Highly Maneuverable Spherical Robots for Underwater Applications

by

Aaron Fittery

Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of

Bachelors of Science in Mechanical Engineering

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Abstract

The direct video inspection of complex underwater systems, like those inside nuclear reactors, is a difficult task to accomplish. Alternatives to underwater remotely operated vehicle (ROV) inspection are very laborious, if possible at all. Current ROVs have difficulty navigating and effectively surveying these systems because walls and extrusions throughout the environment easily damage the external appendages that propel and steer the robots. These damages will often times render the robot useless, leaving it stranded. Continuing off previous work designing externally smooth robots with uniquely designed internalized mechanical components, this work explores the design of new, spherical robots. There exist many benefits to the spherical geometry of vehicles. With zero added mass and identical dynamics moving in all directions, the maneuvering capabilities of these robots are extremely high, making them easy to control and inspect many complex underwater systems.

Thesis Supervisor: H. Harry Asada
Title: Ford Professor of Mechanical Engineering

Acknowledgments

I would like to thank Professor Asada for allowing me to participate in the UROP program in his lab for two years and work on these new, exciting robotics technologies. From the work that I performed over those times he then allowed me to continue on the project and write this thesis on developing new designs for the project.

I am indebted to my good friend and mentor, Ani Mazumdar. My entire experience throughout my time working as a UROP student, working on my thesis, and just my entire life as an MIT student would not have been the same without him. When I first came on to this project I had very few skills that were directly applicable to the technical research he was doing, but he saw my desire to learn and my passion for the project and didn't get frustrated with my initial shortcomings. As the project progressed he not only taught me necessary skills to be successful in designing robots, but also gave me some freedom to apply my new-found skills and creativity to help the project in my own way. Over the next two years he guided me through the rough environment of being an undergraduate student at MIT, helping me find what I truly love to do and the best paths to follow to make the most of my opportunity here at MIT. Without his friendly nature and great mentoring abilities I wouldn't have attained the personal success on this project and at this institute that I've been so fortunate to achieve. Martin Lozano and Wyatt Ubellacker have also been integral to the success of the project and they only helped to improve the environment of the team.

I must finally thank my parents, my sister, and my entire family who have always been a huge part of my life, inspiring me to work hard to achieve the goals I set for myself, while letting me find the things that truly bring enjoyment into my life. Without their dedication to my success the opportunity that MIT presents would not have been possible. They've taken an interest in all of the nerdy work I love to do never stop supporting me along the way.

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Chapter 1

Introduction

1.1 Remotely Operated Underwater Devices

Remotely controlled and autonomous robots are frequently used to assist humans or completely take their place when performing repetitive, tedious, or dangerous tasks. Accessing environments beyond those navigable through human capability or current technology always present fascinating problems to researchers. Many of these environments occur underwater, in places humans simply can't access. Using robots to navigate these areas can open a world of exploration, while also giving humans access to preventing or solving many problems that exist in these underwater environments that already play such an important role in our society.

Underwater Remotely Operated Vehicles (ROVs) provide navigation abilities of submersed vehicles via a control system above the surface of the water. Many of these ROVs use a tethering system to provide power, multiple sources of data feeds, and many other electro-mechanical components that would otherwise be difficult to implement on board the robot. The use of robots like these is well developed and widely used for many purposes ranging from [name of robots and their function with references].

One unique environment that makes use of these vehicles is the cooling systems of nuclear reactors. Complex piping systems with extremely hot, highly pressurized, radioactive water are not suitable for human inspection. The wearing from corrosion that these pipes experience is difficult to continually monitor and inspect without visuals of the inside of the pipes. Because of these issues, current inspection methods are extremely inefficient. Some other non-destructive robots have been used to inspect nuclear reactors and other piping systems. They range from snake-like robots to others that make use of magnetic flux leakage detection [1] [2] [3]. A capable underwater ROV could potentially perform the duties necessary to effectively inspect these systems, but many current ROV designs still present many faults.

Tethers, propellers, fins, and size constraints all pose problems to ROVs in complex environments like these. The designs of tetherless, completely externally smooth robots propelled by jets rather than propellers has been a focus for new underwater ROVs attempting to better navigate complex systems like these [reference old paper]. Previous versions of these robots implemented ellipsoid shapes using multiple pumps for the propulsion system. This thesis will explore redesigning robots like these towards more spherically shaped, single pump driven systems to explore the benefits that these new design features have on navigating and inspecting complex underwater systems.

1.2 Previous Work

There have been significant contributions prior to this work that focused on developing these new breed of small, highly maneuverable underwater ROVs for the purposes of navigating and inspecting in tight quarters. "Eyeball" robots separated the inspection capabilities from the maneuvering capabilities to give the camera the precision as opposed to using the vehicle mobility precision to control the camera [4]. Initial designs focused on achieving high degrees of freedom for maximum control before adding the necessary tools for effective inspection processes. Using a uniquely designed Coanda effect valve for precision maneuvering these robots could effectively maneuver through extremely cluttered environments [5].

One of these initial designs maintained that completely smooth external shell, and made use of an ellipsoid shape. Driven by two internalized pumps this robot shown in Fig. 1-1 was capable of 5 DOFs. This prototype robot successfully proved the capabilities of these robots for the first time, opening up a range of opportunity to firther develop their attributes [6]

Another design, which can be seen in Fig. 1-2 made use of two completely internalized pumps to control the finer movements and actively stabilize the yaw rotational deflections, another external motor with a propeller to achieve faster forward velocities and the capability of diving while accelerating forward [7]. Both these designs did not implement any sort of data acquisition methods for the inspection task, but simply focused on the highest degrees of maneuverability.

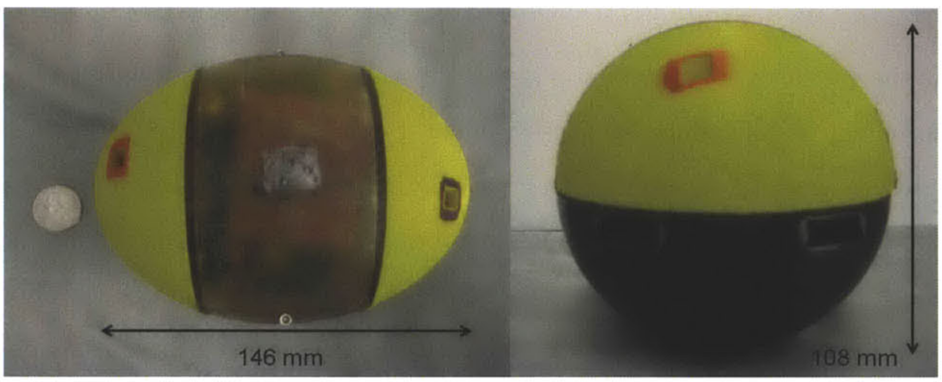


Figure 1-1: Photograph of the initial design internalizing two pumps, capable of 5 DOF motions.

