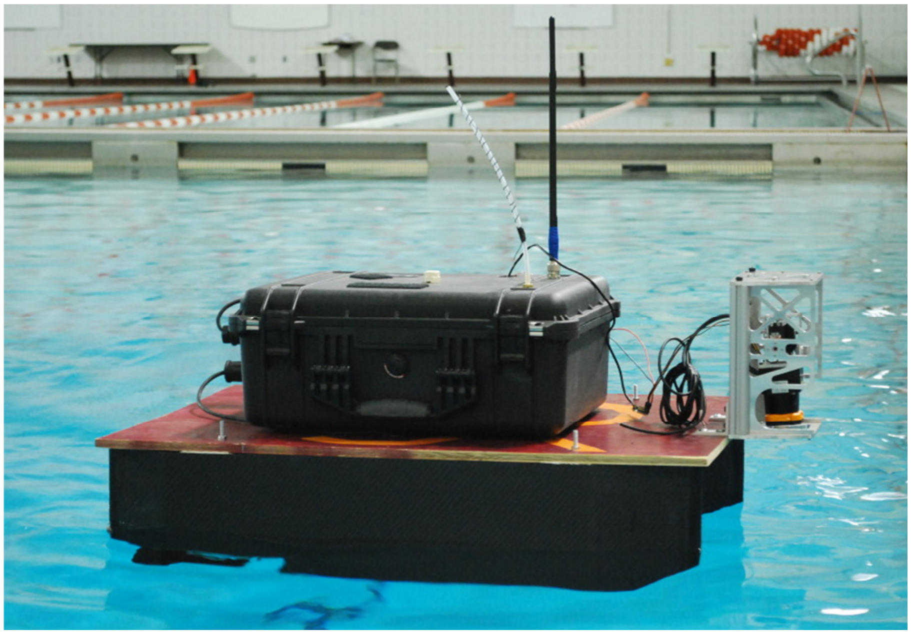
Virginia Polytechnic Institute and State University Team X-4

AUVSI Autonomous Surface Vehicle Journal Paper



ABSTRACT

The Autonomous Systems Team from Virginia Polytechnic Institute and State University is very proud to present the Autonomous Surface Vehicle (ASV) X-4, designed to compete in the 4th Annual International RoboBoats Competition.

X-4 uses a hydrodynamic twin hull design with two hollow carbon fiber (CF) pontoons for hide away storage of components and a large CF deck area for mounting systems to complete mission challenges. Propulsion is provided by two SeaBotix electric thrusters mounted in recessed notches of the pontoons to prevent damaging them when the vessel is placed on the ground. Significant upgrades to the previous navigation vision system were made to improve the reliability and performance of the X-4. Since weight is an important factor in the competition, extra measures were taken to minimize unnecessary components and to use lightweight materials, such as CF, for construction.

The fourth annual ASV competition presents a number of new challenges in navigation, obstacle avoidance and object recognition and manipulation. The X-4 team adopted the best algorithms, hardware, and practices, from previous competition entries, while working hard to find the best approaches to solve the new challenges specific to this competition. At the time of this report, the team had logged 25 hours of pool testing and approximately 45 hours of simulation.

1. INTRODUCTION

An ASV is a floating, untethered robotic boat capable of performing complex tasks without human interaction. X-4 represents a major advance in technology compared to the original Virginia Tech platforms that competed in 2009 and 2010. The vessel features improvements above and below the waterline, including a redesigned central processing computer, upgraded sensor technology, air cooling system and greatly refined software. X-4 itself is a twin hull pontoon design intended to maximize the speed – to – thrust ratio. The lightweight carbon fiber (CF) pontoons are hollow for storage to maximize deck space. All the sensors are located above the waterline and include a color camera and laser range finder (LIDAR) mounted to the front of the deck, as well as a color camera and infra-red (IR) thermometer on a pan-tilt system.

Components inside the redesigned waterproof Pelican Case include the Intel Atom processor running LabVIEW, and an inertial navigation system (INS). Two lithium-ion polymer batteries power the vehicle, one for the propulsions system and one for the computing and sensor subsystem. The case also contains motor controllers, a servo controller, power distribution system that converts the 22.2V of the batteries to the required voltage for each sensor and computing component, a digital compass, and Ubiquiti Networks PicoStation that provides long range wireless communication between the vehicle and base station during testing. These components are described and illustrated in greater detail in Section 4 of this report.

