Chapter 3

Design Objectives and Constraints

This thesis focuses on the development of a new autonomous vehicle. The vehicle was developed in conjunction with the Virginia Tech Autonomous Vehicle Team, or AVT. The vehicle's primary purpose is competition in the Sixth Annual International Autonomous Ground Robotics Competition. The nature and rules of the competition set forth several application-specific goals. The secondary purpose of the vehicle is as a test-bed for sensor fusion and navigation research. This requires imposing design goals beyond those required for competition. The following sections will outline both sets of requirements.

3.1   Application Goals: Competition

The primary motivation for developing a new autonomous vehicle is the Annual Unmanned Ground Robotics Competition. The competition is sponsored by the Association for Unmanned Vehicle Systems International (AUVSI). The competition is split into static and dynamic portions. The static competition judges the uniqueness and quality of the vehicle design. The goal of the dynamic competition is to autonomously navigate an outdoor obstacle course. The nature of the course and competition regulations create sensing, navigation, and mechanical requirements.

The obstacle course is a path bounded by white or yellow lines, 3 to 4 inches wide and approximately 10 feet apart. The course is contained within an area approximately 60 to 80 yards long and 40 to 60 yards wide. The boundary lines can be solid or dashed, and may be painted on grass or asphalt. The actual course shape is variable but usually resembles the outline of the previous winner's home state. The course also contains obstacles such as traffic cones, a

sand trap, and inclines up to 15%. Obstacles may be placed in any arrangement including "traps" leading toward the side of the course. A typical course is shown in Figure 3.1. The 1998 competition also has an added bonus course. The bonus course is laden with different obstacles such as car mufflers and barricades and contains a section where the course forks into two possible routes.
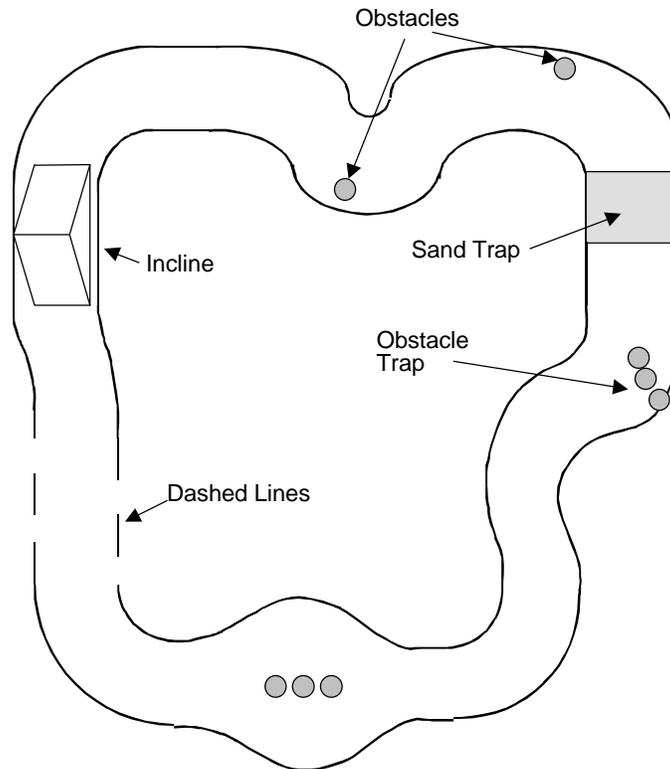

Figure 3.1: Typical Competition Obstacle Course

Dynamic competition standings are based upon completion time or distance traveled in the event that no entrants complete the course. Time and distance penalties are assigned for crossing course boundaries and various types of obstacle collisions.

The course itself sets several requirements for the vehicle's sensing and navigation systems. The vehicle must be able to detect the course boundary lines. Due to varying line color and background, this system must be adaptable to a wide variety of conditions. The vehicle must also be able to detect obstacles that vary greatly in size and location. The use of a single or multiple sensor

system was of concern during development. The navigation system must also be able to deal with varying distance between lines, as depicted in Figure 3.1. Sections containing obstacle "traps" and multiple paths present a unique challenge. Effectively handling such sections requires the vehicle to use sensors capable of collecting data a reasonable distance in front of the vehicle. This data must then be assimilated in a navigation strategy capable of detecting "traps" and choosing among multiple paths.

