The Terregator Mobile Robot

Lee Champeny-Bares, Syd Coppersmith and Kevin Dowling

CMU-RI-TR-93-03

Field Robotics Center
The Robotics Institute
Carnegie Mellon University
Pittsburgh, Pennsylvania 15213

May 1991

This research was sponsored by The Robotics Institute. Later research efforts using the Terregator were sponsored by the US Bureau of Mines, DARPA and the EPA. Views are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the funding agencies.

1. List of Figures

Abstract

The Terrestrial Navigator, or Terregator, is a mobile robot device designed to provide a reliable and rugged testbed for both indoor and outdoor work in robotic navigation, guidance, sensor interpretation, and architectures. The design of mobile robot involves conflicting needs and a wide mix of disciplines. The Terregator design resolves many such needs through flexible and extensible mechanics, electronics, hardware and software. It is a six-wheeled skid-steer machine utilizing compliant tires for suspension, a hybrid power system provides for different modes and environments during operation and a rugged drive system and integral controller provide a complete package for doing robotics research.

1. Introduction

The Terregator (Terrestrial Navigator) is a driverless outdoor vehicle developed for autonomous navigation research. Application areas for autonomous vehicle technology include undersea exploration, transportation, hazardous waste mapping, material handling, and exploration of planetary surfaces.

Terregator subsystems include locomotion, power, computation, controls, wireless telemetry (serial links and two channels of UHF video), orientation sensors, and navigation payloads. The Terregator is more capable, adaptable, and survivable than indoor pilotless vehicles. Its six-wheel drive provides superior locomotion to negotiate three-dimensional terrain, and its power and scale enable it to overcome obstacles and grades that pose entrapment, tipover, or pitfalls to lesser locomotors. The Terregator can subtend moves of millimeter resolution at speeds of zero to several miles per hour. The vehicle is modularized to facilitate fault diagnosis, component changeout and system evolution.

In research to date, the Terregator has deployed three kinds of sensors: video cameras, a sonar ring, and a scanning laser range finder. See Figure 1-1 on page 8. The cameras give reflectance information, the sonar measures distance, and the laser scanner senses both. Using these sensing modes, the Terregator has successfully navigated sidewalks and off-road areas, and has mapped a portion of a mine. The Terregator supports evolution into fuller navigation systems with path planning and mapping capabilities. The extensible options provided by an adaptable vehicle are invaluable to the research setting. This project is committed to making significant advancement towards an autonomous vehicle capable of mobile tasks in an outdoor environment.

Figure 1-1 Terregator with camera and wireless telemetry navigating on CMU sidewalks.

2. Terregator Project Summary

The complete removal of the human "from the loop" is a desirable but distant goal in several industries where the human worker is endangered by unavoidably hazardous duties. Tasks in construction, mining, nuclear facility maintenance, material handling, and the military submit workers to unexpected bombardments by potentially lethal objects and substances such as structural steel, concrete debris, radiation, chemical wastes, and shrapnel. These tasks may also mandate that the worker function at great heights with unstable footing, or in environmental extremes of heat and cold. The human is required in these situations partially because of physical strength and dexterity, but more often it is the human's decision making abilities that make his presence mandatory as the closing arc of a task "loop". In response to this dilemma, that we seek a substitute, or stand-in, to remove the worker from the immediate hazards of such tasks. Although a solution which leaves the human as an interactive bystander, "once-removed" from physical danger, would be satisfactory, the "ultimate" solution should encompass the judgmental responsibilities of the task and perform without human intervention.

The term "autonomous vehicle" is indicative of technological developments destined to meet the needs of hazardous working conditions, but the total definition of this term has not yet been achieved. The abilities of such a vehicle should mirror those of a human to have mobility which is unhindered by a cluttered and unpredictable environment; to communicate with task supervisors; to have moderate dexterity; to be self-sufficient in providing power; and to function in a manner which is non-destructive to the task or operating environment. Attaining such a vehicle requires the successful integration of a mobile base, communications and control networks, sensory devices, and navigational guidance systems to achieve a prototypical "intelligent machine".

A mobile base, or locomotor, which will transport the remaining components of an autonomous vehicle should negotiate through rough terrain and over minimal obstacles without being constrained by the presence of dust or precipitation. The locomotor must be agile, self-powered, controllable, and have some rudimentary navigation method.

Appropriate for the control of this mobility is a complete on-board computer, linked to an off-board intermittent supervisor. The on-board computer will be required to control all vehicle motions, interpret sensory data acquisitions, plan and monitor the execution of navigational trajectories, and perform diagnostic testing on vehicle components.

Communication between the vehicle and its supervisor should be through some form of wireless telemetry so that the vehicle's range is not restricted. The features essential to an appropriate navigation guidance system include a sensory system which can acquire information from any operating environment, while the vehicle is in motion. The guidance system should accurately decipher the vehicle's location and interactively assist in navigation. Finally, all components should not be effected by vibration, shocking blows, temperature, radiation, precipitation or electromagnetic interference.

In the development of autonomous vehicles, no single project has attempted to be inclusive of all features listed above. The goals of most vehicle projects have been justifiably narrowed to produced semi-autonomous, remote, or utility vehicles which operate in predictable environments, performing specified tasks. Automatic guided vehicles (AGVs), used extensively for material transport, have been designed to operate without human guidance in “rigged” indoor environments. These vehicles commonly use rudimentary sensors to follow a cable or stripe of paint, i.e. “rigged” navigation, and cannot negotiate any unexpected obstacles. They do, however, provide good mobility over smooth surfaces. The lunar roving vehicle built for the Apollo space program has contributed to autonomous vehicle technology. Although it was not intended to operate without human passengers, the lunar rover is considered here because it was primarily used to lower the dangers of lengthy exploratory missions in space. The rover was manually controlled, but its environmental hardening, navigational sensors, and extreme mobility are appropriate for many autonomous applications. Other examples of vehicle technology can be found in undersea welding and exploration, transportation, and waste handling. These developments represent several active interests in vehicle technology and the continued efforts which may evolve into a class of vehicles worthy of the term “autonomous”.

Some evolutions in vehicle technology are currently producing specialized devices to enrich a vehicle with more capable control, communications, power and sensing. Two such projects have been ongoing at Carnegie-Mellon University’s Robotics Institute: the development of visual sensing, and acoustic based navigation systems. The recent focus of these projects has been to develop perceptive and guidance abilities for use on an autonomous road following vehicle. These specialized developments have progressed to a stage where they need to be mated to a vehicle for empirical testing and expansion of navigation control. In response to these immediate research needs, and to generally progress toward a successful integration of mobility, control, communication and sensing for use in hazardous environments, the Terregator vehicle project was completed.

The Terregator is viewed as a shuttle whose initial missions will deploy artificial vision for guidance and acoustic sensing for obstacle avoidance. This vehicle will continue to support these experiments as they evolve into fuller navigation systems with path planning and mapping capabilities. The Terregator is evolving as a testbed for these and other experiments, providing an adequate, reliable base which can be utilized by a contingent of sensing and control devices.

The long range goals of the Terregator project are not to produce the autonomous vehicle. This goal is achievable only through progressive developments of system components, integration of these components, and the control and guidance of a working vehicle. This project is committed, however, to making significant advancement towards an autonomous vehicle capable of mobile tasks in an outdoor environment.

3. Vehicle Design Specification

3.1 Vehicle Objectives

The functional objectives of a vehicle system should always be used to discern the appropriate vehicle features and attributes. If decisions made during the design of a vehicle are responsive to too many "desirable" objectives (i.e. indoor/outdoor use, large payload capacity, small working envelope, powerful, quiet operation, fast, maneuverable etc.), then compromise among objectives is imminent. I.e. trying to be all things to all people. Compromise in moderation can create a vehicle system with broad utility; but compromise in excess results only in multitudes of "half" solutions which threaten both immediate and future success of a vehicle system design.

A "multi-purpose" autonomous vehicle is not likely to perform all of its objectives with equal competence. Competition is inherent between drastically differing functional objectives, and the varied motivations to create a "generic" system are an added cause for compromise in design. Generic designs inevitably "miss" on most accounts, partially due to the incomplete consideration of each objective separately, but primarily because it is extremely difficult to solidify design compromises into a satisfactory "middle ground". A vehicle design based on a variety of general objectives does, however, have the redeeming aspect that the generalities of the "multi-purpose" vehicle can be refined and evolved into offspring vehicles of more specialized utility.

If the other extreme is taken to design a single-purpose vehicle, the potential of the project outcome is restricted to a solitary objective. No peripheral considerations of vehicle adaptability, utility, or alternative uses narrow design objectives. Vehicle projects which have been so ambitious as to attempt a "perfect" single purpose vehicle have been confounded often by technological problems or other contingencies which may severely impact the success or timing of deployment. Even when narrow solutions come to fruition, the product may be so limited in its uses that it becomes prematurely obsolete. Vehicles not built with future development in mind rarely provide an adequate foundation from which more advanced systems can evolve. The success of a narrow project is only momentary and limits the evolutionary options provided by an adaptable product.

In a developmental project where objectives are changing "on the fly", it is essential to avoid the extremes of "multi" and "mono" purpose solutions by identifying the primary objectives of the product. In the adolescent field of autonomous vehicles, developments are particularly sensitive to unbalanced design objectives. An appropriately targeted vehicle system will not only insure a successful initial execution, but also the future utility and continuance which an adaptable solution can offer.

The desire to achieve a stable balance between generality and narrowness has heavily influenced the design of the Terregator. The Terregator project has sought to develop a vehicle not governed strictly by either general or specific objectives. The scope of the project has been limited to the production of a land-based vehicle with primarily outdoor capabilities, but the general challenge of producing an advancement in the state of this technology opened an unlimited selection of implementation objectives.

The primary functional objective of the Terregator has been to perform as an exterior shuttle for experimental perceptive navigation devices. The vehicle was also designed to be utilized as a remotely operable working vehicle capable of demonstrating its utility in a variety settings such as mining, hazardous waste disposal, construction, transportation and the military.

To insure that the utility of the vehicle was sufficiently broad, additional applications were considered for the Terregator. If the navigation experiments were discontinued for any reason or no longer utilized the Terregator, the vehicle can be adapted to other applications. However, this desire to maintain the utility of the vehicle was not taken to the extreme of satisfying the entire “wish-list” propagated by experimental payloads; the minimum requirements of the navigation experiments were used to narrow, but not entirely restrict the vehicle capabilities.

