Design of An Unmanned Surface Vehicle for Oil Spill Sampling

Luis Hernandez
Mechanical and Industrial Engineering Department
Texas A&M University Kingsville

Juan Zambrano
Mechanical and Industrial Engineering Department
Texas A&M University Kingsville

Hua Li, Ph.D.
Mechanical and Industrial Engineering Department
Texas A&M University Kingsville

Oscar Garcia, Ph.D.
Water Mapping, LLC.

Abstract

The unmanned surface vehicle is small and lightweight with the modular design concept applied, which makes it easy to be disassembled, transported, assembled, and deployed for oil spill sampling and measurement in the offshore environment. The objective of this project is to design an unmanned surface vehicle as a low-risk and low-cost solution for the remote sampling and measurement of oil spills that can be controlled and monitored in real-time. This unmanned surface vehicle is designed to move across the survey area with a traced route for sampling and measurement through a control algorithm. The control algorithm is developed using mathematical models to increase the stability of the vehicle, which helps optimize the time the vehicle needs to move across the survey area to accomplish its goal. Through simulations and analysis of different boat models, the catamaran is selected for the unmanned surface vehicle in the offshore environment for survey and measurement purposes. SolidWorks fluid and stress simulations are used to determine the design parameters that hold tough conditions in the offshore environment. In addition, technological tools such as the IoT are used for real-time control and monitoring of the vehicle, making the vehicle autonomous and capable of long-range control without any human intervention.

Introduction

Ocean oil spill has been a problem due to the harm to marine ecosystems, contamination of drinking water, and harm to coastal economies that rely on tourism and fishing. The problem starts when a massive loss of marine species is caused by the hydrocarbons, these marine species are food resources that then are digested by humans resulting in toxicity and medical problems for the population. To avoid the spread of the oil in water and damage to the marine ecosystem causing more natural disasters, containment has to be done. However, the oil spill has to be studied and classified first to determine how to proceed to a containment phase. These studies can be conducted by remote sensing and in-site sensing and sampling to determine the characteristics of the oil spilled and how to combat its spread. But getting in-site of an oil spill implies the risk of being intoxicated by getting in contact with the hydrocarbon. This is why an unmanned vehicle is required for this kind of task.

The unmanned surface vehicle (USV) is an automated vehicle with navigation capability across any water surface environment. Remarkable characteristics such as its small volume, high speed, mobile ability, and self-independence in navigation make this type of vehicle appropriate for its use for tasks that can be hazardous or contain a prominent level of risk for humans or are impossible to access for humans operations.[1,2] This type of vehicle represents a cheaper and safer solution to effectively extract data and conduct tasks from remote places with minimum risk. The design of the vehicle requires considering the environment in which it will develop and the task it is going to be effectuating. Also, more technical constraints such as the navigation system, and the communication systems and protocols, have to be established for the monitoring and long-range control of the vessel. This boat intends to replicate the design as many times as possible, so its design has to be considered a low-cost model.

To determine the boat design, structural analysis, as well as flow analysis, and floatability tests are executed using SolidWorks and Float Soft, these analyses are conducted to determine a proper design for the boat. These analyses determine the resistance of each of the proposed design components and the dynamics of the flow of water and the vehicle's buoyancy. Once the results of the analyses are shown, decision-making for selecting the best candidate is made to determine the ideal design to follow.

Vehicle Design

Hull Design

To design the proper vehicle for the task, it must fulfill the environmental and task constraints. This vehicle must be capable of navigating through most of the climate conditions that could be present in the open sea. The climate in the sea is not constant and is in constant change, the vehicle must be prepared for any change in weather while the task is in the run. It must show resistance and stability in rough conditions and protect the internal parts at any moment. The waves are in constant movement and will constantly crash against the vehicle, one vehicle of small volume can easily be rolled over if not designed properly. The vehicle must be transportable and easy to carry, and the operator must be able to transport with ease the vessel in a small volume of baggage so it can be taken to the oil spill site with no problem. The end product must be a low-cost and easy-to-replicate vehicle capable of accomplishing the task, this is because by replicating the vehicle, the easier the task becomes, the more vehicles, and the less time it takes to survey the total area of the oil spill.

