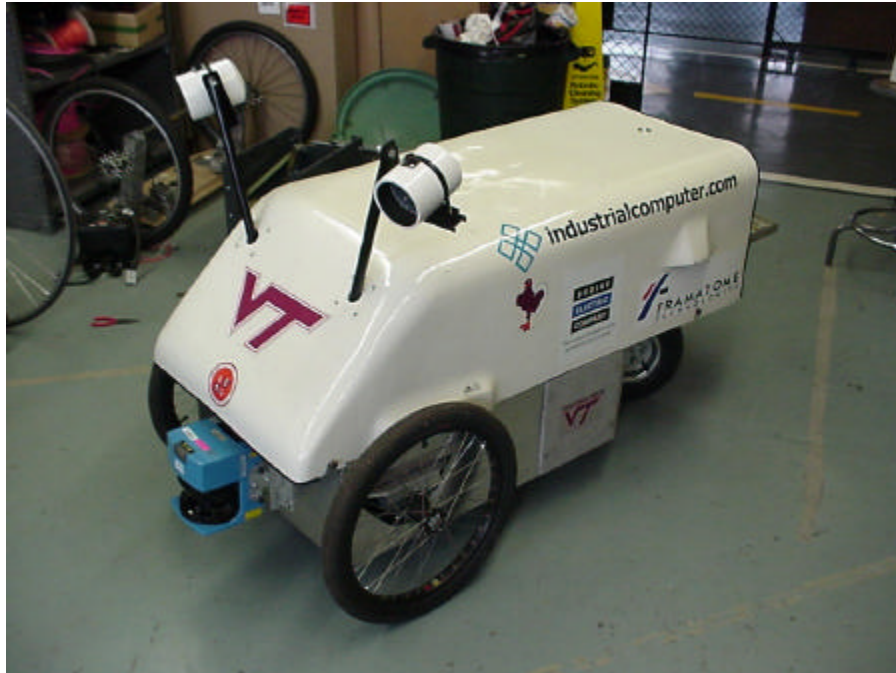


NAVIGATOR



Autonomous Vehicle Team of Virginia Tech May 19, 2001

Required Faculty Advisor Statement

I hereby certify that the Navigator vehicle has undergone a significant redesign from last year's entry in the IGVC. Five students worked on this project. Three of the students received two semesters of senior design credit. A fourth student received independent study credit for a one-semester junior course. The final student developed new software and navigation algorithms as part of his Master's degree work.

Charles Reinholtz
Faculty Advisor
Assistant Department Head and Professor of Mechanical Engineering
Virginia Tech
Phone: (540) 231-7820, email: creinhol@vt.edu

1-INTRODUCTION

This year's Navigator team was presented with the difficult task of substantially modifying and improving an already sound vehicle. The 1999-2000 Navigator team developed an innovative vehicle that competed well at the 8th annual Intelligent Ground Vehicle Competition (IGVC). Navigator placed first in the design competition and among the top five in all four of the performance events. Despite its impressive debut, Navigator had a few shortcomings. In particular, Navigator was overweight and underpowered. Further, Navigator's navigation scheme was based solely on local obstacle avoidance with no overall goal recognition. The task for this year's team was to refine Navigator so that it would perform better in the events by improving the dynamic performance of the vehicle and developing a more complete navigation scheme. The team was comprised of one junior level mechanical engineer, three senior level mechanical engineers, and one graduate level mechanical engineer.

Early in the year, the team analyzed the attributes and shortcomings of the existing vehicle. It was determined that the primary areas of focus would be decreasing the overall weight, increasing the available drive force, and developing a more complete navigation scheme. The design improvements in these areas were addressed using a well-documented design process. The team had an additional constraint, because these improvements had to be made incrementally in order to keep the vehicle in operating condition throughout the year. Reasons for this were twofold; one, it allowed immediate testing of each modification and two, it allowed Navigator to be used for public relation type events. The Autonomous Vehicle Team of Virginia Tech often gives vehicle demonstrations in order to spark enthusiasm about the field of robotics. The team feels that by addressing the shortcomings of last year's vehicle and implementing innovative new ideas, the redesigned Navigator is a very sound vehicle. This report describes the design process used to redesign Navigator, gives an overview of the new design innovations, and outlines the new (more complete) navigation algorithm.