The following required features of a vehicle system are common to the specific purposes of the navigation experiments as well as the utility of other applications:

- Over-Land Mobility: The vehicle should sustain lengthy missions over rough terrain, around and over obstacles.
- Speed: The vehicle should provide controllable low speeds for developmental/ exploratory missions, as well as higher speeds for roadway operations.
- Off-Board Control and Communications: Supervisory real-time control of the vehicle should be performed remotely, by some reliable, wireless form of communication.
- On-Board Control: The vehicle’s low-level motions should be controlled and monitored on-board. The option to perform supervisory control on-board should also be available for the use of navigation support devices.
- Power: The on-board vehicle power should be sufficient for day-long support of all drive, control and communication components, and some unanticipated payload electronics.
- Sensing: The vehicle should be equipped with minimal sensors which will at least prevent it from endangering humans, other objects in the environment, and itself.
- Environmental Hardening: The sensitive components of the vehicle should be protected from weather, dust, shock, and vibration.

In addition to these specific vehicle attributes we intended to produce a vehicle which was an advancement in the field of autonomous vehicles. We specifically sought an integration of rugged locomotion, control, communication and sensing which surpasses previous small-vehicle integrations, remains moderately adaptable, and provides a base for future enhancements of vehicle technology. This was a prevailing objective throughout the project, and there was constant consideration given to system unity rather than ingenious or extravagant designs of individual components.

Secondly we wished to maintain modularity throughout all components in the vehicle system. Modularity, in this sense, is the separation of sub-component groups or individual components based on their functions. Subsystems and interfaces were identified during the early design of the vehicle. Modules, such as control, mechanical drive, sensing, communications, and power, are both physically and functionally separable from one another. Modularity primarily allows for easy component change-outs during production (if a component is inappropriate), after production for purposes of maintenance or for extensibility of the vehicle.

Even without detailing the specific requirements of the vehicle, it is obvious that a consistent method for dealing with conflicting objectives and restrictions was necessary during design. In the interest of maintaining the utility and extensibility of the vehicle, an unspoken rule was operative within the project: If a specific objective of an ad hoc vehicle user sought an extreme compromise which threatened the broad utility of the vehicle, then the objective was not accommodated. For example, the 30 inch vehicle width desired by some (to allow the vehicle pass through interior doorways) was not allowed to dictate the reduction of payload area and the on-board space for the power generator, motors and other systems. The conflict was settled by compromising the 30 inch width requirement, but efforts continued to minimize the vehicle's width. Alternatively, if a specific objective was deemed essential to the vehicle's adequacy as an experiment host, then no effort was spared to meet the requirement.

The functional design objectives outlined above are the rough framework from which the Terregator was designed and implemented. The desired vehicle functions expressed by the specific interests of experimental navigation payloads were used to augment the design of a vehicle which is a successful integration and an advancement as a testbed autonomous vehicle.

3.2 Design and Production Constraints

The Terregator, designed to support various sensors, supplies a mounting surface on the maneuverable base vehicle. The real-time computer control of this base had to be accessible to onboard and offboard navigational devices to allow interactive control of the vehicle's motions.

3.2.1 Design Constraints

The design of the Terregator was initially constrained by the requirements of two sensory navigation modes currently being investigated by Carnegie-Mellon University's Robotics Institute - acoustic navigation and vision navigation. The Terregator was conceived as a controllable, mobile base to deploy and develop these navigation modes. The vehicle, therefore, had to supply a mounting surface on a maneuverable base vehicle; but more importantly, the real-time computer control of this base had to be accessible to on-board or off-board navigational experiments to allow interactive control of the vehicle's motions.

Typical experiments require the vehicle to operate in indoor environments for initial development, and inevitably outdoors to fully test the operation of these navigation experiments. Initially, the size of the vehicle was thought to be extremely important. Principle users of the vehicle were interested in indoor experimentation, but many of the facilities they intended to use are restricted by narrow doorways. The width constraint was relaxed as experimental interests shifted to outdoor operations. The vehicle's width became a non-issue when it was noted that there were sufficient indoor facilities for unrestricted slow, short range, protected testing. The importance of indoor testing was eventually de-emphasized as research focused on navigation in outdoor environments.

3.2.2 Production Constraints

Perhaps the strongest constraint imposed on the production, and hence on the design, of the Terregator was time. When the Terregator project was begun in May, 1984, the deployment of the navigation experiments was intended to begin four months later. Quick production was also required by the urgency of other projects which the Civil Engineering and Construction Robotics Laboratory was to undertake upon completing the Terregator.

The vehicle production was informally constrained to be completed in August 1984, and as a result the production was restricted by material and component availability. If a component or material dictated by the initial design of the vehicle was not available, or would delay the completion of the vehicle, then the component had to be reconsidered. If no substitute was available, then the initial design was revised. Whenever possible, pre-configured items such as gearing or computer components, were commercially obtained. The efforts of even the most capable group of individuals are not likely to result in a product whose quality or price is equal to what may be commercially available. These production guidelines were supported by the project's initial objective of producing a state-of-the-art integration, not simply individual components, in a short time frame.

The universal constraint of available funding, although present, did not unduly force many of the production decisions. The economy of this project will not be further discussed, as this report is primarily to present the technical aspects of the vehicle.

3.3 Design Specifications

The functional objectives and design constraints presented to this point did not provide a sufficiently detailed specification of the vehicle's components. Many decisions about the best system configuration or appropriate components were made in the course of the initial design. Decisions were based on the intent of stated objectives and relied heavily on experience and knowledge of other vehicle projects to produce a workable design. The design specified prior to production of the vehicle is outlined below. Each heading is related to a functional objective or constraint which was considered in the design of the Terregator.

- Climbing, Maneuverable Locomotor. The Terregator's locomotor was designed to fulfill the functional objective of rugged, capable, over-land mobility. Minimum locomotor performance standards, required the ability to get over an obstacle of 6" (i.e. similar to curbs. stairs, small logs etc.), and maintain traction on steep grades. A six wheel drive, skid-steer[1]. locomotor was chosen with a ground clearance of

1. Skid steering indicates that each side of the vehicle is independently powered; a military tank uses this type of steering. Turns are executed on a six wheel vehicle by driving one bank of three wheels forward and the other bank in reverse. Thus, "skidding" occurs when the front and rear wheels are forced sideways in the turn as the vehicle pivots on the center wheels

6” and a drive train capable of steadily dead-lifting 2000 lbs (drawbar pull in excess of total vehicle weight: 1000 lbs estimated for vehicle weight, and 1000 lbs maximum payload).

- Communications. A reliable, wireless form of communication between the vehicle and a remote supervisor using a bi-directional radio link was specific to the initial vehicle design. This form of communication provides a transparent transfer of commands to the vehicle, feedback from the vehicle, and it can be utilized over long range missions.
- Reliable Vehicle Control. To achieve control of the vehicle’s drive mechanisms, as required by the navigation experiments, a single board, augmented computer was specified for use on-board the Terregator. This computer was mounted in an extensible enclosure allowing for future additions to the control electronics. To insure reliability, an uninterruptable power supply was selected to be placed in-line with all control electronics.
- Indoor/Outdoor Operation and Power. The desire to operate the vehicle both indoors and out required that it would produce little noise and pollution when operating in enclosed areas, while not limiting the distance or operation time of outdoor missions. Because outdoor missions could be lengthy, over great distances, and un-manned, a tether link to a stationary power supply was not an option. The use of an on-board battery was also precluded for the same reasons as well as the excess weight, limited life and recharge time which batteries imply. The primary power supply selected for the vehicle was specified as a portable, 4000 Watt, electric generator, sized according to the maximum estimated demand of on-board and payload electronics. For extended indoor use, a tether to a standard 15amp outlet was provided.
- Protective Sensors. To satisfy the objectives of sensing to ensure human and vehicle safety, proximity or contact sensors were intended for use on the vehicle. In addition, a video camera was to be mounted on the vehicle to transmit images to a receiver at some remote location.
- Accurate Dead Reckoning Navigation. To maintain the vehicle’s independence from the sensory-based navigation devices it will deploy, and as a “check on these systems once they are operational, the vehicle should have a minimal self-navigation system. This can be supplied by an accurate dead reckoning drive train. To facilitate accurate dead reckoning navigation[1] the Terregator’s drive train includes DC servo motors with attached high resolution optical shaft encoders, elliptical gearing, a tensioned chain drive to wheel shafts; motor controller boards which access motor shaft position, velocity and acceleration; and a later addition of a directional gyroscope and inclinometers to supplement encoder feedback position readings.

1. Dead reckoning is a rudimentary navigation method in which a continuous count of incremental moves, usually wheel rotations, integrates to provide the vehicle’s position.

- Payload Area. To accommodate experimental or other payloads, one half of the electronics enclosure and the entire top surface of the vehicle were to remain unused by vehicle components.

These descriptions were used as the Terregator's initial design specifications. These vehicle features have evolved into the final configuration described in the following chapters.

4. Terregator Vehicle Description

4.1 Introduction

The Terregator is an outdoor vehicle designed to deploy experimental navigation devices. It is a six wheeled, skid-steer, remotely operable vehicle which can self-navigate to a commanded destination using on-board computer control and orientation sensing devices. Supervisory commands which assist this navigation can also be given by an off-board computer or a human operator through a remote console and a transparent radio link. The vehicle and the experimental navigation devices which it has been designed to carry are both still under development. However, the near future promises a working coordination in which the navigation devices will sense the terrain and obstacles near the vehicle and actively guide the vehicle through unknown environments without human supervision. To explain the vehicle's function, operation, and compatibility with navigation or controlling systems, are the following sections describe of the vehicle's components and their general configuration.

4.2 General Configuration

The Terregator has six major subsystems: locomotion, power, control, communication, orientation, and a remote console. The locomotor consists of a mechanical drivetrain and a support frame. The power system generates and distributes power and protects sensitive components. The control system consists of a microcomputer and periphery. Communication is achieved through wireless RS-232 and microwave links. The orientation system has a gyroscope for heading information and two inclinometers for pitch and roll readings. The remote console houses offboard components for operating the vehicle.