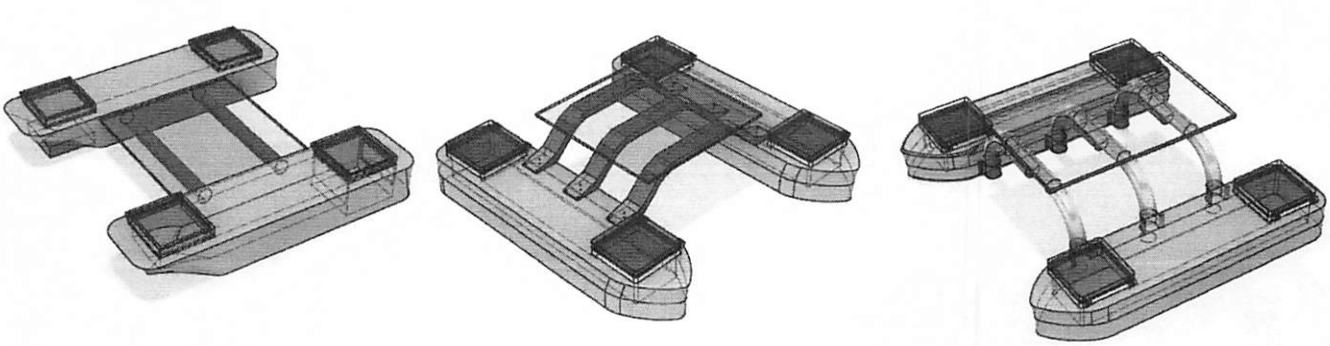
To start designing the construction of the boat, the most important thing is to determine which type of boat to use. There are plenty of types of boats that are capable of carrying the task but do not fulfill the environmental constraints. It is known that the catamaran type is the most stable and rigid type of boat because of the double hull and its low center of mass, it can navigate easily in most of the environmental conditions present in the sea. This type of boat also has the characteristic of increasing the speed by the double allowed by a one-hull type boat due to the double propellers in both of the hulls. It also allows a better load distribution using both compartments inside the hull and a platform that connects both of the hulls. Also, because of the low center of mass, a difference in load between the two hulls will not affect the development or the stability of the vessel as it happens in the monohull boat type.

There are two types of manufacturing processes for the construction of a hull, planking, and carving. The manufacturing process should be decided based on the material. Planking is the method of using wood planks to manufacture a hull. The characteristic of this type of hull is that it's hollow and requires a keelson and a bulkhead that work as a skeleton of the structure, it is used to curve the plies of wood to shape the hull. Then, a layer of fiberglass is added to reinforce the structure of the hull. Carving is the second method of hull manufacturing. It consists of carving a block of the material to use, the most used materials for this method are wood, hard polyurethane, or polystyrene. An additional layer of fiberglass is added to endure the structure, but if the material used is polyurethane or polystyrene, an extra layer of epoxy has to be added before adding the layer of fiberglass.

The constraints to determine the material to use in the manufacturing of the hull are the following, cost, strength, buoyancy, weight, and density. The importance of these constraints lies in two factors, the need for a low-cost model and the efficiency of the boat in the water. For this project, the importance of efficiency is higher than the cost. So, strength, buoyancy, weight, and density are more important. The decision lies in the fact that it is important to make the boat float at all costs. So, the factors of buoyancy and density are considered for this project more important than strength and weight.

Comparing both, polystyrene and wood, taking into account the constraints for the project, it was determined that the polystyrene will have a higher development while proceeding on the tasks. Once knowing the material, the manufacturing process is selected, in this case, the use of polystyrene blocks requires carving on the block to get the form of the hull. A layer of epoxy is required to avoid a chemical reaction between the polystyrene and the resin used in the fiberglass process, this chemical reaction is capable of melting the polystyrene. So, by adding this layer this problem is solved.