1.3 Motivation

So much of our world and the systems humans have created in it are made up of water, yet so many of these environments pose difficult obstacles for navigation and exploration. Humans' natural inability to effectively navigate and explore these areas presents a definite application for the use of robotics to traverse and inspect these re-

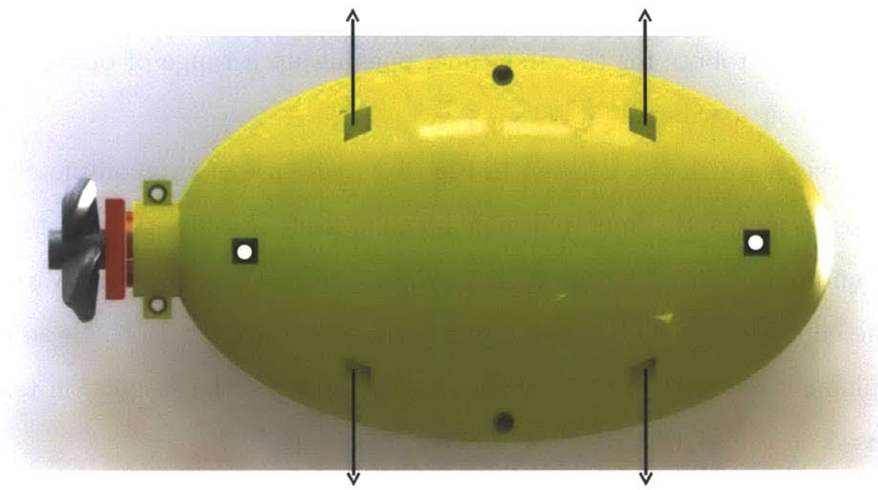


Figure 1-2: Rendering of an initial design internalizing two pumps and using an external motor with a propeller.

gions. As the vast array of underwater systems become more explorable as technology advances, new areas of failure for these vehicles becomes apparent. Certain features of many ROVs must be questioned to creatively improve upon old designs, generating new unforeseen uses for these types of robots. Previous designs of these small, highly maneuverable underwater ROVs have demonstrated some unique capabilities that can be applied to many complex underwater systems. Each design has its pros and cons and the expansion and exploration of new design features for these types of robots will prove to be very useful for the continued improvement on navigation and inspection of these environments using ROV technology.

1.4 Outline of Paper

This thesis starts by answering the question of why the spherical design was used for this newly design ROV, taking a look at previous work focused on the external shape of these types of robots. Next is a review of the unique pump-valve design used in similar ROVs that have been researched during previous work in this lab. Chapter 3 will also review two approaches to using a single unit of this sub-system, high single-planar maneuverability and multi-planar maneuverability. Each will be explored in depth to view the characteristics each system has and how they can be utilized in different environments and scenarios. In chapter 4 the experimental data from testing these two designs will be used to illuminate the features that separate it from previous designs. Finally the paper will conclude with a broad exploration of future work. This will take a look at many potential applications of this type of ROV and how new design features that have yet to be implemented may also expand the capabilities of these types of robots.

Chapter 2

Shell Design Implications

2.1 Shape

As this new type of underwater ROV has been established, one of the areas of significant change between designs has been the shape of the shell. The unique nature of these robots lies in their completely smooth exterior shell that still allows for high maneuverability. Many underwater ROVs used a common shape that has been used for a very long time throughout the history of all underwater vehicles, an elongated ellipsoid, like many submarines. This is the shape that the previous designs of these new vehicles used, and they proved to work very successfully. One of the main focuses of this thesis was to challenge the shortcomings of that particular shape to view how a new shape could be effectively utilized in situations where an elongated ellipsoid may not be as useful. Designing a spherical shell presents some notable benefits and difficulties that will be detailed throughout the following sections as it is compared with the previous ellipsoidal design.

2.1.1 Dynamics

The first criteria that the shell design focused on was how its shape affected the dynamics of the robot. Previous designs that implemented the ellipsoid shape have been studied in previous work. The elongation gives the robot a preferred direc-

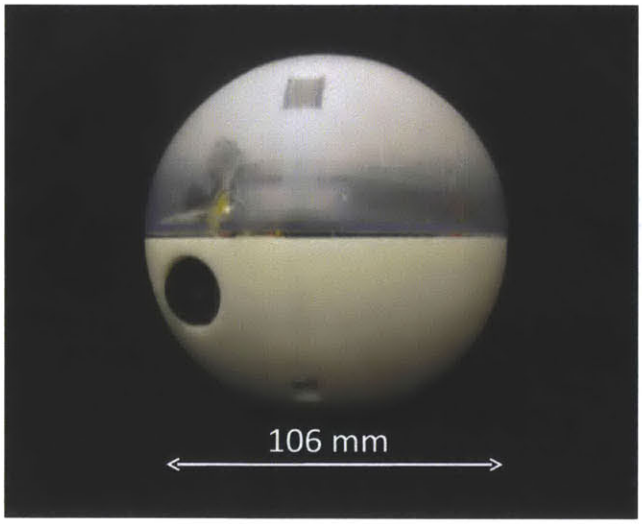


Figure 2-1: Photograph of the new spherical design using an onboard camera.

tion, making it more efficient moving forward, in the direction of the elongation, but significantly less efficient moving sideways because of the large drag forces it must overcome. Having a preferred direction can be beneficial in some instances, but under many circumstances being able to translate and rotate in any direction under the same dynamics makes the user control more intuitive and consistent. This lack of preferred direction allows the vehicle complete freedom of mobility for moving the robot to its desired location. Imagine the elongated vehicle that needs to make a 135 degree turn to reach a destination that is behind and to the left of the vehicle. In wide open water that may seem like a trivial operation, but when enclosed in tight quarters an elongated ellipsoid may face trouble turning, even if it can turn on its yaw axis. The perfect symmetry of a spherical vehicle makes travel in all direction dynamically identical in a neutrally buoyant state underwater. This was one of the great benefits of this spherical design. Previous modeling of the dynamics of spherical underwater vehicles played a crucial role in understanding how these vehicles would perform [8].

Another key shortcoming of the elongated design is the Munk moment it encounters. As the angle of attack increases the vehicle becomes unstable and loses it's desired heading [9]. The elongated shape of these vehicles creates a greater moment as the vehicle first destabilizes, which is one of the areas of interest for designing the spherically shaped robot (note that feedback control systems allow the robot to overcome this moment and maintain stability in the ellipsoidal design). As the spherically shaped robot moves forward it does not experience that same moment that quickly destabilizes the other vehicle. One area that this feature could significantly help in is the power consumption. Because the stabilization on the other design is achieved through the continuous switching of a small motor, it is continuously using power just for stabilization (in addition to the power required for the actual pump propulsion). If the spherical design could be driven forward without the need of continuous stabilization from these motors the power consumption of the robot could be decreased, giving it more operation time. These implications that the dynamics of the vehicle shape have on the robot display some of the helpful attributes that a spherical design may have on the robot. Later in this thesis tests of these implications will be explored in greater detail.

2.2 Size Minimization

Another implication of the shell design is on the size of the robot. As previously discussed, the ability of these robots to be able to move through very tight and complex underwater systems was one of the main focuses of this thesis. This ability hinges greatly on the size of the robot, which is very dependent on the number of propulsion systems implemented into the robot. For this reason, instead of simply thinking about making the shell as small as possible, the focus turned to minimizing the number of pumps that would be used while keeping the robot highly maneuverable.

