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DESIGN OF AN UNMANNED GROUND VEHICLE, TAILGATOR THEORY AND PRACTICE

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ABSTRACT−The purpose of this paper is to describe the design and implementation of an unmanned ground vehicle, called the TailGator at CIMAR (Center for Intelligent Machines and Robotics) of the University of Florida. The TailGator is a gas powered, four-wheeled vehicle that was designed for the AUVSI Intelligent Ground Vehicle Competition and has been tested in the contest for 2 years. The vehicle control model and design of the sensory systems are described. The competition is comprised of two events called the Autonomous Challenge and the Navigation Challenge: For the autonomous challenge, line following, obstacle avoidance, and detection are required. Line following is accomplished with a camera system. Obstacle avoidance and detection are accomplished with a laser scanner. For the navigation challenge, waypoint following and obstacle detection are required. The waypoint navigation is implemented with a global positioning system. The TailGator has provided an educational test bed for not only the contest requirements but also other studies in developing artificial intelligence algorithms such as adaptive control, creative control, automatic calibration, and internet-base control. The significance of this effort is in helping engineering and technology students understand the transition from theory to practice.

KEY WORDS : Unmanned ground vehicle, Line following, Obstacle avoidance, Global position system, Laser scanner

1. INTRODUCTION

Unmanned ground vehicle systems have been the focus of interest of worldwide researchers during the past decade. This research can be applied in a variety of fields: military surveillance, terrain mapping, hazardous environment, and vehicle safety. Unmanned ground vehicle systems research has recently been associated with social infrastructure (Kim and Kim, 2003). Unmanned ground vehicles also are a group of mobile robots with great promising potentials for the future. Space exploration (Elfes *et al.*, 2003; Hirose *et al.*, 1997; Cheok *et al.*, 2004), transportation, material handling (Ito *et al.*, 2002), medical transport of food and patients and future combat vehicles (Letherwood and Gunter, 2001) are areas that traditionally have been emphasized and the laboratory results are beginning to find application in the real world. A power source, control, manipulator and sensory systems are the basic elements of any unmanned ground vehicle (Nillsson, 1980). The University of Florida's TailGator vehicle was designed and built to be compatible with the Joint Architecture for Unmanned Systems (JAUS) reference architecture (Carl, 2004). The selection and application of JAUS to the TailGator project was deemed significant as JAUS is emerging as the DOD standard architecture for all unmanned systems and is currently part of the operational requirements document for the future combat system. The purpose of JAUS is to provide interoperability between various unmanned systems and subsystems for both military and commercial applications. JAUS seeks to achieve this through the development of functionally cohesive building blocks called components whose interface messages are clearly defined. In the language of JAUS, a number of terms are used to delineate position within the overall hierarchy of the system. These terms describe the different levels of the architecture and often imply an internal hierarchical subgrouping. These terms are as follows: system, subsystem, node, and component. A system consists of one or more sub-systems. A sub-system consists of one or more nodes and is usually thought of as a single vehicle. A node consists of one or more components and is typically thought of as a single computing device. This paper mainly deals with the vehicle control model,

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Corresponding author. e-mail: ssanggyum@hanmail.net method and algorithm for obstacle detection, avoidance, and sensory systems design of an unmanned ground vehicle. The TailGator recognized the need to develop an unmanned vehicle to compete in the AUVSI Intelligent Ground Vehicle Competition. This paper essentially focuses on the vehicle system design, and is composed as follows. Section 2 describes the overall block diagram of the system including the sensors and mechanical system. Section 3 describes the sensory systems with emphasis on line following: obstacle avoidance and waypoint navigation sensors. Section 4 and 5 outline the performance prediction and the results.

2. DESIGN

2.1. Design Process

The University of Florida employed a slightly modified version of the design process outlined in Fundamentals of Engineering Design (Barry Hyman). This design consists of seven stages design process is shown as follows:

1. Recognize the need.
2. Develop detailed problem statement.
3. Gather background information.
4. Generate product concepts.
5. Select best concept.
6. Perform detailed design and analysis.
7. Develop prototype and perform testing.