2-DESIGN PROCESS

2.1-Design Methods

To ensure the best and most innovative redesign of Navigator, a strict design process was followed. The team made use of a design process established by Karl T. Ulrich and Steven C. Eppinger¹. This process involves five phases of product design and development. A flow chart of this process is given in Figure 1.

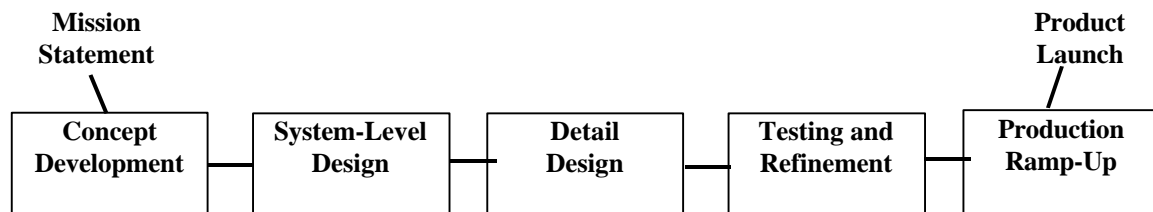


Figure 1: Flow chart of the design process.

Each phase of the design process is iterated until the best design is found. This process was followed during the complete vehicle redesign; however, it was also followed when redesigning individual components such as the front drive wheels, the rear caster wheel, and the frame. The concept development phase consisted of four steps, beginning with the determination of customer needs. For this project, the customers were defined as IGVC judges, the project advisor, and the previous designers. Upon consulting the IGVC rules, interviewing the project advisor, and interviewing past members of the Navigator team, a series of customer needs were established. These needs included reducing the weight of the vehicle, reorienting the center of mass of the vehicle, increasing the available drive force, and developing a more complete navigation algorithm. From the many need statements, a hierarchy was established by ranking the needs according to several criteria. The criteria included safety, functionality, innovation, and feasibility.

¹Eppinger, Steven C., and Karl T. Ulrich, *Product Design and Development*, McGraw-Hill Inc. New York, 1995.

In the second step of phase one, the team determined which of these needs would be addressed. The final two steps of this phase were concept generation and concept selection.

Once the team decided which tasks were going to be undertaken and the new concepts were selected, the new parts of the vehicle were designed and tested following the next three phases of the design process. All of these phases included testing and redesign of components to ensure the best possible design. The final phase of the design process, production ramp-up, was not used because the team only built a prototype. As stated before, the goal of keeping the vehicle in operating condition while making these changes allowed for extensive testing of each newly designed part.

2.2-Design Team Organization

This year's Navigator team consisted of five members. Due to the nature of the redesign (the need to keep the vehicle operational), all members of the team worked together to complete each step of the design. However, individual manufacturing tasks were delegated such that time was used as efficiently as possible. Because the team followed this format, each member had equal input into the design process and extensive knowledge of each part of the vehicle. Table 1 gives the name, level, and academic department of each member.

Table 1: 2000-2001 Navigator team members.

Name	Major	Academic Level
Philip Kedrowski	ME	Graduate
Justin Macken	ME	Senior
David Parnell	ME	Senior
Matt Peppers	ME	Senior
Milivoy Villarroel	ME	Junior

3-MECHANICAL SYSTEM

3.1-Frame and Component Location

An aluminum chassis supports all components of the vehicle. The chassis is constructed using a modular Bosch T-slotted aluminum framing. This aluminum framing is easy to assemble and disassemble

with the use of the supplied connector pieces. Figure 2 shows a small section of the T-slotted aluminum. Sub-assemblies such as the lower bay, drive modules, caster wheel, and console are all mounted upon the frame using four or fewer of these connectors. This aluminum chassis replaced the steel tube chassis used in last year's vehicle. This change was made for two reasons. First, the aluminum frame was considerably lighter than the steel frame, thus addressing our concern about the vehicle's overall weight. Also, this particular steel tubing makes it much easier to remove, move, and install new components as necessary. Figure 3, is a picture of the new fully constructed frame, just before it was installed on Navigator.

