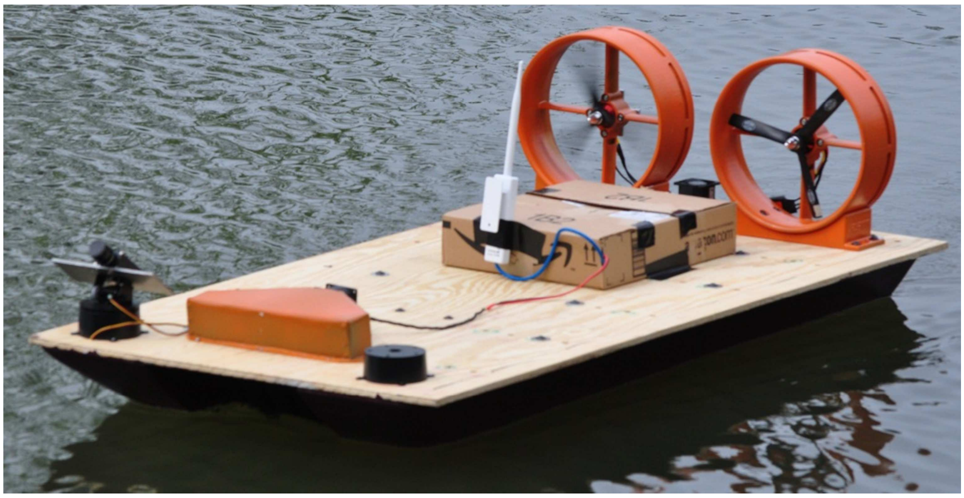
Virginia Polytechnic Institute and State University ASVT

AUVSI Autonomous Surface Vessel Journal Paper



ABSTRACT

The Autonomous Surface Vessel Team from Virginia Polytechnic Institute and State University proudly presents the autonomous surface Vessel (ASV), "Knot So Fast" (Abbreviated KSF throughout the paper), designed to maximize performance in the 5th Annual International RoboBoat Competition.

Utilizing a surface effect ship (SES) design, KSF combines hydrodynamic catamaran style twin hulls with a high-pressure compartment under the deck that acts similar to a hovercraft. When the surface effect is turned on, the draft is cut in half, allowing KSF to achieve higher speeds and move more efficiently through the water. Weight and durability heavily influenced the choice to construct the twin hulls out of fiberglass encased high-density foam. Two 3D printed air propulsion modules were designed to provide KSF with adequate propulsion to achieve planing and navigate the entire competition course. Obstacle identification and channel navigation capability, in addition to challenge station identification, was achieved though stereovision processing, combining region-of-interest isolation and color-lookup routines.

Last year, basic subsystems were developed to complete the challenges of the 4th annual ASV competition. Considering the similarity of the challenges from a design perspective, the 2012 ASVT has built off of previous work to further perfect KSF's approach to the challenges, decision algorithms, and hardware.

1. INTRODUCTION

An ASV is a fully autonomous robotic boat capable of performing complex tasks without human interaction. In recent years, most ASV's competing in the RoboBoat competition were primarily designed around advancements in navigation and vision systems. In addition to this, the 2012 ASVT put emphasis on the design of the mechanical systems of the boat, including the hull, propulsion, and challenges subsystems.

KSF is modeled after a standard catamaran design, having ample stability and providing plenty of deck space for onboard controls and sensors. Many of the improvements featured on KSF were designed with efficiency in mind. One of the most notable improvements is the addition of a surface effect system. Utilizing a high-pressure area under the deck held in by front and rear skirts, the system raises the boat, decreasing draft and ultimately drag. To take full advantage of this system, twin air propellers were designed as the propulsion system. The ducts created to house the propeller blades were 3D printed to be able to accurately construct the revolved NACA 4414 airfoil design, which was chosen to give a significant increase in efficiency.

The materials and construction methods chosen to make the pontoons and deck were heavily influenced by factors such as weight and durability. The final design of the pontoons uses fiberglass reinforced high-density foam, and the deck is made of an aluminum honeycomb sheet.

To provide autonomous navigation and enable challenge station identification, KSF relies on a bow-mounted stereovision camera to both identify and classify objects in front of the vessel. This system maximized reliability, with no moving parts, and is not suceptible to errors caused by pitch and roll of the craft that plague manu LIDAR-based navigation sensors.