The UF design team recognized the need to develop an unmanned vehicle to compete in the AUVSI Intelligent Ground Vehicle Competition. The team developed a detailed description of the problem clearly starting all the specific design parameters that were identified. Research was performed to discover all relevant background information such as the related work of others, as well as patent search results. Concepts were then generated and the ideas developed as potential ways to solve the design problem. Sketches, diagrams and drawings were particularly useful in explaining the different concepts. The best concepts were then selected based on sound reasoning and engineering criteria. The selected best concepts were then developed and presented along with results of analysis that were conducted.

2.2. Vehicle System

The design team first set out to select a base platform for use as a host vehicle for this competition. The team had a number of choices including commercially available platforms and a custom built platform. Due to constraints associated with preparing for the competition, the team's choice came down to primarily a choice between two commercially available platforms, i.e. a 'power wheels' based platform and the Suzuki Mini-Quad. The team selected the Suzuki Mini-Quad as the platform of choice. This choice was made based on a number of advantages of using this design including: increased run time, integrated suspension, rugged design, and payload capacity.

2.2.1. Vehicle specifications

The Suzuki LT-A50, a gas powered, four wheel, all terrain vehicle was chosen as the base platform. The vehicle is shown in Figure 1. This platform was chosen because of its ruggedness as an all terrain vehicle. It is constructed of a tubular steel frame, comes stock with all terrain tires and suspension and built in safety kill switches. Other specifications can be seen in Table 1. The only limitation of the off-the-shelf vehicle is that its transmission does not allow for reverse. After much debate it was decided that the team's current capabilities in both obstacle avoidance and path planning would allow the vehicle to make correct decisions far enough in advance such that a reverse should not be needed.

2.2.2. Vehicle modifications

There were three modifications that needed to be done to the stock chassis in order to improve performance. The first modification was to remove an exhaust restrictor from the exhaust line as seen in Figure 2.

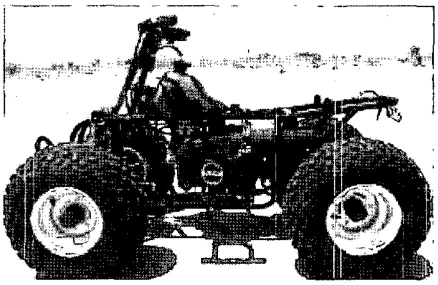


Figure 1. Suzuki LT-A50 mini quad.

Table 1. Suzuki LT-A50 specifications.

Engine	49cc, 2-stroke, air cooled, single cylinder
Transmission	1-speed-automatic
Overall length	1260 mm (49.6 in.)
Overall width	760 mm (29.9 in.)
Overall height	745 mm (29.3 in.)
Ground clearance	120 mm (4.7 in.)
Wheelbase	825 mm (32.5 in.)
Front suspension	Single A-arm., oil damped, Coil spring
Rear suspension	Swingarm, oil damped, coil spring
Fuel tank capacity	2.6 Liter (0.7 gal.)

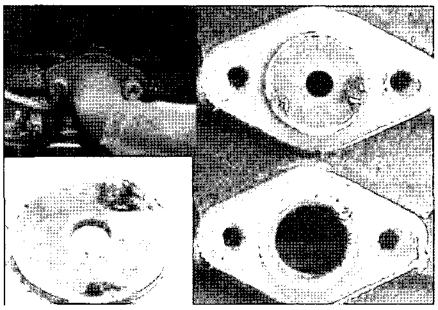


Figure 2. Removal of exhaust restrictor.

After the removal of the restrictor the LT-A50 showed a significant increase in performance. The performance increase included a smoother idle at low speeds, faster throttle response, and an increase in torque and speed. The second modification was necessary in order to increase torque and decrease top speed. This modification was accomplished by changing the output gear ratio from its stock ratio of 37:12 to a ratio of 60:12. Lastly, the steering linkage of the stock vehicle was modified to allow for a tighter turning radius for the vehicle.

2.2.3. Throttle and brake actuation

The throttle and brakes were controlled via a pull cable, the team decided to implement a large-scale servo to pull the cables to the desired position. Testing revealed that the throttle cable needed a minimum of 10 pounds of force to engage while the brake needed a much higher 30 pounds. A large-scale servo capable of providing the required torque was found and incorporated into the design. The associated hardware was finalized and the throttle and brake systems built onto the vehicle. Initial testing revealed flaws in the original design. These flaws were not serious and minor design revisions were made to the system to overcome them.

