An Unmanned Surface Vehicle Robot Model; for Autonomous Sonobuoy deployment, and UAV landing platform

Jordan Gruber 1 and Amir Anvar 2
School of Mechanical Engineering
The University of Adelaide
Adelaide, South Australia, 5005 Australia
1 jordan.gruber@student.adelaide.edu.au
2 amir.anvar@adelaide.edu.au

Abstract— Unmanned Surface Vehicles (USVs) have limitless applications in civil, commercial and defence environments. Development of USVs is an ongoing and exciting field, and modern advances in computing technology give more creative power to the engineer(s). This paper aims to briefly outline the current state of USV robot technology, and the development of a USV concept design to meet the primary goals of autonomous payload deployment. This is inclusive of the generation of an initial concept, and validation of the chosen concept through hand calculations, simulation, and scale model testing. The results of these calculations and tests are summarised with reference to the projects goals, whilst future work entailed within the project is also discussed.

Keywords—USV, Unmanned Surface Vehicle, ASV, UAV, Robot, Sonobuoy, MOOS, Beaglebone.

1. INTRODUCTION
An Unmanned Surface Vehicle (USV) is a marine based autonomous vehicle that operates on the waters’ surface. Applications of USVs are far reaching, and may be used in a variety of environments for civil, commercial and defence purposes. Until recently USVs remained almost purely militarily oriented, and several military USV robots are currently in service around the world. Environmental exploration using USV robots is beginning to become of high interest to commercial companies and hobbyists, and great strides of progress are being made in their development in the civilian world.

The purpose of this paper is to explore current USV technology and apply this learning to the design of a small USV robot. The primary purpose of this USV is to autonomously deploying a payload; however a further goal is to allow the USV to operate as a UAV landing platform. The process in designing the structure of the USV includes extensive research into existing systems, concept generation of various configurations that may fulfill the project goals, and validation of the chosen concept through hand calculations, scale testing, and computer aided design.

1.1 Literature Survey
The speed at which modern USV robots are being developed is incredible in both the military and civilian world. As of the end of 2013 a total of 63 USV systems have reached product maturity and are currently available on the market [1]. These USV systems have either been designed and produced for defence, or commercial applications. Thus it can take widely varying structures.

Rapidly expanding interest within the military in USV robots has led to the creation and implementation of several tens of USV robots by contracted private and government defence companies around the world. Current operational military USV robots include the Israeli developed Protector [2] rigid inflatable boat USV which has been deployed throughout the world to secure and observe national waters, respond to pirates, and has even been implemented to combat cocaine smuggling by ocean boats and ships. Most military USVs share a variety of common features and are quite large in size ranging from around 2 meters to 11 meters in length. Most military USVs draw focus to high speed and maneuverability, intelligent autonomous operations, and in allowing instantaneous operator(s) control. Thus most military USVs are 7 meter or more length monohulls propelled by petrol/diesel Hamilton water jet engines. These USVs utilise high quality Radar, GPS and inertial sensors to provide necessary data for on-board navigation. Communication between the USV and remote operator is often achieved via line of sight satellite or over-the-horizon communication.

Commercial USV systems differ greatly from military USVs but have broken significant ground in autonomous scientific surveying and data collection. One such commercial company in the pursuit of USV development is Liquid Robotic Inc. having broken significant ground in providing reliable, long term deployment USV systems for oceanic surveying. An early model of the Liquid Robotics Inc. Wave Glider famously broke world records after 6 units were launched from San Francisco in November of 2011, one of which travelled 9000 nautical miles to arrive in Australia the following November purely autonomously [3]. During this...
journey the *Wave Glider* was able to interpret commands sent remotely through the Iridium satellite network and return collected data. Commercial USVs such as the *Wave Glider* tend to apply more experimental novelties. Propulsion of commercial USVs is known to range from sail power, wave power, to even solar power. Commercial USV robots utilise GPS and inertial sensors to provide data for remote or on-board navigation. Most commercial USV systems are less than 3 meters in length and based on catamaran, or trimaran hull structures, as they allow a large payload platform and are highly stable in low sea states.

2. Conceptual Design

Concept generation of the USV system was largely based on existing USV systems, however some additional design considerations were made and more novel features were generated. In total four concepts were produced, each utilising a unique hull configuration. The final chosen concept is a monohull primarily built to deploy its sonobuoy payload. Its ability to self-right means that it is capable of being deployed in moderately high sea-states without risk of capsizes. The most important features of the concept in this mode are its planning self-righting hull form, high power vectored water jet propulsion and its large internal payload area. This assembly is also to include a servo mounted video camera to provide a live visual feed to the operator, as well as a multitude of on-board sensors such as accelerometers, GPS, humidity/temperature sensors and a digital compass among other sensors to be added when needed. The on-board computer is a Texas Instruments *Beaglebone Black* [4] microcomputer. This microcomputer has a relatively high processing capability and should be able to process sensor and video data whilst also being able to simultaneously receive and interpret operator instructions from a remote computer. The method of data communication may include any combination of radio, WiFi or wireless internet.