Because the previous design used two pumps, the only way to achieve a smaller, spherical design was to decrease the number of pumps used from two to one. This presents an obvious challenge because only one jet can be utilized at any giving time, making the high DOF capabilities more difficult to obtain. After designing the new pump-valve subunit systems, which will be described in detail in the next chapter, the details of the spherical design started to reveal themselves. The limiting factor on the size was going to be the length of the propulsion system and the sealed chamber that must house the electronics. With the length of the propulsion system very defined by the fluid dynamics of the jet actuators uses, the sphere was designed for a diameter of 106mm. This allowed for ample space to implement the onboard camera, a POV MAC-10 mini action video camera. The area of difficulty would come from finding a way to seal the water tight chamber without taking away too much of the space needed to house the electronics. A unique helical screw cap was designed to both easily and efficiently seal the water tight upper half of the sphere. Making use of an o-ring and the water tight material of the stereolithography machine, this chamber effectively enclosed the electronics while maintaining a slight positive buoyancy.

This spherical shape seemed very promising and a lot of the implications of the design made a case for the high capabilities of a design like this. The two unique approaches for this spherical design will be discussed in the next chapter, but to get a clear vision of how the design was setup Fig. 2-2 and Fig. 2-3 display the two halves of the spherical shell opened up with the key components labeled. With a clear vision of the implication that the shell design has, the rest of the paper will explore how the propulsion systems were implemented and how well the robot performed after testing.

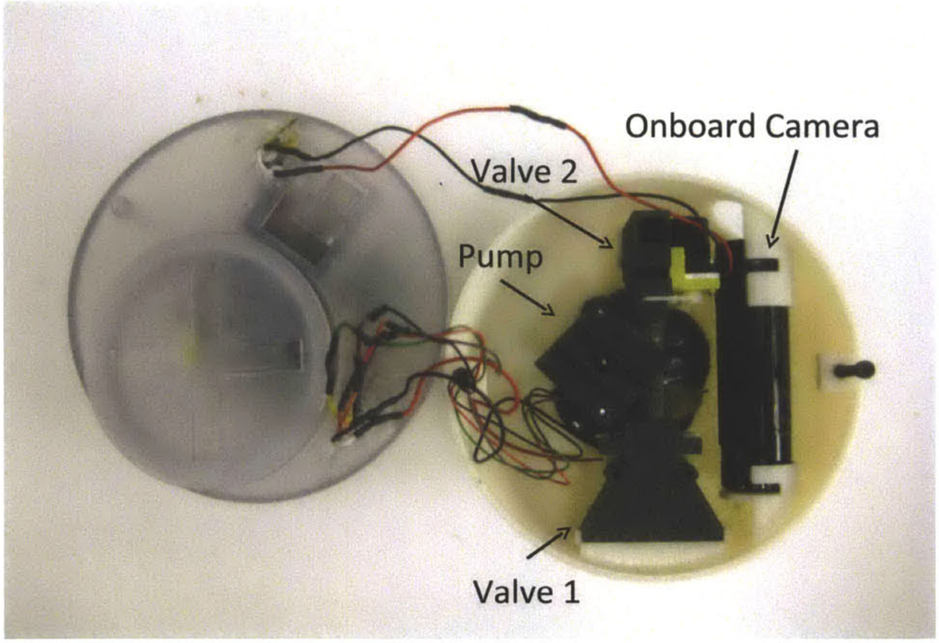


Figure 2-2: Photograph of the new spherical design implementing the multi-planar mobility system approach.

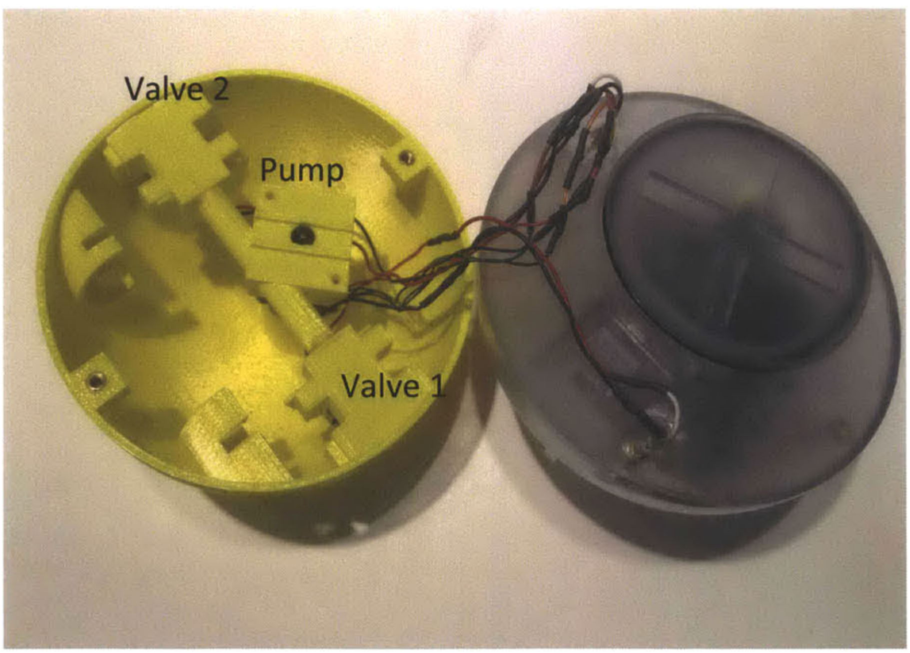


Figure 2-3: This is a photograph of the new spherical design implementing the single planar high mobility approach.

Chapter 3

Pump-Valve System

3.1 Introduction

One of the key components of these robot designs is the unique pump and valve system that was previously developed and used in other underwater ROV designs. Other unique propulsion systems like the vortex ring thruster have been developed to help vehicles move precisely at low speeds [10]. This new system uses a small reversible pump in conjunction with a unique Coanda Effect jet actuator valves similar to those first developed for the actuation of gas flows [11]. The device allows the output jet from the pump to be bent in two distinct directions by creating a pressure drop along either side of the jet. Effectively, one pump allows for four separate jet outlets which can be activated by covering small holes on the sides of the actuator.

Previous robot designs implemented more than one of these subunits and proved effective in developing a highly maneuverable underwater ROV. The research in this thesis focused on use of only one of these units. To maximize the benefits of using a one unit design, multiple iterations of the actuator device and pump- mounting nozzle piece were modeled using the computer aided design (CAD) software SolidWorks. Computational fluid dynamic tests were performed as well to optimize the devices before using a 3D printing system to further test and implement. The rest of this chapter will go into greater deal about the CAD modeling and CFD testing as well as discuss the details of the two different approaches to using the pump-valve systems.

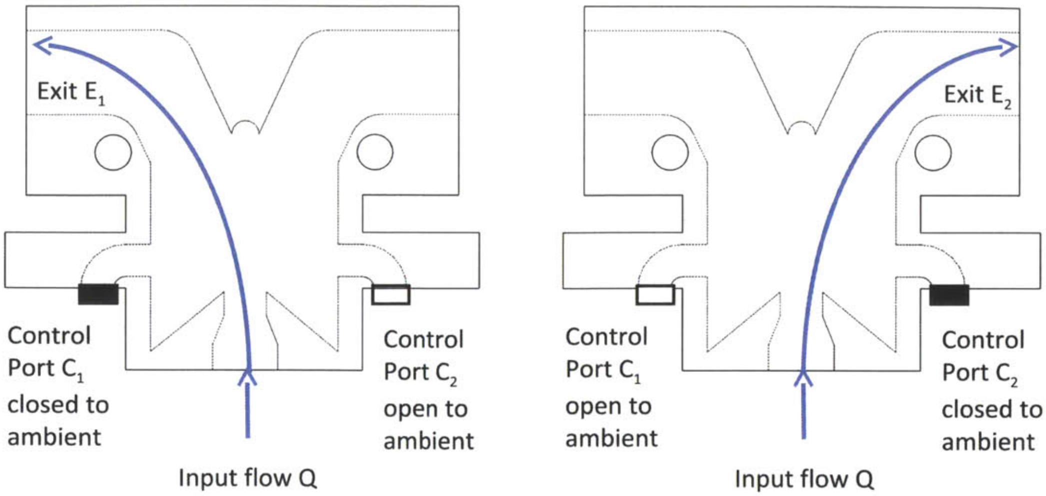


Figure 3-1: This diagram shows the basic functionality of the Coanda effect jet actuators.