Once knowing the type of boat used and the material to use, the design of the boat is the next step.



Multiple designs were developed using Autodesk Fusion 360 software and SolidWorks software to determine which is the most suitable to perform the task of the boat.

Figure 1. Design 1 (left) Design 2 (center) Design 3 (right) for the USV.

As can be seen in Figure 1, the designs are double-hull vessels as mentioned previously changing the form of the hulls and how they are attached to each other. The chosen paint is yellow because of identification purposes. In case of any troubleshooting, the operator will require to identify and rescue the vehicle. The load platform was chosen to be of template crystal because of the strength of the material and resistance to high loads as well as for identifying the components mounted on it. The stabilizing beams change on each of the designs, this is to determine which is the most suitable for the task in the next analyses.

The vessel design takes into account factors such as speed, maneuverability, stability, and seakeeping.[5] To determine the best design, tests and analyses were performed using two different simulators, the SolidWorks Flow Simulation to determine the hydrodynamics of the vessel, the Structural Simulation from SolidWorks was used to perform the structural analysis over the components of each design as well as find the center of mass and the structural stability of the boat, to determine the maximum torque force over the hulls and the connector bridges, and the load reaction of each design.

The simulations were configured to represent tough weather conditions to determine the maximum levels of stress and hydrodynamics that the design could handle as well as to visualize the development in hazardous conditions of the vessel design.

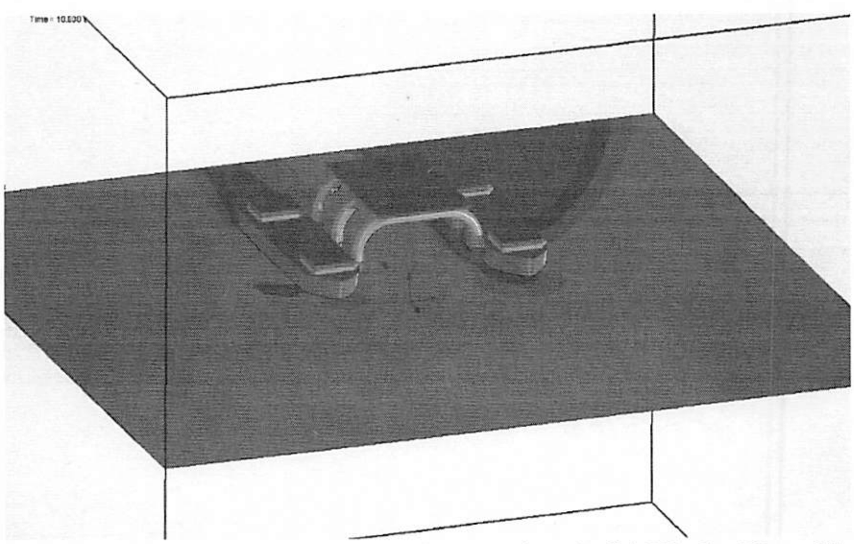


Figure 2. Hydrodynamics analysis of Design 3 using Solid Works Flow Simulation.

The results of the flow simulation and the structural simulation of the three designs show that the most suitable candidate for the task is Design 3, which is capable of resisting the maximum load inside the compartments of the hulls and in the platform without any structural failure, also, shows the best development in the flow simulation which shows lower turbulence in the center as shown in Figure 2. This allows easier sensing and sampling of the oil spill without disturbing the sample.

It needs two motors to move the double-hull vehicle, one in the left hull and the other in the right hull. Each of the motors requires to be brushless motors, both use jet thrusters to move the boat. The intention of using these thrusters is to displace the vehicle's larger distance with less power. The thrusters extract the water from below and eject it generating propulsion and bringing motion power to the boat. The motors selected for this task have to be selected considering the dimensions of the hull. Design 3 has two hulls of a length of 36 inches. To determine the power required (P), and the Kv, the next equations are used.

$$Power = 4.279HL^2 - 163.1HL + 1901.5 \quad (1)$$

$$Kv = \frac{RPM}{V_{nom}} \quad (2)$$

By using these equations, the results were a motor with a power of 800W each to move 1600W, and a Kv of 1600 for each motor. Rocket 4082 brushless motors are capable of moving in 1650 Kv each. The use of two motors alike help in the control, and also allows the boat to move faster without consuming a large amount of power.

