

# **Autonomous Surface Navigation Platform Utilizing GPS and an Ethernet Camera**

ECE4007 Senior Design Project

Section RP1 (GTS), TeamASV  
Project Advisor, Dr. Elliot Moore

Michael Baxter  
Angel Berrocal  
Brandon Groff

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## **Executive Summary**

The Autonomous Surface Navigation Platform (ASNP) is a system that will enable a land or marine surface vehicle to navigate without human intervention. The need for this system has been expressed by the Department of Defense for use in homeland security applications. The ASNP will provide the Georgia Tech Savannah Robotics Team with a basic navigation platform on which to build a vehicle for the Autonomous Surface Vehicle (ASV) competition.

Currently the ASNP is installed on a land-based vehicle capable of autonomous navigation following a path of GPS waypoints and searching for and tracking an object once it reaches the final destination. Additional work with the ASNP will include adding more sensors such as an inertial motion unit and chemical sensors. A marine version of the vehicle will be constructed for conducting networked control system experiments and tracking underwater vehicles.

The ASNP utilizes the CompactRIO controller as the central data processing unit of the system. Sensor data from the Ethernet camera and Garmin GPS receiver is used to determine motor speeds, which are output by the CompactRIO I/O module to a propulsion system. The prototype used to test this system utilized Vex motors for propulsion. Proportional controllers are used to provide a stabilized control of the navigation system.

The ASNP prototype cost is \$7470, with an additional reusable software cost of \$9688. The price is based on the cost of the CompactRIO controller, chassis and I/O module, Axis Ethernet camera, and Garmin GPS receiver.

# **Autonomous Surface Navigation Platform**

## **1. Introduction**

TeamASV is sponsored by Dr. Fumin Zhang of Georgia Tech Savannah to develop an autonomous surface navigation platform (ASNP). This hardware and software platform is capable of autonomously navigating a vehicle to a user-specified location via a path of GPS coordinates also provided by the user. Once arriving at the location it will search for and track an object. The final prototype cost was \$7470.

### **1.1 Objective**

The ASNP is an autonomous navigation solution intended for installation in a vehicle to provide autonomous navigation to a location and find a specified object at that location. The device is fully programmable to allow different navigation paths and objects to find. The target customer for this system is the Department of Defense for homeland security applications.

The system is composed of an Ethernet camera and Global Positioning System (GPS) receiver which provide input to a CompactRIO controller. The CompactRIO processes all sensor data to properly navigate the vehicle. The ASNP is able to control a propulsion system through the use of pulse-width modulated signals (PWM). A graphical user interface (GUI) is provided on a host computer which can monitor progress of the vehicle as well as program new navigation tasks to the system. Once programmed, the vehicle containing the navigation system can be switched on, and it will autonomously navigate from waypoint to waypoint until it reaches the last one. Upon reaching the last waypoint, the system searches for an object using image data from the Ethernet camera. Once the object is found, the vehicle moves to within a short distance of it.

## **1.2 Motivation**

The motivation for the ASNP is to provide a basic platform for the Department of Defense to develop autonomous homeland security systems. This is a new solution as no commercial equivalent yet exists. Tasks such as retrieving unexploded ordinance in both land and sea environments are much preferred to be completed by robots than humans. Robotic systems do not require nearly as much life support systems as humans, and can also enter areas where conditions are too harsh for human survival.

## **2. Project Description and Goals**

TeamASV designed an autonomous navigation platform for the Department of Defense that allows a vehicle to navigate to a specified location via GPS waypoints. Once at the location the navigation platform searches for an object and drives the vehicle towards it. The only interaction between user and the system is through a host PC which allows the waypoints to be entered prior to activation of the system. This system deviates slightly from the originally proposed goals:

- Navigate to a single GPS point
- Drive around obstacles
- Search for a red ball, drive towards it and then stop

The ASNP in its current state can do the following:

- Navigate a collection of GPS waypoints
- Search for a red cylinder, drive towards it and then stop

The goal of avoiding obstacles was not met due to issues with the inertial motion unit (IMU). Designing a proper system to make use of this sensor required more time than was available. Because of this the inertial motion unit was removed. Without the IMU for obstacle

avoidance, the sonar was also no longer necessary. To counteract this loss of functionality, the GPS functionality was expanded. Instead of driving straight to a single point, the system can follow a collection of way points indicating a path. This allows for static object avoidance (i.e. it can be mapped around large buildings but cannot avoid a tree falling in front of it) and partially meets the original design goal. The red ball was swapped for a red cylinder simply because a red cylinder was on hand and served the same purpose of the ball.

Originally the ANSP was proposed to have the following sensors.

- Global Positioning System (GPS) receiver
- Two network cameras
- Inertial motion unit (IMU)
- Sonar

The ANSP now makes use of the following sensors.

- GPS
- One Network Camera

The additional time to implement the IMU was due to large drift (over 20°) of the IMU compass reading. This failure caused the sonar to become unusable because the obstacle avoidance algorithm that used the sonar depended on the IMU working as well. The second camera was also removed because its presence was of no added benefit to the system. Because of the reduction in sensors the price for the prototype changed from \$9,952 to \$7,470.

The project could be expanded back to the original design goals if extra time was available. A proper filtering solution, such as a Kalman filter, is needed for the IMU data to be used properly. A proper design of such a filter would require significant development time as well as the addition of an engineer with a graduate degree. With the proper filtering solution for

the IMU, the sonar could be added and obstacle avoidance could be properly implemented.

A simple test vehicle was built to properly test the platform and software. This was built using on-hand Vex hardware and motors. It is a simple, differential drive vehicle using four Vex motors. The original prototype was intended to be installed on a marine surface vehicle; however, development of this craft took longer than expected and the wheeled platform was used for testing instead.