Because the course is outdoors and the competition is run regardless of weather, the vehicles are required to be robust. Mechanically, the vehicle must be able to handle uneven terrain, inclines, and loose sand. Adequate suspension and power must be provided to allow easy navigation. The course contains short-radius turns and obstacle "traps" that require good vehicle maneuverability. This problem will be discussed further in the next section.

Beyond the obstacle course, there are several competition-imposed regulations that heavily influence the mechanical and electrical design. To qualify for competition the vehicle must meet the following specifications:

1. All computational power, sensing and control equipment must be onboard the vehicle.
2. Maximum vehicle speed is limited to 5 mph.
3. The vehicle must have an onboard E-Stop and remote E-Stop effective from a minimum of 50 feet.
4. The vehicle must be a minimum of 3 feet long, but no greater than 9 feet. Also, the vehicle may not be greater than 5 feet wide or 6 feet tall.
5. Propulsion must be supplied by direct mechanical contact to the ground (wheels, legs, etc.) with power supplied by combustible fuel or electric power.
6. The vehicle must carry a 20-pound payload approximately 18"x8"x8".

Complete rules may be found at the competition home page at Oakland University:

http://www.secs.oakland.edu/SECS_prof_orgs/PROF_AUVSI/index.html

3.2   Design Goals: Navigation Test-Bed

The second function of this new autonomous vehicle is to serve as a test-bed for sensor fusion and navigation research. The design goals presented here are based upon Virginia Tech's past experiences as well as the observation of other teams. The goals are divided into mechanical, sensor, and navigation sections.

3.2.1 Mechanical Goals

Several mechanical issues directly affect a vehicle's usefulness as a test-bed. The size of the vehicle is extremely critical. Vehicles such as Northern Illinois University's "Rover" and Virginia Tech's "Calvin" vehicle are based on EZ-GO Golf Carts (Nagy and Bock, 1995). The size of these vehicles has caused problems during obstacle course navigation. Smaller vehicles are capable of fitting through smaller passages, thus creating more potential paths around obstacles. Transportation and testing of larger vehicles is also difficult. Loading and unloading for travel as well as the simple ability to pass through a standard size door opening make considerable difference when testing.

Maneuverability is greatly affected by the base vehicle layout. A standard *drive-steer* approach was used for Virginia Tech's "Herbie" and "Calvin" vehicles. As noted by McKerrow (1991), this leads to a limited turning radius and decreased maneuverability. It was thus desired to create a base vehicle capable of differential or omni-directional movement. Either of these designs will greatly assist in obstacle avoidance.

Regardless of the vehicle layout, the mechanical design had to be stable. This was a critical issue since the base vehicle was to be fabricated from the ground up and not purchased. The operational environment of this vehicle ranges from smooth, regular indoor areas to fairly rough outdoor terrain such as

sand, gravel, and thick grass. Variations in the outdoor environment must be considered so as to avoid vehicle rollovers. To maintain simplicity, it was felt that the design should be inherently stable and not require active body regulation as in legged vehicles (Messuri and Klein, 1985).

The overall mechanical design goal was simplicity. Vehicle subsystems such as chassis, engine, transmission, etc. can become complex assemblies. Fewer parts in each subsystem make failure detection and maintenance faster and easier. Similarly, designing and building each subsystem from scratch can be extremely time consuming and labor intensive. Nagy et al. (1994) state that off-the-shelf subsystems tend to be more reliable then their counterparts made from scratch. The key lies in NASA's "cheaper, faster, better" design philosophy (Webster et al., 1994). The design focus is placed on the integration of industrially proven components rather than design and fabrication of custom components. This approach requires a willingness to sacrifice certain design goals in the name of development time and cost (Webster et al., 1994). Thus, the overriding goal was to produce a vehicle with the minimum number of components where a maximum number of those components were off-the-shelf. This approach is presently referred to as the *commercial-off-the-shelf* design method, or C.O.T.S.