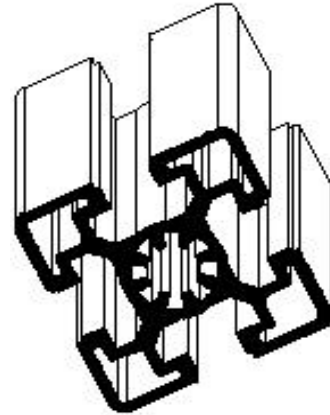
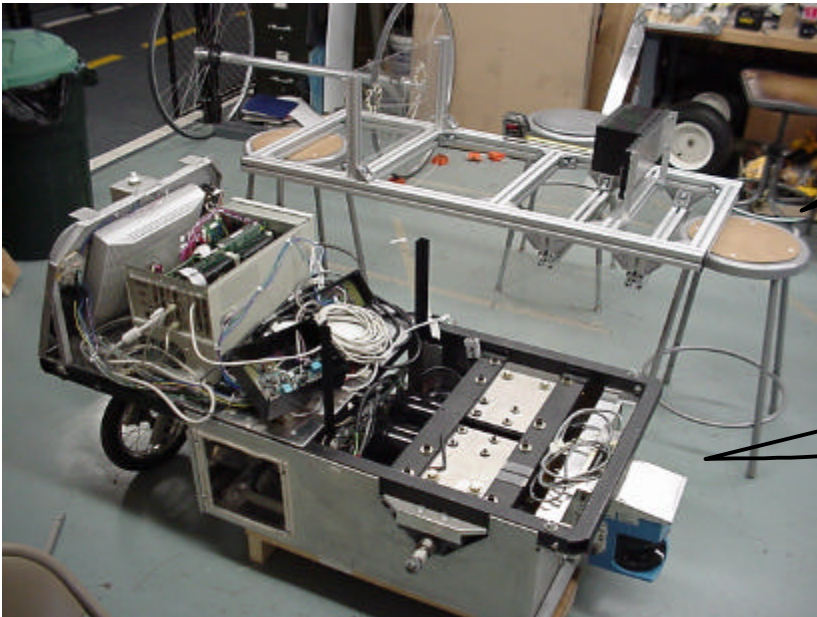


Figure 2: Bosch T-slotted aluminum tubing.

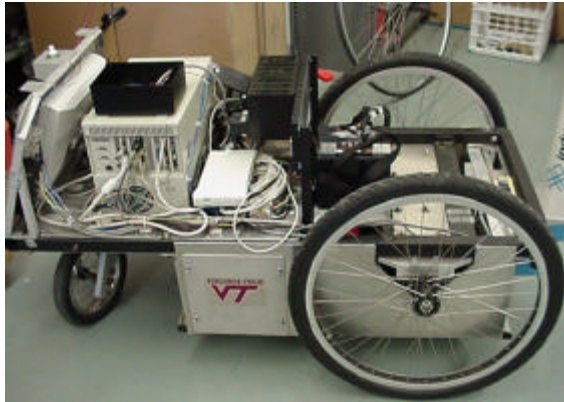


New Chassis

Old Chassis

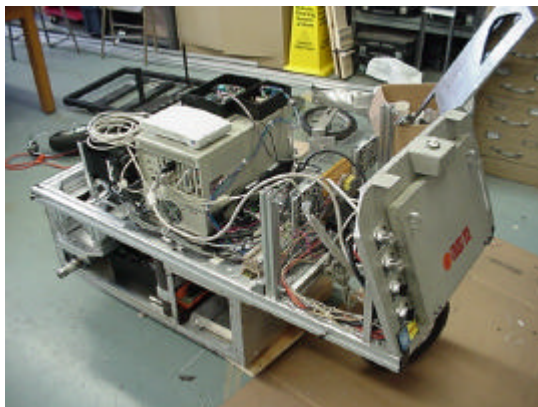
Figure 4: Navigator, just before installing new aluminum chassis.

The center of gravity of the vehicle is located just behind the front drive wheels where the major components of the vehicle are housed. This too is a redesign of last year's vehicle. The center of gravity in the previous design was located closer to the rear of the vehicle. A comparison of the internal component locations is shown in Figure 4.