### 3. Technical Specifications

#### 3.1 Physical Specification

Table 1. Physical Specifications of ASNP and Prototype

	ASNP Target	ASNP Actual	Full Prototype (ASNP & Vehicle)
<b>Weight</b>	7 kg	4.67 kg	6.78 kg
<b>Size</b>			
Length	50 cm	35 cm	39 cm
Width	50 cm	45 cm	45 cm
Height	30 cm	15 cm	29.5 cm
<b>Operational Time</b>	1 hour	2.25 hours	2.25 hours

Table 1 shows the physical specifications of both the ASNP system alone and the ASNP system installed on a prototype platform built with Vex robotics materials. As the table shows, the target specifications were met by the ASNP system. The prototype also meets the specifications despite the target being for the navigation system itself.

#### 3.2 Path Following Specification

Table 2. Path Following Specifications

	Target	Actual
<b>GPS Accuracy</b>	< 3 meters (using WAAS)	< 3 meters
<b>Turning Radius</b>	1.5 meters	< 1 meter

The Garmin GPS uses the Wide Area Augmented System (WAAS). This improves standard GPS accuracy from 10 meters to less than 3 meters. We used this baseline as a target specification for our autonomous navigation platform. During testing, the ASNP guided the prototype vehicle to within a three meter area of the target GPS waypoint.

The turning radius during GPS path following depends on the vehicle it is mounted on and the controller design of the ASNP. Because the prototype vehicle has a turning radius of zero (i.e. can spin in place) any expansion of the turning radius is due to the ASNP and a set baseline for the minimum turning radius of the vehicle. For acceptable navigation, the turning radius should be less than three meters so it can turn within the accuracy of the GPS. During testing we found it to be 1.0 meters which meets the target specification.

### **3.3 Object Search & Recognition Specification**

**Table 3. Object Search Specifications**

	<b>Target</b>	<b>Actual</b>
<b>Search Time</b>	< 30 secs	< 8 secs
<b>Color Recognition</b>	Red Ball	Red Cylinder
<b>Object Match Distance</b>	< 3 meters	3 meters
<b>Stopping Distance</b>	< 1 meter	0.5 meters

The goal of the object search and recognition algorithm was to search for and move toward an object with a red hue. The red cylinder was chosen over the red ball since it was on hand. The red hue was chosen since it is not commonly found in the test environment. Because GPS using WAAS has an accuracy of less than three meters the ASNP should be able to spot the red cylinder at a distance of three meters. The stopping distance should be close enough to the object to demonstrate recognition and tracking.



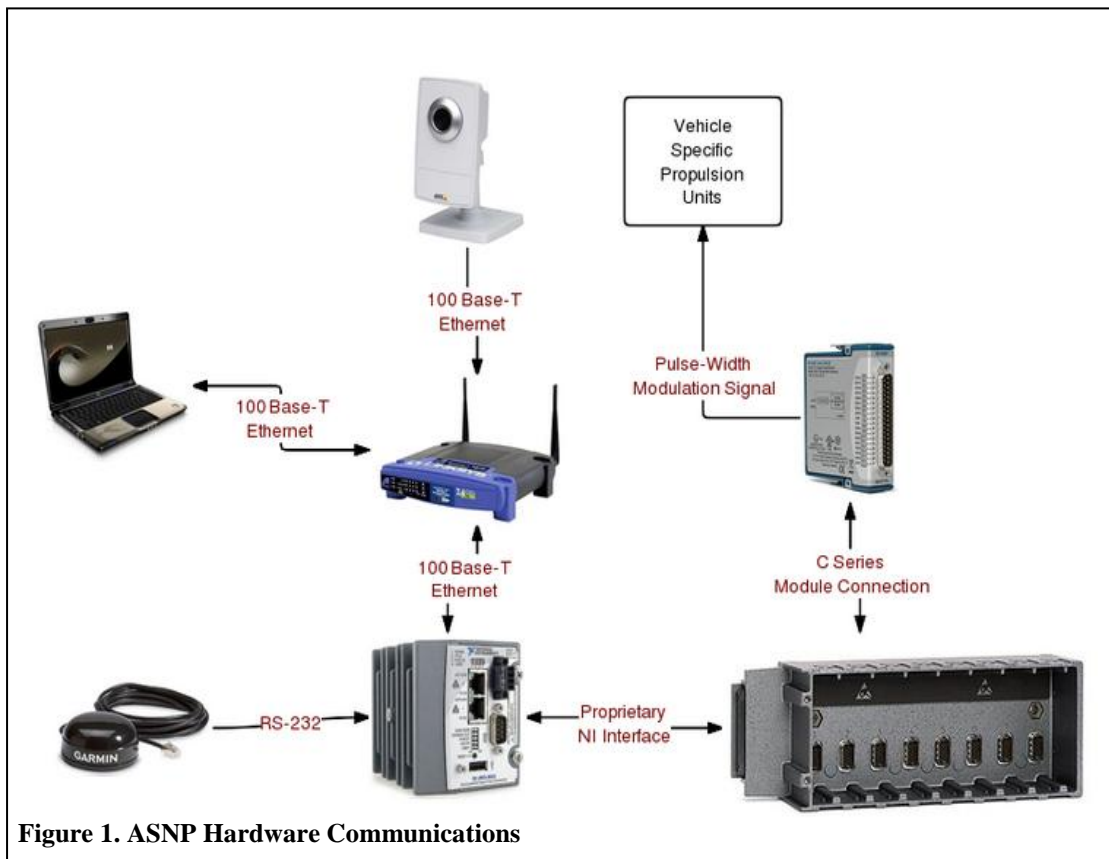
## **4. Design Approach and Details**

### **4.1 Design Details**

The project design is divided into three categories: the electrical hardware integration, which includes the communications between devices and power systems, the software systems, and the test prototype. Additional data sheets and specifications for all devices used are available on our website [1].