The Terregator, Figure 4-1 on page 18, is a rectangular base frame with six wheels, three on either side. From the front and rear of the base frame, four vertical members of the square tube roll frame extend upward. These members support the upper horizontal members of the roll frame that form a rectangular envelope around the top of the vehicle. The rack mount enclosure is suspended from these upper members at six points such that it is not in direct contact with the base frame, isolating the rack mount enclosure from shock or vibration that might be transferred from the base. The sides of the cabinet adjacent to the wheels are covered by removable panels; the top of the cabinet is used as an upper mounting deck. The rack mount enclosure is located above the base frame extending from the front of the vehicle, back about two-thirds of the vehicle's length. The remaining third of the vehicle's top plate is covered by the power generator, mounted directly to the base frame and remaining within the protective envelope of the roll frame. The vehicle is about 3' high, 3.5' wide, and 5.5' long.

Figure 4-1 Terregator

The function of each subsystem is as follows:

- Locomotor: Supports, protects, and mobilizes the vehicle and experimental payloads.
- Power: Generates and distributes power for all vehicle electronics and provides uninterruptable power to sensitive electronics.
- Controller: Processes motion commands and controls vehicle motion.

- Telemetry: Bi-directional link allows high-level commands and data to be transferred between vehicle and supervisor.
- Orientation: Sensors detect the vehicle's orientation and provide feedback to the navigation devices.
- Infrastructure: Supports the vehicle before, during and after its expeditions.

The following descriptions specify each component's function, summarize its appearance and composition, identify its association with other vehicle components, and specify power requirements where appropriate. Additional component drawings, photographs, and wiring diagrams are included in the appendix, along with itemized listings of the vehicle's power

The vehicle presently navigates through its environment and hosts navigation experiments using the integration of on-board components, wireless telemetry, and a remote console. Major on-board components include the mechanical drive train and support frame, the electronic control system, the radio and microwave communication units, the orientation sensing devices, and the power generation, distribution and interrupt protection system. The off-board remote console is a peripheral link to supervisory computers and/or personnel; it houses a radio communication transceiver, a video receiver and monitor, and an operator terminal. Although this station is essential to the operation of the vehicle, it is only a rough composition of peripheral electronics and was not part of the major vehicle development. Therefore, this off-board component will be described only briefly following the specification or the vehicle's on-board control components.

4.3 Locomotor

The locomotor transports, houses, and supports all onboard vehicle components, as well as any experimental devices or payloads. A skid-steer locomotor was chosen with a ground clearance of 6". The locomotor has a drive train capable of steadily dead-lifting 2000 pounds. Two banks of three drive wheels are each linked to two electric motors via chain-on-sprocket drive and gearing. The locomotor's base frame houses these drive components, as well as supporting the upper roll frame, electronics cabinet, and power generator. The three main structural components of the locomotor are the base frame, the roll frame, and the rack mount enclosure. They house and support the vehicle's drive train and electronics. The roll frame is the locomotor's prominent superstructure; it supports and protects the vehicle's rack mount enclosure. The rack mount enclosure houses the vehicle electronics not contained in the base frame and provides additional space for experimental devices or vehicle payloads on the enclosure's upper deck.

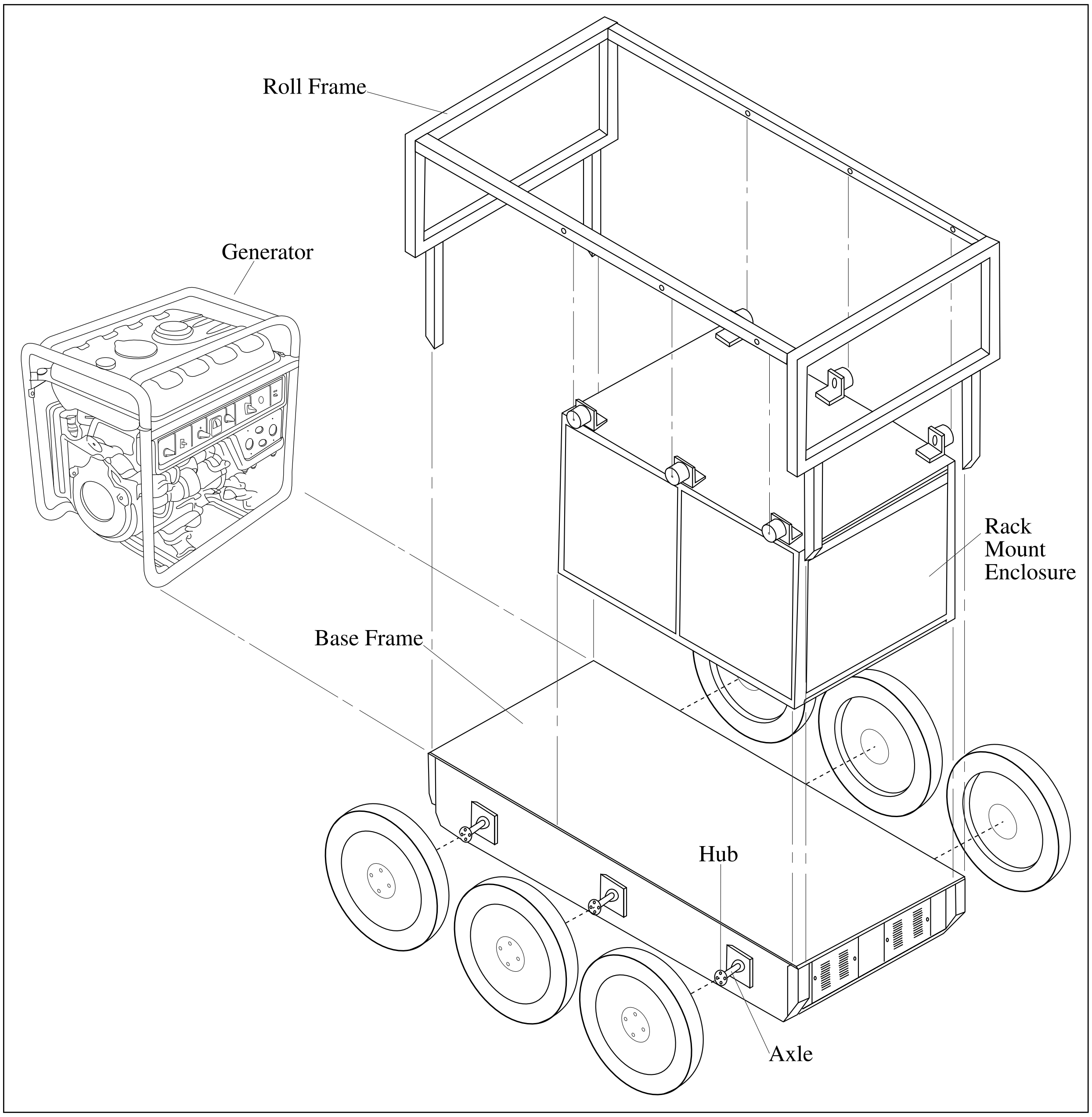

Figure 4-2 Mechanical layout of the Terregator

4.3.1 Base Frame

The rectangular base frame is the enclosed mounting area for the mechanical and electronic components that are directly responsible for the controllable transfer of electrical power into vehicle motion. The base frame is also the foundation for mounting the upper roll frame and the power generator.

The base frame is a steel box, see Figure 4-3 on page 22, 26” wide, 59” long, and 8” deep, elevated 6” above the ground by the vehicle’s wheels. The internal components of the base frame are concealed by a top plate that has threaded mounting holes centered on a four inch grid. This hole pattern is used to attach the generator and other equipment to the base frame. Mounted on the inside of the base frame’s front and rear walls are four ventilation fans that draw cooling air through the base frame. The drive axles extend through six bearing blocks supported by the side walls of the base frame support. Mounting holes through the side and bottom walls of the base frame are used to secure these and the other mechanical drive and electronic components contained within the base frame. A C-section stiffening plate is welded to the underside of the bottom plate to prevent lateral torsion of the base frame. A transverse stiffener across the top of the base frame also prevents the side walls from bowing outward when loaded.

The base frame and its enclosed components form a unit that is electrically and mechanically separable from other vehicle components. Detachable connections between the base frame and the upper roll frame are found at four external mounting blocks on the front and rear walls of the base frame. The generator is also bolted to the base frame on the rear section of the top plate. The only electrical connections to the base frame are two cables that terminate inside the base and have connectors mated inside the rack mount enclosure. One cable provides power to the base frame electronics and the other transfers control signals and data to and from the drive motors.

4.3.2 Motors and Drive Train

Within the enclosure of the base frame, the two drive motors are linked to the mechanical components of the drive train, i.e. gears, sprockets and chains. Each bank (left and right) of three wheels on the vehicle is driven by a single motor linked to an independent gearing set, sprocket combination, chain drive, and set of three wheel axles. The two drive assemblies for the left and right banks of wheels are identical, but they operate independently to steer the vehicle. The motors can be driven in either direction, thus causing the vehicle to move forward, back, left or right.

