377 μA / A for the LMD18200). Measuring the current sense output at the low current draws of the WRS's motors is very difficult. There is also the problem of biases in the current sensing circuitry. For load currents as low as 100 mA, the output of the current sense circuitry is the same as its output for no load current.

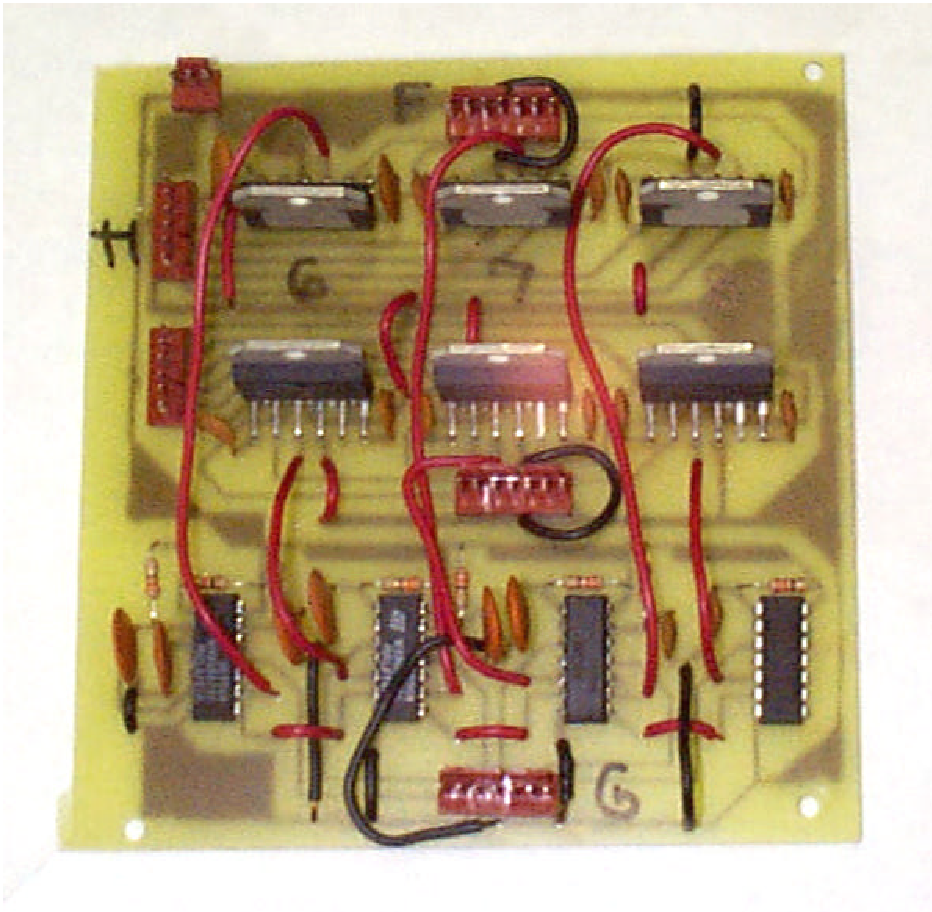


Figure 3.7 Amplifier board

Given current control limitations the motors are voltage controlled. The motors are switched between 0 and 12 volts regulated by the HE-104 (Section 3.2). The additional dynamics introduced by voltage controlling the motors does not play a large role, because the motors' electrical time constant is much faster than the changes in the command signal (not the switching signal) and the low back EMF due to the low speed of the motors.

3.4 Encoder Interface

The WRS's encoders are read and buffered into an interface, which is intermittently read by the processor. The interface is based on US Digital's LS7266R1 dual quadrature encoder chip and is shown in Figure 3.8 (See Appendix B for the circuit diagram and full details). As the encoders change position a counter in the interface increments, recording the change. When the control loop needs position data from the encoders it makes a request to the interface which then sends the data as a series of three 8 bit numbers to the DI/O (Section 3.1.2).

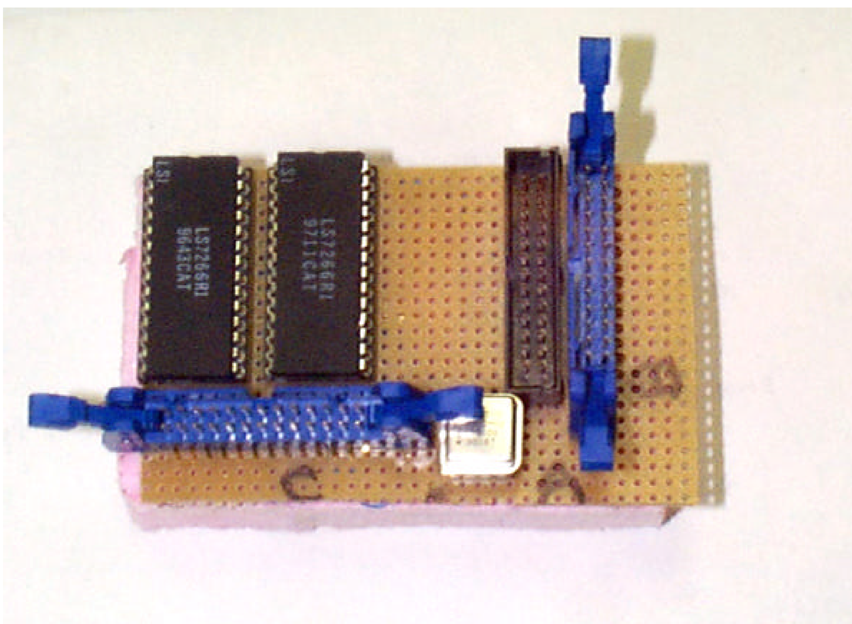


Figure 3.8 Encoder interface shown with two ICs, two more could be added to the bus.

The encoder interface chips are arranged on a bus, so a maximum of four chips can be read by a single DI/O module with 16 channels. Half of the 16 channels are required for the data bus, while the control bus uses 4, and the chips are switched on and off with the remaining 4.

The encoder interface uses a 1 MHz oscillator as a counting digital filter. A change in state of the output of the encoders must last longer than three pulses from the oscillator before it will be registered by the interface. The filter blocks all signals with frequencies greater than 333 kHz, which are assumed to be noise.

Due to the large number of data lines associated with the data and control buses, the interface is wire wrapped rather than mounted on a printed circuit board. The interface requires 5 volts which it draws from the connection to the Garnet DI/O module.

3.5 Sensors

The WRS has several different sensors to measure characteristics of its environment. The sensors can be characterized into two distinct groups, which are discussed separately: digital and analog sensors. The digital sensors are read through the two interfaces on the WRS, the encoder interface and the force torque interface. The analog sensors are read directly by the A/D converters.

3.5.1 Digital Sensors

The force torque sensor and the encoders are the digital sensors on the WRS. The force torque sensor is mounted at the base of the arm and measures the forces and torques between the base of the arm and the arm mount. The sensor, manufactured by JR3, is connected to the computer via the ISA bus receiver board.

The sensor is a 25-pound capacity JR3 model 67M25A force torque sensor and is shown in Figure 3.9. It measures forces on three orthogonal directions and the corresponding moments about those three directions (See Appendix G for capacity, resolution, and the directions of the forces and torques). The sensor, which gives only a digital output, is based on a series of strain gauges arranged in an internal set of rings with integrated electronics. The sensor draws 400 mA from the 12 volt supply and up to 100 mA from the –12 volt supply on the receiver board.

Figure 3.9 Force torque sensor

The digital output of the sensor is read by the force torque receiver board shown in Figure 3.10. This board both filters noise and decouples the six force and torque data streams. The receiver board requires three voltages: 5 volts at 650mA, 12 volts at 25 mA, and –12 volts at 5 mA.

Each of the three arm motors contains an integrated magnetic encoder. The quadrature encoders require 5 volts and output two pulsed signals. The signals from the encoders are read and buffered in the encoder interface (Section 3.4) for use by the computer. The data from the encoder interface can be used to find the position and derivatives of the position of the arm joints.