3.2.2 Sensor Goals

The ideal sensor suite should provide accuracy and reliability with a minimum of sensors. This decreases the difficulty of sensor fusion and possible sensor conflicts inherent in large sensor suites (Hall, 1997). The resolution and accuracy of the suite must be balanced with processing speed. Another goal of our research team is to avoid the use of ultrasonic sensors. While ultrasonics are relatively cheap, their use with Virginia Tech AVT's other vehicles has been troublesome. The limitations of ultrasonics are commonly discussed in literature (Liu and Lewis, 1994; Kam et al., 1997) and were briefly discussed in Chapter 2.

The purpose of the preliminary sensor suite was to prove the viability of integration with the chosen mechanical systems and provide a starting point for

subsequent suite development. Thus, the selection of sensors with a broad range of capabilities seemed appropriate. The ability of a sensor such as computer vision to detect multiple environmental characteristics such as distance and shape makes it very valuable. Such sensors allow the sensor suite to be improved through additional computer algorithms rather than adding more sensors. The team considered the use of only a single computer vision system. However, due to lack of depth information, it was decided to supplement the vision system with a range finding sensor.

3.2.3 Navigation and Computing Resources

The main concern for navigation was the decision between a reactive or planning navigation strategy. Previous Virginia Tech AVT vehicles have focused on reactive navigation strategies. This approach was taken because of the previous competition course layouts. Past competitions have been won by simple line following and reactive obstacle avoidance. The addition of obstacle "traps" and multiple path selection called for a planning strategy. The vehicle had to have the ability to collect information at a distance, recognize "traps", and plan avoidance.

The ability to store sensor data is critical to a planning strategy. Ideally, the navigation strategy should base its decisions upon multiple sets of sensor data. This led to the decision to construct environmental maps. It was felt that this would facilitate data fusion and storage and temper navigation decisions. A map was also deemed a necessary vehicle requirement in the event the vehicle should experience sensor failure or become trapped. A map would allow the vehicle to proceed based on previous data or find an escape route from an obstacle trap. If vehicle were to experience a dead-end situation and could not turn around, the map could also be used to drive the vehicle in reverse without additional sensor information.

The vehicle's computational resources also had to adhere to the cheaper, faster, better approach. Previous Virginia Tech AVT designs have contained numerous custom microcontroller and interface boards. These custom interface

units have been prone to failure and are difficult to troubleshoot. The computing capabilities of many microcontrollers are also limited in speed and storage capabilities. The use of a standard computer system could increase the learning curve and shorten time to implementation due to general computer familiarity among engineers. Standard PC's also overcome many of the processing limitations of smaller microcontrollers. An optimal computing design should utilize as many industrial components as possible. Modularity of design will facilitate quick error location and component swapping. Plug-and-play boards are available for numerous operations such as motor control and computer vision. Many of these systems are supplied with software and could reduce the need for custom written data acquisition and control algorithms.

3.3 Summary

Several design criteria and goals are created by the vehicle's dual role as a competition vehicle and research test-bed. The following list summarizes both sets of goals:

- Compliance to competition regulations
- High level of mobility (differential or omni-directional drive)
- Substantial drive power
- Minimum size and weight (within regulations)
- Minimum of sensor to collect a maximum of information
- Computer based control
- Planning navigation strategy with information storage
- Industrially proven off-the-shelf components
- Modular design both mechanically and electrically

The challenge of designing any vehicle lies in achieving a balance between conflicting goals. Due to Virginia Tech AVT's reliance on corporate sponsors, for example, the vehicle's final size and weight may be largely dependent upon donated components. Thus, some design criteria may be

altered to lower team costs. The next three chapters will present the proposed solution, detailed design, and actual vehicle performance.