2. THE MISSION

The theme for this year's competition is based on the game of poker. The tasks to complete are as follows: generate thrust, navigate through a speed gate, avoid obstacles while navigating a buoy channel, locate an underwater buoy and press a corresponding E-stop button, retrieve a poker chip (hockey puck) on a dock, recognize a hot playing card and report its location, shoot water through a blue bordered rectangular target on a playing card, play a game of 5 card poker, 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 set of 5 playing cards 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

KSF was developed to meet the requirements specified in the 2012 RoboBoat Competition rules and the AUVSI forum. The emphasis of this year's vessel redesign was on weight, performance, efficiency, safety, and reliability.

KSF is a 60" x 30" x 7" electrically propelled twin hull SES driven by two 3D printed air propellers. The entire vessel, shown in Figure 1 below, including the deck, pontoons, cameras and mounts, propellers, electronics enclosure, hockey puck retrieval system, pan-tilt block (composed of a camera, thermal camera, and water cannon nozzle), and water pump weighs just below 65 pounds.

Figure 1: *KSF nearing the end of the construction phase*

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 KSF PLATFORM

Weight and durability heavily influenced the choices for materials and construction methods used to make KSF's deck and pontoons. Ultimately, high density foam was chosen as the base material upon which to build the twin pontoons, because it is lightweight and easy to form into complex shapes. A hot-wire CNC machine was used to cut the foam into the designed pontoon geometry. To keep the foam core protected, an outer layer of fiberglass was applied as shown in Figure 2 below.

Figure 2: *Pontoons shown during and after the fiberglassing process*

For the deck, the ASVT was able to obtain an aluminum honeycomb sheet. It is lightweight while maintaining the necessary durability and rigidity to provide a large stable platform for all of the boat's systems. A cross-section of this deck is shown in Figure 3.

Figure 3: *Side view of the aluminum honeycomb deck*

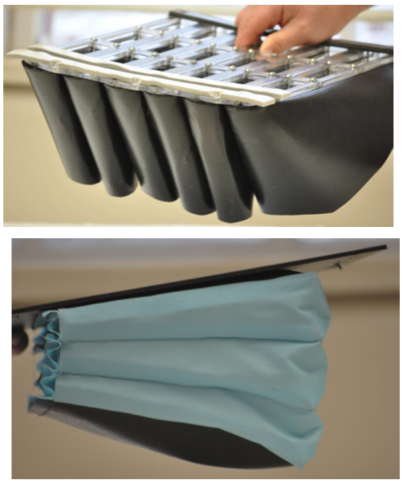
An innovative method was found to attach the aluminum deck to the foam pontoons. Conventional screws could not be used, because they would be torn out too easily from the foam. Instead, small pits were cut into the foam and back filled with epoxy. Threaded inserts were placed into these pits, held in by the hardening epoxy. With this system in place, conventional screws are able to be used.

3.2 SURFACE EFFECT SYSTEM

KSF utilizes an innovative surface effect system. SES's are usually modeled after a basic catamaran design. However, uses a fan to create a high-pressure area underneath the deck, held in by a front and rear skirt, that raises the boat some distance. The idea is that as the boat rides higher on this high-pressure pocket of air, the draft decreases along with the drag.

To accomplish the addition of the surface effect system, front and rear skirts were designed, tested, and refined. Problems such as cobblestoning, weight, and drag were all minimized when designing the skirts. The final front and rear skirts are pictured below in Figure 4.

The front skirt is a typical "finger" skirt made of vinyl-coated polyester held in place by an acrylic frame, allowing water and obstacles to pass easily between the pontoons to minimize drag and tears, while maintaining an air tight seal.



a.

b.

Figure 4: *(a) Front skirt (b) Rear skirt*

The rear skirt is based on a bellow design that uses several air chambers, made from the same vinyl-coated polyester, resting on one another to dampen the vibrations the naturally occur due to waves and air leakage. This rear skirt design leaks air at a slow and controlled rate, which is ideal for the SES design.

KSF has a draft of 3" with all systems onboard and the SE turned off. With the addition of the SE system, KSF shows a draft reduction of 1.5" or 50%. After testing, this draft reduction allowed KSF to reach a top speed of 4.7 m/s, up from 3.6 m/s.