2.2.4. Steering actuation

Steering actuation was accomplished by mounting a Smart-motor 3000 and a 20:1 planetary gear-head in line with the steering column through the use of a coupling. The Smart-motor is a fully integrated motor that houses all of its drive components within its housing. The Smart-motor can be programmed and only needs direction signals and power. In order to protect the Smart-motor from being back-driven, a slip coupling was designed and integrated into the steering column coupling fixture as shown in Figure 3.

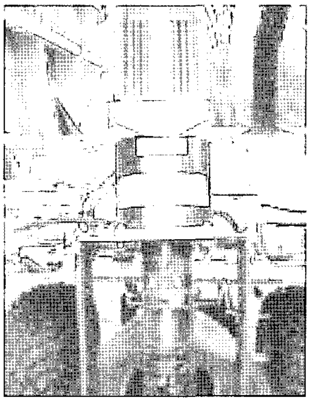


Figure 3. Steering actuation with slip coupling.

The slip coupling was designed by cutting a thin slot in the steering shaft, which is hollow, and putting a slightly smaller coupling over the shaft in order to clamp down on the steering shaft that in turn will clamp down on the motor's shaft creating a friction slip fit. This slip coupling was then tightened to 40 ft-lb of torque and will fail by slipping before the motor is back driven.

2.2.5. Power systems

The TailGator vehicle employs the use of a very robust and flexible power storage and distribution system. The team's goal of having the maximum possible runtime was accomplished through the use of a Honda EU1000i lightweight generator. This provides the vehicle's primary power source. The AC generator is used to charge an uninterruptible power supply on the vehicle that serves as a temporary power backup and also as a filter for the output power.

The AC power is converted to both 12-volts DC and 24-volts DC using AC-to-DC power supplies. The 12-volt power is used to run all vehicle electronics and computing resources. The 24-volt power is used solely to drive the steering motor. While the laser range finder also requires a 24-volt supply, the team decided not to power it from the 24-volt supply provided by the AC power supply. Instead each subsystem on the vehicle is required to take as input 12-volts and use that supply to create any other voltages needed by the system to power its various components. Thus the detection and mapping unit which is included in the mobility control unit is required to convert 12-volts to 24-volts for the laser. This ensures interoperability across a number of vehicle systems. Power distribution is accomplished inside a custom-built enclosure at the rear of the vehicle. This enclosure incorporates the use of female Amphenol connectors on its front panel to ensure that individuals cannot hurt themselves or equipment by shorting across the terminals.

2.3. System Diagram

The major functional subsystems are shown in Figure 4.

The Sub-System Commander Component (SSC) provides the connectivity of all of the vehicle's sensors and actuators to the higher-level software. The SSC links all of the computing units to achieve the desired overall

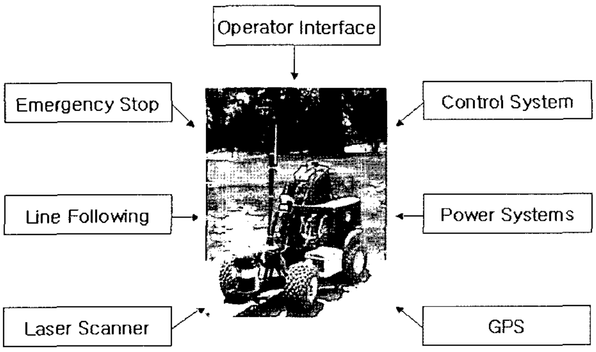


Figure 4. Major functional subsystems.