Since weight is a factor in the competition, the team worked diligently for 16 weeks to redesign the vessel using lightweight CF for the deck and pontoons. The total weight of the deck and pontoons is 12 pounds. This is a significant reduction in weight when compared to the 2010 entry.

2. THE MISSION

The theme for this year's competition is based on the following four elements: Earth, fire, air, and water. The tasks to complete are as follows: generate thrust, navigate through a speed gate, avoid obstacles while navigating a buoy channel, stop a waterfall by pushing a button behind it, retrieve a tennis ball on a dock, recognize a hot sign and report its location, shoot water through a red bordered rectangular target, and return to the starting gate. The mission requires that the vessel is water resistant, has a top speed of less than ten knots, and can carry a supplied camera payload provided at the competition. The vessel must autonomously navigate the speed gates and a minimum of three sets of buoys in the buoy channel before any of the other challenges can be attempted. The entire course and related challenges must be completed autonomously in 20 minutes.

3. DESIGN OVERVIEW

X-4 was developed to meet the requirements specified in the 2011 RoboBoat Competition rules and the AUVSI forum. The emphasis of this year's vehicle redesign was on minimizing the overall weight and size of the vessel while maximizing performance, safety, and reliability. Figure 1 shows X-4 in the pool.

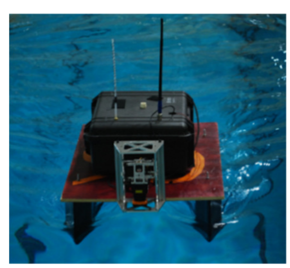


Figure 1: *Testing X-4 in the pool*

Although X-4 is intended to perform its mission autonomously, it must be prepared, launched and recovered by a shore based team. For this reason, a cart, shown in Figure 2, was designed as a means of holding the X-4 upright for transport, maintenance and launching purposes.

Figure 2: *Picture of current launching cart*

The X-4 is a 2' x 4' x 1' electrically propelled twin hull pontoon boat driven by two SeaBotix BTD150 thrusters. The entire vessel, including the deck, hulls, LIDAR and camera mount, thrusters, electronics enclosure, tennis ball retrieval system, pan-tilt block (composed of a camera, IR thermometer, and water cannon nozzle), and water pump weighs just below 50 pounds. To help improve the reliability of X-4, off the shelf components were incorporated into the design as much as possible.

The electronics enclosure provides a dry environment for the onboard electronics, including a custom built computer, a servo controller, multiplexer (MUX), power distribution system, two 24V lithium-ion polymer batteries, a wireless router with high gain antenna for remote communication when needed, INS, digital compass, and fan cooling unit to prevent overheating.

3.1 X-4 PLATFORM

The all new X-4 hull and deck was constructed entirely from CF at Material Sciences Corporation by a team member who works there. CF is a lightweight material which is very strong and easily formed into various shapes. One goal of this year's team was to create a pontoon design with places to mount the thrusters in such a way that the vessel could be placed out the ground without damaging the thrusters. A CAD model, shown in Figure 3, was first developed, and then a prototype was created from insulation foam.

Figure 3: *Original CAD model of X-4*

With the foam prototype and the CAD model, a balsa wood mold of half a pontoon, shown in Figure 4, was milled.

Figure 4: *Milled balsa wood pontoon mold*

When laid out on the mold, vacuum sealed in a bag, and heated, the wet CF sheets hardened to form one half of a pontoon, as shown in Figure 5.

Figure 5: *Half of one CF pontoon*

Two halves were glued together, and then the seams were trimmed, coated in silicone, and covered with CF tape to produce two watertight pontoons, as shown in Figure 6.

Figure 6: *Two completed pontoons*

3.2 ELECTRONICS ENCLOSURE

In 2010, the electronics enclosure used was a large, heavy Pelican 1550 Case because a laptop running LabVIEW was contained within it. This year, in an effort to lower the overall weight of the boat, a much smaller Pelican 1470 Case was used. The laptop was replaced by a Toradex Robin embedded computer. The current components within the electronics enclosure are shown in Figure 7.