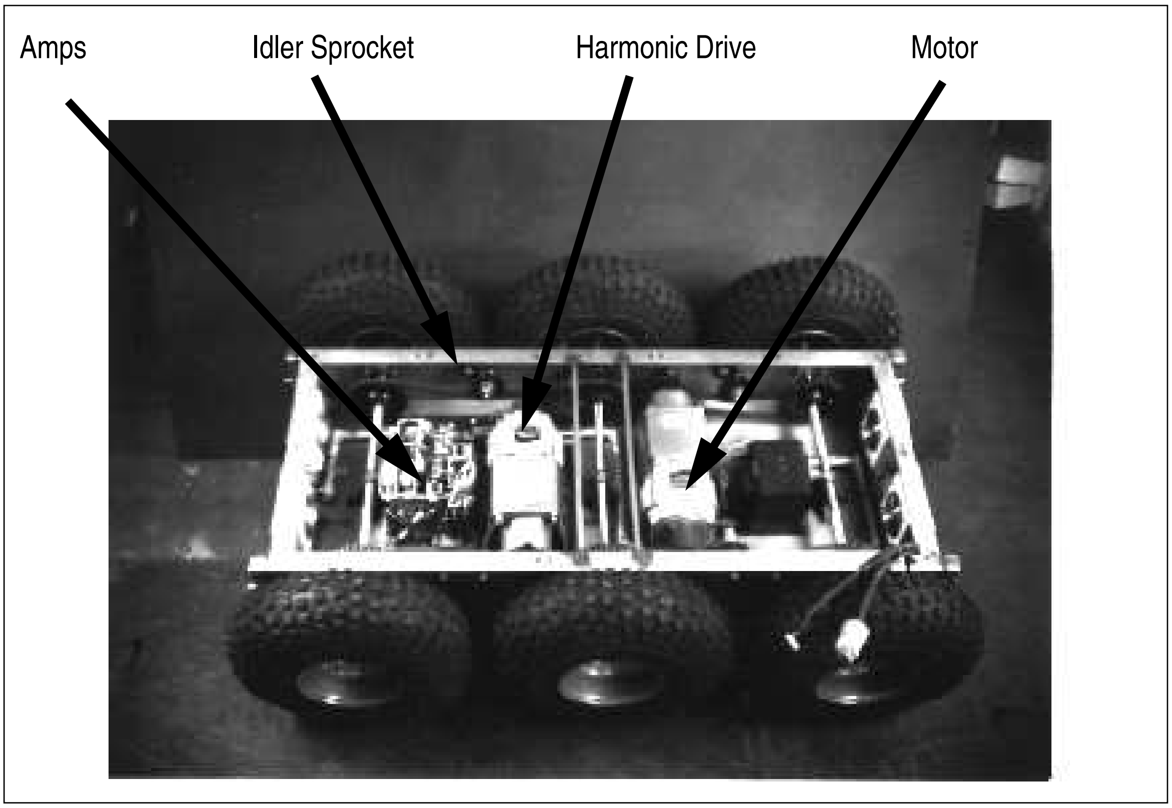

Figure 4-3 Terregator base frame and interior components.

The motors are brushed, electric, 120 VDC with attached optical shaft encoders. Each motor is coupled to Harmonic Drive gearing through an adapter plate, and the output from these gearing units is 80:1. The main drive sprocket attached to the output shaft of the gear unit can be changed to alter the vehicle's top speed and climbing torque. The top speed available from such a change-out is 4.8 mph.

The motor and gear assembly drives the wheel axles through a series of drive chains and sprockets, See Figure 4-4 on page 23. The first, or primary chain, passes around the main drive sprocket on the gear assembly out put shaft and then onto the center axle sprocket. The center axle sprocket then drives the front and rear axle sprockets through the secondary chains. All drive chains are #58 5/8 lifetime lubricated chains. The chains are isolated from the environment by the confines of the base frame, but are not shielded further.

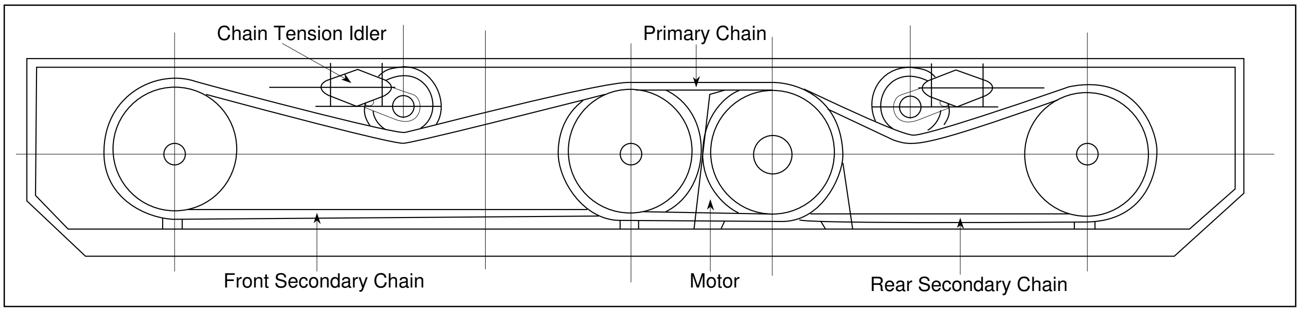

Figure 4-4 Axle Assembly

During assembly and periodic maintenance, both sets of chains can be tensioned independently. The primary chains are tensioned by loosening the motor mounts, sliding the motors to reposition the main drive sprocket, and then tightening the mounts. The secondary chains are tensioned using stationary idlers attached to the interior side wall. On each side wall there are two stationary tensioners: one between the center and rear axles to tension the rear secondary chain, and one between the center and front axles to tension the front secondary chain.

Each of the six driven wheel axles carries a drive sprocket on the interior of the base frame and extends through the side walls to support a hub and wheel. See Figure 4-6 on page 26. The axles are aligned and supported along the center line of the base frame on independent stubs, and again at the side wall by a greased flange roller bearing. All sprockets in the drive train are held in place on their respective axles by split taper bushings and key-ways. Hubs, located on the outside portion of each wheel axle, are mounted in a similar manner and can be positioned anywhere along the exterior portion of the axles. This flexible positioning of the hubs accommodates wheels of differing widths. The wheel rims are bolted to the four studs on each hub.

Several different wheels, each consisting of a rim and pneumatic tire, can be used on the vehicle for a range of traction, ground clearance, side clearance, and dead reckoning accuracy. The tires are all-terrain vehicle tires. Low pressure, 20” x 7” knobby tires provide a large amount of traction and are designed primarily for climbing over obstacles or steep inclines. These tires elevate the base frame about 5” off the ground and make the vehicle 41” wide, but decrease the dead-reckoned precision because of their compliance.

Other tires used include high pressure, 20.5” x 5”, shallow tread tires that are used for small farm equipment and have fair traction characteristics. On the vehicle, these tires are used for low grades and flat surfaces, and they are still able to carry the vehicle over obstacles such as stairs. With these tires, the vehicle’s ground clearance is about 6” and the vehicle width is 37”. These high-pressure tires increase the vehicle’s dead reckoning accuracy because they do not deform significantly. Both types of wheels can be mounted on the hubs, and although the standard configuration is to have all six tires of the same type, alternate configurations include mixing tire types among the six wheels. Experiments with the vehicle primarily use all six knobby tires, although a configuration of knobby tires on the center wheels and smoother tires on the front and rear has been tried successfully.

Electronics

The components enclosed by the base frame include several electronic devices to maintain the flow of power to the drive motors. After the main power and signal communications cables enter the base frame through a grommet in the top plate, they are contained by two separate metal conduits that are routed along the bottom interior surface of the base frame. One conduit is devoted to carrying power cables. It routes a 120 VAC line from the primary power source to a grounded distribution strip accessed by the 4000 watt power transformer and the rear cooling fans.

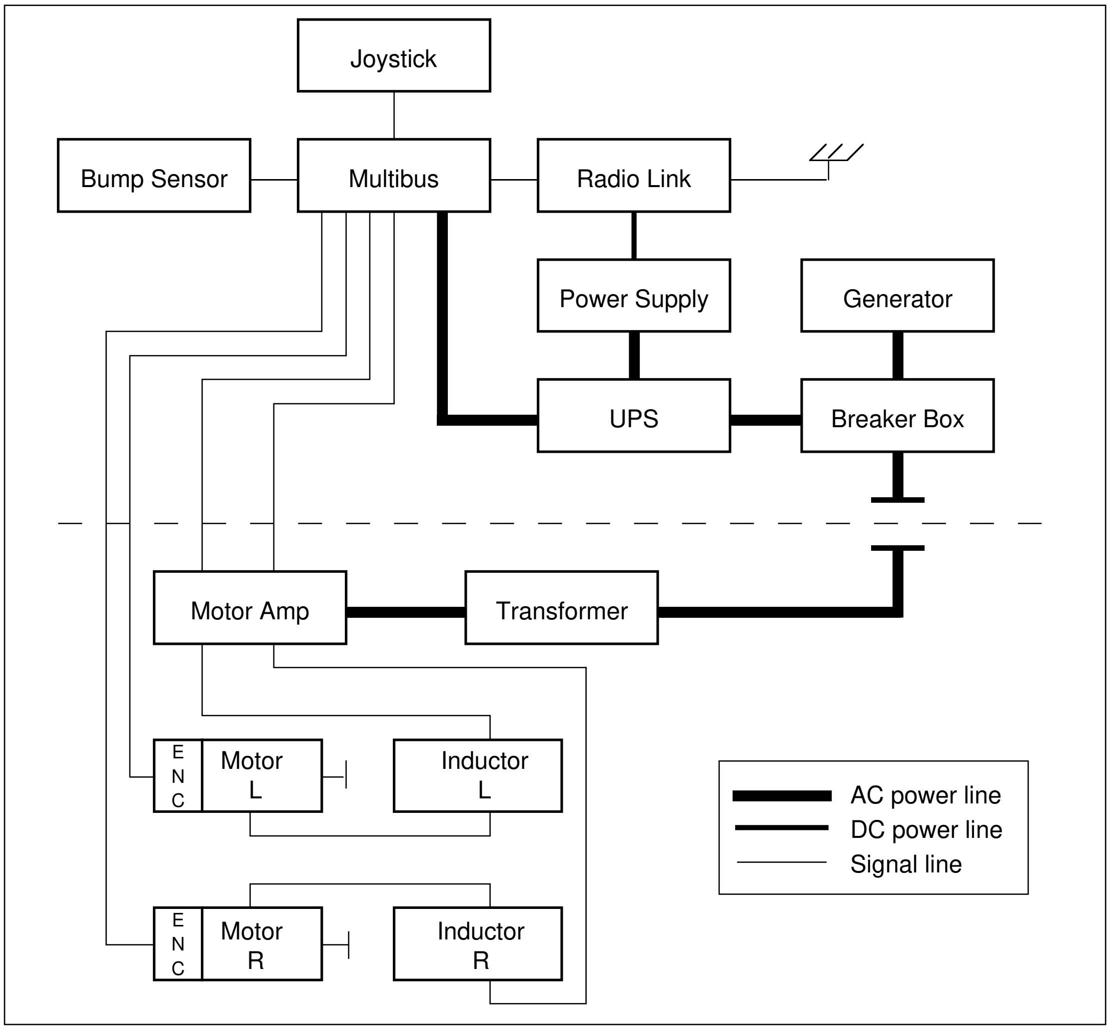

Figure 4-5 Electrical layout for the Terregator

Power is transformed from 120 VAC to 72 VAC and returned to the power routing conduit by the terminal strip; it is then routed around both motors and to the power amplifying unit. This unit contains two pulse width modulated amplifiers, a capacitor, a diode bridge, and two inductors. The second routing conduit also terminates at the amplifying unit after carrying the signal communications line in a similar but continuous route from the wire duct around the motors.