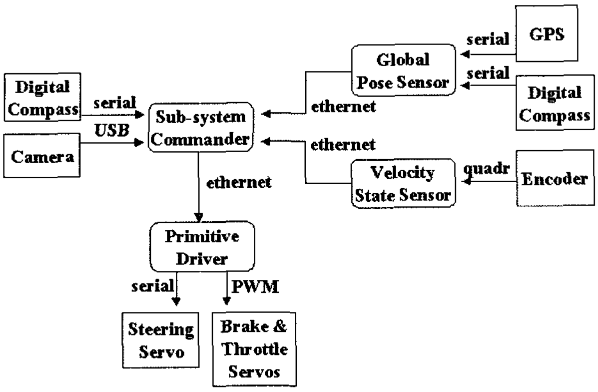


Figure 5. System components and signals.

system control. By connecting all of the lower level computing units and software to this system, the SSC can coordinate vehicle automation by receiving and issuing JAUS messages. The JAUS message framework provides a robust and concrete methodology for system integration in this regard. Figure 5 shows the overall system organization with all of the data connections for the various parts of the autonomous ground vehicle system.

2.4. Vehicle Control

The elements of the throttle, steering, and brake servo system implemented on the TailGator are displayed in block diagram form in Figure 6. The motion controller is the independent processor responsible for performing the calculations necessary to accomplish closed loop control of the actuator position. During autonomous operation, the TailGator receives platform mobility commands from higher level navigation control components, and translates them into an absolute postion commands for the corresponding throttle, steering, or brake actuators.

2.4.1. Throttle control model

The function of the throttle control is to cause the vehicle to drive at a certain speed. To develop this controller the speed dynamics of the vehicle were modelled as a first order lag. The control was accomplished using proportional and integral terms. Figure 7 shows the block diagram of TialGator for throttle control. The motor controller then reads the data from the motor-mounted HP encoders in order to close the control loop and facilitate speed control.

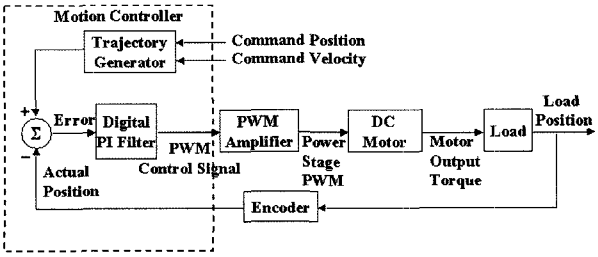


Figure 6. Block diagram of servo system implemented on the TailGator actuators.

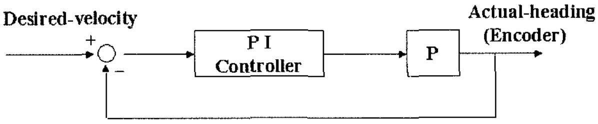


Figure 7. Throttle control block diagram of TailGator.

2.4.2. Steering control model

The steering actuator for accurate steering control uses a Smart-motor 3000, which uses a coupling to connect with the steering column. To develop this controller the lateral dynamics (steer angle to yaw rate) of the vehicle were determined to be second order with a natural frequency of approximately 2 Hz and change with the speed of the vehicle. Gaines for yaw rate and heading error were calculated to place the closed-loop poles at a desired heading angle and natural frequency. These gains were modified to keep the closed-loop dynamics constant regardless of the vehicle speed. Figure 8 shows the block diagram of TialGator for steering control. The motor controller then reads the data from the motor-mounted digital compass for accurate steer angle measurement.

2.4.3. Brake control model

The motion controller integrator into the Smart actuator used for the braking system utilizes an enhanced digital PID filter. Additional sampling rate filters and feedforward terms have been added to the control algorithm with the intent of creating a more robust and better performing closed loop position controller. In place of the

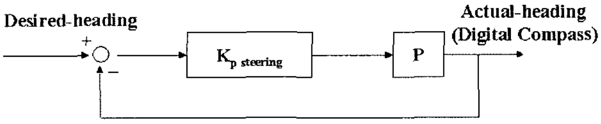


Figure 8. Steering control block diagram of TailGator.

single derivative filter element of the traditional PID controller, this enhanced version uses two cascading velocity feedback gain terms that use velocity feedback information that has been passed through one or both of two user configurable low pass filters. Also, a velocity feed-forward term is added to the algorithm in order to compensate for the position lag introduced by the negative velocity feedback gain terms. An acceleration feedback gain term and an acceleration feed-forward term are included in the control filter. The acceleration feedback term counteracts rapid changes in shaft velocity like a virtual flywheel, which contributes to overall system smoothness. Similar to the velocity feed-forward term, the acceleration feed-forward term is added to compensate for any position lag that could be caused by the negative acceleration feedback filter action.