Chapter 4

Proposed Solution

The design criteria presented in Chapter 3 were used to formulate a generalized vehicle concept. Basic parameters such as vehicle configuration and computing resources were determined. The transition from this concept vehicle to detailed design was influenced by several factors. Sponsoring companies donated numerous vehicle components. Thus, final vehicle dimensions were dependent upon the donated motors and transmission components. The goal was to maintain the basic principles of the concept vehicle during final implementation.

4.1   Vehicle Configuration

The configuration of the base vehicle directly addresses design criteria such as mobility and size. It was desired to achieve extreme mobility to aid in obstacle avoidance. To achieve this end, a zero-turn-radius (ZTR) approach was adopted. A ZTR capability allows the vehicle to maneuver around obstacles, in some cases even if physical contact has been made. Standard *steer-drive* configurations would require the vehicle to reverse direction before proceeding around an obstacle that has been contacted. Reverse procedures could render the vehicle blind in the direction of travel unless the sensor suite completely surrounds the vehicle. A ZTR capability allows the vehicle to be oriented in any direction without vehicle translation. This allows the use of a limited, forward facing sensor suite, since it will always be facing the direction of travel. This also eliminates the need for conventional vehicle reverse procedures.

The most common ZTR configurations are synchronous, omni-directional, skid-steering, and differential drive. Synchronous drive configurations are

capable of sideways motion and rotation about the vehicle's center. Separate motors control drive and steering. The orientation of the vehicle platform is dependent upon vehicle orientation. To maintain a "forward facing" platform requires either an additional upper turret assembly or complex orientation tracking (Borenstein, 1995). The high mobility of synchronous drive configurations comes at the expense of difficult vehicle control. The next possible approach utilizes omni-directional wheels. The vehicle's outdoor operating environment includes uneven, rough terrain. The poor operation of omni-directional wheels on rough surfaces coupled with mechanical complexity and difficult control make them unattractive for the given application (Angeles, 1997; Borenstein, 1995). Omni-directional wheels are also difficult to control since ZTR maneuvers require the coordination of the wheels and the additional rollers surrounding the wheels.

Skid-steering with a tracked or multi-wheeled vehicle is another alternative. Skid-steering allows for ZTR maneuvers and is fairly easy to control. The use of a tracked or multiply powered wheels also provides for large power output (McKerrow, 1991). Both designs also provide good ground traction. The drawback, however, is a substantial loss in odometry accuracy. Accurate odometry is essential to correlating vehicle and obstacle locations. Poor odometry could greatly diminish the usefulness of a planning navigation approach. Skid-steering vehicles also tend to damage the surface on which they operate.

The final option is a differential drive system. This configuration provides the same ZTR capability of skid-steering but uses only two powered drive wheels. The odometry errors of skid-steering are overcome since there is no side slippage during turning. This arrangement also avoids the tire "scrubbing" inherent in most four-wheel and skid-steering configurations. While control is not complex, precise motor control and accurate mechanical assembly are necessary to achieve smooth vehicle movement (McKerrow, 1991).

The vehicle development team decided upon a differential drive configuration for several reasons. A differential drive vehicle would be able to

provide the desired maneuverability. While control must be precise, the system must only handle two drive wheels. Past Virginia Tech AVT designs have used *steer-drive* strategies which require the coordination of two dissimilar control loops: one based on speed and one based on angular position. A differential drive configuration requires the coordination of two similar speed loops. Differential drive would also simplify the mechanical component selection. Instead of selecting dissimilar drive and steering motors, the differential system required two matching drive motors. The same idea applies to the motor amplifiers and controllers.

4.2   Conceptual Design

Once the basic vehicle configuration had been decided upon, the main component specifications had to be determined to begin the detailed design process. The areas of consideration were the power system, drive motors, wheel selection, computing architecture, and sensing and navigation approach.