3.2 CAD modeling and CFD

CAD modeling and CFD analysis both played crucial roles in the development of new designs for these pump and valve systems. Despite previous work that may have suggested optimal ways to orient and design both the pump nozzle mount and the actuator valve, this work re-explored new ways to create both of these components. By creating parameters to describe certain features of both the pump nozzle mount and actuator components, design changes were tracked to numerically define the apparent optimal design. Fluid dynamics plays a huge role in the effectiveness of these components so they were rigorously tested in theory and practice to optimize their functionality [12]

3.2.1 Pump Nozzle Mount

Redesigning this system started with the pump nozzle mount. The micropumps used for this robot are reversible despite asymmetry of the impeller so this design was non-trivial to find an optimal way to route the two outlets from the pump nozzle mount. Previous work using the same methods applied here, though for different strategies for the overall robot design, showed that using adjacent edges and a 90 degree angle between outlets worked optimally. Because that former design implemented two pumps, the symmetry along the vehicles forward translational axis was achieved despite the asymmetric nature of the individual system. For use of only a single pump-valve system, this asymmetry would not generate ideal vehicle dynamics so a new approach needed to be researched. To create the jet symmetry about the vehicle's forward axis a 180 degree angle between the jet outlets was the ideal approach.

The first iteration that placed the outlets perpendicular to the side walls of the mount proved faulty after CFD analysis. Significant backflow emerged from the undesired outlet which would cause a decrease in the force generated by the desired jet, plus an increase in the force of the undesired jet as seen in Fig. 3-2. A new idea emerged. Placing the jets at the corner of the mount (angled 45 degrees from perpendicular to two adjacent walls) would allow the desired jet to better draw any potential backflow into its desired stream 3-3. As Fig. 3-4 displays, this idea was confirmed using CFD analysis. From there, the main adjustment criterium was the distance of the nozzle to the center of the pump. Intuitively it seemed like the best center distance would be the radius of the impeller as to allow all the water inside the cavity to be directly forced out by the impeller blade rather. After multiple iterations adjusting this distance, a slightly larger distance performed best as it created some inflow from the opposing outlet nozzle. With this new pump nozzle mount design, a new pump-valve system design had an effective starting point.

3.2.2 Jet Actuator Valve

Creating an effective pump nozzle mount that maintained the desired symmetry for the outlet jets allowed for the redesign of the key component of this pump-valve system, the jet actuator valve. A lot of work was previously done on optimizing these devices, though mainly focused solely on routing the jet 90 degrees in either direction from the inlet. This method of routing worked well when designing for uses of two of these systems, but did not allow for effective control if only one pump was used. Because the jet outlets would be collinear with the previous design (bent 90 degrees

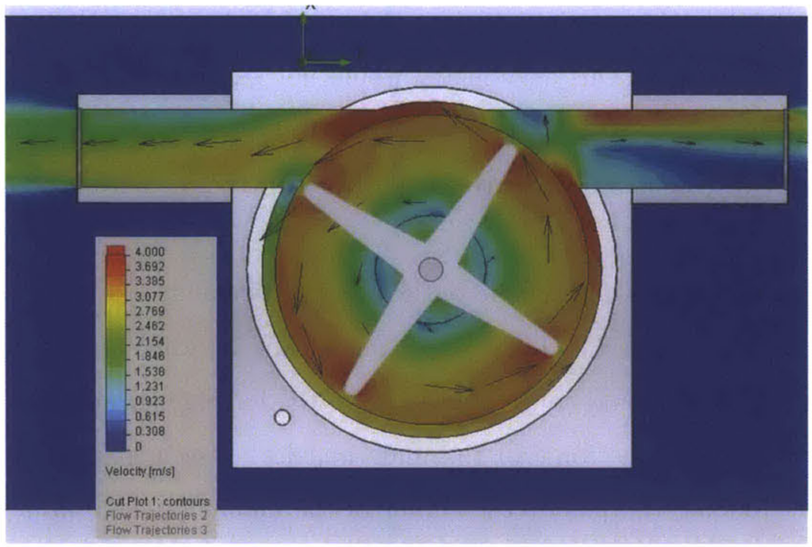


Figure 3-2: CFD on the first iteration of the pump nozzle mount shows some faults in the flow optimization

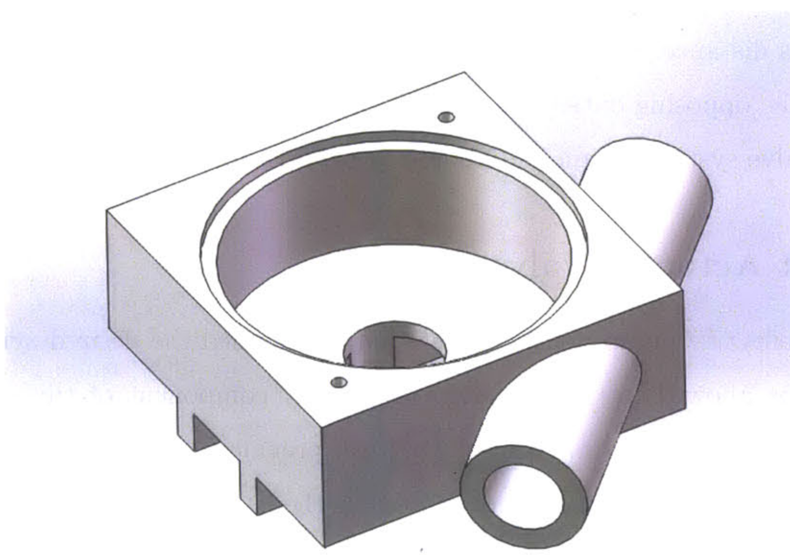


Figure 3-3: CAD model of the final design of the pump nozzle mount.