3.3 PROPULSION SYSTEM

In past years, only water propellers were used. With the addition of the SE system, the draft of the boat changes significantly throughout the competition. An easy way around any complications was to design twin air propellers. Due to safety concerns, ducts are needed to shroud the propeller blades. The ducts were designed to actually increase the efficiency of the propellers. Figure 5 shows a CAD model of an isometric view and cross-section of the ducts. Each duct utilizes a revolved NACA 4414 airfoil cross-section to increase efficiency and minimize tip losses.

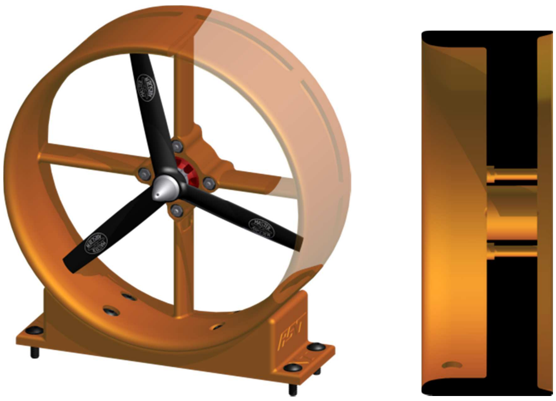


Figure 5: *CAD model of propulsion ducts*

Due to the complex geometry of the design, a large 3D printer was used to construct the ducts. To add more rigidity and durability, the ducts are coated in a light layer of epoxy. As validation of the duct design, a thrust test was performed on the the air propeller with and without a duct. As shown in Figure 6 below, the duct provides a 10% increase in the power efficiency of the propeller.

3.4 THE POKER CHIP

The Poker Chip Challenge will be accomplished this year by deploying an amphibious "tank" from the deck of KSF to retrieve the hockey puck. The amphibious system itself is not autonomous. Instead, it gather visual information via a mounted camera and transmits the data using an XBee Pro communication module to KSF.

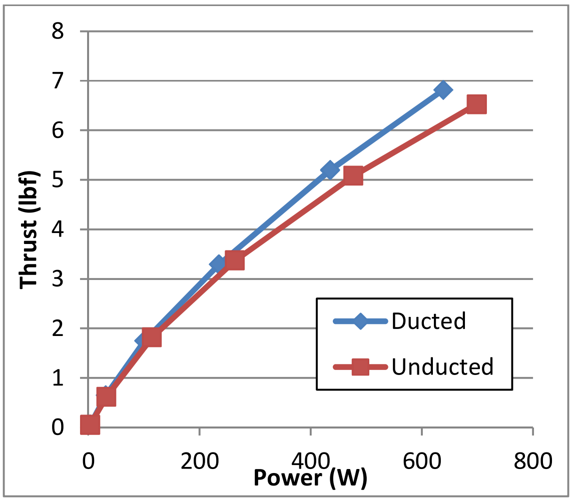


Figure 6: *Ducted vs. unducted thrust testing*

KSF then analyzes the data and sends instruction back to the tank, which uses a serial motor controller to follow KSF's commands. On the front of the tank is a Velcro grabber arm that will hold onto the hockey puck. The tank in its current configuration is shown in Figure 7.

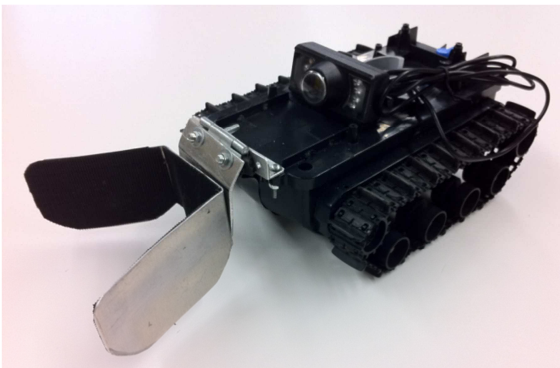


Figure 7: *Amphibious hockey puck retriever*

Once the hockey puck is determined to be in the target position relative to the grabber using the camera, a winch system, will reel in the subsystem to KSF.

3.5 THE JACKPOT

The jackpot challenge requires that KSF identify a buoy held beneath the surface of the water. To accomplish this, a Little Frog Waterproof webcam is used. This unit is shown in Figure 8.