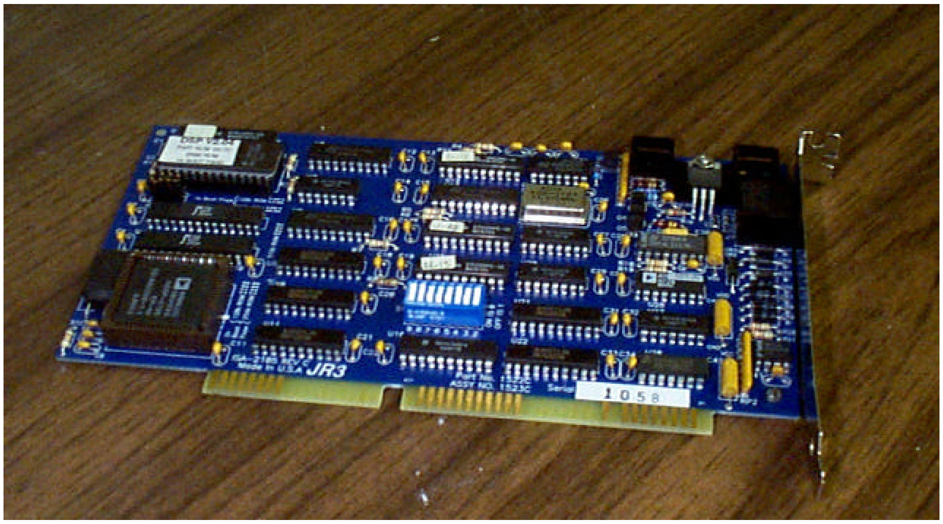


Figure 3.10 Force torque ISA receiver board

3.5.2 Analog Sensors

The tachometers, potentiometers, and accelerometer are all analog sensors. The output of each sensor is read by the A/D converters on one of the two Diamond modules (Section 3.1.2). The tachometers, which measure the rotational speed of the drive motors, tend to have poor signal to noise ratio and so are read using differential mode A/D. The potentiometers and accelerometer generate signals with respect to ground and thus are read by single ended A/D converters. The A/D modules can be configured so that either all channels are single ended or all are differential. Therefore the WRS uses one Diamond in single ended mode and the other in differential mode.

The accelerometer and tachometers give information about the position. By measuring the acceleration due to gravity, the WRS's orientation can be determined. The position of the WRS can be found by integrating the signals from the tachometers and the accelerometer, although this measurement is not completely accurate due to sensor drift.

3.6 Packaging

The electronics of the WRS are all within the body of the WRS. The body is a stamped and drawn aluminum box of dimension 200mm x 360mm x 100mm (8in x 14in x 4in).

The orientation of the various electronics within the housing is shown in Figure 3.11 with a block diagram view in Figure 3.12. The PC/104 motherboard is placed near the rear of the WRS so that the weight of the stackable modules offsets the weight of the arm and arm mount on the front of the vehicle. The motherboard sits above the central frame held in place by several aluminum standoffs. The amplifier boards and encoder interface are mounted in the front of the body. The two amplifier boards and the encoder interface are stacked with the encoder interface on top. Although there is sufficient space for batteries under the PC/104 motherboard, they are kept on the outside of the body for ease of removal and recharging.

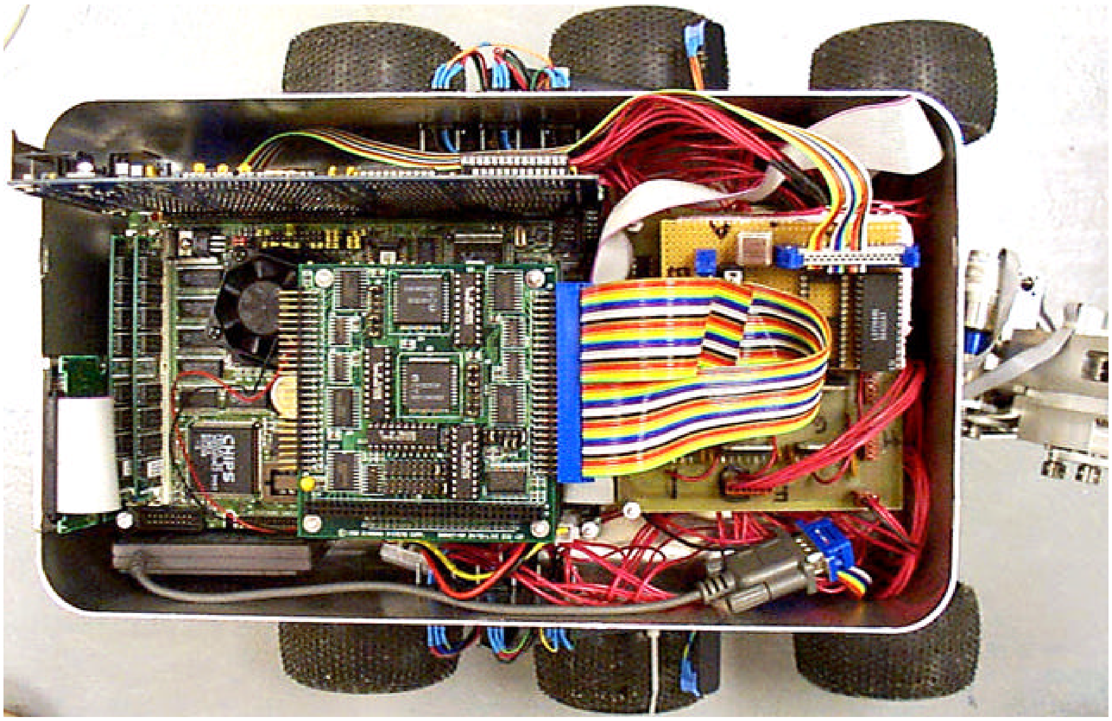


Figure 3.11 Overhead view of the WRS

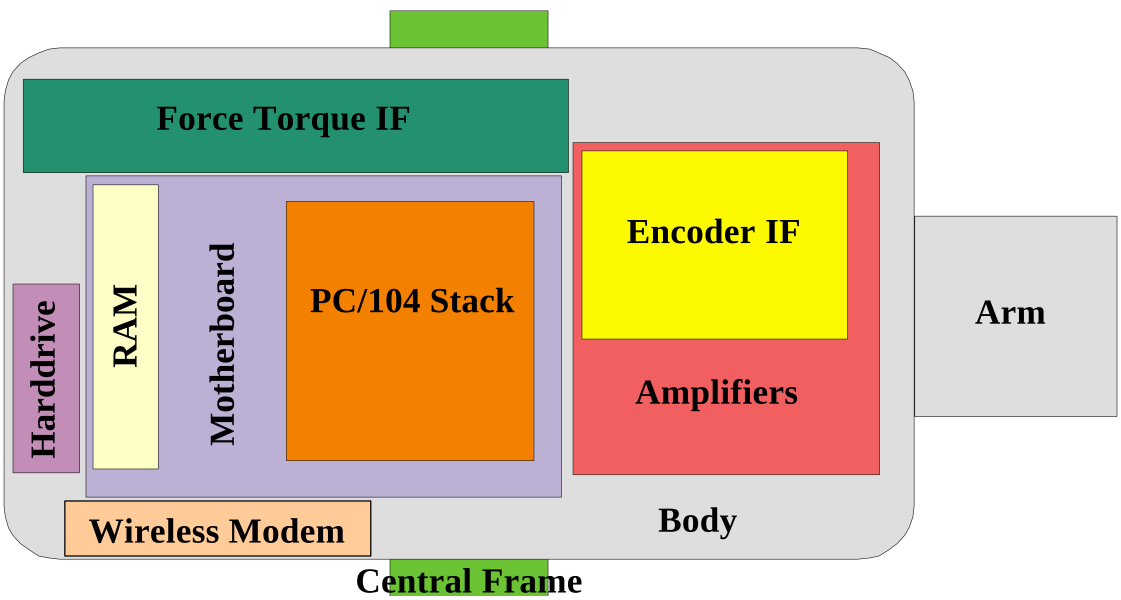


Figure 3.12 Block diagram view of components in the WRS

Chapter 4 System Software Design

This chapter discusses the software used to test and control the WRS. First the general control loop is described, then the low level control of the modules is discussed. The relation of several functions to the hardware is explained in Appendix J.