Inside the amplifying unit, +10 volt and -10 volt signals from the motor controllers are used by each amplifier to modulate the power to the motors, which is in the form of 100 VDC pulses. This requires that the 72 VAC from the transformer be changed to 100 VDC through a diode bridge before entering the amplifiers. Each motor is regulated through independent amplifiers. As modulated power exits each amplifier, it is cleaned by an inductor and then routed back through the power conduit to each motor. Once power is received and consumed by the motors, encoder feedback of motor shaft rotation is routed through the signal communications conduit and returned to the motor controllers. The amplifying unit also provides 120 VAC for the front cooling fans.

4.3.3 Roll Frame

The roll frame protects and supports the rack mount enclosure. It protects the enclosure from possible damage inflicted either by obstacles protruding into the enclosure or by sudden contact with the ground during a roll-over. The roll frame supports the rack mount enclosure from six mounts along its upper horizontal members. These mounts are compliant neoprene cylinders that act in pure shear to prevent large impulsive forces from being transferred to sensitive electronics housed in the rack mount enclosure. This mounting system suspends the enclosure 2” above the top plate and allows it to displace vertically and horizontally while dissipating jolts.

The roll frame forms a protective envelope of 1.5” square steel tubing around the rack mount enclosure and the generator. See Figure 4-2 on page 20. The vertical end frames, bolted to the front and rear of the base frame, extend slightly beyond the leading edges of the generator, the rack mount enclosure, and the base frame. These end frames are permanently welded to the horizontal upper members. The upper members run along the length of the vehicle, above the enclosures and generator, and are spaced slightly wider than the base frame to protect the sides of the enclosure and generator, closing the roll frame's protective envelope.

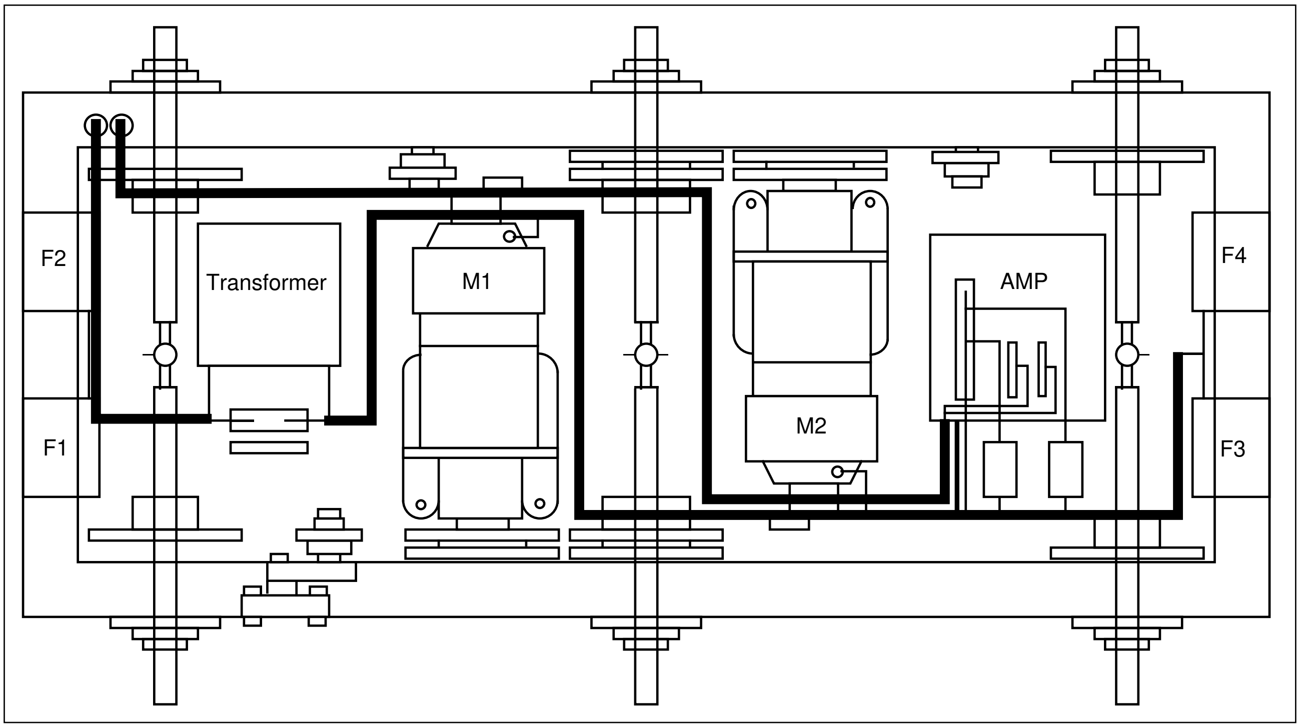

Figure 4-6 Base frame mechanical layout and cabling layout

4.3.4 Rack Mount Enclosure

The rack mount enclosure provides a protected, accessible mounting area for electronic components not contained within the vehicle's base frame. The enclosure also prevents foreign objects from damaging the electronic components. This seclusion of the electronics within the rack mount enclosure does not, however, prevent access or removal of these components for maintenance or adjustment. The top surface of the enclosure also provides additional mounting area for components such as video cameras and radio antennae. The upper mounting deck does not protect against damage, but does protect against large jarring forces. The entire enclosure is protected by the roll frame and its neoprene shock mounts.

The enclosure is composed of two steel sided, aluminum frame rack mount compartments securely bolted together and joined across the top by the upper mounting deck. Together, these two cabinets form an enclosure that is 26" wide, 41" long, and 19" high. The accessible sides of the enclosure open out over the right and left sides of the vehicle and are normally covered by removable panels. The front, rear, and bottom walls of the enclosure are permanently sealed and have only one opening for conductors entering and exiting the enclosure. This opening is located in the wall of the rear compartment (adjacent to the generator) and is a rectangular hole, 2.5" x 2", lined with a neoprene grommet. The interior of the enclosure is fitted with standard rack mount hardware that secures the following components:

Front Compartment

- The Multibus Enclosure for onboard computing electronics is mounted on rack mount sliding guides in the upper half of the cabinet. This unit can slide out over the right side of the vehicle and is covered by a 7” wide panel on the exterior of the enclosure.
- The Uninterruptable Power Supply (UPS), located directly below the Multi-bus enclosure in the front compartment, is bolted to the rack mount frame. The front of the UPS is covered by a 10.25” louvered ventilation panel located on the right side of the enclosure.
- Two Cooling Fans are mounted on the interior of the front cabinet, immediately behind the Multibus enclosure. They are attached to the 8.75” panel that covers the rear of the Multibus enclosure, located on the left side of the front cabinet. The fans draw air through two grilled openings in this panel and into the rack mount enclosure to cool the electronics and the UPS.
- The Power Distribution Box, located below the cooling fans on the left side of the front cabinet, is bolted to the rack mount frame directly behind the UPS. The box is covered by an 8.75” panel and has a block of four circuit breakers extending through an opening in the panel.

Rear Compartment

- The Radio Transceiver, mounted on sliding rack mount guides in the bottom of the rear cabinet, has a cover panel permanently attached to its face. This unit can be accessed by sliding it out over the right side of the vehicle. When the rack mount enclosure is mounted on the vehicle, this operation also requires removal of the right center wheel because the radio unit is located slightly below the top of this tire. The rear of this unit is covered by a 7” panel on the left side of the enclosure.
- The Orientation Sensing Unit, containing one gyroscope and two inclinometers, is mounted above the radio transceiver on sliding guides. It is covered by a 12.25” panel and can slide out over the left side of the vehicle, above the wheels. The rear of this unit is covered by a 12.25” panel on the left side of the rack mount enclosure.
- The Switching Panel provides on/off control of devices mounted on the Terregator.

The rack mount cabinet is located over the front two-thirds of the base frame, but it does not come into direct contact with the base frame. The enclosure is shock mounted to the roll frame and rides 2” above the top plate. The rack mount enclosure can be detached from the vehicle by unbolting the roll frame and lifting it off with the enclosure attached, or by unbolting the enclosure from its mounts on the roll frame and lifting it off independently. When the enclosure is removed from the vehicle, the power and control cables routed into the enclosure from the generator and base frame must be disconnected. The cable that brings power to the vehicle (via the generator or wall outlet) is routed from its soldered connection at the power distribution box within the enclosure, through the enclosure’s wire duct, to a 30 amp connector outside the enclosure. When removing the enclosure, this cable is disconnected and the length of cable with the female connector end remains with the enclosure.

A second cable, transferring power to the base frame, is routed from an outlet plug on the distribution box to a soldered connection in the base. The routing of the signal communication line from the Multi-bus enclosure to the base frame is made in a similar way using an RS-232 connector at the rear of the Multi-bus enclosure and a soldered connection to the amplifying unit in the base frame. Both of these conductors, which terminate in the base frame, must be disconnected inside the rack mount enclosure and threaded out through the wire duct when the enclosure is being removed from the vehicle.

4.4 On-Board Control System

An augmented mono-board microcomputer controls the vehicle's drive mechanisms onboard. This microcomputer is mounted in an extensible enclosure allowing for future additions to the control electronics.

The two primary operations of the onboard control system are the processing of motion commands and position information. Both of these operations are essential to the complete execution of command flow from offboard supervisors to the vehicle's positioning systems. The vehicle's onboard control system consists of a central processing unit (CPU) linked to motor controllers, an analog-to-digital converter (ADC), a serial line expander, and orientation devices. The CPU receives commands from an offboard supervisor and executes programs residing in onboard memory to transfer the appropriate signal communications to the motor controllers. The onboard supervisory software programs are continuously evolving to meet the needs of experimental deployments by offering a variety of commands to operate the vehicle.

The offboard supervisory control is distinguished as high-level control in comparison to low-level, onboard control. This distinction is made to emphasize the different types of control that are involved in the vehicle's operation. At the remote console, the supervisor (either a human user or a another computer) makes high-level decisions that specify goal destinations and orientations. These complex commands are conveyed to the vehicle and then decomposed by the CPU into low-level commands that directly control the onboard devices responsible for the vehicle's motion, position, and orientation.