Figure 8: *Little Frog Waterproof Webcam*

Once the buoy is identified by the Little Frog webcam, a robotic arm specially designed for this competition will be used to reach out and push the corresponding E-stop button. The robotic arm is comprised of two Dynamixel RX-24F Robot Servo Actuators, one at the shoulder joint and one at the elbow joint, connected by 11/16” carbon fiber tubes. A Dynamixel EX-106+ Robot Servo Actuator is used at the shoulder join just above the Lynxmotion Rotation Base Mount, because it is subjected to the largest moment. The arm is shown in Figure 9.

Figure 9: *3DOF robotic arm*

3.6 THE CHEATER’S HAND

A LynxB pan-tilt system is mounted to the deck of the boat to help complete The Cheater’s Hand challenge. A Basler scA640-70gc vision system is mounted on top of the pan-tilt, which will locate and identify the blue square on the playing card of interest. While the pan-tilt/camera system tracks the blue square, a water pump will draw water from the lake to spray through a nozzle also mounted atop the pan-tilt assembly. The nozzle is aimed at the same central location as the camera.

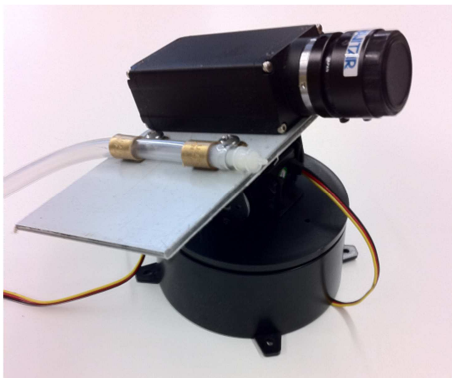


Figure 10: *Pan-tilt with mounted camera and water nozzle*

From testing, it is known that the water pump and nozzle system can accurately hit a 3” x 3” target from 7.5’ away with a flow rate of 0.156 ft^3/min. At this flow rate, it will take approximately 12 seconds to fill the ½ cup required to raise the red flag and complete the challenge.

3.7 THE ‘HOT’ SUIT

The ‘Hot’ Suit Challenge will be completed using the same pan-tilt system as shown in Figure 10 above. However, an addition thermal camera is mounted to the pan-tilt assembly which can identify the card with the highest temperature. Once the card is known, the vision system utilized for navigation by KSF will be able to triangulate the card’s location.

3.8 THE CARD EXCHANGE

The Card Exchange Challenge requires that KSF have some way to pick up and replace playing cards from platforms that are potentially several feet away from the boat. To perform this task, KSF will use the same robotic arm described in the section 3.6: The Jackpot. The carbon fiber tubes that serve as the main arm structure are hollow. A Parker BTC Series Miniature Diaphragm Pump mounted to KSF’s deck will draw air through a plastic tube that runs through the hollow channels of the carbon fiber tubes out to the end of the arm. At the far end of the robotic arm, the air pump tube connects to a small suction cup. The pump can provide up to 20 psi, far more than will be necessary to pick up the playing cards. The pump/suction cup system was chosen because of its simplicity and reliability.

4. ELECTRICAL DESIGN

The integration of sensing, actuation, and computing subsystems with each other and with a central power distribution and monitoring system was done with great care taken to maximize both efficiency and reliability. Past experience with both land- and waterborne systems has hammered home the necessity of stiffening power rails that experience transients to avoid component damage.

4.1 POWER SYSTEMS

The KSF operaes within a power envelope of 270 Wh, provided by three 4500 mAh, 6s LiFePO4 battery packs. Two of these are reserved to power the main drive fans, and because the drive system undergoes frequent large amplitude transient loads, it is completely electrically isolated from the rest of the craft power system. The third battery powers the remainder of the electrical systems on the vessel via an M4-ATX switching power supply. The M4-ATX provides stabilized 12V and 5V rails each able to source 10A. Additional stiffening capacitor banks are implemented at the terminals of components with large transient power demands, such as the water pump and robot arm servos.

4.2 SENSING

KSF utilizes multiple vision systems for channel navigation and challenge completion, augmented by the GPS and INS capabilities of an onboard Microstrain 3DM-GX3-35 AHRS sensor. Disparity data for buoy identification, channel navigation and obstacle avoidance is gathered with a Point Grey Bumblebee XB3 stereovision camera. The 3DM-GX3-35 is configured to stream multiple data types to the navigational software: a GPS fix at 4 Hz, and a magnetometer-stabilized heading and angular rates 20 Hz. A number of additional analog cameras are integrated into challenge subsystems, as previously described.