The software was written in the C programming language using Borland C++ 5.02 and was compiled for use under DOS. The goal of the software design was to control the specific hardware in a logical and straightforward fashion, reducing the future time necessary to understand the software and implement different controllers.

The body of the software consists of a control loop and register calls to the various I/O modules. This chapter discusses the controller and low level communication with the I/O boards.

4.1 Controller

Although the WRS will eventually require an interrupt service routine to precisely set the sampling period of the control loop, the initial version of the controller simply runs on a loop as fast as the computer will allow. Under this scheme the entire control loop repeats every 10 milliseconds, which is the sampling period. Every sampling period, the controller samples the sensors, performs digital control computations, looks for input from the user, and sends output to the motors.

A proportional integral (PI) velocity controller accomplishes the control of the drive wheels (See Appendix D for the controller code). The output of the controller to the drive motors is calculated from the immediate velocity and position of the wheels.

With this type of controller there is no steady state error in velocity. The bandwidth of the motors is relatively low, but since the WRS is a slow moving vehicle fast response of the drive motors is not necessary (Volpe, 1996).

For system testing purposes the arm operates under open loop control, the encoders were read but this information was not compared with the command signal. Unlike the six drive motors, the arm does not need to have all of its motors coordinated for validating that the system operates, and thus a closed loop controller was not needed.

4.2 Low Level Software

Each of the I/O modules and the force torque receiver communicate with the software via register calls. The Diamond Systems PC/104 modules come with various drivers which attempt to make the register calls transparent to the user. However, these are written in a specific version of C and are intended to be used as object files, which makes them usable only in that specific version of C. Borland C++ 5.02 and Microsoft Visual C++ 5.0 were not able to properly compile the object files, which were written in Visual C++ 1.52, Quick C 2.0, and Microsoft C 5.1.

Control of the PC/104 modules was done using a system of cases, which are specialized variables defined for use with specific functions of the various I/O cards, developed for PAMM (Kozono, 1998). This system arranged all of the various register addressing into a set of header and C files, which are linked to the main program. Using these, a variable is defined using a certain case for each of the modules. Using pointers to the variables, information can be sent to the modules without the need to deal with registers.

Accessing the force torque receiver is done directly via registers. The force torque receiver has far fewer functions than the other I/O modules, so register direct communication is reasonably simple (see Appendix E).

Chapter 5 Use of the Wireless Rover System

The WRS is a remarkably stable system. The PC/104 computer and I/O modules have no conflicts, slight bumping and jarring of the hard drive cause no ill effects, and power glitches are not an issue. However, a few notes on using the system are necessary. This chapter first discusses using the WRS and then explains expanding it for other functions or experiments.

5.1 Using the Wireless Rover System

The major causes for concern with the WRS are the DC/DC converter, overloading the vehicle, and static discharge.

5.1.1 Power

DC/DC converters very effectively filter and accept a wide range of input voltages. However they do not have polarity safeguards, and any voltage of incorrect polarity will instantly destroy the HE-104. Fortunately only the DC/DC converter will be damaged. The polarity of power voltage must always be checked before powering up the WRS.

On startup the WRS draws nearly 100 watts. This is only a brief transient, but the power supply should be rated to source at least this much. The NiCad batteries used in the WRS are well suited to source this much power, as are lead acid and nickel metal hydride batteries. Reasonable numbers of alkaline and lithium ion cells cannot provide this much power and should not be used to power the WRS. Fortunately if alkaline cells are used, it will only damage the cells, rather than the WRS.

In addition to high startup currents, the HE-104 induces significant inductor effects. Care should be taken when applying and disconnecting power to the WRS as current may arc, possibly damaging the power supply or switch.

During experimental testing (for which it is not critical the WRS be totally wireless) a medium gauge wire connection to a standard computer power supply may be used. Medium gauge wire imparts only very minimal forces on the WRS and has the advantage of eliminating both battery mass and downtime for recharging.

5.1.2 Overload

The WRS can be physically overloaded in two major ways: too much force on a motor gearhead, and overloading the force torque sensor. It is safe to load each gear head to 20 N. The kinematically stable configuration of three wheels supporting the WRS is within this limit, but a two wheel configuration is not. Care must be taken to prevent the WRS from being supported by only two or fewer of its wheels. Three wheels are required for kinematic stability with rigid wheels, yet the deformable wheels of the WRS may stabilize the vehicle in a two wheel configuration, although this is very unlikely.

The force torque sensor is a 25 pound capacity sensor without overload stops. Simply, the sensor is a series of strain gauges, which detect very small movements in its aluminum body. The single axis permissible overloads are given in Appendix G. Since these are reasonably large forces, it is unlikely that an overload condition will occur in a single axis. A single strain gauge does not read a single axis, so a multiaxis overload should not exceed the rated overload in any one of the axes involved divided by the total number of axes involved. This does not present a problem for normal use of the WRS as the arm cannot exert forces and torques this large. A crash involving the manipulator, however, might generate forces high enough to damage the sensor, and should be avoided for this and other safety reasons.

Assuming an elastic collision between the WRS and a solid body, the force, F, generated is given by:

$$\mathbf{F} = \sqrt{\mathbf{m}\mathbf{v}^2\mathbf{k}} : \qquad \textbf{(3)}$$

where m is the mass of the WRS, v is the velocity of the WRS just before the time of impact, and k is the stiffness of the force torque sensor in the direction of the collision. A collision in only the the Fx direction of the sensor with initial velocity 80 mm/s generates 60% of the overload force in that axis. Again, exclusively single axis collisions are highly unlikely.

5.1.3 Static Discharge

The PC/104 computer and particularly the I/O modules are susceptible to damage from static discharge. The best way to prevent damage by discharge is to avoid handling the electronics unless it is required. Before physically touching any of the components one should in the least touch something grounded, such as plumbing, if not using a grounded wrist band.

Several steps have been taken to prevent accidental discharge, the greatest of which is the conductive body of the WRS itself. The A/D and D/A modules tend to be more sensitive to static electricity compared to other modules, and are located near the bottom of the PC/104 stack. Keeping a cover on the WRS can also protect against static discharges.

5.2 Expanding the Wireless Rover System

Each subsystem of the WRS is a module that can be upgraded or removed for different functionality. The modular design allows the system to maintain some operability while missing modules. Although this makes the system tolerant to various problems associated with the possible failure of subsystems, the major advantage is upgradability.

For example, with a minimal number of changes, the WRS could control several more motors and read more encoders. The WRS could also be changed in a more substantial way, by incorporating a localization system or vision system, without affecting the other components and with little more effort than physically adding and mounting the new hardware.

The interconnections between the subsystems of the WRS are specifically designed to facilitate changing and upgrading. All of the wire connections are made via headers and matching connections. Any module can be removed by undoing the mechanical connections and disconnecting the wires, and nothing needs to be cut or desoldered.

The PC/104 computer also allows for quick connection and addition of new components. New modules can simply be stacked onto the PC/104 bus to be integrated into the system (see Appendix F for information on available I/O space). Also the computing power of the computer can be increased with a faster CPU, more RAM, or a greater capacity hard drive.

Thus the modular design of the WRS's subsystems allows the system to be used and modified for many years without losing utility. New systems can easily be added, changing the functionality and allowing the WRS to be used to study different aspects of planetary exploration. A modular design is the best, most adaptable way to construct this type of robotic system.

Chapter 6 Summary and Conclusion

6.1 Contributions of this work

This work has built upon the rover test bed, making it wireless. Beyond designing and building the Mod 3 iteration, this project has built upon previous work and laid the groundwork for future forms of the system. As current knowledge and the need for future technology for space exploration change, the WRS will continue to be a useful tool for developing and learning about the use of robotic explorers on other planets. Though the hardware of the WRS will at some point become outdated, new modules and new ideas can easily be added to the system.