The second mode of operation is shown in Fig. 2. This second mode operates in conjunction with the first with the addition of an easily attachable catamaran platform. This platform provides the additional support required to operate the USV as a moving UAV landing platform. The outriggers of the platform provide additional stability to the entire USV, minimising the magnitude of roll, whilst also being wide enough to house additional components such as solar panels, small hydrogen fuel cells, and charging batteries. The method of securing the UAV to the USV once landed is still to be finalised. Current concepts include the use of a hinged net on the platform, or a series of magnets attached to the UAV that will bond to computer controlled electromagnets on the platform surface. To release the UAV in the second concept the electromagnets are switched on such that the magnetic force binding the USV to the platform in negated allowing the UAV to move freely.

3. Design Validation and Testing

Using the chosen concept design as a base to work from, design verifications were made to ensure the concept would perform as anticipated through hand calculations, computer aided design and scale model testing. These methods were used with conjunction with one another to help understand primary characteristics of USV concept including its apparent stability, hull strength, and speed. As with most USV systems the lower hull structure was based on pre-existing designs, and small design changes were made for this particular USV application.

3.1. Preliminary Stability Calculations

Hand calculations were used as a preliminary measure to help ensure that the concept was viable and could then be verified further through more complex analysis. The main characteristic to be roughly estimated was the stability of the USV in mode 1.

3.1.1. Stability Estimation

Calculations of the stability of the USV concept were considered for mode 1 only with particular interest to determining if the vessel geometry would be self-righting. Although computer programs do exist that are capable of more accurately forming cross-curves of stability, the method
outlined could be done at near zero cost and with relatively little technical knowledge. However the degree of error could be large and the method has not been professionally verified. This stability estimation used a solid 3D model of the concept made with Autodesk Inventor Professional, and the procedure for estimating the maximum height of the centre of gravity is as follows.

A solid model representation of the USV in mode 1 was created in Autodesk Inventor. This solid model was given a density of seawater (SG = 1.025) and sliced at a specific angle of heel using an intersecting extrusion. A rectangular area was extruded from the plane at the stern whilst also altering the taper of the intersecting extrusion. Once the COG of the sliced model was in the same vertical place as the expected prototype (275 mm from the stern) and the mass of the sliced model equaled the expected displacement of the prototype the maximum height of COG at each angle of heel could be calculated. An example of the sliced model can be seen below in Figure 3.

![Figure 3: 3D slice of hull at 45 degree heel, for 8kg displacement.](image)

A constant centreline exists in the vertical direction through the centre plane of the symmetrical hull. By drawing a line perpendicular to the waterline slice and through the centre of buoyancy a point of intersection was created between this line and the hull centreline. The distance from the intersecting point to the hull transform is the maximum height of the centre of gravity 275mm from the stern in the horizontal plane.

![Figure 4: Estimating maximum height of COG for self-righting to occur at 45 degree heel with 8kg displacement.](image)

The data collected was then collaborated into a single graph of maximum centre of gravity versus angle of heel. The graph shown in Figure 5: Maximum COG vs angle of heel for self-righting at displacement of 8kg, indicates that a for the 8kg vessel to self-right in mode 1, the height of the COG above the lowest point of the boat must not exceed 110mm. As the vessel is symmetrical an unstable equilibrium point will exist at 180 degree, however small disturbances will return the vessel to its normal orientation naturally.

![Figure 5: Maximum COG vs angle of heel for self-righting at displacement of 8kg.](image)

3.2. Scale Model Testing

The purpose of scale testing was to absolutely verify that the hull geometry is self-righting for a given mass and COG, and to conduct drag tests to determine the speed and planning characteristics of the hull at different masses. The model was generated by producing a 1:5 scale 3D model of the prototype in Autodesk Inventor Professional which was then used to create a 3D printed model. The 3D printed model is a scaled identical in terms of exterior geometry, however on the inside vertical rods were printed to allow metal nuts to be placed to shift the models centre of gravity and change its mass. Photos of the completed 3D printed model can be seen in Fig. 6.

![Figure 6: The complete 3D printed model.](image)

3.2.1. Scale Model Stability Testing

To test the stability of the 3D model weights in the form of metal nuts were placed in various configurations on the vertical rods to shift the location of the centre of gravity. The model was then placed in water upside down to observe if it
would self-right. Through this method the model was found to be self-right for several different weight configurations. At a model weight of 100 grams with a centre of gravity at a height of half the bottom hull height and a third the length from the stern, the model was found to self-right. Thus for the same scaled geometry and mass distribution of a 12kg prototype the vessel will self-right. Through this method the self-righting design of the concept was validated and will be used in the future to predict how the addition of weighted components will cause the prototype to behave.