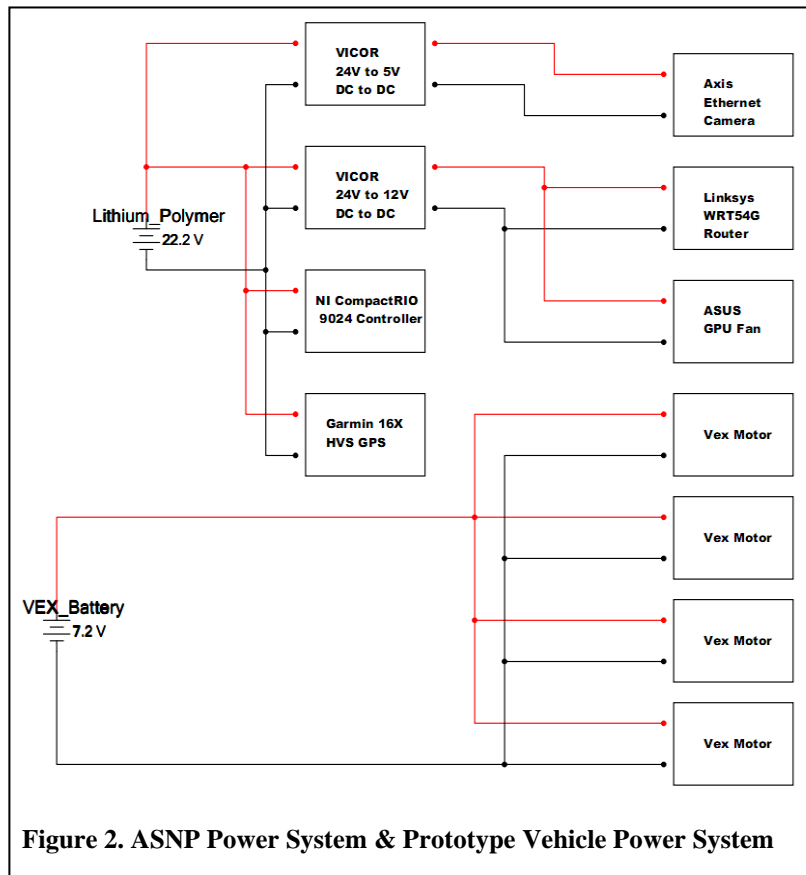
#### **4.1.1 Electrical Hardware Integration**

The overall hardware design of the ASNP system is shown in Figure 1. All software runs on the NI cRIO controller, with the laptop only being used to monitor data and program flow. The CompactRIO is the hub, receiving sensor data from both the Garmin GPS receiver and the Axis Ethernet camera. The output from the CompactRIO is pulse-width modulation signals to the FPGA which interfaces with the digital I/O module and transmits motor speeds to a propulsion system. All parts other than the Garmin GPS receiver were already on hand through the Georgia Tech Savannah robotics team.



**Figure 1. ASNP Hardware Communications**

The ASNP power system is composed of a 22.2V lithium polymer battery. The prototype vehicle also uses a 7.2V Nickel Cadmium Vex robotics battery to power its propulsion system. In order to power the Axis Ethernet camera, a 24V to 5V DC to DC converter is used in the ASNP. A 24V to 12V DC to DC converter is used to power the Linksys wireless router and the GPU fan. The GPU fan was used to keep the 24V to 5V DC to DC converter cool as one failed presumably due to overheating. Figure 2 shows a schematic of the power systems.