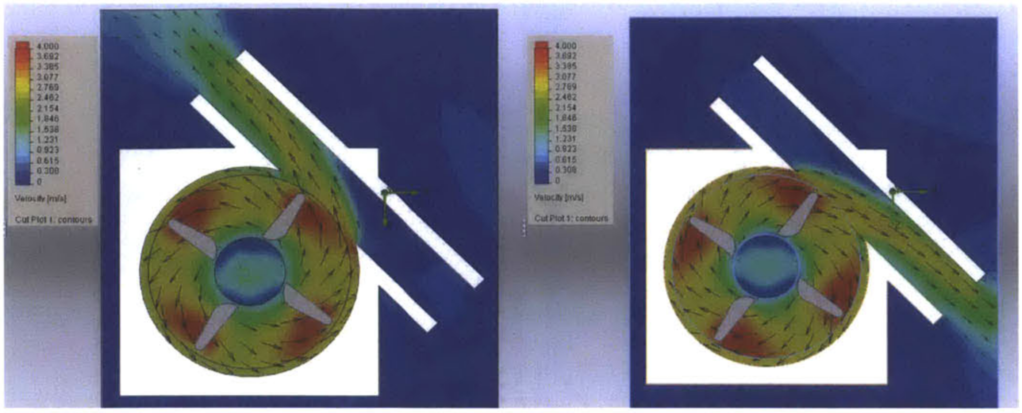


Figure 3-4: CFD on the final iteration for the pump nozzle mount shows its efficiency

from the inlet in opposite direction), there wouldn't be a way to effectively overcome the monk moment when attempting to propel the robot forward. With this thought basis, the actuator must be designed in such a way that the single valve acts like the combined systems from previous designs. Each jet must provide significant force opposite the robot's desired forward direction (as to propel it forward), but also must apply a significant enough moment on the robot to allow for stabilization and quick turning capabilities. The influence that thruster dynamics has on vehicle behavior helps to better understand how these jet actuators can be implemented [13]

The first idea was to continue the 90 degree bend's trajectory until it became a 180 degree bend. Doubts arose for this idea because of the obvious force losses that would come from the long bends. Performing CFD analysis proved the intuition that this design was highly suboptimal as Fig. 3-5 portrays. The next idea was to shorten the bend to only roughly 30 degrees, enough to have two distinct jet outlets while still providing the sufficient thrust force as previously mentioned. After redesigning the CAD model 3-6 and testing it using more CFD analysis (shown in Fig. 3-7), the effectiveness of this approach seemed to fit the needs for the desired maneuverability of the new robot. This new actuator type was used throughout the next process of deciding how to now implement this new pump-valve system into a smaller, spherical robot.

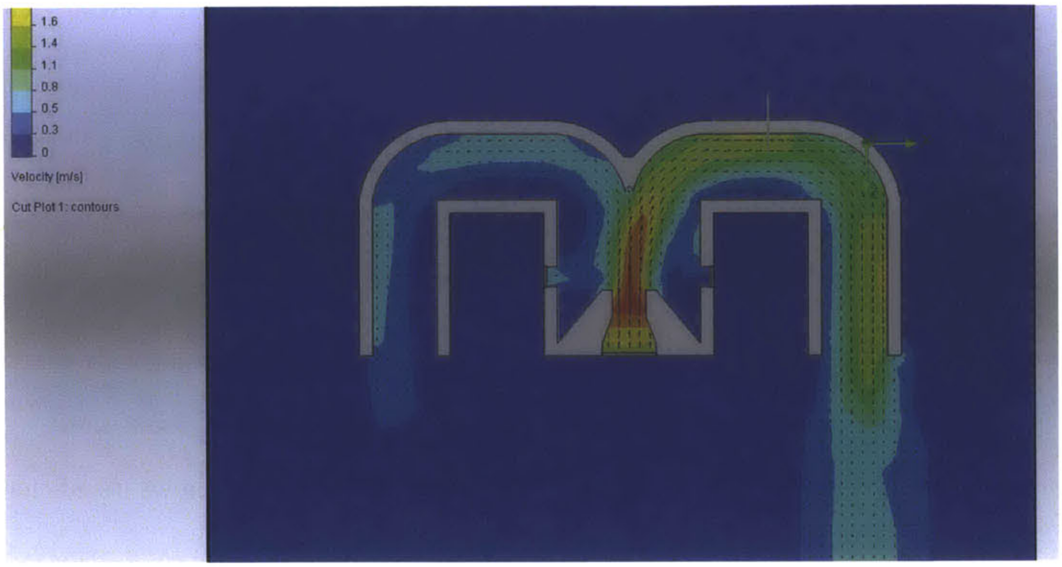


Figure 3-5: A CFD fluid velocity plot proves the shortcomings of the 180-degree-bend actuator.

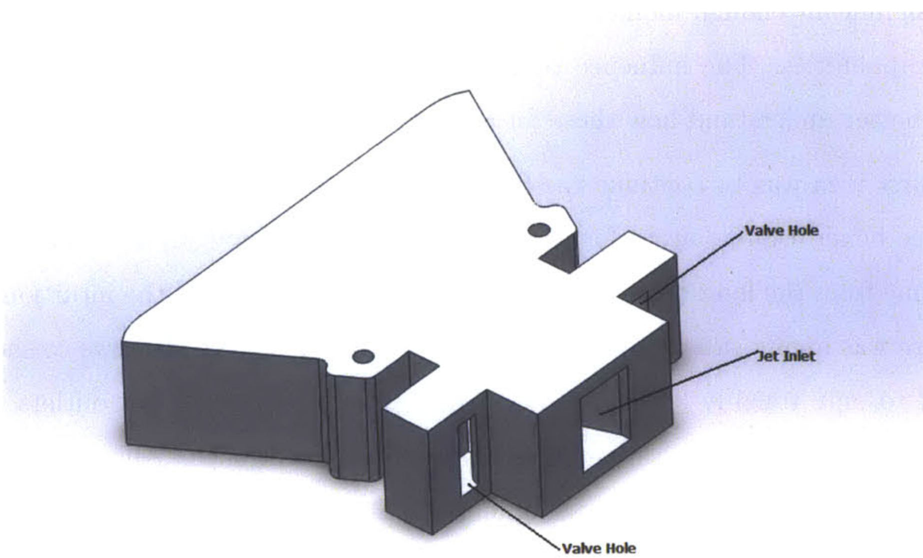


Figure 3-6: CAD model of the final design of the 30 degree bend actuator.

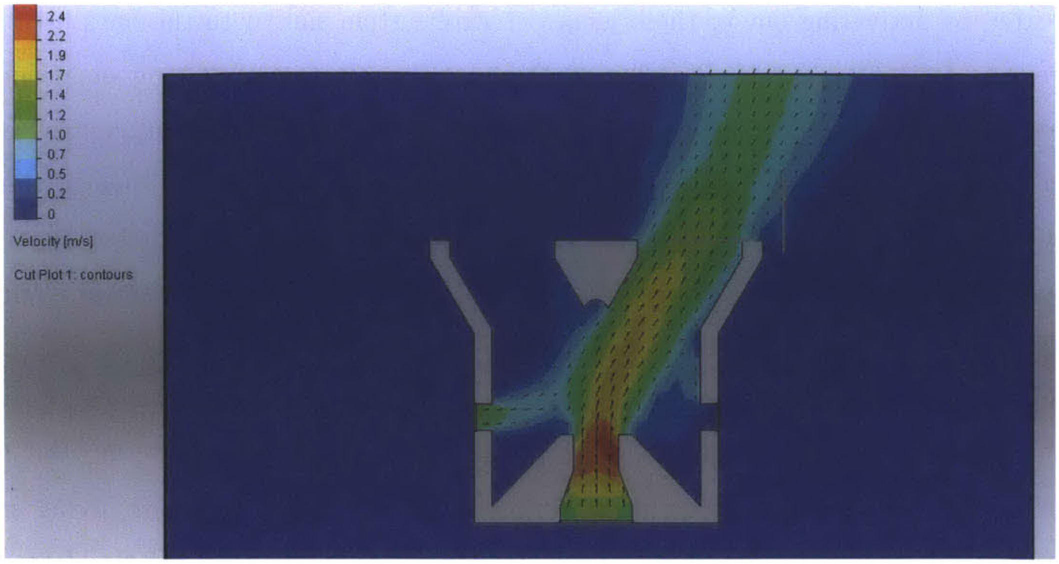


Figure 3-7: CFD fluid velocity plot shows the 20-degree-bend actuator worked effectively.