4.2.1 Power System

An autonomous vehicle's onboard power system affects the selection of drive motors, sensors, and computing resources. All of Virginia Tech AVT's vehicles have utilized various configurations of standard car batteries to produce AC and DC power buses. AC/DC inverters were used to provide power for AC motors and onboard computers and monitors. Alternatively, completely DC vehicles often use numerous batteries in series to produce necessary voltage levels. One such example is West Virginia's "ANT II" which uses eight, 12-volt car batteries wired in series to provide power for drive motors, sensors, and computers (Banta, 1995). Configurations such as this can result in lethal voltage levels and are quite heavy.

It was decided to design Virginia Tech's new vehicle around a completely DC, 24-volt power bus. This approach eliminates the need for heavy, onboard inverters and decreases high voltage hazards. The batteries were to be specified so as to provide enough power for approximately two competition

course runs. It was hoped that this would decrease battery size and weight. This decision reflects one of the numerous compromises in design specifications. In this case, decreased vehicle size and weight is achieved at the expense of shortened testing and run time capabilities.

4.2.2 Drive Motors

Once a voltage source was selected the next step in vehicle development was drive motor selection. Basic calculations were performed to get an estimate of the necessary horsepower requirements. An estimated gross vehicle weight of 200 pounds was used. The calculations use the competition obstacle course incline at the maximum 5-MPH speed as the worst case scenario as shown in Figure 4.1.
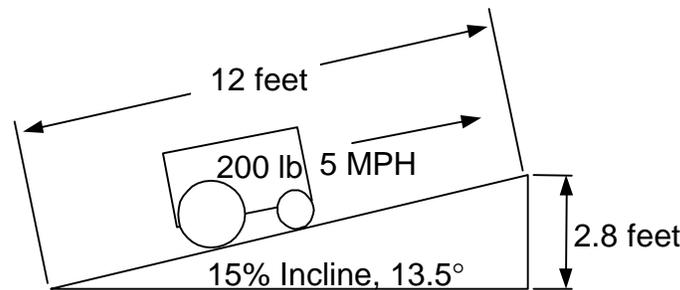

Figure 4.1: Horsepower Calculations

A preliminary horsepower requirement was then found as:

$$Power = \frac{(Height)(Speed)}{Time} = \frac{(200lb)(2.8ft)}{1.64\sec} = 342.3\frac{ft \cdot lb}{\sec} = 0.622HP$$

Thus, by including a factor of safety we may assume a total requirement of 1 HP. This safety factor also accounts for the lack of consideration to vehicle acceleration. Using two motors for differential drive would require two, ½ HP motors. The motors would also be required to run on the 24 volt DC bus. Since

the motors were to be donated by corporate sponsors, certain motor specifications were eventually compromised to reduce the vehicle's cost.

Since typical DC motors provide low torque at high speeds it was determined that a gear reduction system would be necessary. In keeping with the off-the-shelf approach, an industrial available gear reducer would be used to lower motor output speed and increase torque. The specifications of the gear reducer are based on the final drive motor specifications and wheel size. This is discussed in the next chapter.

4.2.3 Wheel Selection

Tire selection was also critical to vehicle mobility. The type of tire selected can greatly affect traction and suspension requirements. It was decided that pneumatic rubber tires would be used due to commercial availability, good on and off road traction, and their ability to cushion the vehicle from minor surface irregularities (Wong, 1978). Due to low vehicle speeds, the use of pneumatic tires also promised to eliminate the need for substantial vehicle suspension. Pneumatic tires could produce variable accuracy in odometry however. Differences in manufacturing, alignment, or inflation pressure could cause the two drive wheels to travel different distances per revolution (Borenstein, 1995). The actual effect of pneumatic tire odometry errors upon vehicle performance is discussed in Chapter 6.

The competition bonus course allows the vehicle to drive over certain objects. The tire size had to be adequate to clear obstacles such as a car muffler and 2x4 lumber. To allow clearance, the drive tires had to be at least twice the height of the largest obstacle. Providing for a generous safety factor, a preliminary tire diameter of 16 inches will be used assuming the maximum obstacle height is 4 inches.