Old Component Layout

Figure 4. Comparison of component layout for old and new c



With the previous layout, weight was distributed such that more than 50% of the total vehicle weight rested on the rear castor wheel. This caused problems when performing small or zero radius turns. The heavy internal components such as the computer and the PLC are mounted on a single aluminum plate, which is mounted to the frame. By moving this plate and the attached components forward 18 inches, the center of gravity was moved directly behind the front drive wheels. Further, the batteries were moved to the lower bay, which both lowered the center of gravity and allowed easy access through the side hatches. Although this redesign took much of the weight off the castor wheel, it did raise concern about the vehicle tipping forward during sudden stops. It was found that placing the batteries in the lower bay kept the center of gravity low enough on the vehicle that this problem was alleviated, while still keeping most of the weight off the castor wheel.

After all the internal components were moved forward on the vehicle, a considerable amount of space was left at the rear of the vehicle. Since our existing payload area now housed our batteries, the team decided that at the rear of the vehicle would be the best new payload location.

3.2-Drive Train

Navigator is powered by two Bodine 24-volt, 15-amp, 0.45 hp, brush type DC servomotors. These motors are attached to the drive wheels via two 90-degree, 33:1 gearheads. One of the main concerns with the previous design of Navigator was that it was underpowered. The first and most obvious solution for increasing the drive force was to use larger motors. However, the motors that were considered proved undesirable since they were costly, heavier, geometrically larger, and required substantial redesign of the motor mounting brackets. Upon further inspection, it was determined that decreasing the diameter of the drive wheels would serve to increase the drive force without having to replace the existing motors. This concept is illustrated in Figure 5.

T_{max}



$$T_{max} = F_{max} l$$

Figure

It is easily seen that... wheels were replaced with 10" radius wheels. This gave... shown in Equation 1.

$$\frac{F_{new}}{F_{old}} = \frac{T_{max}/l_{new}}{T_{max}/l_{old}} = \frac{l_{old}}{l_{new}} = \frac{13''}{10''} (100) = 130\% \quad (1)$$

This change allowed us to both keep the existing drive motors and reduce the vehicle weight slightly by implementing smaller wheels. However, it did require the motors to be mounted 3" lower in order to maintain an overall vehicle ground clearance of 5.5". It was calculated that this clearance is necessary for the vehicle to traverse the peak of the ramp during competition. Lowering the motors required the addition of a motor mounting bracket. Further, when designing the new mounting bracket, it was discovered that an estimated 2 lbs (0.91 kg) would be saved by machining the motor mounting plates out of 3/8" aluminum sheet instead of the existing 1/2" aluminum sheet. Figures 6 a and b show the smaller mounting plate and mounting bracket respectively.

A)



B)

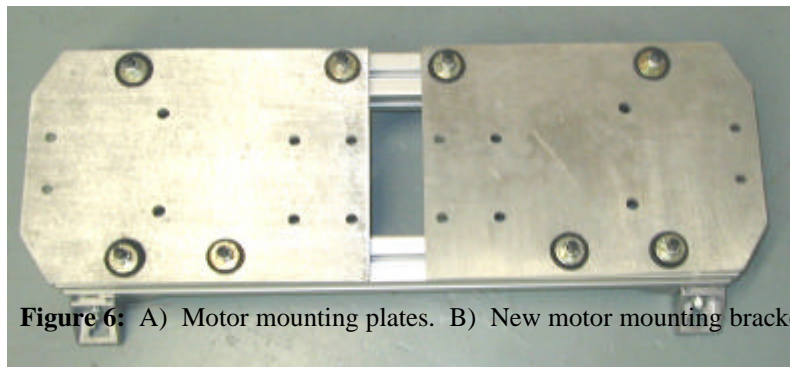


Figure 6: A) Motor mounting plates. B) New motor mounting bracket.

One disadvantage with this redesign is the lowered maximum velocity. While the vehicle will gain 30 percent more drive force, it will also lose 30 percent of its top speed. This was deemed a worthy tradeoff, since the vehicle rarely travels at top speed when navigating autonomously.