3.3 Two Unique Approaches

One of the main focuses of this thesis was to creatively design new versions of these pump-valve systems. Previous work which implemented more than one of these systems would not work in the single system case. New approaches were developed in such a way as to maximize the maneuvering capabilities similar to the previous designs, while keeping the robot small and efficient. With the aforementioned redesigns of the pump nozzle mount and actuator valve, two unique approaches became evident to create a new type of robot that maintained high levels of mobility and a small, efficient size. The first approach was a robot with multi-planar motion capabilities, and the second implemented features for highly mobile single planar mobility.

3.3.1 Multi-planar

The fist approach focused on designing the robot to efficiently move forward, rotate about its yaw axis, and dive. With the redesigns made to the propulsion devices, the implementation of this subunit system was fairly apparent. To achieve the forward motion, the 30-degree-split actuator design must be used. Because of the moment created by activating one of these jets, a control system similar to the ones used in previous designs were used. Rapidly switching between the two rear facing jets propels the robot forward while constantly overcoming the subsequent moment it creates from each burst. Rotational capability was trivial as seen by the moment each of these jets creates when run continuously. The only factor that needed adjustment was the location of the jet. The distance from the jet outlet to the forward axis defined how well it rotated. To create the greatest moment and thus the best turning capabilities, the jets were placed as close to that axis as possible. Both of those features allowed for motion in the surface plane using only one of the actuators. This allowed for the use of another actuator at the opposite outlet of the nozzle to create diving and surfacing capabilities. Just like the previous versions that implemented this feature, the 90-degree-bend actuator was used with one outlet directed upwards to propel the robot down and another facing downwards to provide surfacing ability. These three degrees of freedom to create a multi-planar motion capable robot were successfully achieved and the resulting tests of just how well these features work will be displayed in the following chapter.

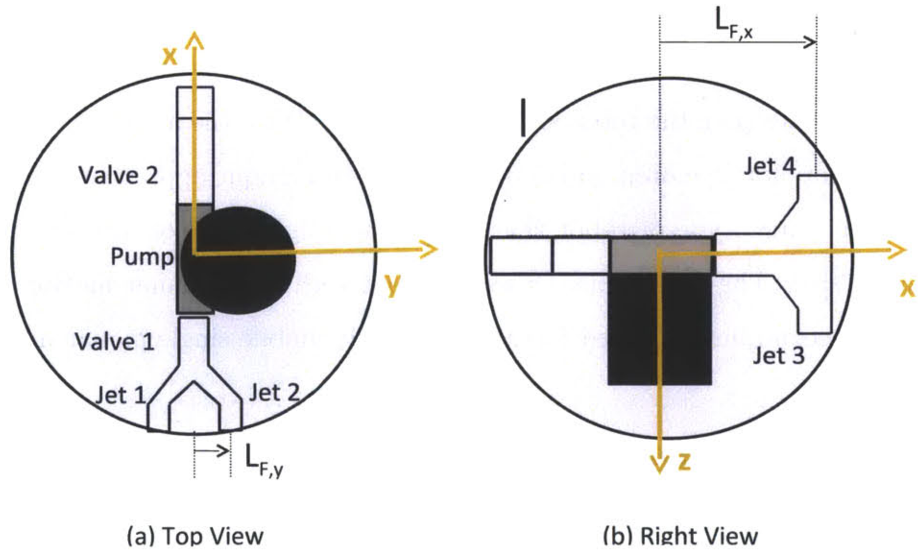


Figure 3-8: A diagram showing the orientation of the valve system creating multi-planar motion capabilities.

3.3.2 Single Planar

After designing for the first approach and realizing that the high mobility in a single plane was very helpful in controlling an underwater ROV, like those of previous designs, the second approach was developed. This focused on not only being able to move in the forward direction in one plane, but also backwards and side to side. This new design would still have three degrees of freedom, but allow for more precise control in a single plane while giving up the diving capability. To mimic these characteristics that were achieved in previous designs that used two pump-valve systems two of the same type of actuators must be used. Using two of the 30-degree-bend actuators facing in opposite directions would clearly achieve the forward and backwards motion as described in the multi-planar design section. The side to side motion was trickier to obtain, but implemented the same type of control system as the forward motion propulsion. Instead of constantly switching between the two jets of one actuator, the reversibility of the pump was used to constantly switch between the jets of two different actuators, propelling the bot sideways, though intuitively slower than the forward direction because of the smaller force contribution of each jet in the side direction. Finally, the rotational capability of this design was the same, allowing for yaw rotation. However, since the two separate jets contribute to the same moment, but opposite translational forces, the rotation would be more stable, keeping the robot from drifting as much. Results from this new design will be presented in the following chapter.

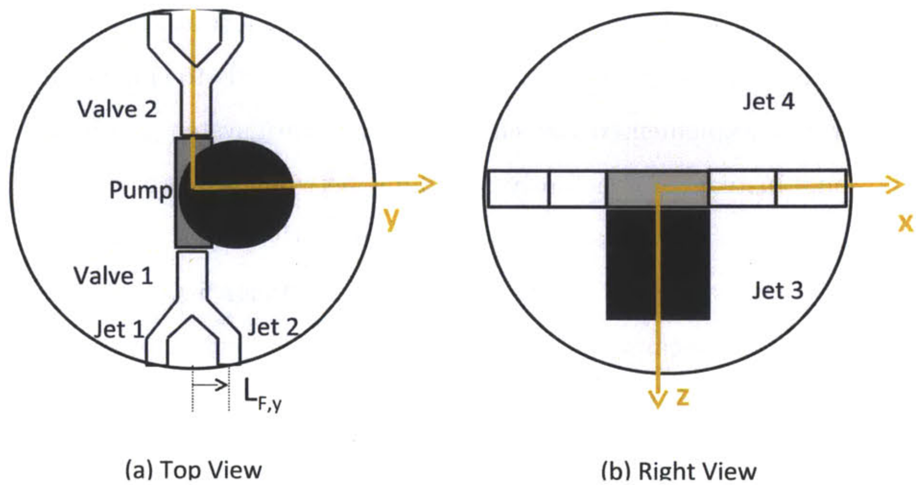


Figure 3-9: A diagram showing the orientation of the valve system creating high single planar motion capabilities.

Chapter 4

Experimental Results

4.1 Overview

Throughout the design process there was a lot learned about the potential capabilities of a small, spherical, highly maneuverable underwater ROV. Theories about how well a robot like this would perform in scenarios it was designed for were tested to either confirm or refute its presumed attributes. This same series of tests were performed on a previous design called the "Omni-Egg" and the results were very successful in proving the high maneuverability it was designed for [14]. After a series of design and modeling iterations the final robot components were fabricated. The half of the spherical shell that housed the electronics was printed using a Stereolithography machine because of the denser nature of the material created by that process. The other half of the shell and the actuators were both printed using an ABS plastic 3D printing machine because those components allowed for the slightly porous nature created in this process. One key electronic component, the gyro and compass, tracked the vehicles heading to allow real time heading correction.

Using a similar feedback control system as previous work developed using Arduino, the maneuvering capabilities of the robot were tested using Matlab. These custom electronics and feedback control program were very similar to those previously designed and implemented into earlier prototypes [15] [16]. Theoretical data was generated using Matlab and actual data was recorded through the use of a video recordings and a tracking software that maps the movements of the vehicle in the video [17] [18]. The following data displays the functioning attributes of the two robot designs and potential situations where each maneuver could be beneficial to the robot.