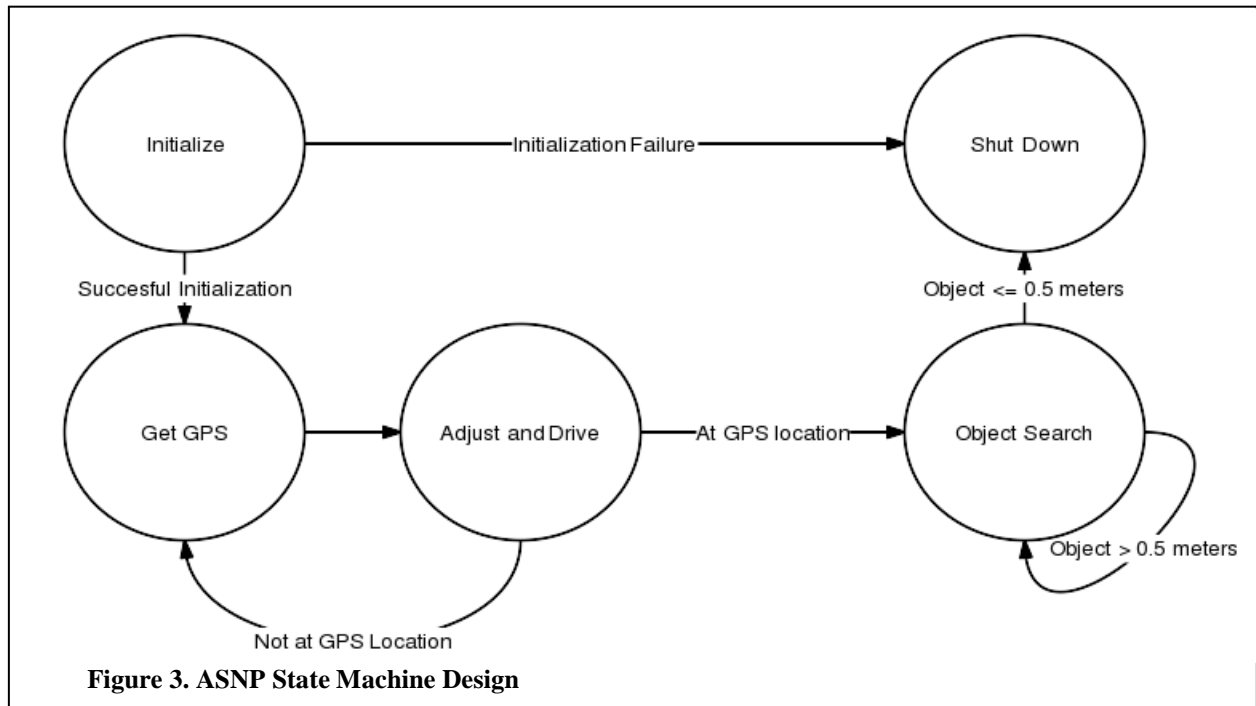


## 4.1.2 Software Design

### 4.1.2.1 Overall Program Design

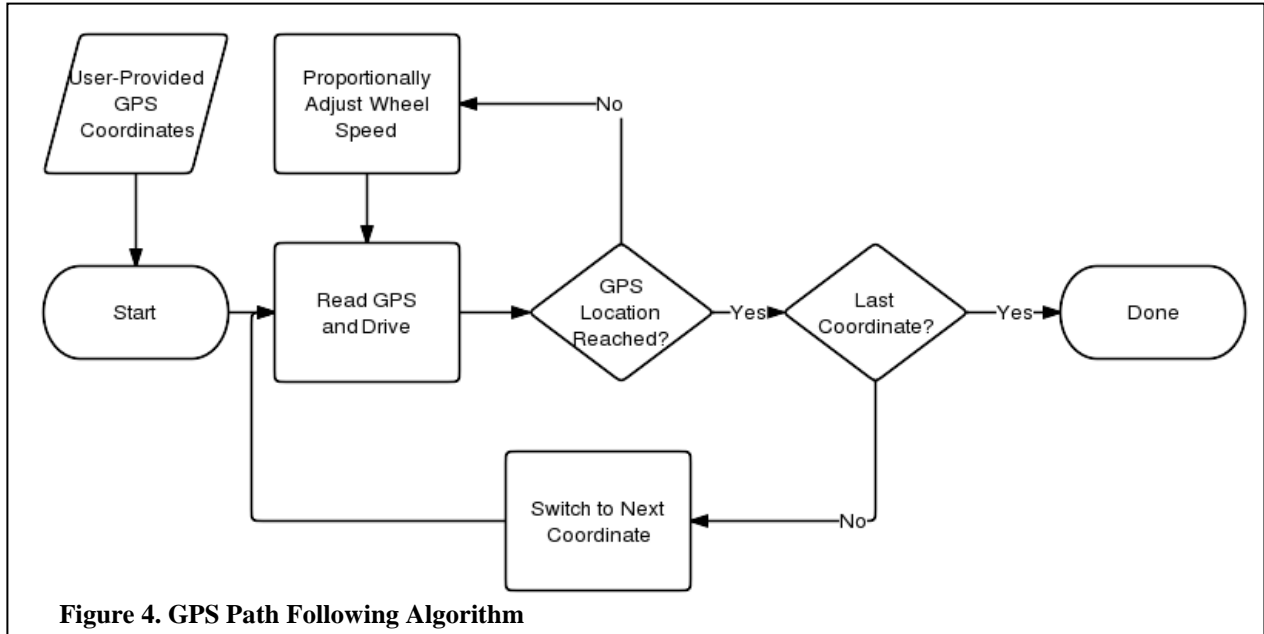
The overall architecture of the ASNP software system is a state machine. Five states are used in the current implementation, with two states for initialization and shut down. The three remaining states are used to complete GPS path following and object search and recognition.

Figure 3 shows the state machine diagram for the current ASNP software.



#### 4.1.2.2 GPS Path Following

GPS path following composes two states of the overall state machine. One state gets a GPS reading and one proportionally adjusts the wheel speeds of the vehicle. If the vehicle comes within  $0.00001^\circ$  of both the latitude and longitude of the desired GPS location, the system will switch to the next GPS coordinate in the desired path or move to the object search state if it has reached the last GPS point. Figure 4 shows the software flow chart for the GPS path following algorithm.



The proportional control used for GPS path following is a mathematical method for modeling the relationship between the current and desired heading of the vehicle with motor speeds. The current and desired headings are determined from the current, previous, and destination GPS locations.

First the latitude is defined as  $\alpha$  and longitude is defined as  $\beta$ . It then follows that  $\Delta\alpha$  and  $\Delta\beta$  are the differences between two locations in latitude and longitude, respectively.

$$\Delta\alpha = \alpha_a - \alpha_b$$

$$\Delta\beta = \beta_a - \beta_b$$

It then follows that the distance between the two points on the spherical surface can be calculated as  $x_a - x_b$  and  $y_a - y_b$ . This calculation uses the radius of the Earth,  $R_E$ , as 6371 km.

$$x_a - x_b = R_E \cos(\alpha_a) \sin(\Delta\beta)$$

$$y_a - y_b = R_E \sin(\Delta\alpha)$$

Using these two distances, the heading between the two points can be found as  $\theta$ . The equation below shows this calculation.

$$\theta = \tan^{-1}(x_a - x_b, y_a - y_b)$$

This heading is calculated twice, once to find heading to the object and once to find the actual heading of the vehicle. The heading to the object is calculated using the destination location and the current location, while the actual heading is calculated using the current location and previous location.

Finally,  $\dot{\theta}$  is calculated as a scaled version of turning speed.  $K$  is a proportional scale factor which controls the turning radius of the vehicle as well as scales  $\dot{\theta}$  to a usable quantity for pulse-width modulation signals. For the current platform,  $K$  is 15.

$$\dot{\theta} = K(\theta_{heading} - \theta_{object})$$

For the current prototype vehicle, the following two equations are used to relate  $\dot{\theta}$  to individual motor speeds.