During vehicle operations, the onboard computer maintains a data structure to inform the supervisor about available high-level command options and the status of the low-level control operations. The user can access information about valid commands, the vehicle's location, and its orientation. This information is displayed on the remote station terminal or can be accessed by the offboard computer. The display is always available during vehicle operations that involve low-level control by programs residing in onboard memory.

All programs for the on-board control of the vehicle are written in the C programing language and are retained by the CPU's. non-volatile memory. Additional or alternate software can be down-loaded to the vehicle's processor from off-board computers, allowing a variety of operating schemes. The operating scheme presently in use on the vehicle offers the user numerous commands, some of which are point to point moves comprising the following basic commands:

- The Move command takes as its argument a distance measured in millimeters. The vehicle then translates either forward or backward.

- The Turn command takes as its argument an angle measured in degrees. The vehicle then pivots to the right or left on its center wheels.
- The Arc command executes an arc-shaped path between two points. The arguments required are a distance in the Y direction (along an axis running from the center to the front of the vehicle), the X direction (transverse to the Y axis), and an angle orienting the destination state relative to the initial state. As with the previous commands, distances are measured in millimeters and angles in degrees.

Also available are several commands which can be used to “drive” the vehicle while it is in motion. As the vehicle travels in a continuous path composed of arcs, the direction of its path can be altered at any time by the user. However, as these are recent software developments, the details of these commands will not be documented here.

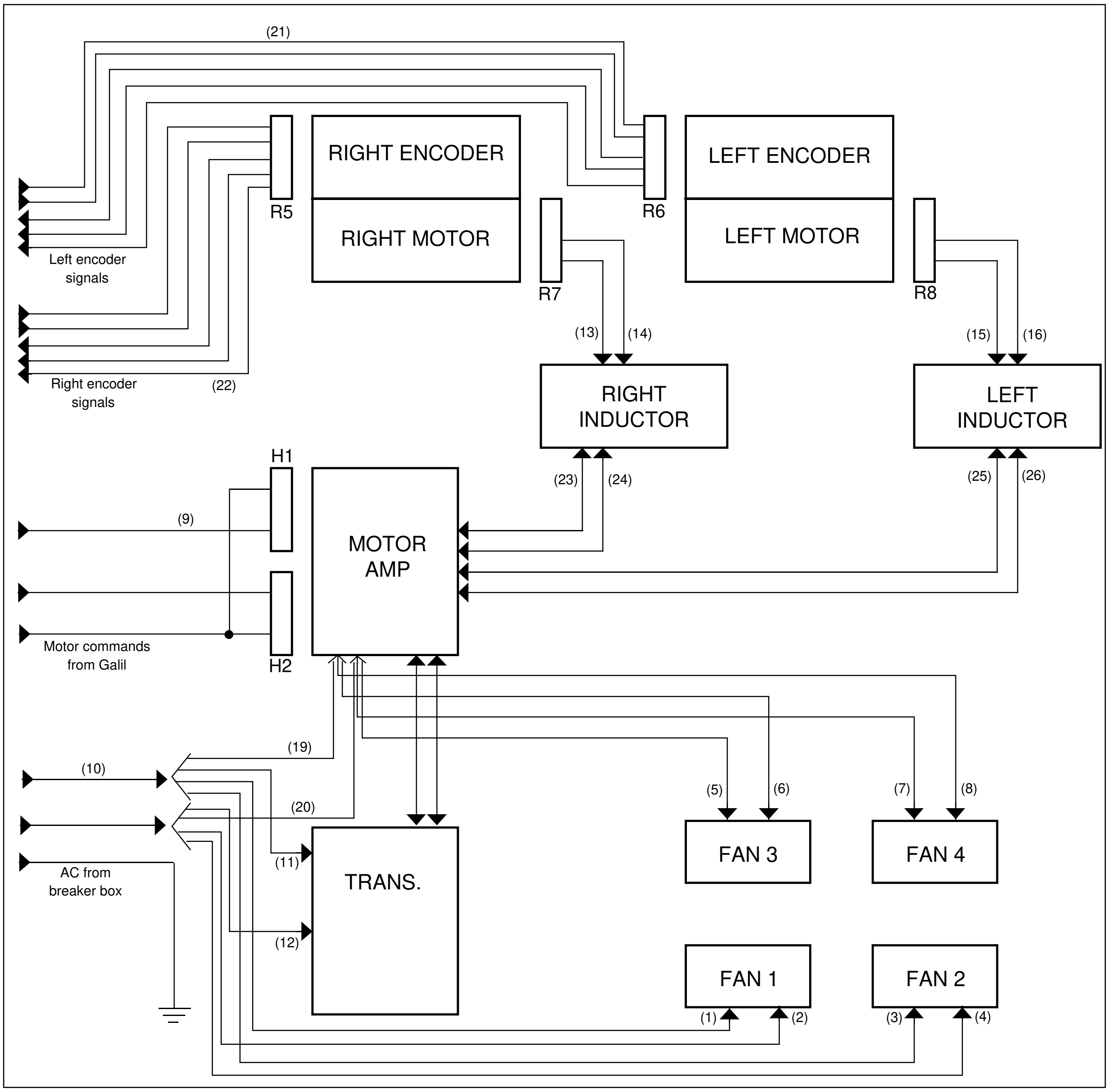

Figure 4-7 Terregator command and control signals

Command processing on the Terregator is performed by a Motorola 68000 single board CPU with 256K of non-volatile memory and two serial communication ports. During normal vehicle operations, one port is linked through the vehicle's bi-directional radio transceiver to the display/command terminal located in the remote command station. This terminal is used to display information on low level operations and to accept user commands. The other communication port on the CPU remains open to be linked with any processors that may be placed on-board to supplement experimental payload operations.

Control signals communicated to the CPU over the bi-directional radio link are processed by the CPU and then routed through a serial expansion board and a 16/32 channel A/D board. Low level commands corresponding to motor control are routed from the CPU, through the interrupt driven serial expansion board, to the motor controllers. The A/D board (also interrupt driven) is accessed by the CPU to obtain position and orientation readings from the gyroscope and inclinometers. These devices are remote to the multi-bus enclosure, but are connected to the unit through a ribbon cable entering the front of the multi-bus. The A/D board, located on a board adjacent to the serial board, also returns encoder status to the CPU along the same route.

Control of the vehicle's drive motors is performed by two DC servo motor controllers mounted together on a blank board inside the multi-bus enclosure. Each motor has a devoted controller, which receives instructions from the CPU and operates the power amplifiers located in the base frame. The motor controllers operate using direct position feedback from the motor encoders, and can be operated to control the motor position, velocity and acceleration.

Each electronic component is mounted in one of ten slots provided by the enclosure's bus strip. Power is provided to electronic components inside the Multibus through a 40 watt power supply connected to the UPS. These components are cooled by two 50 cfm fans mounted inside the Multibus enclosure. The enclosure was slightly modified by attaching rack mount sliding guides and replacing the front panel on the unit. The Multibus is located in the front compartment of the vehicle's rack mount enclosure and can slide out over the left side of the vehicle. The electrical power for this unit, supplied by the UPS, is accessed through a terminal strip in the rear cabinet. Power to the radio transceiver from one of two 110 VAC outlets is also located in the rear of the unit.

4.4.1 Joystick Controller

A joystick controller allows manual operation of the vehicle. When in use, this device is set to override any other control systems, i.e. the on-board computer or off-board supervisor. The joy stick is used primarily as a method of maneuvering the vehicle while software maintenance and development are ongoing. This device is considered only a temporary method of controlling the vehicle, and will no longer be of use once the vehicle's software control is completed.

The joystick is a rectangular metal box, approximately 4" by 5", with several switches on its top surface. The joystick is connected directly to the vehicle's motor controller boards via a tether. The control override button which is located on the joystick is used to shift the vehicle between computer control and joystick control, and also serves as an emergency kill button, immediately stopping the vehicle's motion. Separate control of the vehicle's left and right banks of wheels can be achieved using two independent toggle switches located adjacent to the override button. A final button, located in the center of the joystick, is depressed to enable the drive motors. Note that the motor velocity and acceleration cannot be set from the joystick, (programed default values are used) and vehicle position and orientation information is not available.

4.5 Remote Console

This console houses the off-board components associated with the vehicle's operation. It provides rack mount storage areas for communication and control components such as an operator's terminal, the stationary radio transceiver, the microwave receiver, and video monitors. The remote console is mounted on castors, and is thus moderately portable.

4.6 Telemetry System

Two telemetry links transfer information between the vehicle and the remote command station. The primary information link is a bidirectional radio transceiver that is used to transmit control and feedback data. A secondary link is provided by a microwave video transmitter that sends images from the vehicle to the remote command station.

4.6.1 Radio Serial Rs-232 Link

The radio link is formed by two identical transceiver units; each unit is capable of both transmission and reception of signals on the appropriate wavelength. One unit is located in the remote command station, and serves to transmit supervisory commands to the vehicle. This stationary unit also receives data on the vehicle's position, orientation and the commands which are available through the vehicle's on-board computer. The other transceiver, mounted on the vehicle, transmits the position, orientation and command status, and receives the supervisory control commands from the remote station. The information exchange between these two transceivers forms a transparent link that facilitates controlled vehicle operations in areas remote from the command station.

Radio transmissions occur over licensed FM frequency in the 400 MHz range. Each transceiver is an RS232 full duplex modem, transmitting data at 1200 baud, and using manchester keying protocol. The power requirements of this unit are provided by a 12 Volt power supply attached to the back of the transceiver. The mobile radio transceiver is rack mounted on the vehicle and slides into the bottom of the rear cabinet. The antenna for this unit is bolted to the top plate of the rack mount enclosure.

4.6.2 Microwave Video Link

The microwave video link is a 2 GHz system that transmits visual images from a single camera on-board the vehicle to a monitor in the remote console. This information is used primarily to test vision-based navigation experiments.

The camera is mounted on a rigid tripod which reaches to a height of about 6 ft. This assembly is bolted to the top plate of the rack mount enclosure and can be relocated anywhere on the top plate. An actuated, self-leveling pan and tilt for this camera is being developed to replace the tripod, and will reside on top of the front compartment of the rack mount enclosure.