Another important feature of the drive train, which remains unchanged from the previous design, is the use of a fail-safe brake. This brake is directly coupled to each motor, but remains disengaged during normal operation of the vehicle. The brakes are only engaged in case of an emergency stop or a sudden loss of power to the vehicle. This is a critical safety feature of Navigator.

3.3-Lower Bay

The lower bay of Navigator is an aluminum cage mounted to the bottom of the base frame. It is constructed of 1/32" aluminum sheet, which is fastened using pressure sensitive 3M Very High Bond tape. High Bond tape was used in order to eliminate the drilling holes, thus the lower bay serves to completely protect Navigator's undercarriage from the elements. This area of the vehicle is designed to house many of the heaviest components of the vehicle. The previous design of the vehicle only made use of the lower bay to house the motor amplifiers and power inverter. The redesign of the vehicle moved the batteries to the rear portion of the lower bay as well. This effectively lowered the center of gravity while giving more room in the upper portion of the vehicle to move other components. Another advantage of having the batteries in the lower bay is that they are now easily accessible through the side hatches. With the old design, the entire shell of the vehicle had to be removed in order to replace the batteries. The access hatches are attached to the vehicle using four butterfly nuts.

3.4-Caster Wheels

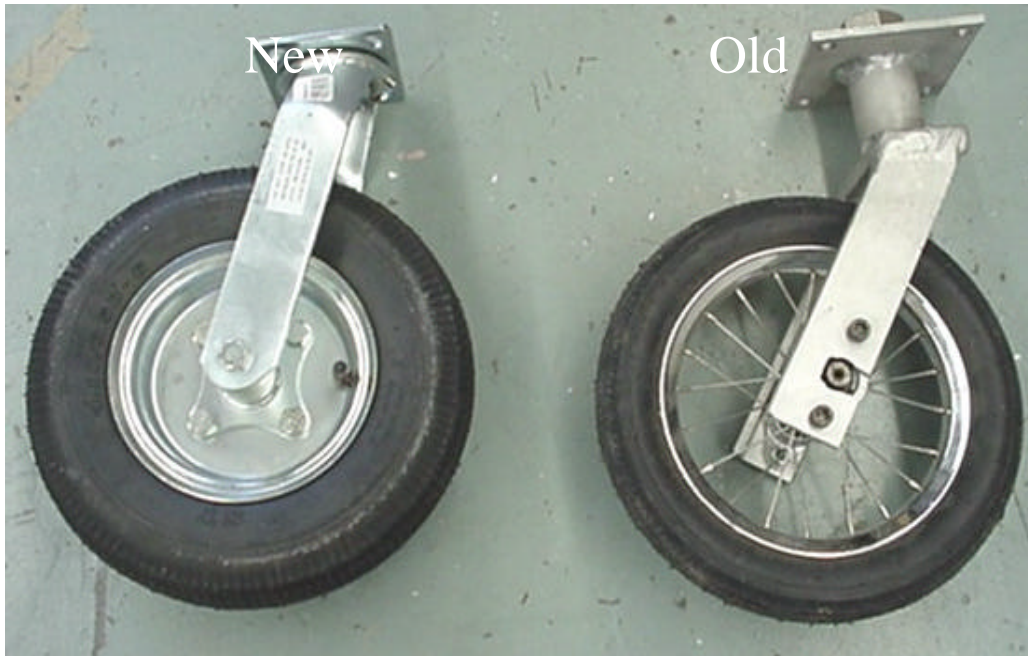
The previous Navigator team used a custom made caster wheel. When loaded, this caster wheel had difficulty turning because it implemented a bushing type revolute. It was decided to replace the existing custom made caster wheel with a commercially manufactured caster wheel. The commercially manufactured caster wheel that was chosen uses a thrust type revolute and is designed to handle loads up to 650 lbf. The new caster wheel can be seen in comparison to the old in Figure 7.

**Thrust
Bearing
Revolute**



**Bushing
Revolute**





3.5-Console

With the previous design of Navigator, the console portion was used to house the monitor, the on/off switches, battery voltage indicators, and status indicators. With the new design of the vehicle,

wireless Ethernet was installed so that Navigator's PC could be networked with an off-board laptop computer. This allowed removal the on-board monitor, it's power supply, and it's power inverter. The area that formally housed the monitor is now empty. There is also added space in this area because the major components that were located directly behind the monitor were moved 18 inches forward on the vehicle. This left a considerable space where the payload is now loaded. The fold down access panel that used to contain the keyboard is now used as a hatch to conveniently load and remove the payload as needed. A plastic divider separates and protects the internal components from this payload area. Mounted on this divider are two of four cooling fans properly positioned to insure the Personal Computer (PC) and Programmable Logic Controller (PLC) do not overheat during operation.