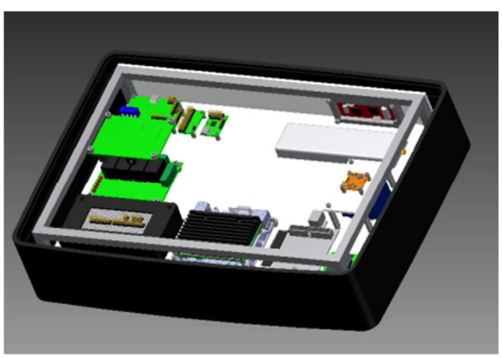


Figure 7: *CAD model of electronics enclosure packaging*

The case, waterproof straight from the manufacturer, can easily be drilled and modified while maintaining watertight integrity using fittings and sealant. An air cooling system was added to prevent overheating of electrical components while operating out in the hot sun. There is a strong possibility the outside of the enclosure will be painted white as an additional measure for preventing overheating.

3.3 NAVIGATION VISION SYSTEM

At the heart of the navigation vision system is the laser range finder (LIDAR), which is a 12V DC Hokuyo model UTM-30LX. The device needs to be placed as close to the water as possible in order to most efficiently see the objects in its path. Improving upon the crude LIDAR mount from the 2010 boat, the X-4 features a rigid, adjustable mounting system. Another problem with the 2010 entry was that the LIDAR device was mounted directly to the boat and pitched and rolled with the boat, thus decreasing the range of usable data. The 2011 entry addresses this problem by mounting the camera and LIDAR device to a custom built pan-tilt servo system, as shown in Figure 8. The pan-tilt system is controlled using orientation data from the onboard INS to automatically level the camera and LIDAR.

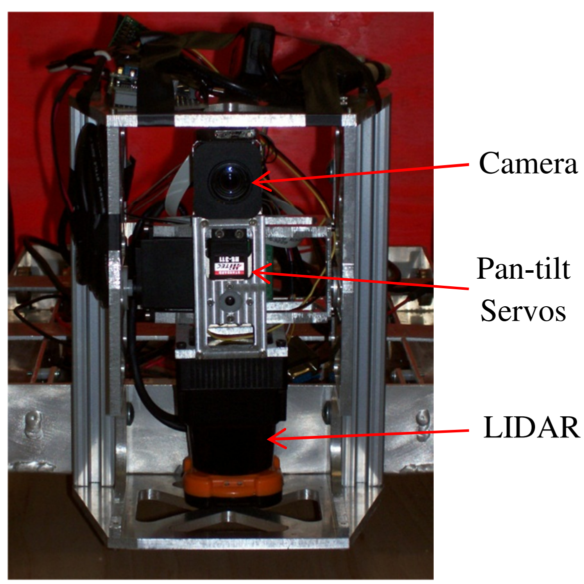


Figure 8: *Automatically leveling camera/LIDAR mount*

As previously mentioned, a camera is mounted in tandem with the LIDAR. The reason for this is because the LIDAR is color blind, only seeing objects in its path and their distances from the vehicle. During last year's competition, it was determined that the buoy channel could not be navigated successfully using LIDAR data alone. With the addition of the camera, the vehicle can now recognize objects from the LIDAR data and determine the colors of them. The use of this information will be described in Section 5.2 in greater detail.

3.5 EARTH CHALLENGE

The Earth challenge part of the mission this year will be accomplished by deploying an amphibious subsystem from the X-4 to retrieve a Head Penn Pink Championship XD tennis ball from atop a dock. The X-4 will act as the mother-ship by wirelessly providing the high level autonomy to the subsystem. The retrieval system consists of a small amphibious remote control (RC) tank equipped with an XBee Pro communication module and serial motor controller. A Velcro grabber arm will retrieve the tennis ball and a wireless color camera mounted to the ground vehicle will provide data to guide the subsystem to the tennis ball. Figure 9 shows the vehicle in its current configuration.