The WRS will help further the understanding of several concepts. The WRS is highly suited for studies involving moving base manipulator control and soil tire traction interaction. It can also be easily modified for use in experiments concerning visually guided servo control and lightweight robotic drilling and coring. The WRS could also serve as a platform for use with lightweight deployable structures and the actuation of such structures.

The WRS puts all of the control and power systems of the Mod 2 iteration of the FSRL rover into the actual vehicle. A block diagram of the system is shown in Figure 6.1. A PC/104 single board computer, communicating through analog to digital and digital to analog converters and digital input output stackable modules, is the brain of the system. PWM amplifiers control both the arm and drive motors. A six axis force torque sensor measures the base forces from the arm and is read by the computer using a digital signal processing receiver board. The system uses a wireless modem for communication with another computer. Encoders on the arm motors are used to feed back position information from the arm, while tachometers are used to measure the velocity of the drive motors, and potentiometers are used to measure the angles of the rocker and bogies. An accelerometer is used to determine the position of the body with respect to gravity. Nickel cadmium batteries supply power, which is filtered and converted to the proper voltages by a DC/DC converter. The self contained rover cost $5868.8 in addition to the cost of the Mod 2 rover.

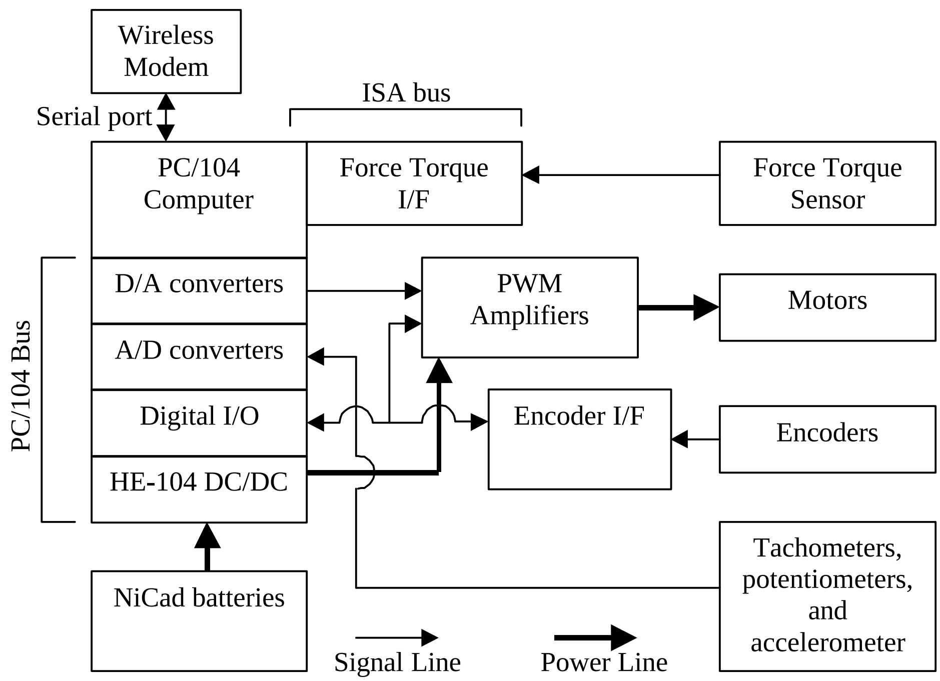


Figure 6.1 Block diagram of the components and connections in the WRS

Table 6.1 Summary of available and expandable features

	Current system	Free	Upgradable to	With the addition of
Number of encoders read	4	1	16	Six LS7266R1's two on the current interface and four on a separate interface
Number of motors PWM controllable	12	3	Limited by the number of free D/A channels	More LMD18200 and 556 based amplifiers
A/D converters	8 differential	2	?	Analog I/O modules
A/D converters	16 single ended	9	?	Analog I/O modules
D/A converters	16	7	?	Analog I/O modules
DI/O	80	46	?	Digital I/O modules
CPU	486 DX2/66MHz		586 133 Mhz	Faster CPU chip
RAM	32 MB		64 MB	Two 32 MB SIMMs
Hard disk storage	1.4 GB	800 MB	?	IDE Hard drive

6.2 Future Work

Work in the immediate future includes communication and some mechanical redesign of the packaging. Work which lies further in the future includes implementing base sensor control of the manipulator, porting the fuzzy logic controller to the WRS (Hacot 1998), and implementing a vision system.

The communication between the WRS and another computer is operable and has been marginally tested. More tests should be performed to determine if the 3 meter range of the modems is stable enough for laboratory work or whether new hardware is required. The AirShare modems used in the WRS have been discontinued by the manufacturer and technical supported dropped.

A first generation cover for the WRS was thermoformed using the aluminum body as a mold. The cover acts to keep dust, dirt, and sand out of the WRS interior and physically protects the electronics. Ascetically this cover leaves much to be desired, but it can be used to create plaster molds for future covers.

The aluminum body of the WRS does not need to be a full tub. The body can be machined from a tub to a more skeletal form, reducing its mass if future modules are in danger of putting the WRS over the safe loading limit of the gearheads. A thin sheet of plastic, which would prevent sand and dirt from entering, could then cover the holes machined into the aluminum body.

The high friction in the manipulator makes it a good candidate for base sensor control (BSC). All the hardware already exists on the WRS for BSC, so implementation requires only the development of a kinematic model of the arm and the necessary control code (Liu, 1998).

Porting the fuzzy logic controller developed by Hacot from the Mod 2 computer to the WRS would allow the fuzzy logic controller to be tested in a wider range of environments and possible scenarios a robot might encounter while exploring. This would require updating the kinematics used in the fuzzy logic controller's model of the vehicle to that of the WRS and writing the fuzzy logic algorithms to use the hardware of the WRS.

A vision system on the WRS could be used to explore visual feedback of the manipulator position and localization of the vehicle in its environment. A frame grabber module exists and has been tested on the WRS.

6.3 Conclusion

Starting with the Mod 2 iteration of the FSRL rover, a set of requirements for transition of the system to a wireless state was developed. To meet these requirements, the alternatives were considered and formed into a complete system, which was then built. The WRS is useful because it eliminates the problems of a tether, and allows the FSRL rover to maintain compatibility both within the lab and with experiments done by other planetary exploration labs. The WRS will continue to be a useful tool because of its modular design and ease of upgrade and system change.

References

Burn, R., *Design of a Laboratory Test Bed for Planetary Rover Systems*, MS Thesis, Mechanical Engineering Department, Massachusetts Institute of Technology, Cambridge, MA, 1998.

Dan, P., "How to Choose a Lithium Battery," Port Washington, NY, 1998.

Diamond Systems Corporation, "Ruby-MM 8 Channel Analog Output Module User Manual V3.0." Diamond Systems Publishing, Palo Alto, CA, 1998.

Diamond Systems Corporation, "Diamond-MM-16 16-Bit Analog I/O Module User Manual V1.0." Diamond Systems Publishing, Palo Alto, CA, 1997.

Diamond Systems Corporation, "Garnet-MM Digital I/O PC/104 Module User Manual V1.2." Diamond Systems Publishing, Palo Alto, CA, 1996.

Dongarra, J., *Performance of Various Computers Using Standard Linear Equations Software*, Computer Science Department, University of Tennessee, CS-89-85, 1994.

Hacot, H., *Analysis and Traction Control of a Rocker-Bogie Planetary Rover*, M.Sc. Thesis, Mechanical Engineering Department, Massachusetts Institute of Technology, Cambridge, MA, 1998.

S. Hayati, R. Volpe, et al., "The Rocky 7 Rover: A Mars Sciencecraft Prototype." *Proceedings of the IEEE International Conference on Robotics and Automation*, Albuquerque NM, April 20-25 1997.

Horowitz, P., Hill, W., *The Art of Electronics*, Cambridge University Press, New York, 1989.

Iagnemma, K., Personal communication, 1998.

JR3, Inc. "DSP-Based Force Sensor Receivers Software and Installation Manual." Woodland, CA, 1994.

Kozono, H., Personal communication, 1998.