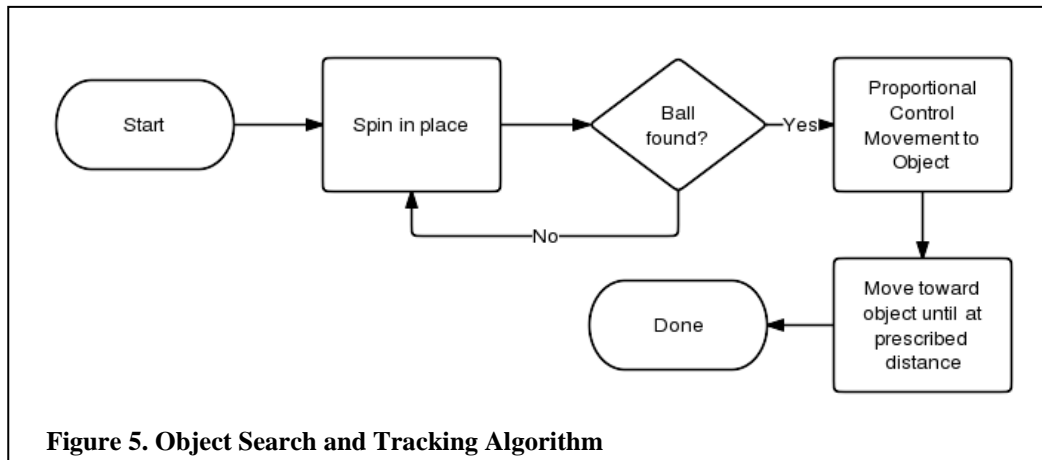
$$\dot{\phi}_L = 50 - K + \dot{\theta}$$

$$\dot{\phi}_R = 50 - K - \dot{\theta}$$

$\dot{\phi}_L$  and  $\dot{\phi}_R$  are sent as pulse-width values to a custom-written driver which converts these values to a 1-2ms pulse which sets the wheel speed of the Vex motors on the current prototype platform. The actual implementation of the GPS following algorithm can be found in the “Get GPS” and “Adjust and Drive” states shown in Appendix B.

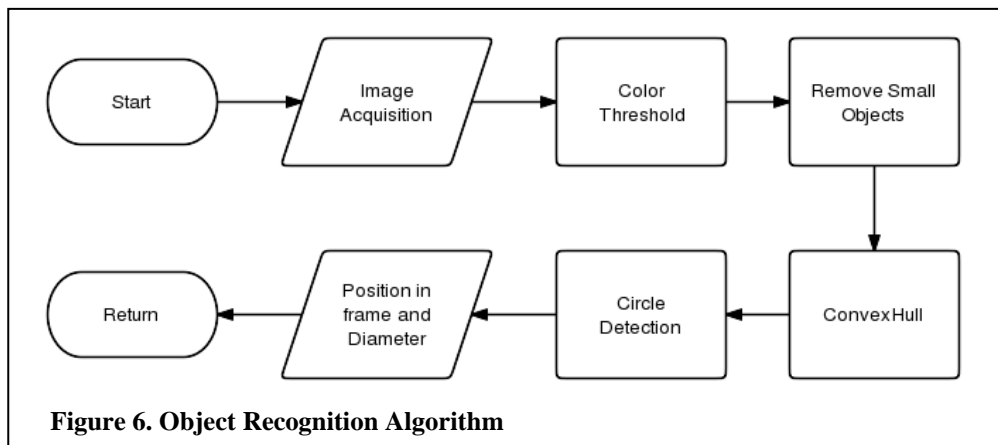
### 4.1.2.3 Object Search and Recognition

The object search algorithm composes a single state of the state machine which does a simple search followed by proportional movement to the objective. It moves toward the objective until it is within 0.5 meters of it. Figure 5 shows the software flow chart for this algorithm.



**Figure 5. Object Search and Tracking Algorithm**

The recognition of the object is done with the use of LabVIEW Vision Assistant. This allows a simple block diagram to be constructed of image processing commands which isolates the object in the image frame and returns the position and diameter of the object in pixels. Figure 6 shows the process of image processing commands used in LabVIEW Vision Assistant to obtain the object's position and diameter in the image frame.



**Figure 6. Object Recognition Algorithm**

The proportional wheel speed adjustment for object search and tracking is done using the same method as the GPS proportional control. The only difference is the scale factors, including K. K is 0.1 for the object search controller. The following equations show the mathematical model used, where S is the speed of the motor offset.  $x$  is the pixel location of the object on the horizontal axis. The value of 160 is used since it is the center pixel in a 320x240 image.

$$\dot{\varphi}_R = s - K(x - 160)$$

$$\dot{\varphi}_L = s + K(x - 160)$$

The actual implementation of the object search and recognition algorithm can be found in the “Object Search” state shown in Appendix B.

### **4.1.3 Prototype Design**

The prototype platform built for testing the ASNP was composed completely of Vex robotics kit parts and motors. It uses a treaded design, with each tread powered by two Vex motors. A flat platform 39 cm by 39 cm is the mounting surface for all ASNP components, with a slightly raised platform for the GPS receiver. The platform is a differential drive robot, which is instrumental in the models used to calculate motor speeds.

## **4.2 Codes and Standards**

Ethernet communications are used between the National Instruments controller, network camera, and router. 10/100 BASE-T Ethernet is standardized as IEEE 802.3 and sends data grouped in packets [2]. In addition, the computer used to program the user GPS coordinates into the platform uses IEEE 802.11g wireless Ethernet to connect to the controller through the router. Each device on the communications network has an address which is used for specifying both



the destination of packets as well as the source. LabVIEW uses Ethernet to communicate between a PC, where the programming is implemented, and the controller and FPGA. After the software is developed on a PC, it is deployed to the controller and FPGA via Ethernet. Due to multiple Ethernet devices being used on the platform, an Ethernet router must be used to allow connectivity between all devices.