3. SENSORY SYSTEMS

3.1. Autonomous Challenge Line Following and Obstacle Detection

For the autonomous challenge, the vehicle must drive between two white lines. The TailGator is designed to negotiate around an outdoor obstacle course in a prescribed time while staying within the 5 mph speed limit, traversing ramps with 15% incline, and avoiding physical obstacles on the track.

3.2. Vision System

The TailGator's vision system for the autonomous challenge is comprised of one camera for line following and for pothole detection. So several advanced image processing and classification algorithms were developed to extract the white lines and potholes. An industrial, color CCD camera with an auto-iris lens is used to gather visual information about the environment. The maximum likelihood estimation (ML) technique is a statistical modeling technique that can be applied to multi-dimensional data sets. By using the model created by this technique the probability of each pixel is calculated which is used for classification. Figure 9 depicts the method by which the probability of each pixel is calculated and presents sample image data and classified data. The classification performance is affected by tuning the probability threshold.

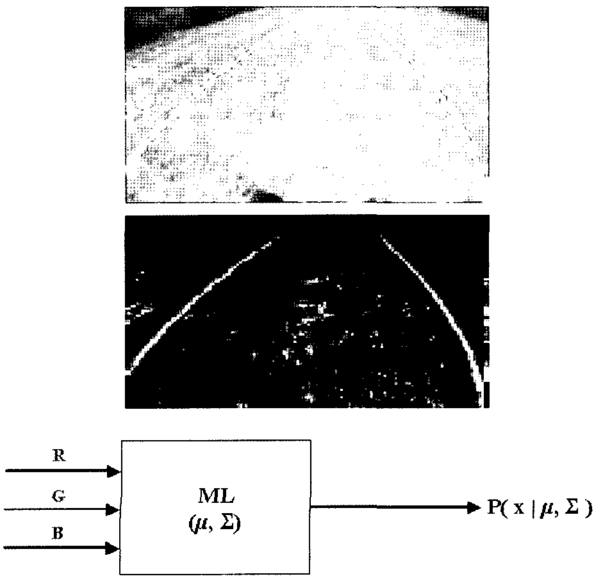


Figure 9. Maximum likelihood estimation technique and results.

The next method that was developed utilized an artificial neural network (ANN) to classify the image data. A classifier was developed using a single hidden layer, multiplayer perception network. The neural network was trained using sample image data. The algorithm operates similar to the maximum likelihood technique except that this technique takes the pixel data and passes it through a trained artificial neural network with a non-linear response. Figure 10 illustrates the concept of the neural network algorithm and corresponding results.

Another algorithm was developed so that classification could be performed without the need for a color model. The idea was to develop a classifier based solely on spatial properties of regions of similar color and proximity. The spatial statistics classifier (SSC) utilizes preprocessing techniques such as principal component ana-

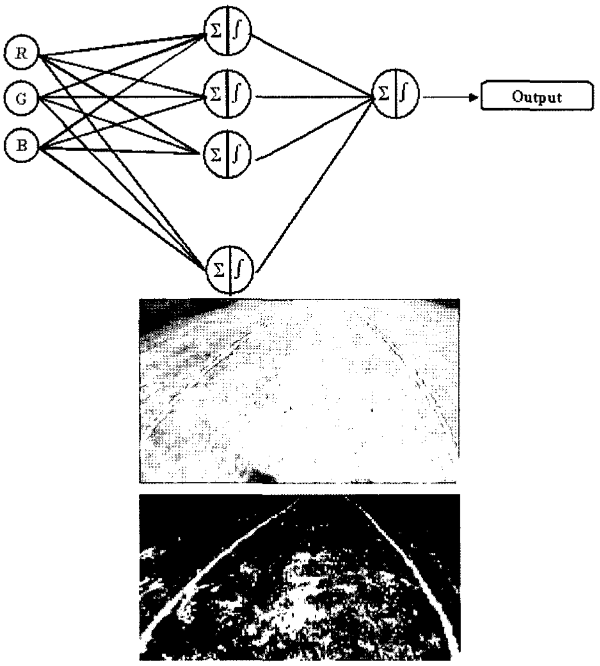
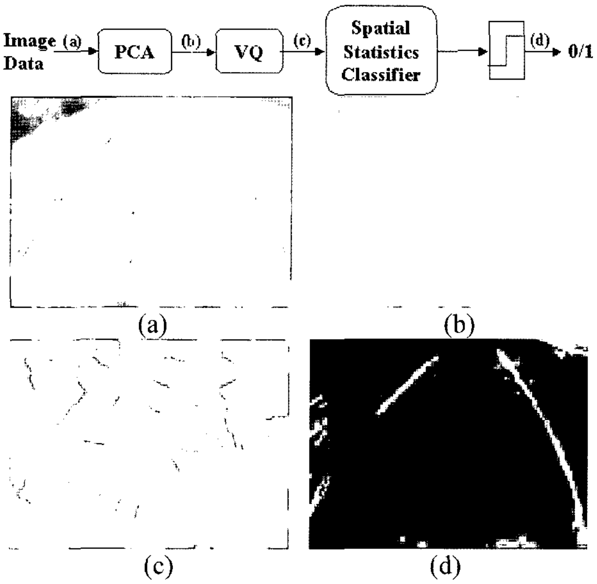