Liu, G., Iagnemma, K., Dubowsky, S. and Morel, G. "A Base Force/Torque Sensor Approach to Robot Manipulator Inertial Parameter Estimation." *1998 IEEE International Conference on Robotics and Automation*, Leuven, Belgium, May 1998.

McKay D. S., Gibson E. K. Jr., Thomas-Keprta K. L., Vali H., Romanek C. S., Clemett S. J., Chillier X. D. F., Maechling C. R., and Zare R. N. “Search for past life on Mars: Possible relic biogenic activity in martian meteorite ALH 84001.” Science 273, 924-930, 1996.

Mims, F., *555 Timer IC Circuits*, Siliconcepts, Fort Worth TX, 1993.

National Semiconductor, “LMD18200 3A, 55V H-Bridge.” Application and Technical Notes, Sunnyvale, CA. April 1998.

PCM-4890 User’s Manual. Aaeon Publishing, Taiwan, 1996.

Schenker, P., et al., “Lightweight Rovers for Mars Science Exploration and Sample Return,” *Intelligent Robotics and Computer Vision XVI* (Ed. D. Casasent et al.), SPIE Proc. 3208, 13 pp., Pittsburgh, PA, Oct.14-17 1997.

Schildt, H. *Teach Yourself C*, McGraw-Hill, New York, 1990.

Sujan, V., Personal communication, 1998.

U.S. Digital, “LS7266R1 Encoder to Microprocessor Interface Chip Technical Data,” Rev. 9.01.98, September 1998.

R. Volpe, J. Balaram, T. Ohm, R. Ivlev. “The Rocky 7 Mars Rover Prototype.” *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems,* Osaka Japan, November 4-8 1996.

Appendix A

Pulse Width Modulation Amplifiers

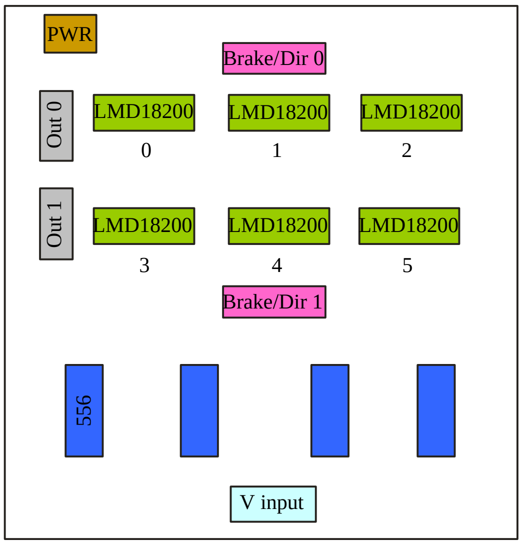


Figure A.1 Block diagram of PWM amplifiers

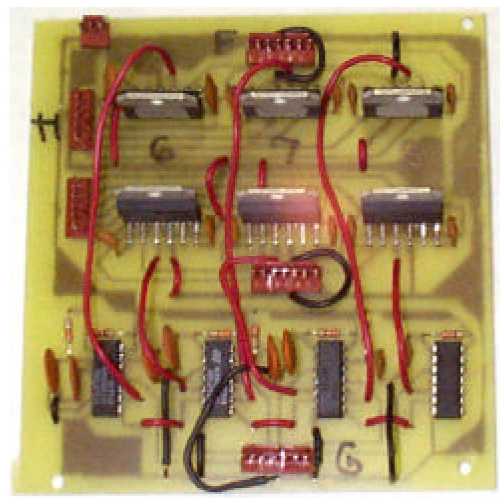


Figure A.2 Picture of PWM amplifiers

An amplifier board and block diagram are shown in Figure A.1 and Figure A.2. The PWM wave forms are generated by the seven timers on the board (each of the four 556's has two timers, and the eighth timer is unused). The first timer is set for astable oscillation, and switches between an on and an off state at 87 kHz. This 87 kHz clock signal is fed into the triggers of the other six timers, which are set to operate in monostable mode. When a monostable timer receives a trigger signal, it changes state from off (0 volts) to on (5 volts) for an amount of time set by the input voltage. The maximum time is approximately 75% the period of the astable clock signal and the minimum time is zero. By varying the input voltages, each monostable timer will generate a 87 kHz square wave with duty cycle between 0 and 75%. The LMD18200 chips act simply as digital switches controlled by the output of the timers and by the brake and direction digital inputs (discussed in Appendix J).

The schematic of three of the six amplifiers is shown in Figure A.3. The first timer on the left side of the figure is the astable timer, while the other three timers are monostable timers.

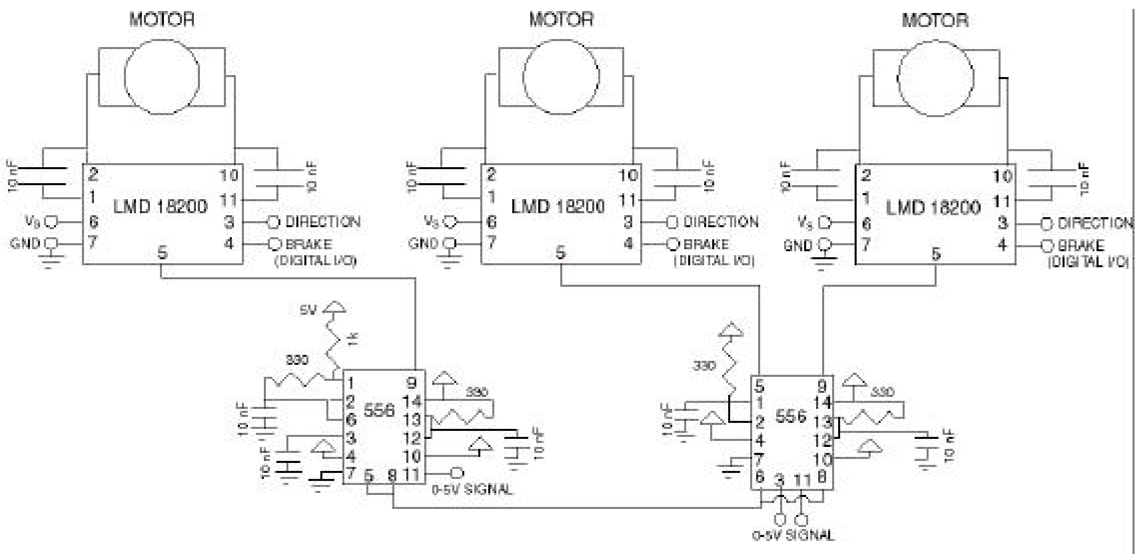


Figure A.3 Schematic of amplifier boards

The pinouts for the six headers on the amplifier board are shown in Figure A.4, Figure A.5, Figure A.6, Figure A.7, Figure A.8, and Figure A.9. The trace used to make the printed circuit board is shown in Figure A.10.

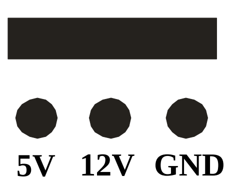


Figure A.4 Amplifier power header pinout

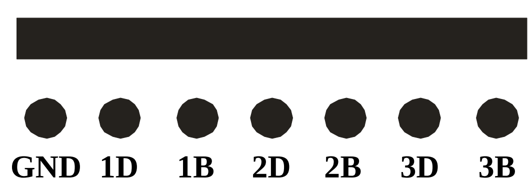


Figure A.5 Amps 0, 1, 2 digital input (header Brake/Dir 0 in Figure A.1)

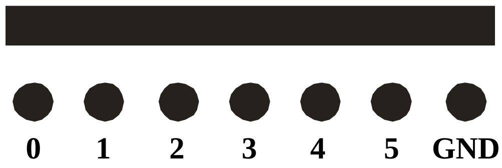


Figure A.6 Amplifier analog voltage input (header V input in Figure A.1)

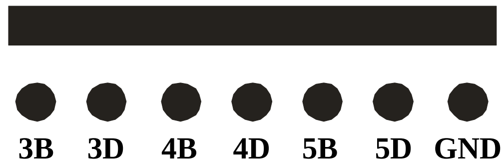


Figure A.7 Amps 3, 4, 5 digital input (header 1 Brake/Dir 1 in Figure A.1)