RS-232 serial communication is used between the controller and the Garmin GPS receiver. A serial port on the controller will provide this interface and a LabVIEW driver for the unit is provided by National Instruments.

The NMEA 0183 version 2.0 standard is used by the Garmin GPS to indicate absolute position. This standard defines the format for data transmission in marine electronic devices [3]. The GPS returns ASCII strings of data in the NMEA 0183 version 2.0 GPRMC string format which is interpreted by the National Instruments LabVIEW driver.

## **5. Schedule, Tasks, and Milestones**

The autonomous navigation platform was designed, and implemented in 85 days. The demonstration of the ASNP will be demonstrated on May 7th, 2010. Table 4 shows the major tasks in bold and the milestones in italics.

**Table 4. Schedule of Tasks and Milestones**

<b>Task Name</b>	<b>Start</b>	<b>End</b>
<b>HARDWARE COMPONENT</b>	<b>1/11/2010</b>	<b>4/15/2010</b>
Build Prototype using Vex	1/19/2010	1/26/2010
Ehternet Camera interface with LabVIEW	1/25/2010	1/27/2010
GPS Interface with CompactRIO	4/12/2010	4/12/2010
Power System	4/1/2010	4/15/2010
<b>LabVIEW PROGRAMMING</b>	<b>2/1/2010</b>	<b>4/30/2010</b>
Navigation System Design	4/1/2010	4/7/2010
<i>Object Search and Recognition</i>	<i>4/8/2010</i>	<i>4/16/2010</i>
<i>GPS Path Following</i>	<i>4/8/2010</i>	<i>4/29/2010</i>
Overall Program Flow	4/1/2010	4/29/2010
Optimization and Testing	4/27/2010	4/30/2010
<b>PROTOTYPE FINALIZATION</b>	<b>4/19/2010</b>	<b>4/21/2010</b>
<i>Finalized Assembly of Prototype</i>	<i>4/21/2010</i>	<i>4/21/2010</i>
<b>DEMO</b>	<b>5/3/2010</b>	<b>5/7/2010</b>
Final Demonstration	5/7/2010	5/7/2010

The project was divided into four major tasks: a hardware component, software programming, prototype design, and demonstration as indicated above. Michael Baxter and Angel Berrocal were responsible for building the Vex prototype, as well as much of the modeling for the GPS Path Following task. Brandon Groff was responsible for much of the interfacing between hardware and software, as well as LabVIEW programming. All software design and development was done as a group. The Gantt chart in Appendix A shows these tasks in greater detail.

## **6. Results and Acceptance Testing**

Acceptance testing was done in three stages. The first set of tests was designed to test the ASNP's ability to track and move towards an object. The second set of tests were focused on GPS path following and guidance. The final tests put GPS path following and object searching together in the environment of the final demonstration. Tests regarding collision avoidance were discarded as the removal of sonar and the IMU caused the obstacle avoidance algorithm to be

discarded from implementation.

The first assessment tested the ASNP's ability to drive towards a green ball. These tests were done indoors in various lighting conditions. During these tests the robot would spin until the green ball was in sight and start driving towards it. If the ball ever moved into the peripheral vision of the camera the ASNP would turn the prototype vehicle to align itself with the ball. Once the green ball was close enough the ASNP would stop the vehicle. During these tests the ASNP could detect the green ball from a distance of 3 to 6 meters depending on the lighting of the environment. If the ball remained stationary, the robot would successfully drive up to the ball and stop within a range of 0.4 to 0.7 meters of it. If the ball left the view of the ANSP, the vehicle would rotate at a speed of approximately 20 cm/s until reacquisition of the ball.

In the second set of tests the ASNP was placed outside where the GPS could acquire a signal. In this set of tests the robot was first placed at the desired destination of the vehicle and a GPS reading was recorded as the new destination location. During these tests the ASNP was placed at various locations with varying orientations and verified that it returns to the destination location. The vehicle was able to make turns within a 1.0 meter radius and drive at a forward speed of 23 cm/s. During testing the ASNP could navigate the vehicle to the target location within 3 meters of accuracy as dictated by the GPS standard (using WAAS).

During the final tests, slight modifications were made so that the ASNP could follow a path of multiple GPS waypoints and then look for a red cylinder instead of a green ball. For these tests, the GPS coordinates were pulled from Google Maps. The ASNP moved from waypoint to waypoint within an accuracy of less than three meters. Again during these tests the turning radius was about 1.0 meters and forward speed was 23 cm/s. When it arrived at the target location the vision system could detect the red cylinder from a distance of about three meters away. This

slightly shorter distance is due to the increased visual noise from being outside. In most tests the ASNP could complete the run without interference. However there were a few occasions where the ASNP would drive into an obstacle due to the slight inaccuracy GPS and/or turning radius.

The demonstration for this project is similar to the last set of tests. The difference is that during the demonstration the GPS path is set and the red cylinder can be moved around. The path chosen is below in Figure 1.



**Figure 7. GPS Coordinates Used for Demonstration Run (Image © Google Maps)**

The instructions for the demonstration are as follows. Before the ASNP is taken to the drive location the GPS coordinates must be entered. To do this, a host PC running LabView 2009 must be connected to the powered on navigation system. The LabView front panel will allow the user to set the GPS waypoints. The waypoints are entered in descending order so that point 0 is the last point (location of object). After the waypoints are entered, the LabView program is uploaded and stored to the ASNP. The LabView front panel is below in Figure 2 with the area to

enter the GPS location highlighted.