Figure 10. Artificial neural network algorithm and results.



(a) (b)

(c) (d)

Figure 11. Spatial statistics classifier.

lysis and vector quantization to reduce the data set and to break the image into regions of similar properties. Illustration of the spatial statistics classifier and sample image data and corresponding results are shown in Figure 11.

These three methods were combined to form two "mixture of experts" algorithms. The first mixture of experts algorithm is composed of the ML and SSC algorithms. The second mixture of experts algorithm is composed of the ANN and SSC algorithms. Figure 12 compares the image data and the two mixture of experts techniques. Both techniques provide adequate results and process in approximately the same time at a rate of 1 Hz.

3.3. Obstacle Detection, Avoidance and Path Planning

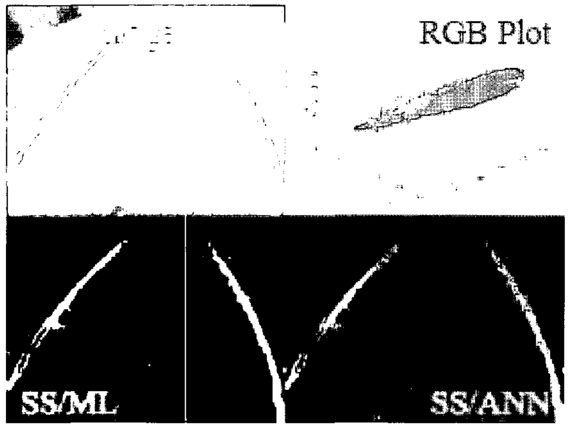


Figure 12. Comparison of spatial statistics coupled with Maximum likelihood and spatial statistics coupled with artificial neural network outputs.

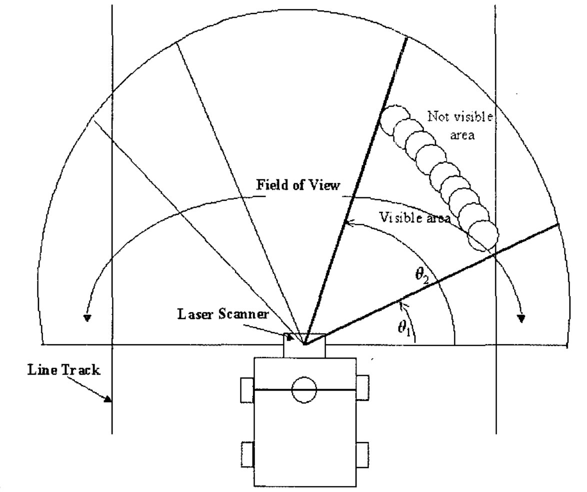


Figure 13. Field of view of the laser scanner.