Control System Design

The boat requires to drive multiple tasks at the same time, for this, the system used is based on VxWorks, to perform three main tasks, communication task, data collection, and maneuvering control.[2,3] The system objective of the Maneuvering Control System is to make the USV accomplish the entire survey following the waypoints geolocated while the sensors recover the data from the surface and establish communication between the operator and the vehicle for the data transmission for measuring and control purposes. The control concept of this vehicle is based on the motion and navigation system. A GPS module obtains the necessary information for the vehicle to operate. However, an accelerometer is needed as feedback for better control over the angular position and the direction to determine where the USV should head.

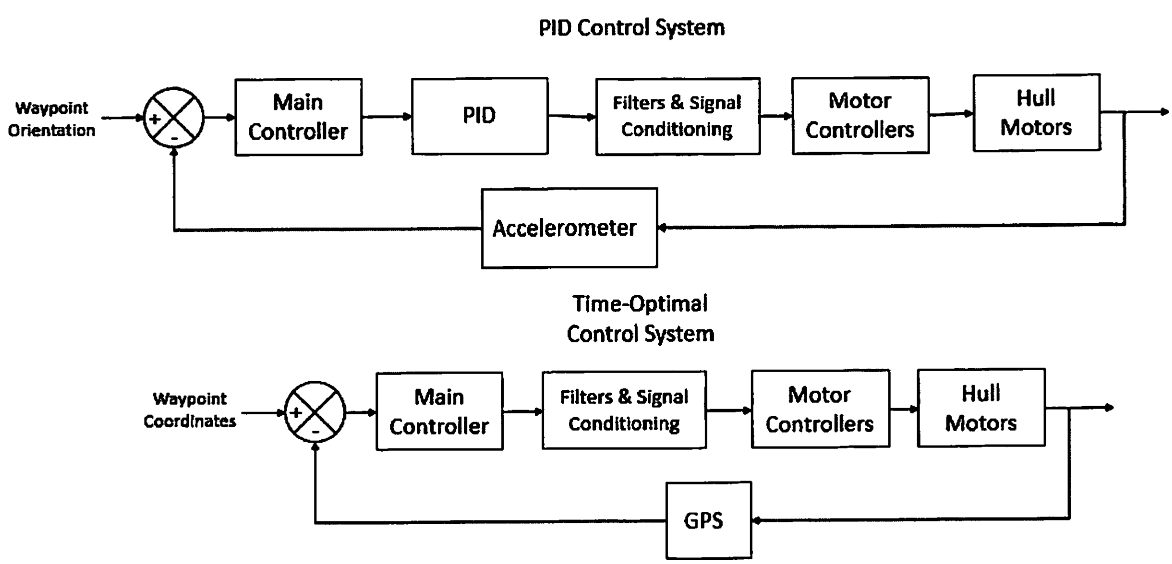


Figure 3. Time-Optimal controller and PID controller block diagram for the navigation system.

The control strategy taken from this project combines the PID controller and a time-optimal controller. As Figure 3 shows, the PID focuses on the control by the error of the direction, the time-optimal controller is designated in the displacement of the vehicle from the surface to the next waypoint. The main system executes multiple processes, all of them being executed simultaneously. The system is encored in the controller which divides into subsystems to develop different processes. It has seven inputs and five main outputs. Separated into three different tasks, navigation, measuring, and communication.

The system requires certain characteristics to execute properly each process. It needs a processor capable of managing all the processes almost at the same time. For this, a drone flight controller is chosen for this project to control the whole system. This allows the execution of a substantial number of instructions in an exceedingly small fraction of time. The microcontroller inside the flight controller allows the system a memory capability of 4 MB in its internal flash memory, being useful for storing important data. Another important reason for the use of this flight controller is power consumption. While other systems are known to use much power, the flight controller is a low-power consumer microcontroller. This is a particularly important constraint to cover, due to the fact that the USV has to move across an open large area and the motors need to consume much of the supply's power.