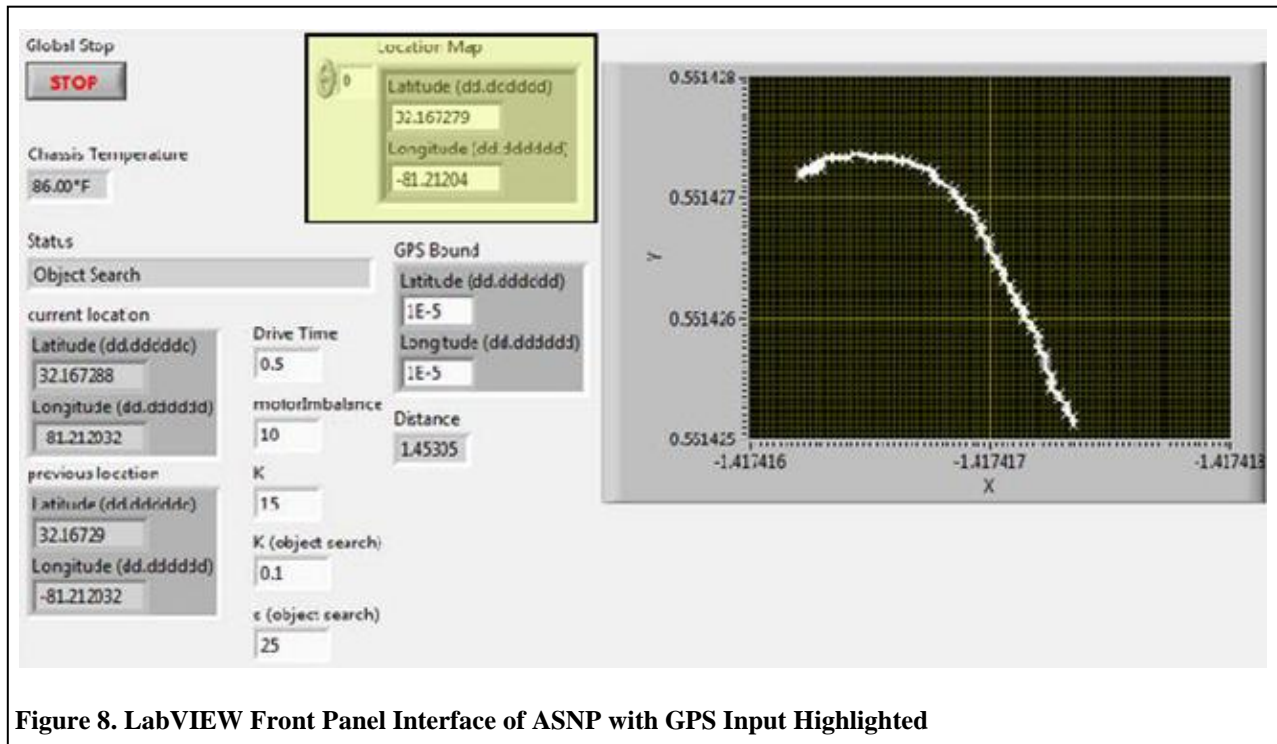


Figure 8. LabVIEW Front Panel Interface of ASNP with GPS Input Highlighted

Once the program is successfully sent to the ASNP it can be shutdown and moved to the starting position for the demonstration. The red cylinder should also be placed at the end position. Once in position the ASNP can be powered on and then left alone. After about 30 seconds the ASNP will finish initializing and drive towards the first waypoint. It will continue driving from waypoint to waypoint until it reaches its destination. Once there, it will begin searching for the red cylinder. After it has acquired a visual of the test object it will drive towards it. At this point the red cylinder can be moved around and the ASNP will drive the vehicle to follow it. The ASNP will continue following until it comes within about 0.5 meters of the object. Once within range it will stop. At this point the ASNP can be powered down and moved back to the starting position for another demonstration.

## 7. Budget and Cost Analysis

The necessary hardware to build the ASNP was purchased and provided by Dr. Fumin Zhang. The parts include the CompactRIO microcontroller and FPGA chassis, NI Digital I/O Module, Garmin 16x HVS GPS receiver, Axis Ethernet camera, 24V to 5V DC to DC converter, 24V to 12V DC to DC converter, RJ-45 breakout connector, and RS-232 breakout connector. Utilized software includes LabVIEW 2009 with the Robotics and Vision Modules. Total expenditures for hardware and software were \$17,158. The costs of individual components are below.

**Table 5. Hardware and Software Costs**

<b>Product Description</b>	<b>Quantity</b>	<b>Price</b>
NI cRIO 9024 Controller	1	\$3,999.00
NI cRIO 9104 Chassis	1	\$2,799.00
NI 9403 Digital I/O Module	1	\$369.00
Axis M1011 Network Camera	1	\$180.00
Garmin 16x HVS GPS	1	\$109.00
RS-232 & RJ-45 Breakout Connectors	1	\$14.00
<b>Total Hardware Cost</b>		<b>\$7,470.00</b>
LabVIEW Software	1	\$9,688.00
<b>Total Software Cost</b>		<b>\$9,688.00</b>
<b>Total Parts Cost</b>		<b>\$17,158.00</b>

The original budget for hardware was \$9,952. This included an extra AXIS camera, a S.E.A. cRIO GPS Module instead of the Garmin GPS receiver, a Vex Sonar, and a Microstrain IMU. Because the IMU and sonar were dropped, and a different GPS device was purchased, the prototype cost dropped \$2482.

Other parts that were included in the prototype vehicle but not actually part of the ASNP are the Vex motor units, Vex hardware for building prototype frame, ASUS GPU fan, and a red coffee can used as the red cylinder. These parts were all readily available on hand and did not require additional purchase.

## 7 Conclusions and Future Work

The ASNP is now fully capable of GPS path following and object searching upon arrival at the final point. Although the system does not complete dynamic collision avoidance, this was a secondary objective compared to actual navigation. The successful implementation of static collision avoidance of objects capable of being mapped around is significantly more important.