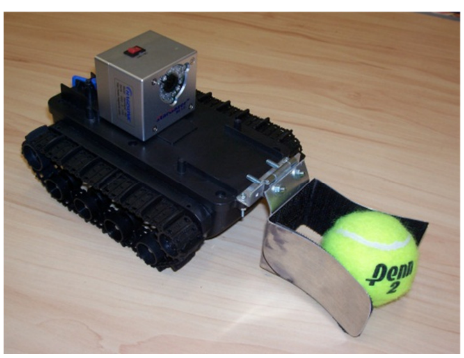


Figure 9: *Tennis ball retrieval subsystem*

Once the tennis ball is determined to be in the target position relative to the grabber using the camera, a winch system, similar to the setup shown in Figure 10, will reel in the subsystem and tennis ball to the X-4.

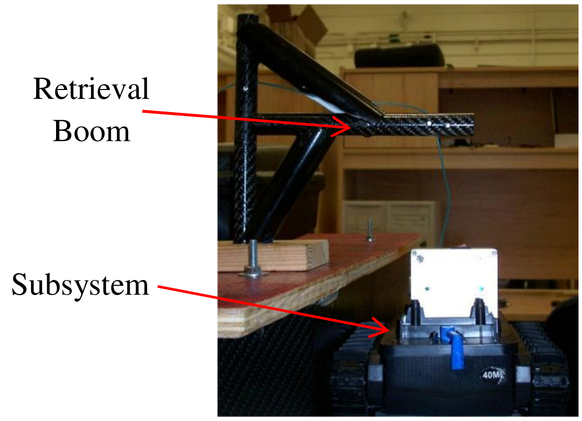


Figure 10: *Subsystem retrieval winch boom*

3.6 FIRE CHALLENGE

The water cannon is fed by a 24V DC, flexible impeller, automotive windshield washer pump, donated to the team by ACI Auto. Pumping lake water through tubing to an automotive windshield washer fluid nozzle, the cannon fires water over 11 feet. The nozzle is connected to a project box mounted on a pan-tilt servo. The project box and pan-tilt assembly, shown in Figure 11, was modified to hold the IR thermometer, water cannon nozzle, and camera for aiming them at targets.

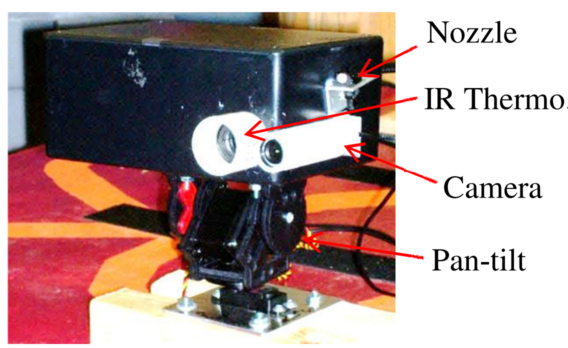


Figure 11: *Project box assembly mounted to pan-tilt*

3.7 AIR CHALLENGE

To accomplish the air challenge portion of the mission, the IR temperature sensor and color camera, previously described in Section 3.6, will identify and measure the temperatures of the hanging targets. The IR temperature sensor is an Omega OSDT500 handheld IR temperature gun, modified to output an analog voltage which is proportional to the measured temperature in degrees Fahrenheit. The entire unit is packaged inside the waterproof project box described earlier and shown in Figure 11. The color camera is an analog waterproof bullet camera attached to a USB frame grabber. The IR temperature sensor and color camera package are mounted in parallel and sit on a pan-tilt unit at the bow of the X-4. The strategy is to run an object recognition vision algorithm and use visual servo control to align the temperature sensor with, and measure the temperature of, the identified target. Once the "hot" target is identified, an estimate of the direction and distance to the target is calculated from INS, LIDAR, and the camera data. Finally, this estimated location will be transmitted to the judges.

3.8 WATER CHALLENGE

All mission and control hardware was designed to be contained in waterproof enclosures. Consequently, to press the button, the X-4 will back through the waterfall and use a rear bumper to press the E-stop. The same color camera used for the fire and air challenges will also be used to navigate the boat in reverse toward the red button.

4. ELECTRICAL DESIGN

The X-4 features various cost effective and high performance electrical components critical to the success of the mission. Electronic components on the boat fall into four broad categories: power systems, sensors, controls, and processors. For example, the computer falls into the category of processors. Details are provided in the following sections.