4.2 Multi-Planar Design

The multi-planar version of this robot was designed for three distinct degrees of freedom: forward translation, yaw rotation, and diving translation. Similar to the single planar design, this version still maintains the ability to precisely maneuver in the surface plane. A transparent CAD model can be seen in Fig. 4-1 Actual capabilities can be seen in each features subsequent section.

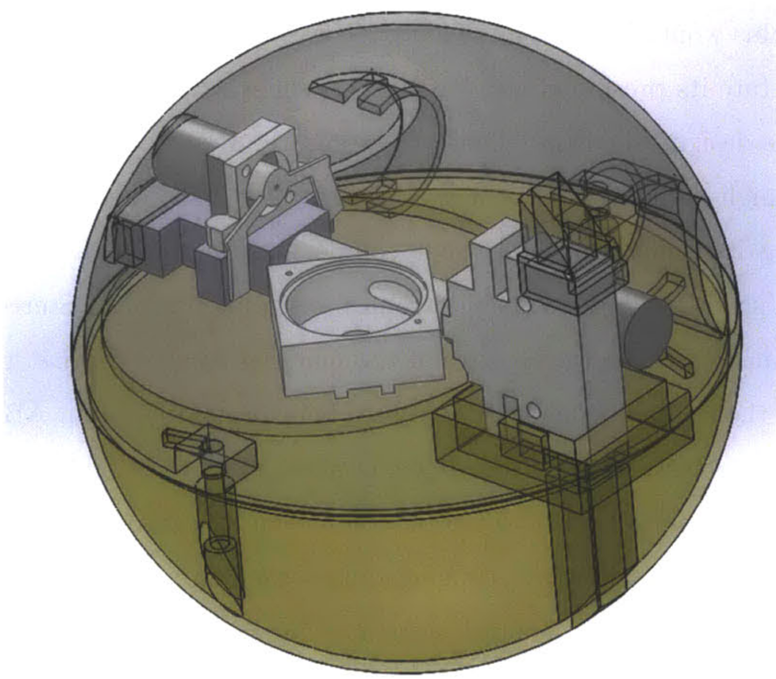


Figure 4-1: CAD model of the final design for the multi-planar design robot.

4.2.1 Heading Control

Heading control for the robot is achieved by activating the actuator that directs the two jet outlets rearwards of the vehicle. When called to translate forward, the control system notes the desired heading and then adjusts to any rotational changes and disturbances. This allows for the smooth forward translation. Fig. 4-2 compares the open loop attempt to translate forward with that using the control system to stabilize the unwanted moments inherent to the jet locations. This also shows the effective capability to maintain the desired heading when encountering an undesired disturbance. The robot rejects the disturbance, realigning itself in its desired direction and continuing forward. The necessary ability to translate in the forward direction works effectively. Disturbance rejection, a feature that helps the robot stay its course when navigating through complex and cluttered environments, proves to be another successful design feature.

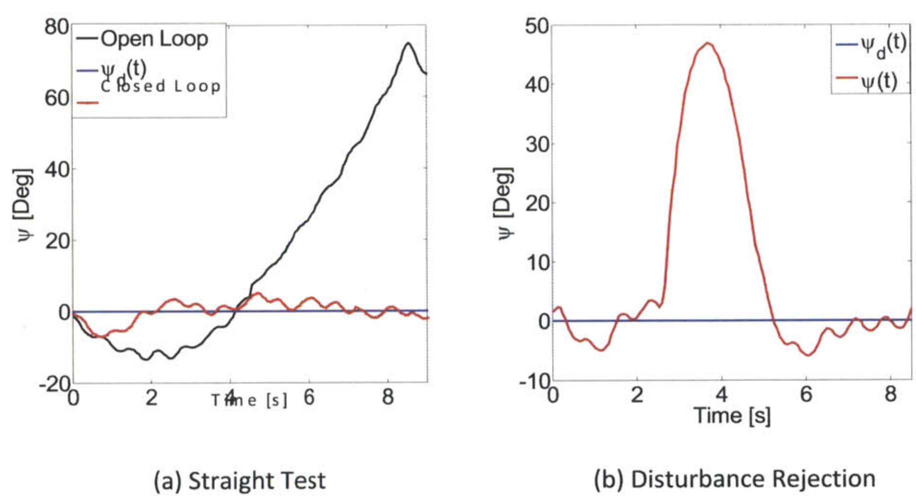
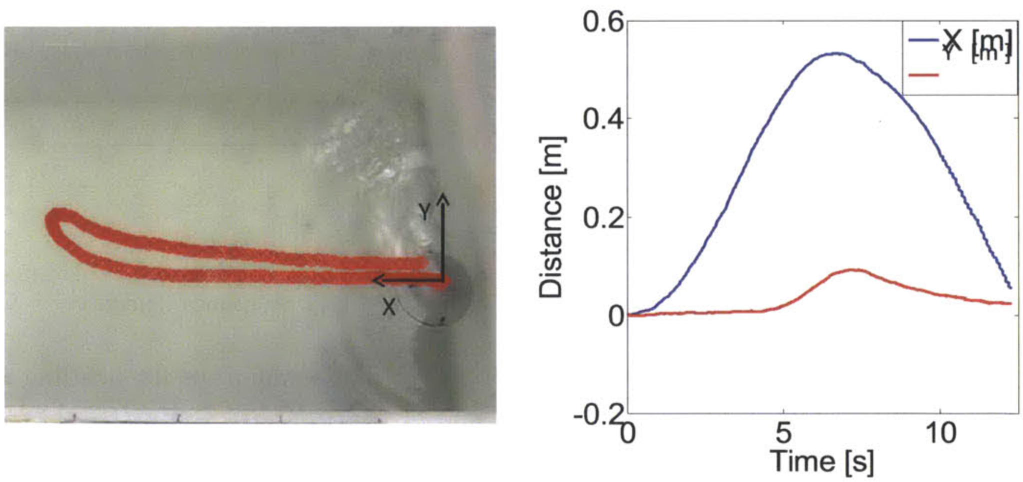


Figure 4-2: These data show the ability of the robot to maintain its heading and reject path disturbances.

4.2.2 Rotational Capabilities

This robot was designed to move in multiple planes. It's ability to dive came at the cost of more highly maneuverable planar mobility. Since the robot can only translate forward, the ease of motion is highly dependent on it rotational capabilities. Any time the ROV travels to a destination not directly in front of it, it must make some kind of turn about its yaw axis. This ability is displayed in Fig. 4-3, mapping the trajectory of the robot as the it translates forwards and then proceeds to make a 180 degree turn in order to return to its original destination. The data in part "b" of the graph shows the small drift that the robot encounters as it makes this turn. Note that although this drift is about the width of the robot, it does in fact return to almost its exact original destination.

The speed of these yaw rotations was recorded in the following test that gave the robot an input heading by simply telling it the desired angle, thus causing it to rotate and settle at that angle. This feature is crucial for the robot's ability to achieve its desired destination. Inaccuracies in the actual final heading may cause it to end up in the wrong place. Fig. 4-4 shows the robot's ability to settle on a desired angle (90 and 180 degree turns were used). They come to rest within only a few degrees of their input heading while turning at a rate of about 1 revolution every 3.5 seconds. These tests showed the success of the robot's turning capabilities



(a) Vehicle Path

(b) Time Trajectory

Figure 4-3: This photograph displays the robot making a 180 turn while moving forward and the data tracking its location over time.