4.3 ACTUATION

To control the various actuators present on KSF, several drivers are integrated onboard. Each main drive fan is commutated with a 60A HURC hobby-grade brushless motor controller, with the drive stage optically isolated from the control stage to prevent PWM noise from propogating through associated electrical systems. The standard servo-control signal that these require is generated using a USB-connected Pololu Micro Maestro 6ch servo controller. The Micro Maestro is also used to control the pan-tilt mechanism used in the Cheater's Hand and Hot Suit challenges.

The high-powered Dynamixel servomotors that are used in both the robot arm and the amphibious tank deployment system are controlled directly over RS-422 serial, using an addressed protocol that enables them to be daisy-chained, minimizing the amount of redundant wiring.

4.4 COMPUTATION

All computer control and data processing is handled by an onboard Pandora MP-67D compact computer. KSF is heavily dependent on machine vision, which is computationally demanding, and the Pandora PC has been equipped accordingly, with a four-core i7 processor, 8 GB of ram, and an 80 GB solid-state drive. The Pandora PC has been retrofitted with a Firewire 800 interface to enable inmage acquisition via the Point Grey stereovision camera. Power management features of the i7 architecture and the inclusion of an SSD also keep the power consumption of the Pandora PC low, peaking at 30W and averaging 18W.

5. SOFTWARE DESIGN

All software development was done with the goals of rapid implementation, modular code design, and future accessibility in mind. To this end, LabView 2011 and associated add-on toolkits were employed for all authored code. Pre-existing libraries were integrated into our software using the external-library wrapper tools available in LabView.

The navigation and autonomy capabilities of KSF were developed from the bottom up, first building a robust low-level control foundation, and then including additional routines for object identification and classification that build upon the software capabilities of the LLC.

5.1 LOW LEVEL CONTROL

The LLC includes routines for autonomously maintaining a given heading and speed, as well as navigation to a waypoint given as a set of Lat/Lon coordinates or through a given sequence of waypoints.

Heading and speed control is accomplished using a PID control scheme, with a modified integral term with gain scheduling using a gaussian distribution and special conditions for integrator reset. This controller can optionally be augmented using a model-reference adaptive controller that dynamically estimates optimal controller gains, and is useful for dealing with parameter variations caused by wind, waves, and other variables that cannot be reliably estimated.

5.2 OBJECT DETECTION

In order to navigate a buoy channel and avoid obstacles, it is necessary to both locate the position of obstacles relative to the vessel and reliably identify their color.

In order to complete this task, objects in the forward visual field are identified through identifying the disparity between paired images provided by the Point Grey stereovision camera mounted on the bow of the vessel. Once objects are detected, if their color classification is required (during the buoy channel navigation task for example) the raw image frame from the camera is then analyzed. To process the image, a region of interest (ROI) is defined corresponding to the location of the objects of interest determined from the disparity 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.

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. CONCLUSIONS

KSF is a completely autonomous surface vessel designed and manufactured by the engineering students at Virginia Polytechnic Institute and State University. Through the development of KSF, 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 KSF will attract the attention os all those attending the competition and set a new standard for future boats. Our innovative design and creative approaches to accomplish the mission tasks are sure to catch the interest of spectators.

7. TEAM ORGANIZATION

The 2012 ASVT consisted of nine ME undergraduate students, a graduate advisor, 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

Matthew Pyrak – BSME; Graduate Advisor, Hardware, Software, Vision Processing, Navigation, Sensors

Hayden Shea – BSME; Team Leader, Challenge Subsystems, Papers, Presentations

Alexander Gage – BSME; Pontoon Design, Propulsion Design and Selection, Materials

Trevor Helderman – BSME, BMath; Surface Effect Design, Material Selection, Challenge Subsystems, Presentations

Bradley Howard – BSME; Deck Design and Selection, Card Exchange, Cheater's Hand, Competition Videos

Daniel Licht – BSME; Hull Design, Surface Effect Design, Challenge Subsystems, In-Water Testing

Bryan Murray – BSEE; Pontoon Design, Construction Methods, Creative Challenge Solutions

Ehsan Qaium – BSME; Deck Selection, Challenge Subsystems

John Roller – BSME, BEc; Website, The Jackpot, The Poker Chip, Testing

Will Workman – BSME; The Jackpot, The Poker Chip, Electronics, Propulsion

8. SPONSORSHIP

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