4.1 POWER SYSTEMS

Two 24V lithium-ion polymer batteries supply power to electronic components onboard the X-4. The motors and water pump are supplied by one battery, while all of the computing and sensing components are powered by the other. This is done to isolate the electronic components from the current spikes that can be caused by the mechanical components.

The power to the computing and sensing systems is provided by a power management system. The power management system is based around a picoPSU DC-DC ATX power supply, shown in Figure 12. The power supply receives a 24V input from the batteries. It then splits the supplied voltage into 12V, 5V, and 3.3V sources that are used to supply power to all of the electronic components on board.

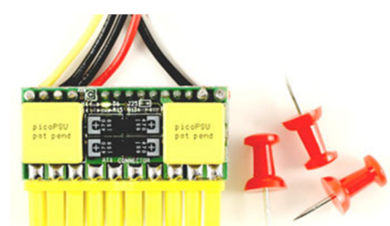


Figure 12: *DC-DC ATX power supply*

4.2 SENSORS

The X-4 features a wide variety of sensors for localization, navigation, and completion of the mission tasks. A Microbotics MIDG II inertial navigation system, which combines an onboard inertial measurement unit (IMU) with a GPS unit, was used to provide localization data to the X-4. To accurately determine the local position of the boat, the high frequency acceleration and angular rate data from the IMU is combined with the low frequency GPS data, using a Kalman filter. The INS provides the ability to use additional sensor data to increase the accuracy of the position and orientation estimate. In the case of the X-4, an Oceanserver 5000 digital compass is used to aid the position estimate of the INS.

The Hokuyo UTM-30LX LIDAR device, shown in Figure 8, senses the obstacles in front of the X-4. It has a maximum range of 30 meters; and in conjunction with the front camera, can effectively detect objects at a range of 9 meters. It provides up to a 270 degree scan range in front of the boat.

4.3 CONTROLS

Two Pololu mini-maestro servo controllers are used to control all servos and motors on the X-4. The servo controllers provide control signals which are fed to the thruster motor controllers and the servos for each of the pan-tilt systems.

Two Pololu Simple Motor Controllers drive the SeaBotix thrusters. The controllers take standard servo control signals as input and convert them to the desired voltage required by the motors.

4.3 PROCESSING

Onboard the X-4 is a Toradex Robin computer with an Intel Atom 1.6GHz processor running Windows 7. All control software was developed in LabVIEW which runs on the Toradex.

The X-4 features several different methods of wireless communication. The X-4 uses a PicoStation wireless network router to communicate with an onshore base station. This approach provides a method of efficient monitoring while testing. By remotely logging into the computer located on the vehicle, all of the sensor data can be viewed in real time during a session, and changes can be made to the software remotely.

In addition to the wireless networking capabilities of the X-4, a RC receiver and multiplexer (MUX) unit are available to take control of the boat in the event of system failure. The MUX allows for the control signal being supplied to the motor controllers to be switched between the RC receiver and the servo controller being controlled by the onboard computer.

5. SOFTWARE DESIGN

The following sections describe in detail the software design relating to low level control, object detection, and mission selection of the X-4 ASV.

5.1 LOW LEVEL CONTROL

All the control software is designed to drive the vehicle to a desired heading at a desired velocity. In order to obtain the desired heading and velocity, a set of simple proportional – integral – derivative (PID) controllers are used to generate the control signals to be supplied to the motors. The use of PID controllers was selected because they are simple to implement in software. Additionally, tuning methods for PID controllers have been extensively researched and discussed in published literature such as textbooks and journal papers.

5.2 OBJECT DETECTION

As previously discussed, a vision system was designed to combine LIDAR and camera data for determining the location of objects relative to the vehicle, and for classifying them based upon color when necessary. In order to complete this task, the LIDAR data is processed to determine any objects of interest that are currently in front of the vehicle and that fall into the range of the LIDAR. Once objects are detected, if their color classification is required (during the buoy channel navigation task for example) the video stream frame from the camera mounted with the LIDAR is then processed. To process the image, a region of interest (ROI) is added to the image that corresponds to the location of the objects of interest determined from the LIDAR data. After the ROI is added to the image, all of the pixels that fall inside of that ROI are processed by a color lookup table to classify them into a color class. Once all of the pixels in the ROI have been processed, the color classification that makes up the majority of the pixels in the ROI is the color classification that is given to the object. The results of this classification process can be seen Figure 13.