4.7 Orientation Sensors

Two kinds of on-board orientation sensors provide information on the vehicle's orientation relative to a set coordinate frame. The primary sensor is a directional gyroscope which reports the angle through which the vehicle rotates in the horizontal plane. The secondary sensor is a dual axis inclinometers which determines the vehicle's rotation about its lateral and transverse axis. The information provided by both sensors is used by the vehicle's navigational software to maneuver the vehicle through turns and/or maintain a constant heading. These sensors are mounted on a common plate in the rack mount enclosure along with the accessory electronics, such as power supplies and data processing units, that they required to operate.

4.8 Power Supply System

The power supply components supply, distribute, and protect against interruption of electrical power onboard the vehicle. Power is supplied to the vehicle either by the onboard generator or an extension cord connected to a wall outlet. These alternate power sources are available to cater to different operating modes. The onboard generator is used during outdoor operations that may cover large distances. A stationary, offboard power source for the vehicle is used when the vehicle is operated in confined areas where noise and fumes from the generator are offensive. Power distribution to all onboard electronics originates from the main distribution box and is transferred to vehicle electronics through a conductor network. An Uninterruptable Power Supply provides clean, continuous power to the vehicle's control system and maintains the controlling software in the event of a loss of normal power.

4.8.1 Generation

When operating outdoors, the vehicle uses a gasoline powered, 4000 watt, portable generator to supply all onboard power. See Figure 4-8 on page 34. This unit is positioned between the vehicle's rear wheels and mounted to the top plate of the base frame. It supplies 120 VAC directly to the distribution box via a 50 amp connector and cable.

The generator consists of an air cooled, electric start, 4-stroke, single cylinder engine with a displacement of 406cc and a compression ratio of 6.8:1. It operates at 3600 rpm and has a rated draw of 32 amp. The rated AC output frequency is 60 Hz and the DC output is sufficient to charge a 12 volt starting battery. The generator is approximately 26" long, 17" wide, 24" high, and weighs 187 lbs. A 4.4 gallon gas tank allows the generator to run for six hours. Vibration insulating mounts are situated between the mounting tabs and the engine mounts to prevent the transfer of excess vibrations.

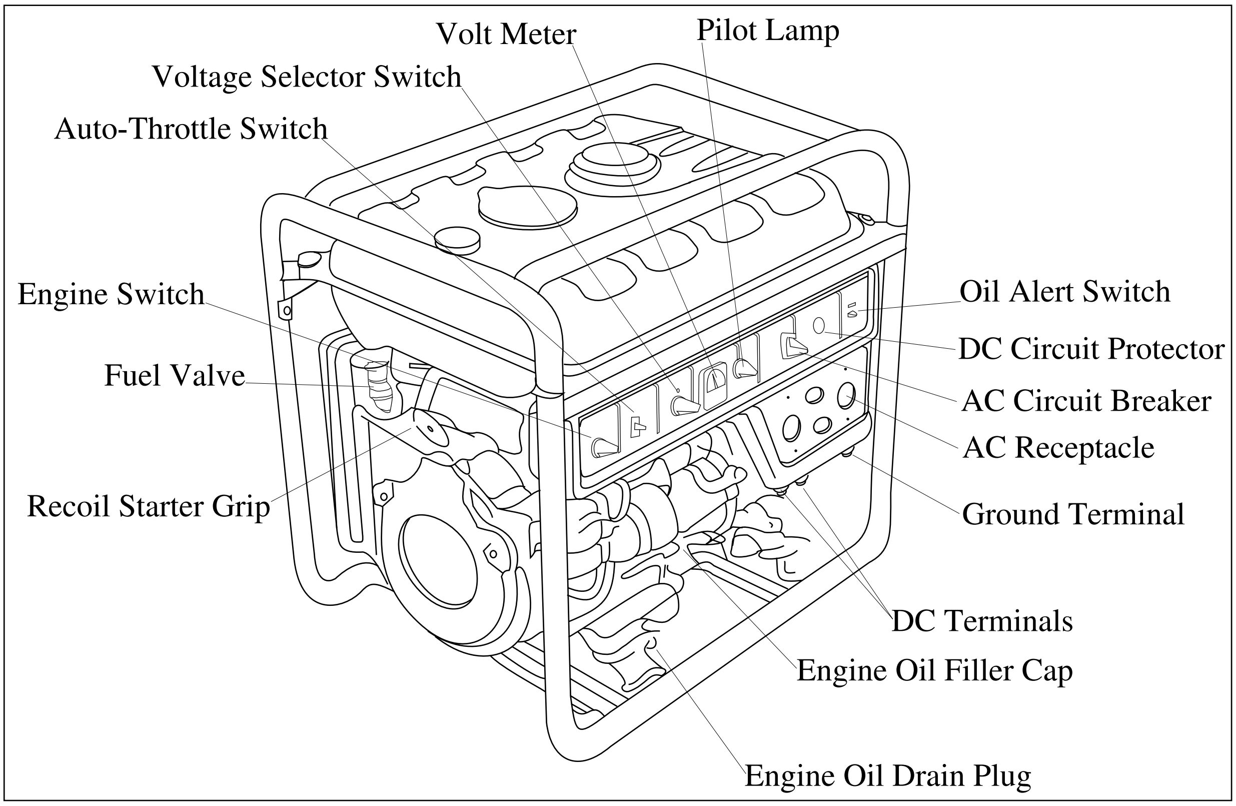

Figure 4-8 Power Generator

Modifications made to the generator for use on the vehicle included altering the output plug, redesigning the battery mount, and mounting the generator to the base frame. Because the generator is positioned directly behind the rack mount enclosure, the original outlet plug was not accessible by the conductor coming from the distribution box. An outlet box was made from stainless steel and attached to the left side of the generator (over the left side of the vehicle). This outlet contains a 50 amp female receptacle that has been wired to the original generator outlet. Attached to the present receptacle is the re-designed battery mount. The battery mount was relocated because the original mount extended outside of the roll frame’s protective envelope. The present mount is a stainless steel box, open on top, and supported by a bar attached to the generator’s frame. The generator was mounted to the base frame with a steel plate bolted over the generator’s mounting frame. This plate holds the generator stationary and did not require any modification of the generator’s mounting frame.

For prolonged periods of operation indoors, the vehicle can be connected to any available 120 VAC outlet equipped with a 15 amp grounded receptacle. A 100’ extension cable was made specifically for this purpose. It has a 50 amp, twist lock, female connector that attaches to the vehicle and a 15 amp male connector to plug into wall outlets.

4.8.2 Distribution Power

The distribution box allocates power to the vehicle's electronic components and prevents these components from overloading the main electrical circuit. The distribution box routes the main power through a block of circuit breakers to the base frame, the Uninterruptable Power Supply (UPS), and the rack mount enclosure's cooling fans.

The cable that transmits power to the circuit breakers, wired directly to the block of four breakers and a ground strip, passes through a strain-relief duct in the wall of the distribution box. There are three 15 amp breakers and one 30 amp breaker. All breakers, except an unused 15 amp breaker, are wired to bulk-head connectors in the side of the distribution box. The 30 amp connector is devoted to the conductor that transmits power to the base frame electronics. One 15 amp connector is used to transmit power to the UPS, and the remaining connector is used to supply power to the rack mount enclosure's cooling fans.

The distribution box is a modified commercial enclosure and can be accessed through the bottom panel on the left side of the rack mount enclosure. The box is 10" x 8" x 4" and contains the four-breaker block, a ground strip, and three bulkhead connectors. The box is attached to an aluminum mounting bracket and bolted to the bottom of the rack mount enclosure, directly behind the UPS. The interior of the box can be accessed by removing the panel that covers this portion of the enclosure. The circuit breakers remain exposed through a square cut-out and can be reset without removing the panel.

4.8.3 Protection

In addition to the circuit protection provided by breakers in the distribution box, the Uninterruptable Power Supply (UPS) protects the vehicle's electronics from being over or under powered. The UPS insures uninterruptable power to the computing components, especially in the event of a loss of primary power to the vehicle. The UPS also provides continuous, regulated, and noise-free power to the computing components during normal power supply conditions.

The UPS consists of three basic parts: the rectifier, the inverter, and the battery. The rectifier takes in AC power, delivers DC to the inverter, and recharges the battery. The inverter converts DC power to AC power at 120 VAC. The battery is continuously charged by the rectifier until the power fluctuates or is interrupted. This power filtration system alleviates various problems that can occur during motor-generated power such as voltage dips, black outs, frequency variation, or momentary interruption.

The UPS on the vehicle is rated by the manufacturer to have an output of 750 watts at a frequency of 60 Hz and 120 VAC.

5. Evaluation and Conclusions

5.1 Evaluations

As the Terregator is part of an evolving technology, it is essential to acknowledge the successes and failures of this vehicle's design. This evaluation will begin with a discussion of the vehicle's failures and successes in meeting the specific objectives outlined in earlier chapters. The vehicle satisfies most of the design objectives, and therefore this evaluation will only discuss points of extreme failure or success.

Perhaps the vehicle's largest shortcoming is its inability to self-navigate over great range and variable terrain. The indeterminacy of skid steering limits the achievable accuracy of dead reckoning by step counting. The inherent skidding which occurs during turning motions limits the usefulness of maintaining incremental counts of wheel rotations as a determinate measure of travel distance. This source of somewhat subtle error is not easily nullified by some "fudge factor". The error incurred in a turning depends on the roughness and inclination of the ground surface.

Deficiencies of the locomotor include its incomplete seal against moisture. One problem is the ventilation into the base; although filtered for dust, the ducts can inhale water into the base, threatening the operation of several electronic components. Additionally, there is an upper bound on onboard power available for experimental payloads. Payloads are also limited by available space on top of the Terregator and by the number of components inside the rack mount enclosure.

Distinguishing features of the Terregator include its climbing and maneuvering ability. Stairs, curbs and other obstacles approximately 6 inches high pose no difficulties. Skid steering has given the vehicle considerable maneuverability with mechanical simplicity not found in complex axle steering mechanisms. Pivoting turns allow navigation in constricted areas and precludes the need for complex planning and maneuvering required to navigate three-point turns. Finally, the vehicle's motion control is flexible, motor acceleration and velocity control is precise, and the Terregator is compatible with interactive navigation experiments.

5.2 Experiments

Brief descriptions of three Terregator experiments that demonstrated perceptive navigation, and a fourth in progress, follow. More detailed descriptions of these experiments can be found in articles listed in Appendix II: Terregator Research.