3.6-Weatherproofing and Shell

Navigator was designed to operate in all types of weather. The main focus was to ensure the vehicle was waterproof, so that the internal components (PC and PLC) would not be damaged during inclement weather. In order to accomplish this, Navigator was designed with features including a glass fiber composite shell cover, camera enclosures, and sealed paneling. The shell mounts via shoulder bolts directly to the chassis and is designed for easy removal. The two color Charge Coupled Device (CCD) cameras, and emergency stop (E-stop) are all mounted on the shell. The E-stop required extra weatherproofing efforts because it protrudes through a hole in the top of the shell. Therefore, the E-stop was sealed using a rubber O-ring to prevent water from penetrating the shell.

The camera mounts were the only component of this system to be improved during the redesign of the vehicle. The concern with the previous design of the camera mounts was that they did not allow for very fine orientation adjustments of the CCD cameras. The old design made use of several holes in which the cameras could be mounted, each hole being spaced evenly in a 360° circular pattern. Although this design allowed for the cameras to be repositioned easily, the team felt a redesign would allow for higher resolution adjustments when positioning of the cameras. The redesign involved creating a camera mount in

which the camera could rotate through a slot and stabilized via a compression screw, thus allowing for very slight changes in camera angles. The new design is illustrated in Figure 8.



4-ELECTRICAL SYSTEM

4.1-Electrical Components

Navigator implements two computing machines, a Personal Computer (PC) and an industrial view B) camera rotated.

Programmable Logic Controller (PLC). The Personal Computer (PC) consists of a dual 450Mhz processor and 512 Megabytes of memory. The PC is responsible for processing the sensor data and making navigation decisions. The PLC is manufactured by GE Fanuc and is responsible for the kinematic calculations and motor controls.

Two types of sensors are used for interpreting the environment, a Sick Optic Laser Range Finder (LRF) and dual Charge Coupled Device (CCD) color cameras. The cameras are use for detecting two-dimensional obstacles such as lines and the LRF is responsible for detecting three-dimensional obstacles such as barrels. A more detailed description of the electronic hardware architecture can be found in the report submitted at the 8th annual IGVC.

4.1-Wireless Ethernet

The Navigator team focused on one major improvement to the electrical system. This improvement involved the installation of wireless Ethernet on the vehicle. Wireless Ethernet served several purposes in the redesign of the vehicle. As previously mentioned, it allowed the on-board monitor to be removed, thus reducing the weight of the vehicle by approximately 27 lbs.

With wireless Ethernet, the vehicle's computer system is accessed from a remote location using a laptop computer. This is an innovative aspect of the redesign of Navigator. By making use of this relatively new technology, the operator can monitor the vehicle's status and performance without having to follow the vehicle around as it runs. Furthermore, Maximus (Virginia Tech's newest autonomous vehicle) also installed a wireless Ethernet card, allowing Navigator and the new vehicle to communicate with each other as well as the off-board laptop computer. This innovation opens the door for multiple robotics research in the future. In particular, it may be of interest to the United States Army by allowing communication between vehicles in large convoys led by a single human driver. In this manor, commands such as starting, stopping, and turning can be passed from vehicle to vehicle.