The obstacle avoidance system detects an obstacle on the navigation course. The TailGator uses the Sick Laser Measurement System (LMS 200) for sensing obstacles in the path. The power supply to the unit is through a 24Volt, 1.8 Amp adapter. The unit communicates with the central computer using a RS232/422 serial interface card. The maximum range of the scanner is 32 meters. For the contest, a range of 8 meters with a resolution of 1has been selected. The scanner data is used to get information about the distance of the obstacle from the robot. This can be used to calculate the size of the obstacle. The scanner is mounted at a height of 10 inches above the ground to facilitate the detection of short as well as tall objects. Figure 13 shows the field of view of the laser scanner.

The visual local grid map and spatial local grid map are combined to form an overall local grid map. The local grid map and the vehicle parameters are utilized by the path planner to determine an unobstructed desired heading. During the autonomous challenge, the local grid map data from the image processing software is fused with the spatial data. This combined data is run through the path planner to find the optimal desired heading. In the

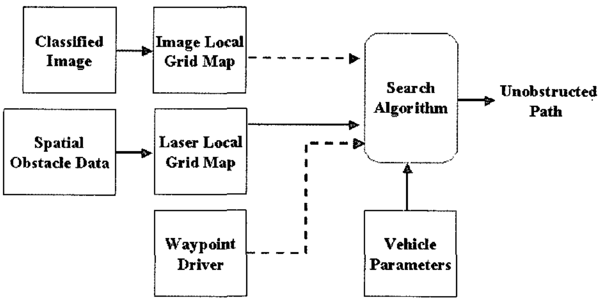


Figure 14. Collision avoidance algorithm.

navigation challenge the spatial data is combined with the waypoint driver output to find the optimal path. The diagram in Figure 14 illustrates the collision avoidance algorithm.

3.4. Navigation Challenge

The goal of the navigation challenge is to navigate the TailGator to a series of predefined waypoints while avoiding obstacles. For this a global positioning system (GPS) is used to obtain the robot position, then tracking is used to move the robot from one point to the next, updating the new base with every pass. The laser scanning system was used to detect and avoid obstacles en route to the target waypoints. Wheel encoders on the vehicle were used to track the path navigated and make decisions about the distance to travel and angle to steer to reach a target point.

The position system onboard the Tailgator, is a combination of GPS, shaft encoder, and magnetic compass information. The system uses a Novatel GPS and a PNI digital compass. The position system is used to determine the vehicle's global position, and forward velocity. The system combines the data from all three of its sensors in a weighted averaging filter to improve the stability and minimize the drift of the GPS. The shaft encoder is mounted to the rear axle of the TailGator and outputs quadrature signals that indicate the axle rotation angle and direction of rotation. These signals are decoded by a microcontroller, which stores the relative encoder position in integer form. The microcontroller is also used to read and parse the digital compass serially transmitted data. The information for both the encoder and compass is collected at a rate of 10 Hz and then sent to a single board computer running Linux via a serial port. The GPS data is also received and parsed by the single board computer. Once the Linux computer has received the data from the shaft encoder, GPS, and digital compass, it filters the data together using a weighted average filter. Figure 15 shows simulated results of this filtering method.

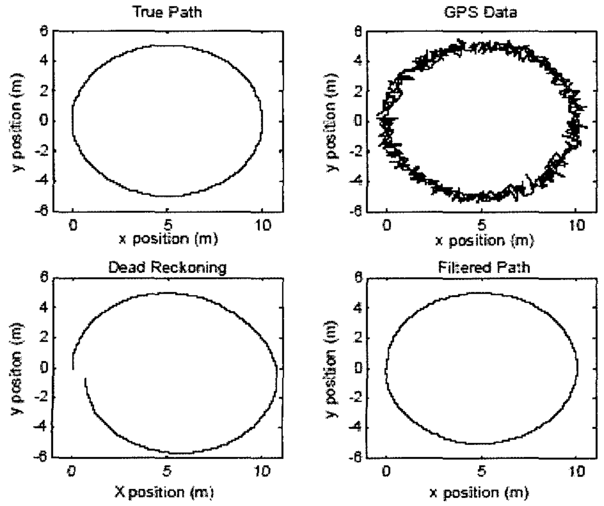


Figure 15. Weighted filter results.