The batteries used to power the whole system are two LiPo batteries of 6 cells, 22.2V and 20 AH, this is enough power to supply the whole system for an hour. The use of these batteries is considered because of their low weight and dimensions. This makes capable for the vehicle to have better control over the direction and does not need much power to move its own weight.
For the navigation system, first, it must be established the motion equations for the control of the vehicle.

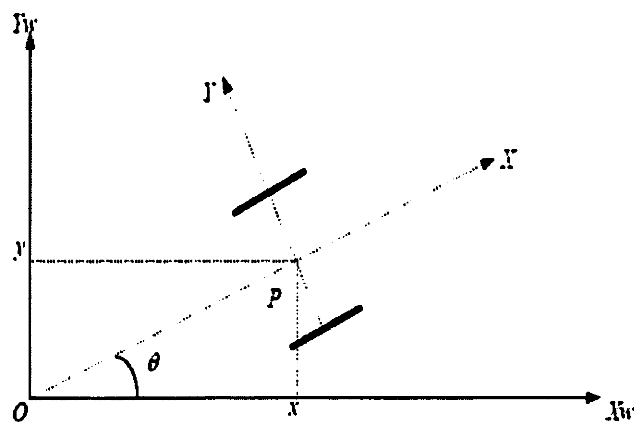


Figure 4. Coordinate System for navigation of the USV.

In Figure 4, the X_w and Y_w represent the stationary coordinate system, while X, Y, and P represent the moving system. PX is the representation of the direction of the USV[4].

$$x(t) = \int_0^t (v_r(t) + v_l(t)) \cos\theta(t)\, dt \qquad (3)$$

$$y(t) = \int_0^t (v_r(t) + v_l(t)) \sin\theta(t)\, dt \qquad (4)$$

$$\theta(t) = \frac{1}{L}\int_0^t (v_r(t) - v_l(t))dt \qquad (5)$$

Where,

L is the length between the two propellers,

$v_r(t)$ is the velocity of the right propeller,

$v_l(t)$ is the velocity of the left propeller,[4]

When the direction is the same for the vehicle and the static position, the position in $x(t) = 2v_r(t) * t$, $y(t) = 0$, $\theta(t) = 0$ so the movement is linear. In case that the direction of the vehicle is adverse, $x(t) = 0, y(t) = 0, \theta(t) = \frac{2v_r*t}{L}$, this means that the vehicle needs to rotate, this is when the data of the accelerometer is necessary to estimate the correct direction of the vessel. When the vehicle arrives to the waypoint, it needs to take another direction. This is the base of the time optimal control previously mentioned[4].

Communication System
Large boats could displace the stain of oil in the water and spoil the sample. So, a small, unmanned surface vehicle at low speed could accomplish the task. The boat would get away from the deployment location and survey the affected zone remotely. But how the vessel could send the data to the operator that locates in a very distant location? And how could the operator send instructions and control the vessel from a large distance in real time without spoiling the sample?

This is one of the main constraints for the design of this system. The USV must be capable of getting into remote areas of difficult access and sending the data retrieved from the oil spill in almost real time. The data is shown in the operator's interface, moments later after the controller sent the information, as well as it must receive information from the operator for the control and navigation of the device. This issue leads to a few options for how the communication process can be managed. Therefore, the used communication system must be capable of using IoT technology.

IoT technology is the use of devices, modules, or controllers capable of sending and receiving information wirelessly from and to the internet where the information can be stored and manipulated for the monitoring and control of devices or research purposes, all of this in real-time.