5-SOFTWARE DESIGN

5.1 - Existing Navigation (Local VFH)

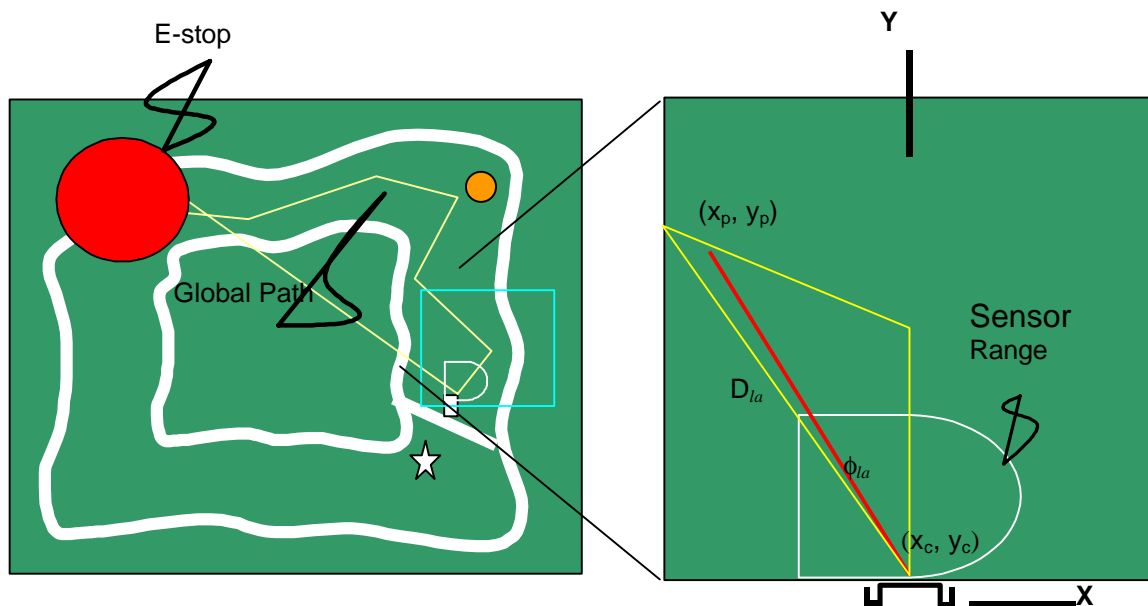
The navigation scheme employed previously by Navigator interpreted the surroundings of the local environment. The local environment, or local map, refers to the area sensed by the two CCD cameras and the Sick Optic Laser Range Finder (approximately 2.5 meters). The images from the cameras are processed such that the pixels above a certain brightness threshold are set to a white intensity value and all others are set to a black intensity value. The LRF emits pulses of light in a 180-degree spectrum in half-degree increments. Light reflecting off obstacles is measured, and by recording the time traveled by the light, the distance to the object is determined. These two sets of data are then fused together in the form of a Vector Field Histogram (VFH). The VFH is then used to avoid obstacles (lines, barrels, etc.) in the

vicinity of the vehicle. The VFH is updated at approximately 5Hz. A more thorough description of this process can be found in the design report submitted to the 8th annual IGVC