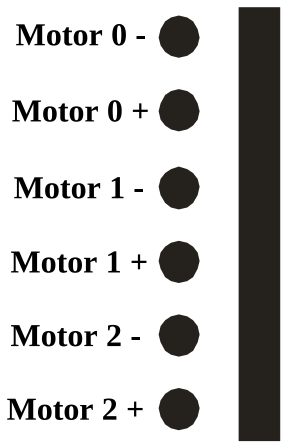


Figure A.8 Amps 0, 1, 2 output (header Out 0 in Figure A.1)

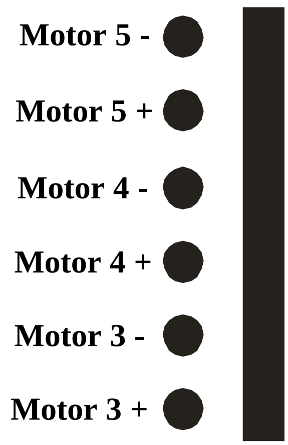
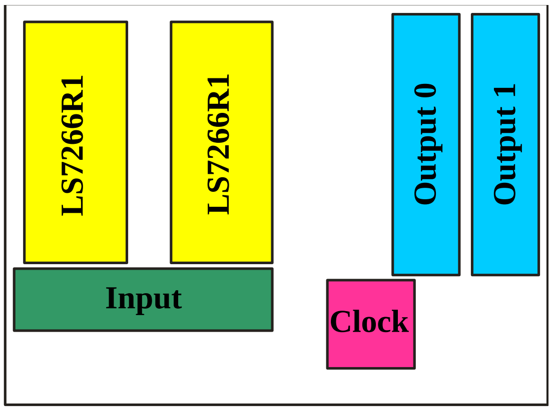


Figure A.9 Amps 3, 4, 5 output (header Out 1 in Figure A.1)

Figure A.10 Trace of amplifier printed circuit board

Appendix B

Encoder Interface



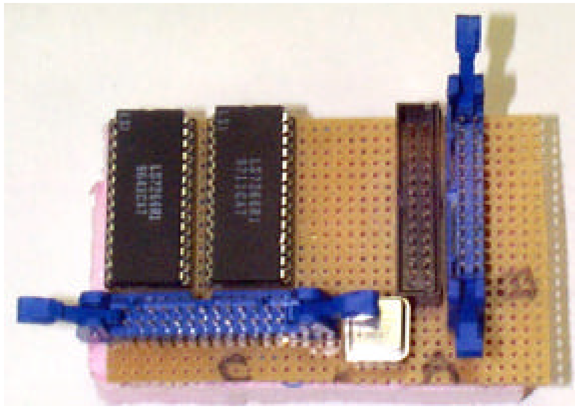


Figure B.1 Block diagram of encoder interface **Figure B.2 Picture of the encoder interface**

The encoder interface is based on the U.S. Digital's LS7266R1 quadrature dual encoder IC. The LS7266R1 decodes the pulses from the encoders and stores the information in a 24 bit counter. When prompted, the IC will give this information to the computer in a series of three 8 bit numbers. The interface has the ICs arranged on a bus to reduce the total number of digital I/O lines required as shown in the schematic of the circuit in Figure B.3. The encoder interface bus has sufficient space for two more LS7266R1 chips, bringing the number of encoders to 8.

The first output header (labeled Output 0 in Figure B.1) has 26 pins, the first 25 of which connect to the first 25 pins of the Garnet DI/O (Section 3.1.2). The second output header (labeled Output 1 in Figure B.1) also has 26 pins, the first 25 of which connect to pins 26 – 50 on the Garnet DI/O. In both headers, pin 26 is unused.

The input header connects to the encoders. The pinouts are shown in Table B.1.

Table B.1 Pinouts for output of encoder interface

Pin number	Ribbon cable color	Arm Joint	Connected to:
1	Green	Pivot	Motor +
2	Yellow		5volts (encoder power)
3	Orange		Encoder A signal
4	Red		Encoder B signal
5	Brown		GND (encoder ground)
6	Black		Motor -
7	White	Shoulder	Motor +
8	Grey		5 volts
9	Purple		A
10	Blue		B
11	Green		GND
12	Yellow		Motor -
13	Orange	Elbow	Motor +
14	Red		5 volts
15	Brown		A
16	Black		B
17	White		GND
18	Grey		Motor -

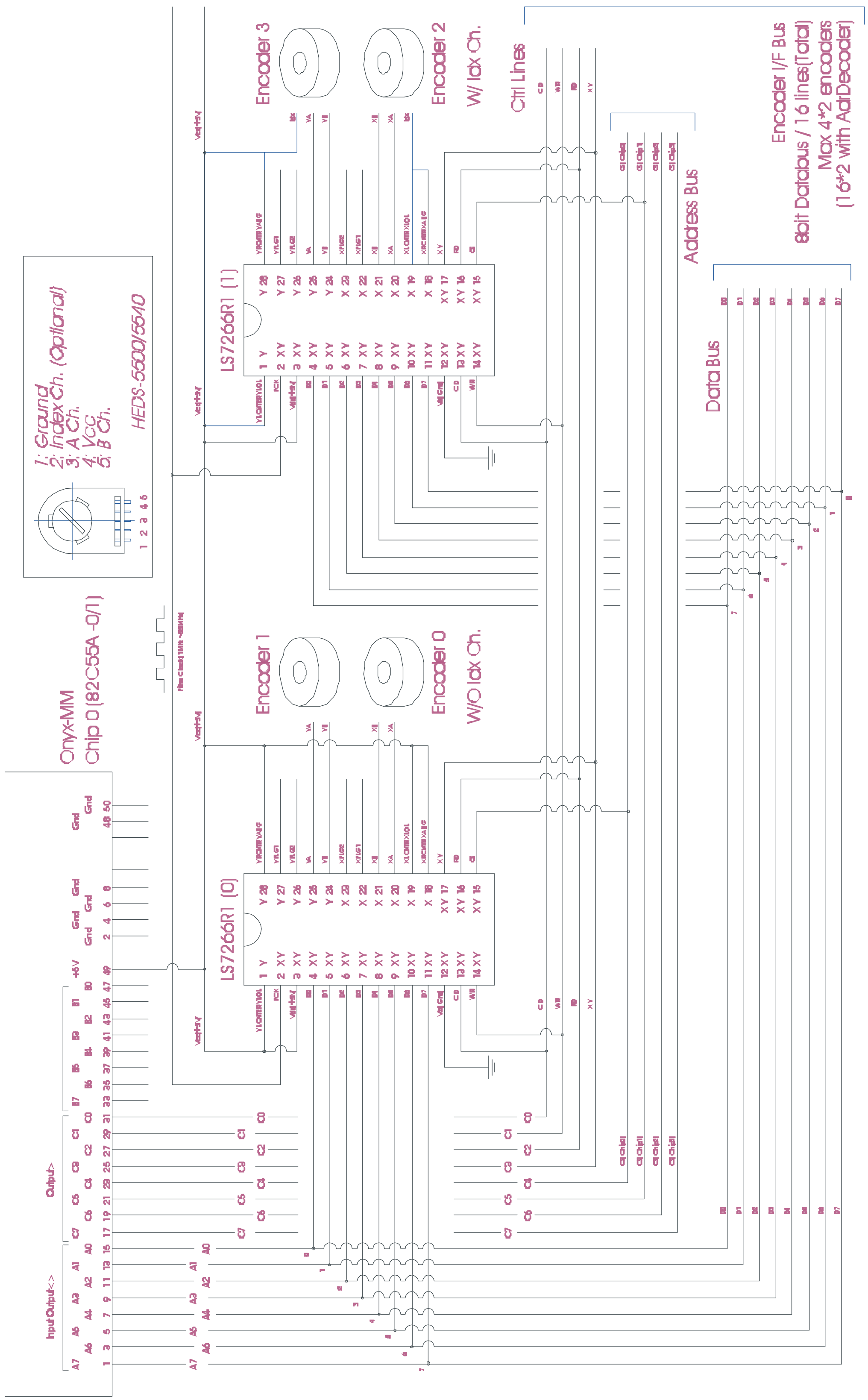


Figure B.3 Circuit diagram of encoder interface (Kozono, 1998)

Appendix C

PC/104 Standard

The PC/104 standard is a packaging or form factor for an IBM-PC compatible computer. Developed in the late 1980's by Ampro Computers, the PC/104 takes all the functionality of a desktop computer and places it in a smaller, more power efficient package. The name is taken from the common name of a computer, PC, and the 104 pins of the stackable bus.