3.2.2. Scale Model Drag Testing

To examine the drag properties of the hull geometry a low cost experimental setup was created. This setup was made from inexpensive everyday components and has provided sufficient data to be able to predict the drag behavior of the full scale prototype by Froude scaling.

The scale experiment involved use of a small 4.2 metre towing tank built from plywood, wooden beams and waterproof tarpaulin as seen in Fig. 7.

A unique towing and drag measurement mechanism was built using a speed controllable power drill, fishing line and reel, a kitchen scale and a wooden frame. The speed of the model being dragged is directly controlled by the drill speed, and the drag at each speed was read from the kitchen scale. To ensure the kitchen scale reads accurately it was mounted in the vertical position and the tension in the fishing line during the experiment was redirected to the kitchen scale through fishing line pullies of negligible resistance. The kitchen scale itself could measure drag forces up to 500 grams in increments of 5 grams and had been calibrated with known weights prior to the experiment. Photos of this experimental equipment can be seen below in Fig. 8.

Using this experimental setup the 3D printed model (mode 1 only) of known weight was pulled at various speeds and the drag recorded. Using a 1.2 metre rule and video footage of known framerate, the speed the model in each run was calculated and then plotted against the measured drag. The data of the drag experiment with a model weight of 95 grams and known COG is shown in Fig. 9.

Using the results of the model test the prototype drag and speed curve was subsequently produced. Froude’s scaling laws dictate the scaled mass and geometry of the prototype relative to the model [5]. For the geometrically scaled model 1:5 (\(\lambda = 0.2\)) size of the prototype, the prototype takes on the following properties.

\[
\text{mass}_{\text{prototype}} = \frac{\text{mass}_{\text{model}}}{\lambda^3}
\]

\[
= \frac{0.095}{0.2^3} = 11.875 \text{ kg}
\]

\[
\text{drag}_{\text{prototype}} = \frac{\text{drag}_{\text{model}}}{\lambda^3}
\]

\[
= \frac{\text{drag}_{\text{model}}}{0.008} = \frac{\text{speed}_{\text{model}}}{0.04}
\]

By Froude’s scaling law the expected drag to speed plot was produced, which can be seen below in Figure 10. This plot shows the prototype’s transition from low speed displacement mode, to planning speed where large gains in speed are made with little increase in drag. The estimated prototype drag to speed plot will later be used to help design the propulsion
system of the USV to help ensure the USV will operate in the
most efficient planning region for a given jet propulsion unit
and motor configuration.

![Graph showing estimated speed versus drag test results for prototype mass 11.875 kg.](image)

Figure 10: Estimated speed versus drag test results for prototype of mass 11.875 kg.

The model and prototype drag to speed plots closely resembles
those of other planning vessels. From the data displayed in
Fig. 10, the ideal stable thrust required to overcome drag whilst
operating in the high speed planning region is between
approximately 250 to 300 Newtons. This thrust capability will
enable the USV to cruise with relative ease to speeds of up to
18 knots.

Large gaps between data points can be attributed to the
method of speed control. The power drill used to control
speed was highly sensitive to small changes in torque, thus it
was difficult to alter the speed to give a better spread of data.

4. FUTURE WORK

Further work is required to fully verify the total concept
design for detailed design and manufacture. Specifically, the
catamaran required to operate in mode 2 needs to be fully
characterised in terms of stability and drag. Scale testing with
the catamaran attachment is to be completed in the future, and
design changes made if needed.

As stated earlier, results of the scale drag testing will be
used to design the propulsion system. This system will be
optimised to allow high speed, whilst also allowing a
significant runtime at cruising speed.

To introduce autonomy to the USV platform the onboard
Beaglebone Black (Texas Instruments, 2014) will be
utilised along with the open source Mission Oriented
Operating Suite [6]. MOOS is a collection of open source C++
modules that provide autonomy to marine robotic systems. Future work required includes interfacing sensors to the
Beaglebone, and implementing the necessary control
algorithms and functions through MOOS to allow the USV to
perform autonomously, whilst also allowing for full
instantaneous operator control.

5. CONCLUSION

USV systems have widespread applications in both the civilian
and military environment. Based upon research into existing
USV systems a USV concept was created. The USV concept
discussed will be capable of both fast payload deployment
robot as a self-righting planning monohull, as well as operating as a trimaran UAV landing and charging platform
station. Design validation through hand calculations, computer
aided design, and scale model testing using a 3D printed
model was conducted to validate the design of the USV in the
first mode as a self-righting and capable of high speed
maritime surface robot. Further work includes the verification
of the trimaran design (Mode 2) through scale testing, design
of the propulsion system, and implementation of MOOS [6] to
provide autonomy and intelligence.

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