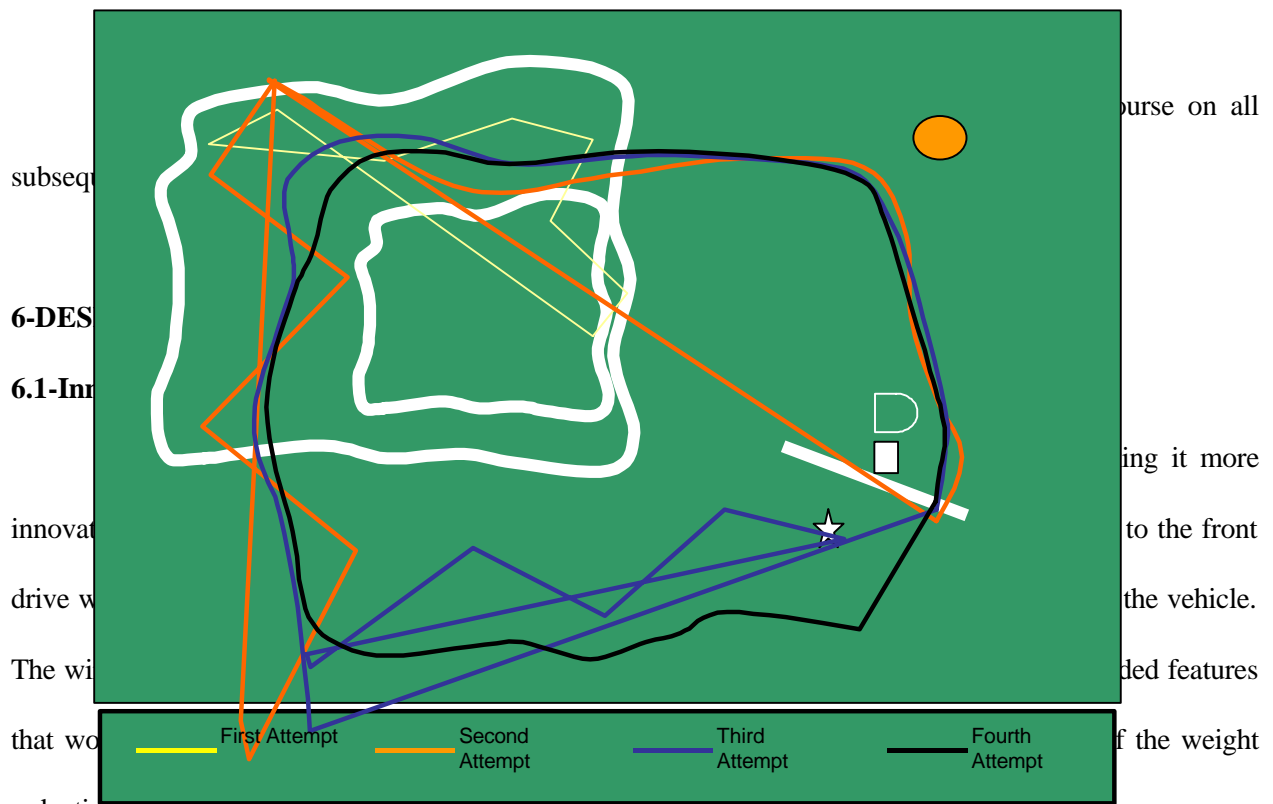
This navigation scheme worked well at the 2000 IGRC competition, however it has no overall goal recognition. Therefore, it was possible for Navigator to be traversing obstacle course in the wrong direction even though the navigation algorithm was working correctly. Typically, a local obstacle avoidance algorithm (such as the VFH) is coupled with a global map in order to form a complete navigation scheme. Unfortunately, the IGRVC rules don't allow prior knowledge of the obstacle course so initializing a global map was not an option. However, vehicles are encouraged to take multiple (9 max) attempts at completing the course. This sparked the idea of having Navigator record it's trajectory, via motor encoder feedback, during early runs and use that data on subsequent runs to give global look-ahead points.

5.2 – New Navigation (Adding Global Look-Ahead)

The general idea of the global map-building algorithm is to construct a map of the obstacle course by recording Navigators trajectory on exploratory runs. Then during subsequent attempts, the vehicle will look-ahead at this map data and initiate turns sooner allowing for a more efficient traversal of the course. This concept is illustrated in Figure 9. Notice that one exploratory run has already taken place and Navigator is looking-ahead at the map (internal to the software) in order to begin turning before sensing the line.



The global map improves in both length and quality with each successive attempt at completing the course. Figure 10 gives a visual example of how the global map develops with multiple runs.



reduction of the vehicle due to the redesign.

Figure 10: Vehicle trajectory with global map building over multiple attempts.

Table 2: List of components removed from previous design and approximate weight reduction.

Component Removed	Weight Removed (lbs)
LCD Monitor	18
DC to AC Inverter	9
Steel to Aluminum Frame	21
Total Weight Removed	48

Initial testing has shown that the 15% weight reduction and 30% increase drive force has greatly enhanced Navigator's dynamic performance.

6.2-Predicted Performance

Navigator was originally designed to travel up a 15% grade at 5 mph. Last year's team found that Navigator could only achieve speeds of 4 mph up the incline due to the weight of the vehicle. With the redesign of Navigator, the vehicle's weight was reduced by 15%, but the use of smaller drive wheels does slow the vehicle somewhat. Calculations performed by the team showed that the smaller drive wheels provide 30% more drive force, but the vehicle would also lose 30% of its speed. Since Navigator rarely travels at top speed when navigating autonomously, this was considered a good tradeoff.

The new navigation algorithm is also expected to improve Navigator's outcome at the competition. During initial testing, Navigator was able to completely map the practice course at Virginia Tech.