Future work for this vehicle will build on the navigation foundation, allowing easier programming of a GPS path, as well as adding sensors and additional features. The most imminent additions to the ASNP are the following:

- Implementation of a prototype on a marine surface vehicle
- Addition of inertial motion unit (IMU) using a Kalman filter for improved heading accuracy
- Utilizing accelerometer data (pitch and roll) to reduce instability in marine surface vehicle prototype

Longer-term work to be completed with the marine surface vehicle prototype includes the following:

- Entrance in the ASV competition sponsored by ONR and AUVSI [4]
- Chemical field profiling experiments using Rhodamine
- Installation of an underwater modem on marine surface prototype

- Networked control system testing using marine surface prototype and autonomous underwater vehicle (AUV)
- Installation of a camera through a clear section of the hull
- Visual tracking of remotely-operated and autonomous underwater vehicles



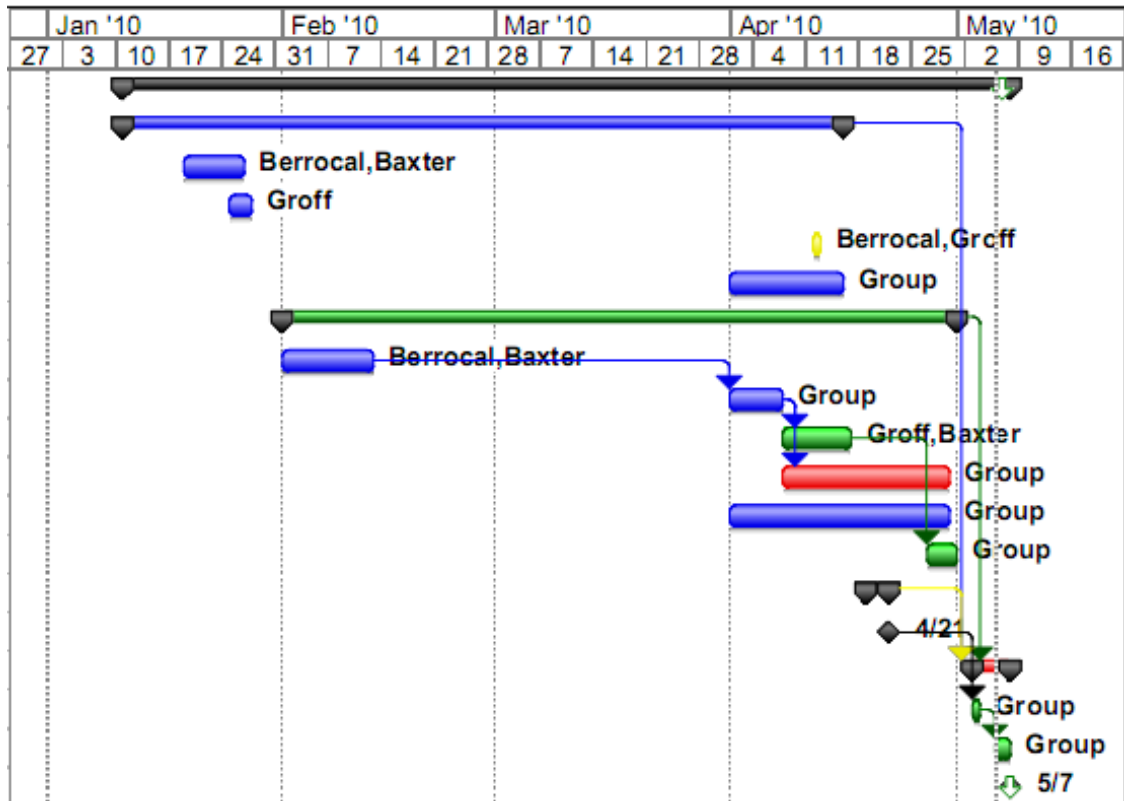
## 9. References

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# Appendix A

Table A1. Gantt chart Details

ID	Task Name	Duration	Start	Finish
1	<b>SENIOR DESIGN PROJECT ASV SOFTWARE PLATFORM</b>	85 days	Mon 1/11/10	Fri 5/7/10
2	<b>HARDWARE COMPONENT</b>	69 days	Mon 1/11/10	Thu 4/15/10
3	Build Prototype using Vex	6 days	Tue 1/19/10	Tue 1/26/10
4	Ehernet Camera interface with LabVIEW	3 days	Mon 1/25/10	Wed 1/27/10
5	GPS Interface with CompactRIO	1 day	Mon 4/12/10	Mon 4/12/10
6	Power System	11 days	Thu 4/1/10	Thu 4/15/10
7	<b>LabVIEW PROGRAMMING</b>	65 days	Mon 2/1/10	Fri 4/30/10
8	LabVIEW	10 days	Mon 2/1/10	Fri 2/12/10
9	Navigation System Design	5 days	Thu 4/1/10	Wed 4/7/10
10	Object Search and Recognition	7 days	Thu 4/8/10	Fri 4/16/10
11	GPS Path Following	16 days	Thu 4/8/10	Thu 4/29/10
12	Overall Program Flow	21 days	Thu 4/1/10	Thu 4/29/10
13	Optimization and Testing	4 days	Tue 4/27/10	Fri 4/30/10
14	<b>PROTOTYPE FINALIZATION</b>	3 days	Mon 4/19/10	Wed 4/21/10
15	Finalized Assembly of Prototype	1 day	Wed 4/21/10	Wed 4/21/10
16	<b>DEMO</b>	5 days	Mon 5/3/10	Fri 5/7/10
17	Demonstration Plan	1 day	Mon 5/3/10	Mon 5/3/10
18	Preparation	2 days	Thu 5/6/10	Fri 5/7/10
19	Final Demonstration	1 day	Fri 5/7/10	Fri 5/7/10



# Appendix B