In the first experiment, the Terregator followed a road through a park. Using a video camera to collect data about the road, the system computed gradients throughout the image to detect the road edges, and then plotted a course down the middle of the road. In another exercise, the Terregator navigated off road using range data (sonar, laser, or stereo video) to navigate around trees.

In the second experiment, we adapted the Terregator to navigate a network of campus sidewalks. See Figure 1-1 on page 8. This adapted system consisted of a vision subsystem, a navigator, a predictor, a position estimator, and a map of the network. Given the goal "proceed to intersection seven," the Terregator plotted a course through the network, calculated a predicted model of the scenery expected on the way, and used the observed sensor data to verify its course, correcting the estimated position along each step of the path.

In the third experiment, the Terregator mapped and navigated a portion of a coal mine. This experiment integrated the Terregator's local navigation software and acoustic sensing with a composite model builder. The Terregator traversed a short piece of the mine, mapping the walls and creating a network of seventeen goal positions. The map was proven to be accurate and the integrated system performed flawlessly. Subsequently, the Terregator navigated the same mine using data from the scanning laser range finder and made turning decisions based on its generated map. See Figure 5-1 below.

The Terregator currently deploys a mobile scanner used for experiments in mapping subsurface pipes. The scanner, a wheel mounted, single axis gantry, deploys various sensors along a path transverse to the vehicle's motion. The Terregator was selected as the deployment vehicle because it allows controlled maneuvering of the gantry, is equipped with a suite of sensors for position encoding, can host necessary scanner computing, and is proven for field use.

Figure 5-1 Terregator with laser scanner navigating in a coal mine.

5.3 Conclusion

The Terregator has been a very successful project. The vehicle is transporting and interacting with experimental payloads in outdoor environments. The Terregator has been well conceived, speedily produced, and well received. The vehicle is modular and remains adaptable to a variety of uses and operating environments.

This project did not intend to create the “ultimate” autonomous vehicle, and it is not surprising that there is a call for upgrades to the present vehicle. These may include additional on-board power, computing, payload area, and improved navigation abilities. The Terregator can endure some extensive revisions and change-outs without losing its initial identity or negating its purpose. But when these alterations become significant enough the threaten that identity, then it is perhaps prudent to allow newer vehicles, siblings to the Terregator, to overcome its deficiencies

A. Weight and Power Budgets

A.1 Itemized Vehicle Weight

- Locomotor Weight
    - Wheels and axles: 6 at 27 lbs. — 162 lbs.
    - Chains and sprockets: — 50 lbs.
    - Chassis frame: — 170 lbs.
    - Gearing: 2 at 60 lbs. — 120 lbs.
    - Motors: 2 at 27 lbs. — 54 lbs.
    - Amplifier: — 16 lbs.
    - Fans: 4 at 3 lbs. — 12 lbs.
    - Roll Frame: — 70 lbs.

Subtotal — 654 lbs.

- Environmental Enclosure
    - Breaker Box: — 12 lbs.
    - Enclosure housing: — 105 lbs.
    - Multibus: — 40 lbs.
    - Uninterruptable power supply (with batteries): — 120 lbs.
    - Radio: — 30 lbs.
    - Fans: 2 at 3 lbs. — 6 lbs.
    - Power Supply: — 5 lbs.
    - Hardware: — 10 lbs

Subtotal — 328 lbs.

- Primary Power Supply
    - Generator: — 200 lbs.
    - Battery: — 5 lbs.

Subtotal — 205 lbs.

- Collision Prevention Device
    - Bumper — 15 lbs.

Total Vehicle Weight: — 1530 lbs.

A.2 Itemized Power Budget

Maximum Demands for Vehicle Operations

• Drive motor amplifiers (2 at 1400 watts each)	2800 watts
• Motor control boards	40 watts *
• Multibus	225 watts *
• 68 K boards	60 watts *
• Radio	60 watts *
• Ventilation fans (6 at 50 watts each)	300 watts
• IR collision sensors	60 watts *
Total	3545 watts
Maximum Power Supplied to Vehicle	4000 watts
Maximum Power Available for User	455 watts

* UPS Protected 445 watts

B. Bibliography

1) Adams, Walt, “Robot Vehicles Move Into Manufacturing”, Robotics Today ‘82 Annual Edition, Robotics International Society of Manufacturing Engineers, Dearborn,Michigan; 1982.

2) Apollo Program Summary Report, “Vehicle Development and Performance, Lunar Surface Mobility”, National Aeronautics and Space Administration Houston, Texas; 1975.

3) Billet, A.B., “RCV-150 Remotely Operated Vehicle and its Operation in the Hostile Undersea Environment”, Proceedings of the Robotics and Remote Handling in Hostile Environments National Topical Meeting, April 23-27, 1984; American Nuclear Society Inc., Chicago, Illinois.

4) Boyle, Stanley Robert, “Remote Working Vehicles For Use in Nuclear Environments”, Masters Thesis Submitted to Civil Engineering Dept., Carnegie-Mellon University July 1984

5) Dobson, J.S.;Penoyre, S., “Automatically Controlled Road Vehicles”, Conference on Control Aspects of New Forms of Guided Land Transport, Institution of Electrical Engineers; Savoy Place, London WC2; 1974

6) McNair, James M., “Designing Robots For Demilitarization of Obsolete Chemical Munitions”, In Proceedings of the Robotics and Remote Handling in Hostile Environments National Topical Meeting, April 23-27, 1984; American Nuclear Society Inc., Illinois.

7) Pollard, Brian W., “RAM for Robots: Reliability, Availability, Maintainability”, Robotics Today ‘82 Annual Edition, Robotics International, Society of Manufacturing Engineers, Dearborn,Michigan; 1982.

8) Whittaker, William L., “Terrestrial Navigator - Terregator”, A Proposal Submitted to The Defense Advanced Research Projects Agency, The Robotics Institute, Carnegie-Mellon University; July 1984.

9) Whittaker, William L., Personal Conversations Feb. 1983 - Dec. 1984.

B.1 Personnel Acknowledgments

The following persons were responsible for the design, production and early use of the Terregator Vehicle:

John Bares, Spencer Barrett, Steve Berman, Dale Birosh, Lee Bares (nee Champeny), Kevin Dowling, Kerien Fitzpatrick, Chris Fromme, Chris Harrington, Herman Hueng, Kathy Kelleher, Jim Kelly, Doug Larson, Keith Lay, Kai Lee, Rob Markovich, Jim Martin, Don Maszle, Tom Puckett, Susan Simone, John Wadsworth, Chuck Whittaker, Red Whittaker.

C. Addendum 1991

This Terregator Report has not seen the light of day for years due to many reasons, mostly other projects. In December of 1984 Lee Champeny had compiled the first major draft of the document and in the following year Syd Coppersmith edited it. The effort never reached critical mass and I picked it up in early 1991. In the meantime, the mysterious Terregator technical report had been referenced many times by the CMU community!

I acquired the old Scribe versions from backups stored in salt mines. They were done an an ancient DEC-20 machine and later versions were done on a VAX-750, also in Scribe. I then reformatted the documents in Framemaker, visciously edited the text and finished it. Thanks to Mary Jo Dowling for creating shiny new Postscript versions of the drawings and diagrams and to Mike Blackwell for getting this stubborn creature to print!

Over the years Terregator has become the centerpiece of many robotic works and as of this writing is being used by Jim Osborn's Site Investigation Robot group to support deployment of ground penetrating radar devices for sub-surface mapping.

Terregator technical developments have moved to other machines and evolved over years into large programs. This includes the Navigation Laboratory and HMMWV, driverless vehicles for studying outdoor navigation and also the Locomotion Emulator for mine vehicle emulation. This also includes the more recent planetary rover developments such as the Ambler, Erebus and APEX programs. Additionally, some of the earliest development in robot software architectures were first tested on the Terregator.

Changes over the years have included upgraded controllers and wiring. The original Multibus 68K board system gave way to a i386 Multibus system using PL/M for development. In the late 1980's a complete revamping of electronics resulted in a versatile electronic patching system and a new VME bus based 68020 controller. New amplifiers were also installed at that time. Additional telemetry to support high-bandwidth devices such as new cameras and laser scanners were also added.

Through all of this, the general configuration and purpose of the machine has not changed. Plus, it keeps on ticking.

Kevin Dowling May 1991.

D. Recent Terregator Research

1) Christian, D.A., B. Motazed, J.F. Osborn, and D. White, "Automated Subsurface Mapping," 1989 Annual Research Review, The Robotics Institute, Carnegie Mellon University, 1990.

2) Goto, Y., K. Matsuzaki, I. Kweon, and T. Obatake, "CMU Sidewalk Navigation System, Proc. of Fall Joint Computer Conference, pp 105-113, Nov. 1986

3) Hebert, M. and T. Kanade, "Outdoor Scene Analysis Using Range Data," Proceedings, IEEE Conference on Robotics and Automation, April 1986.

4) Kanade, T., C. Thorpe, and W. Whittaker, "Autonomous Land Vehicle Project at CMU," Proceedings, ACM Computer Conference, Cincinnati, OH, February 1986.

5) Osborn, J.F., "Automated Subsurface Mapping," Proceedings of the Second International Symposium on Field Screening Methods for Hazardous Waste and Toxic Chemicals, Las Vegas, February, 1991.

6) Wallace, R., K. Matsuzaki, Y. Goto, J. Webb, J. Crisman, and T. Kanade, "Progress in Robot Road Following," Proceedings, IEEE Robotics and Automation Conference, April 1986.

7) Wallace, R. A. Stentz, C. Thorpe, H. Moravec. W. Whittaker, and T. Kanade, "First Results in Robot Road Following," Proceedings, International Joint Conference on Artificial Intelligence, Los Angeles, CA, August 1985.

8) Whittaker, W., "Cognitive Robots for Construction," Annual Research Review, The Robotics Institute, Carnegie Mellon University, Pittsburgh, PA, December 1985.

9) Whittaker, W. et al., "Mine Mapping by a Robot with Acoustic Sensors," Proceedings of the Second International Conference on Robotics in Construction, Pittsburgh, PA, May 1985.

Whittaker, W. and I. Oppenheim, "Demonstration of Robotic Mapping of Mine Spaces," Technical Report, Construction Robotics Laboratory, Pittsburgh, PA, April 1985.