The stackable bus eliminates the need for card cages and large motherboards, and increases reliability. A typical PC/104 module can have other modules attached on two sides of the physical bus connection. This allows nearly any number of modules to be placed together in minimal volume. The PC/104+ (plus) standard is functionally identical to the PCI bus. An additional 120 pins sit opposite the PC/104 header on a PC/104+ module.

At 4mA, the PC/104 has a reduced signal bus drive compared to a desktop PC. This decreases the power of each module to 1 – 2 watts each.

Appendix D

Proportional Integral Velocity Controller C Code

The loop, which calculates the command signal sent to the drive motors, is shown below with additional comments.

```
Tachvolt[0] = dmm16.A2D(7);
tachvolt[1] = dmm16.A2D(6);
tachvolt[2] = dmm16.A2D(5);
tachvolt[3] = dmm16.A2D(4);
tachvolt[4] = dmm16.A2D(3);
tachvolt[5] = dmm16.A2D(2);
```

This section gets the current voltages on the six drive tachometers, and puts it in an array called *tachvolt*.

```
Gotoxy(11, 18);
for (I = 0; I <= 5;I++) {printf("%9.2lf", tachvolt[I]);  }
```

This section displays to the screen the voltages on each tachometer.

```
Gotoxy(11, 22);
for(I = 0; I <= 5;I++) {
    if(I <= 2) error[I] = (rmotors + tachvolt[I]);
    if (I >= 3) error[I] = (-lmotors + tachvolt[I]);
    printf("%9.2lf", error[I]);
```

This section calculates the error on each motor compared to a reference signal that is constant over the left and right sides of the WRS and prints it to the screen.

```
    Ki = 0.1;
    integral[I] = integral[I] + ki * error[I];
```

This section computes the integral term of controller, which is the current error plus the error last sampling period times a constant. This is a backwards difference method of finding the integral of the signal.

```
    Kp = 10;
    command[I] = kp * error[I] + integral[I];
    if (command[I] > 5.0) command[I] = 5.0;
    if (command[I] < -5.0) command[I] = -5.0;
}
```

This last section calculates the command signal, which is the integral term plus the proportional term. The proportional term is the current error times a constant.

Appendix E

Force Torque Receiver Board

Retrieving data from the force torque sensor is accomplished through addressing registers on the force torque receiver board (Section 3.5.1). Below is an example set of functions in the C programming language for addressing the receiver board.

```
Void force(float *f_t_data)
{
    int I, axload;

    for (I = 0; I <= 5; I++) {
    axload = getdata(board1, f3add + I);
    f_t_data[I] = full_scale[I] * ((float)axload / 16384);
    }
}
```

This section reads the 6 axes starting with Fx from filter 3.

```
Void zerooffs (void)
{
    outport(board1, comm0);
    outport(board1 + 2, 0x0800);
}
```

This section writes to command word 0. Command to zero offsets is $800.

```
Int getdata (int baseadd, int addr)
{
    outport(baseadd, addr);
    return (inport(baseadd + 2));
}
```

This section writes the location from which to read the data, then actually reads the data.

```
Void get_full_scales(void)
{
```

```
    int I;

    for (I = 0; I <= 5; I++) {
        full_scale[I] = getdata(board1, fulls_add + I);
    }
}
```

This section is used to initially get the full scale data from the sensor.

Appendix F

PC/104 Motherboard Settings

The PC/104 motherboard has a number of jumpers, which set various useful properties. The most important jumpers are the ones which control the CPU voltage and clock signal. Their settings for the AMD DX2-66 CPU are shown in Table F.1.

Table F.1 PC/104 Motherboard jumper settings

Jumper Number	Function	Current setting
J1	CPU power supply	Closed 1-3 and 2-4
J2	CPU power supply	Closed 3-4
J3	CPU type setting	All open
J4	CPU type setting	All open
J5	CPU type setting	All closed
J7	CPU brand setting	Closed 2-3
J9	CPU type setting	Closed 1-2
J10	CPU type setting	Closed 1-2
J11	CPU type setting	Closed
J12	WT/WB control	Open
J13	CLKMUL control	Closed
J14	Clock mode selection	Closed
J16	CPU clock select	Closed 1-2
J17	CPU clock select	Closed 2-3
J18	CPU clock select	Closed 2-3

The number of modules stacked onto the PC/104 motherboard is not physically limited, but there is an upper bound. Each module takes up a certain amount of I/O space. The locations and amount of I/O space required by each board is shown in Table F.2.

Table F.2 PC/104 Motherboard I/O space

Module	Base address (hexadecimal)	I/O space
Force torque receiver	0314	4 bytes
Diamond DMM-16 (board 0)	0280	16 bytes
Diamond DMM-16 (board 1)	0340	16 bytes
Ruby D/A	0240	16 bytes
Garnet DI/O	02E0	8 bytes

Appendix G

Force Torque Sensor Specifications

The specifications of the force torque sensor are given in Table G.1. The sensor samples at 8kHz and outputs digital data in a 2 Mbit/s stream. The direction of each axis on the sensor is shown in Figure G.1. On the top face of the sensor there are two holes which are not mounting holes. The direction of Fy is along the line defined by these holes, and can be used to find the other directions.

Table G.1 JR3 Model No. 67M25A-U562 Specifications

	Fx and Fy	Fz	Mx and My	Mz
Capacity	25 lbs (100 N)	50 lbs (200 N)	65 in-lbs (6.3 Nm)	65 in-lbs (6.3 Nm)
Resolution	0.01 lbs	0.02 lbs	0.03 in-lbs	0.03 in-lbs
Stiffness	44 klbs/in	420 klbs/in	310 kin-lbs/rad	81 kin-lbs/rad
Permissible Single Axis Overload	180 lbs	500 lbs	280 in-lbs	230 in-lbs

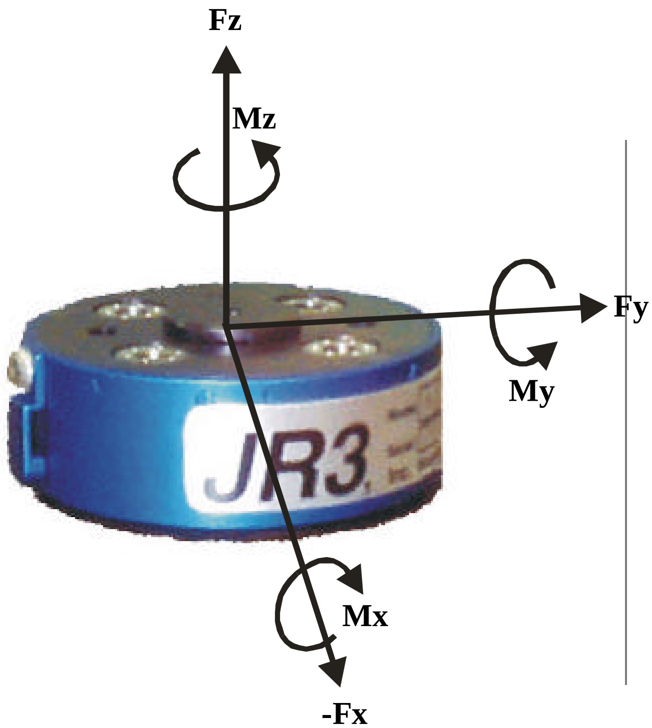


Figure G.1 Force and torque directions of the force torque sensor (note that negative Fx is shown)