4.2.4 Computing Considerations

To maintain a commercial-off-the-shelf (C.O.T.S.) mentality, a commercially available personal computer (PC) was chosen for all computing

needs. Previous designs have shown that custom-built microcontroller units tend to have limited processing capabilities, are prone to failure, and are difficult to trouble shoot. The ever decreasing cost and increasing speed of PCs made them an excellent alternative to individual microcontrollers. It was also felt that the familiarity with PC's among both mechanical and electrical engineers would decrease the learning curve and time to implementation. Commercially available "plug-and-play" interface boards for tasks such as computer vision and motor control also simplify system integration. Thus, a PC was chosen to centralize all sensor fusion, navigation, and motor control.

4.2.5 Sensing and Navigation

The vehicle's sensor suite would initially consist of a computer vision system and a ranging device. Computer vision is capable of providing a large amount of environmental data using a single sensor (Fu et al., 1987; Huber et al., 1992). In the competition arena, computer vision opens the possibility to detect both boundaries and obstacles simultaneously. Virginia Tech AVT's prior experience with computer vision also lent a distinct advantage. Since the vehicle was also to be used as a test-bed, a computer vision system provided the rudimentary resources for research in the areas of stereo vision, color recognition, and moving target tracking. Due to the inaccuracies of monocular vision ranging, a secondary ranging device would also be needed. Numerous commercial solutions are available. Due to the questionable performance of ultrasonic systems in outdoor environments, laser and radar ranging units were considered for implementation. The added accuracy of these devices would need to be balanced by their relatively high cost. The final system was chosen based on sponsor donations.

A planning and mapping approach was selected for the sensor fusion and navigation strategy. A planning approach would provide the capability to detect competition obstacle course "traps" and multiple routes at a distance down course. A grid-based map was selected for data fusion and storage. Grid based mapping provides several overall advantages. Grid maps may employ certainty

or occupancy models depending on the desired sensor fusion strategy. The ability to modify grid resolution provides for the addition of sensors of various accuracy and resolution. The basic grid map may also act as the basis to test a variety of different navigation strategies, such as A* and potential field algorithms, without altering the front-end sensor data fusion and mapping. This follows a modular approach such that a single mapping algorithm might be perfected and then used by numerous navigation algorithms.

The planning and mapping approach also helps to orient the vehicle in the global environment. Reactive methods could lose track of global vehicle orientation during ZTR maneuvers. The use of a map and global goal planning helps to track the vehicle's position and orientation in relation to the global goal. Thus, even after a 180° ZTR maneuver, the vehicle could be easily reoriented towards the goal.

4.3   CAD Implementation

Early in vehicle development it was determined that CAD would be a key design tool. A minimum of CAD was used during previous Virginia Tech AVT design efforts. This minimal usage can be attributed directly to the implementation of prefabricated base vehicles. The benefits of CAD are obvious when the base vehicle is to be built from scratch. Off-the-shelf components can be accurately modeled and integrated into the overall system. Multiple vehicle designs can be easily produced and compared. Solid modeling systems can help reduce "dead" space since component layout can quickly be altered. Drawings for manufactured parts can be produced or altered quickly and accurately.

The greatest benefit of CAD use is the ability to communicate the design intent among numerous team members. Ambiguous design descriptions can be eliminated. CAD will be used for mechanical and electric designs before any components are built or assembled. This can greatly reduce time to completion. The mechanical CAD package used is AutoCad version 13. MicroSim's P-Spice will be used to produce wiring schematics.

4.4   Summary

The preliminary design proposed a differential drive, zero-turn-radius (ZTR) vehicle. The vehicle was to be powered on a 24-volt DC bus and would centralize sensing and control systems within a standard personal computer. The initial sensor suite would use computer vision and a yet to be determined ranging device. The design was intended to produce a viable vehicle using proven components. Chapter 5 will discuss the final detailed design and how it differs from the preliminary design.