This technology uses an architecture that consists of 8 elements, a database, external interfaces, analytics additional tools, visualization processing, action management, device management, and connectivity and normalization[7]. The advantages of using this type of connection are the good environmental adaptability, this connection can resist harsh conditions without failure. Good self-organization increases the robustness of the communication network. Better sensing and monitoring, allows a real-time communication with the operator while the vessel collects the data of the ocean and then is sent for monitoring.[6]

For this project, a database service is used. This service provides 1 TB of data for the user and unlimited domains for web pages. This fits perfectly for the project; it allows third-party interfaces to connect with the database and provides a cybersecurity service for the user encrypting the data stored in the database. This service allows the creation of a safe webpage for the data visualization of the data and control of the USV navigation.

For the project, a LoRa (Long Range radio frequency) module is used embedded in the system. The module used for the connectivity and normalization uses a transmission frequency of 900 MHz and a bandwidth of 125 kHz[8]. and has a range of 21km. This kind of communication allows having a wide range connection which allows a full duplex wireless communication by the use of the LoRaWAN communication protocol.[3] The system sends through the module the data into a LoRa IoT gateway that is located in the deployment boat, this gateway helps as a node for the transmission of the data into the cloud. Also, this gateway ensures that the interaction between the vehicle and the cloud keeps connected as part of the device management of the IoT. The gateway is connected to the boat's satellite internet connection to send and receive data for the monitoring and control of the USV. This allows the operator to operate the vessel from any location. Since the oil spills to be measured are near the coast of the US, the system is able to connect to a stable connection. To establish better communication between the controller and the gateway, a high-gain long-range antenna is used. With this, the system is able to stay connected at the most possible time making it possible to go far from the coast to sample the oil spills.

In terms of how the communication of the system works, before the deployment, a deployment boat operator ensures that the USV LoRa module is connected to the gateway. Once the vessel is in the water, the control operator establishes the waypoints where the vessel must travel. As part of the processing and action management, once the boat starts moving, the system recovers the data retrieved from the sensors. The data is sent from the controller including the GPS coordinates to the gateway through LoRa and then to the cloud database through an internet connection[9]. There, the data is directed to a webpage (that only the operator can open), where the information is shown. All this happening in real time. The analytics element and the additional tools are not contemplated in this project, but a future implementation of deep machine learning could be used for an optimized connection.

Conclusions

In summary, the unmanned surface vehicle is required for tasks that are difficult for human resources to have access to. The advantage of using these vehicles is that it does not require manual control and can develop the designated task without human intervention. The oil spill research field requires the assistance of this kind of vehicle for in-site studies with the objective to develop strategies for oil spill containment. The design of a USV for an oil spill study requires analytic decision-making to determine the most suitable materials and resources to elaborate the vehicle by using the physical factors that affect the development of the resources in the field to determine the best decision. By comparing the materials using the factors of the task, it can be said that the best material to use for this project is polystyrene because of its buoyancy characteristics that allow better floatability for the vessel and higher motion development in water. The use of software for structural analyses and flow analyses is a suitable solution to determine the modeling design capable of accomplishing the tasks designated.

The use of mathematical models for modeling boats is a suitable way to determine the ideal motor for the vessel, resulting in the selection of jet thrusters that are capable of moving long distances with low consuming power in a lesser time than other types of motors. The navigation system is in charge of the displacement of the vehicle to the designated waypoint, for that, the use of PID control and time-optimal control allows a good performance and ease for the boat to navigate with help of multiple modules such as accelerometers and GPS that acquire the coordinate and motion data to determine the optimal path. Also, the use of mathematical models based on displacement coordinate systems allows the vehicle to have a time-optimal solution for the navigation control by determination the action to take depending on the approximation to the following waypoint. Also, the use of long-range communication is a vital part of the vehicle because it allows the transmission of data remotely in real-time, this can be achieved with the use of LoRa modules, gateways and the use of the IoT (Internet of the Things) that delivers to the operator in real-time the required information for the monitoring and control of the vehicle.

In the future, when the project reaches the manufacturing process, these vehicles are intended to be a low-cost solution for the in-site study of the oil spills. The continuous development of these project will result in the production of unmanned, automated double-hulled vehicles that can survey large surfaces in a short period of time and have an effective reaction to the oil spill contingency.

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