Figure 13: *Object color classification results*

5.3 MISSION SELECTION

Once the buoy channel is successfully navigated, a magnetic heading is given from the end of the buoy channel toward the location of the four different missions. At the beginning of the mission subroutine, each of the four missions is given an equal weighting value, and a search routine begins. Once a mission is found, its completion subroutine begins. If the mission completes successfully, then it is removed from the mission list; however, if it fails or times out, then the mission weight is decreased so that it moves to the bottom of the list. Then, the searching routine starts again until the next highest weighted mission is found. Once all of the other missions are completed, if time allows, any failed missions are then reattempted. If time does not allow, then the vehicle begins the return to dock subroutine that will drive the vehicle back through the buoy channel toward the dock.

6. SYSTEM CONNECTIONS AND TESTING

The X-4 is the result of a very thorough design and development process. Every system of the boat must be able to function independently, as well as in conjunction with the other systems. The systems of the boat fall into four main categories: hardware, software, electrical, or mechanical. Each system has a common connection point.

Hardware, such as the sensors, is commonly connected to a central point. Likewise, the software is run on the processor. Electrical systems all connect to a power distribution center. And mechanically, all systems are mounted to the hull and deck of the boat.

Testing was conducted on land using a car and LIDAR mount, as shown in Figure 14, aquatically through the use of a pool and via LabVIEW simulation.

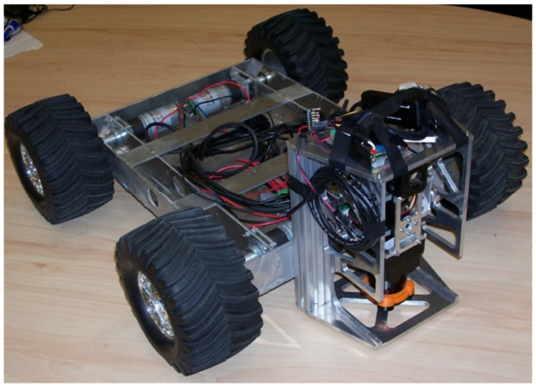


Figure 14: *Object color classification results*

7. CONCLUSIONS

The X-4 is a completely autonomous surface vehicle designed and manufactured by the engineering students at Virginia Polytechnic Institute and State University. Through the development of the X-4, the team set new standards based on previous entries and exceeded all of them. Solid, reliable solutions to hardware, software, electrical, and mechanical challenges were the result of a highly selective design process. We believe that the X-4 will perform well and attract the attention of all those attending the competition. Our innovative design and creative approaches to accomplish the mission tasks are sure to catch the interest of spectators.

8. TEAM ORGANIZATION

Team X-4 consisted of nine ME undergraduate students, three graduate advisors, and a Professor of ME at Virginia Tech. Every member contributed in some way to the design of the vessel.

Dr. Alexander Leonessa – Ph.D. AE; Faculty Advisor, Project Head

Christopher Cain – BSME, CS; Electrical, Hardware, Software, Vision Processing, Navigation, Sensors

Paul D'Angio – BSME; Electrical, Mechanical, Software, Vision Processing, Navigation, Sensors

Kevin Sevilla – BSME; Engineering Education, Robotic Development Research, Scientific Creativity

Jeremy Smith – BSME; Team Leader, Budget, Website, Papers, Mechanical Design, Water

Anthony Caiazzo – BSME; Mechanical Design, Manufacturing

Phillip Caspers – BSME; Electrical Design, Software, Sensors, Air

Robert Cracker – BSME; Electrical, Mechanical, Air, Water

Nick Lefevre – BSME; Mechanical, Earth

Pierce Schreiber – BSME; Website, Mechanical, Earth

Andrea Shen – BSME; Website, Photographer, Mechanical, Propulsion, Air

Varun Tandon – BSME; Mechanical Design, Manufacturing, Fire

Andrew Wasilewski – BSME; Mechanical Design, Manufacturing, Fire

9. SPONSORSHIP

We most gratefully acknowledge the contribution of the following sponsors who have contributed to the completion of our project:

10. REFERENCES

[1] "2011 Official Rules and Mission," Association for Unmanned Vehicle Systems International. San Diego, California