Appendix H

Pinout connections for I/O modules

Table H.1 Pinouts of Ruby to Amplifier board 1

Pin number	Color	On Ruby	On Amplifier Board	Controls
1	Green	GND	Not connected	
2	Yellow	D/A V0	Amp 6 Vin	Arm waist
3	Orange	GND	Not connected	
4	Red	D/A V1	Amp 7 Vin	Arm shoulder
5	Brown	GND	Not connected	
6	Black	D/A V2	Amp 8 Vin	Arm elbow
7	White	Not connected	Not connected	
24	Purple	Not connected	Not connected	
25	Blue	Dout A7	Amp 6 brake	Arm waist
26	Green	Dout A6	Amp 6 direction	
27	Yellow	Dout A5	Amp 7 brake	Arm shoulder
28	Orange	Dout A4	Amp 7 direction	
29	Red	Dout A3	Amp 8 brake	Arm elbow
30	Brown	Dout A2	Amp 8 direction	

Table H.2 Pinouts of DMM-16 board 0 to amplifier board 0

Pin number	Pin number on DMM-16	Color	On DMM-16 board 0	On amplifier board 0	Controls
1	19	Green	Analog GND	Not connected	
2	20	Yellow	D/A V0	Amp 0 Vin	Drive motor 0
3	21	Orange	Analog GND	Not connected	
4	22	Red	D/A V1	Amp 1 Vin	Drive motor 1
5	23	Brown	Analog GND	Not connected	
6	24	Black	+15V	Not connected	
7	25	White	-15V	Not connected	
8	26	Grey	D/A V2	Amp 2 Vin	Drive motor 2
9	27	Purple	Analog GND	Not connected	
14	32	Red	Out 2	Not connected	
15	33	Brown	Dout 7	Amp 0 brake	Drive motor 0
16	34	Black	Dout 6	Amp 0 direction	
17	35	White	Dout 5	Amp 1 brake	Drive motor 1
18	36	Grey	Dout 4	Amp 1 direction	
19	37	Purple	Dout 3	Amp 2 brake	Drive motor 2
20	38	Blue	Dout 2	Amp 2 direction	

Table H.3 Pinouts of DMM-16 board 1 to amplifier board 0

Pin number	Pin number on DMM-16	Color	On DMM-16 board 1	On amplifier board 0	Controls
1	19	Green	Analog GND	Not connected	
2	20	Yellow	D/A V0	Amp 3 Vin	Drive motor 3
3	21	Orange	Analog GND	Not connected	
4	22	Red	D/A V1	Amp 4 Vin	Drive motor 4
5	23	Brown	Analog GND	Not connected	
6	24	Black	+15V	Not connected	
7	25	White	-15V	Not connected	
8	26	Grey	D/A V2	Amp 5 Vin	Drive motor 5
9	27	Purple	Analog GND	Not connected	
14	32	Red	Out 2	Not connected	
15	33	Brown	Dout 7	Amp 3 brake	Drive motor 3
16	34	Black	Dout 6	Amp 3 direction	
17	35	White	Dout 5	Amp 4 brake	Drive motor 4
18	36	Grey	Dout 4	Amp 4 direction	
19	37	Purple	Dout 3	Amp 5 brake	Drive motor 5
20	38	Blue	Dout 2	Amp 5 direction	

Appendix I

Mass Budget of Components

Table I.1 Mass budget

Mass of Mod 3 components			
Component	Units	Weight (oz) per unit	Component Mass (kg)
Amplifiers	2	3.5	0.198
Arm	1	13.8	0.391
Diamond A/D D/A	2	3	0.170
Encoder I/F	1	4	0.113
Force Torque I/F board	1	5	0.142
Force Torque sensor	1	6	0.170
Garnet DI/O	1	2.5	0.071
Hard drive	1	5	0.142
HE-104	1	6	0.170
NiCad battery pack	2	12	0.679
PC/104 Motherboard	1	15.5	0.439
Rover chassis, body, arm mount, and drive motors	1	110	3.113
Ruby D/A	1	3	0.085
Wireless Modem	1	3.5	0.099
Total		**211.3**	**5.98**

Appendix J

Functions

This appendix describes some of the functions used in the control code of the WRS and their relation to the hardware.

Drive

The *drive* function takes three inputs, sends information to the PWM amplifiers (Section 3.3) to control the motors, and returns no output. The three inputs are stored in variables called Factor, Direction, and Ampnumber. Factor is a floating point number between 0 and 5 which corresponds to the voltage to be output from the D/A converters to the amplifiers. Direction is either 0 (positive) or 1 (negative), giving the desired direction of rotation of the motor. Ampnumber is an integer denoting which motor is to be controlled.

The amplifiers are controlled by three inputs: a 0 – 5 volt analog input, a digital brake bit, and a digital direction bit. The analog input sets the duty cycle of the PWM output to the motors, while the digital inputs control which outputs of the amplifiers are positive and negative.

The D/A converters are set for unipolar operation between 0 – 5 volts. Giving the D/A's a value greater than 5 or less then zero will crash the control loop. *Drive* does not check the value of Factor, because the control loop is assumed to check if the commanded output is at the rails. Additionally, voltages above 5 volts may damage the inputs of the amplifiers.

Armdrive

Armdrive is identical to *drive*, but is used for the arm motors.

Stop

The *stop* function outputs 0 volts on all of the D/A converters used with the amplifiers and sets the brake bit of each amplifier to be high. This effectively makes the amplifiers open circuits as seen by the motors. *Stop* can be used to prevent integral windup when all the motors are desired to have zero velocity.

Brake

The *brake* function sets all the brake bits to be high and sets the output of all D/A's used with the amplifiers to be 5 volts. This shorts the outputs of the amplifiers and forces the terminals of the motors to the same voltage, preventing the rotors from turning. *Brake* is used to lock the position of the motors, and can be used to stop the WRS on a very steep slope or to hold the arm in a certain position with no power consumption in the motors.

Appendix K

Index of Manufacturers and Distributors

Component	Manufacturer	Manufacturer contact info	Distributor	Distributor contact info
PC/104 Motherboard	Aaeon Electronics	732-203-9300 www.aaeon.com	Tri-M Engineering	800-665-5600 www.tri-m.com
I/O Modules	Diamond Systems	800-36-PC104 www.diamondsys.com	Same	
HE-104 DC/DC	Tri-M Engineering	800-665-5600 www.tri-m.com	Same	
Force Torque Sensor	JR3	503-661-3677 www.jr3.com	Same	
Hard drive	Toshiba	www.toshiba.com	Compu-d	800-929-9333 www.compu-d.com
RAM	?		PC's for Everyone	617-868-0068 www.pcsforeveryone.com
Batteries	Makita	www.makita.com	Home Depot	
Aluminum body				
Encoder ICs LS7266R1	?		US Digital	800-736-0194 www.usdigital.com
Amplifiers LMD18200	National Semiconductor	www.national.com	Same for samples	
Connectors, cables, and various ICs	?		Digikey	800-DIGI-KEY www.digikey.com
Framelocker framegrabber board	Ajeco	358-9-7003-9200 www.ajeco.fi	Zytronix	408-749-1326 www.zytronix.com
Wireless Modems	National Semiconductor	www.national.com	Discontinued	

Appendix L

Budget

Grouping	What	From whom	Cost
PC/104 Computer			
	Motherboard ACM-4980	Tri-M	520
	Cable set	Tri-M	51
	DC/DC converter HE-104	Tri-M	330
	RAM	PCs for Everyone	62
	CPU	Ron Hummel	34.75
	CPU Fan	PCs for Everyone	13
	Hard drive	Compu-D	175
	Hard drive connector	Dalco	13
	Keyboard connector	Microcenter	4
	Floppy Drive	PCs for Everyone	26
I/O Cards			
	A/D DMM-16 x2	Diamond	891
	D/A RMM-8	Diamond	332.1
	Digital I/O GMM	Diamond	134.1
	Encoder Boards	Custom built	59.6
Misc			
	Misc connectors and cables	Digikey	298.13
	Batteries	Home Depot	65.86
	Force/Torque Sensor	JR3	2703
	Aluminum housing		119.26
	Wireless modem connectors	CompUSA	37
Total			5868.8