The image in the upper left of Figure 13 represents the simulated true path of the vehicle. The image in the upper right represented simulated GPS data. The image in the lower left is the simulated output from the encoder modeled with wheel slip error. The image in the lower right represents the weighted average output of the two. Testing on the vehicle platform has shown similar repeatable and reliable results. A discrete time derivative of the encoder data is also calculated in order to determine the vehicle speed. The position and velocity data is transmitted to the sub-system commander via the Global Pose Sensor and Velocity State Sensor messages outlined in the JAUS document.

4. PROTOTYPE DEVELOPMENT AND TESTING

During testing of the prototype vehicle and its various subcomponents, we discovered areas of concern in the vehicle's performance. The areas included vehicle torque performance and the performance of the position system

4.1. Torque Requirements

Upon initial testing of the original vehicle, it was found that the torque required to climb a ramp was lacking. With a payload of approximately 120 pounds the vehicle would begin to climb the ramp and stall before reaching the peak of the ramp. Changing the rear sprocket on the vehicle solved this problem. The original sprocket had 37 teeth. We were able to obtain a sprocket that was larger, i.e. had more teeth, and specifically designed for this model vehicle. The new sprocket has 60 teeth. This modification provided a 66% torque increase. The new sprocket is shown in Figure 16.

4.2. Position System Component Micro Controller

The original designs for the position system component included the use of a RabbitCore 3200 microprocessor to

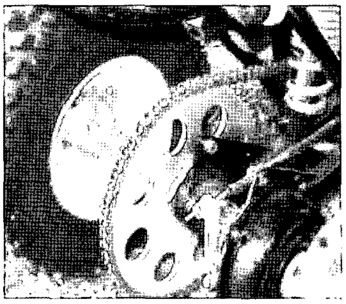


Figure 16. New rear sprocket.

parse and filter the data and transmit the appropriate JAUS message. After completion of the original system, we struggled with achieving sufficient GPS accuracy from the system. Further inspection of the situation showed that the lack of floating point hardware on the RabbitCore module caused a loss of precision in the data beyond the fourth decimal place. This fourth decimal place corresponds to about 600 inches. Another solution had to be found that would ensure higher accuracy. The encoder unit requires quadrature decoding. The RabbitCore module included quadrature decoding in its functionality and no other method to decode the signal was readily available. A hybrid solution was chosen and implemented. The microprocessor is used to decode the quadrature signal and parse the data from the digital compass. This data is then sent via RS232 to a single board computer running Linux. The single board computer also takes in the serial data from the GPS, combines it with the data from the microprocessor and transmits the Global Pose Sensor and Velocity State Sensor JAUS messages. The flexibility of the JAUS architecture made this transition less time consuming and relatively painless for the design.

4.3. Vehicle Performance Analysis

The TailGator vehicle meets or exceeds all performance criteria placed on it by both the design team's goals and the IGVC competition. The gear train on the system has been modified to provide more low-end torque, therefore reducing the vehicle's top speed to just below five miles per hour and increasing ramp climbing ability. In testing, the vehicle has traversed inclines in excess of 30. The use of a gasoline-powered vehicle coupled with an AC generator provides TailGator with an extended runtime, limited only by the supply of fuel. The laser range finder onboard the vehicle is capable of detecting obstacles at a distance of 80 meters, giving the path planning algorithm significant time to devise a reliable path around obstacles while avoiding traps and dead ends. The Novatel GPS uses WAAS correction signals to achieve sub-meter accuracy while the PNI compass module provides heading data accurate +/– one degree. Testing has shown waypoint accuracy of approximately one meter. The weighted average filter essentially eliminates lateral deviation of the vehicle's position.

5. CONCLUSION

This paper has described the process by which the "UF TailGator" was designed and developed. Several aspects of the design and implementation of an unmanned ground vehicle were explained. The main sensory systems and algorithms for line following, waypoint navigation, and pothole detection were described. The design has proved to be robust in the ground vehicle competition as well as many other experiments. The UF CIMAR TailGator team currently is using the lessons learned from this project to design a completely new vehicle called NaviGator and is preparing to compete in the 2005 DARPA Grand Challenge with the new vehicle. Overall, with a maximum speed of 37 miles per hour, the new vehicle will be able to perform image processing, obstacle detection and avoidance, sensor fusion, waypoint navigation, and path planning.

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