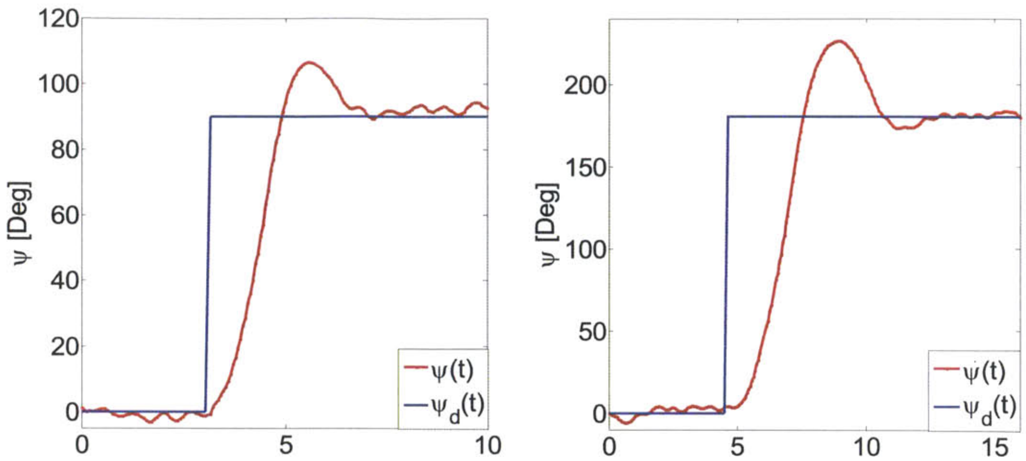


Figure 4-4: These data show the yaw rotational speed and accuracy of turning to a desired direction.

4.2.3 Dive Capabilities

Finally, the diving capabilities of the robot were tested. For testing purposes the vehicle was always maintained at a slightly positive buoyancy to ensure that it never became stranded at the bottom of the test tank and potential break. Ideally the robot would be neutrally buoyant, which is a feature that could later be fine tuned and implemented. Because of these reasons, the dive testing was simply empirical, noting the ability of the jet to provide a significant force to overcome the positive buoyancy. In Fig. 4-5 the trajectory of a diving and surfacing sequence displays that the robot can in fact maneuver in this way. Note the jet protruding from the surface of the water. Though the robot cannot dive as it maneuvers within the forward translational plane, this feature could be useful in translating to a subsurface level before then maneuvering through a new planar level.

4.3 Single Planar Design

The single planar prototype of this robot focused on achieving the highest degree of mobility in the surface plane of the vehicle to allow the most precise maneuvers

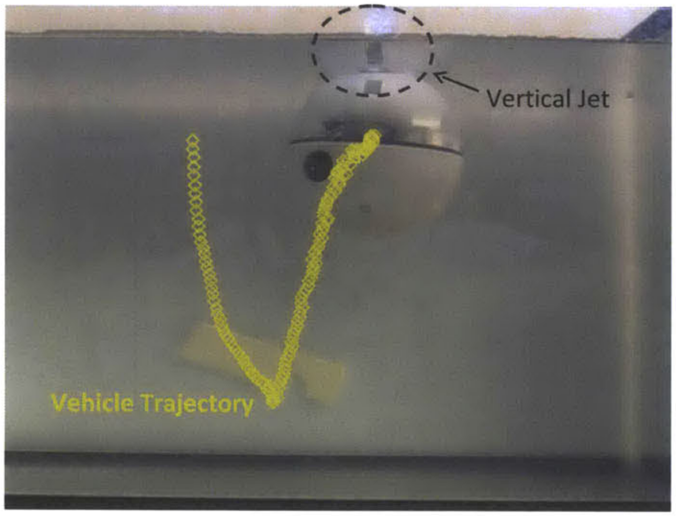
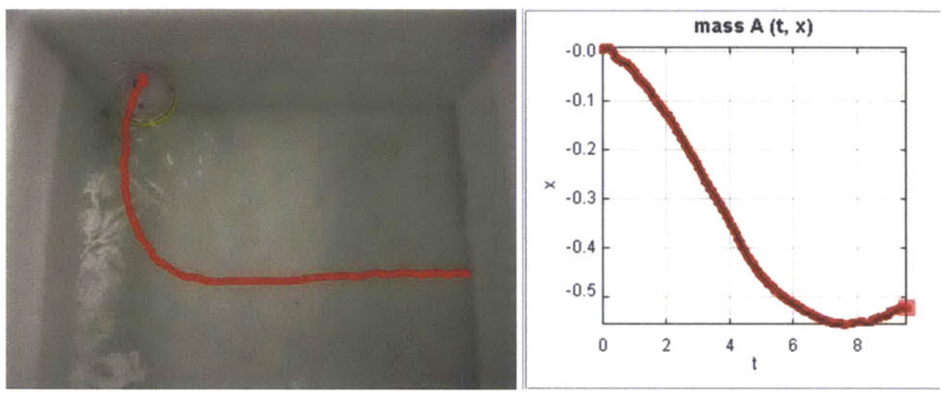


Figure 4-5: This image shows the dive capability of the robot.

possible. Capable of forward and backwards translation, yaw rotation, and both sidewards translations, the viewing capabilities of the onboard camera can be finely controlled to focus in on any small visual destination. The planar movements of the single planar design are achieved similarly to that of the multi-planar robot, but instead of only having rearward facing jets it has both forward and rearward. Better turning capabilities performed using this trait can be understood visually with the following experimental results.

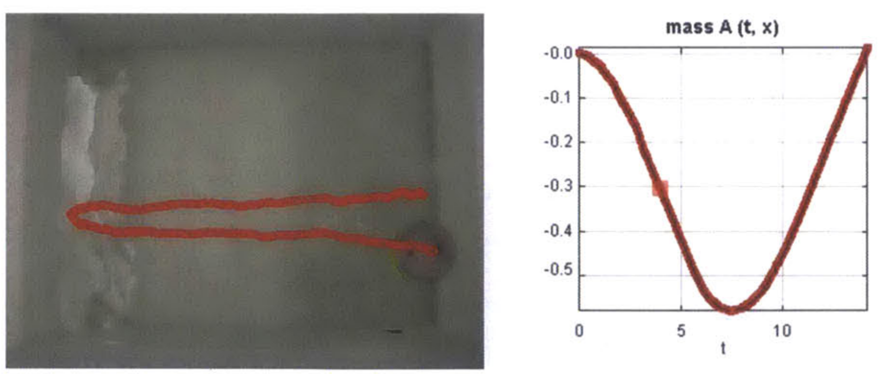
4.3.1 Turning Capabilities

Turning data presented earlier that showed the abilities of the multi-planar robot revealed the drifting caused by having jet outlets at only one end of the robot. The moment created by one jet is much smaller than that created by two while it also causes a higher translational force because it doesn't have the opposite jet to counteract it. Using the switching methods previously discussed to change the desired outlet jet, the single planar robot is able to make more efficient turns, minimizing drift and the time taken to finish the turn. Fig. 4-6 displays the high spped 90 degree turn. Comparing the trajectory to that of the multi-planar robot, there is noticeably less drift and the turn speed is significantly quicker. One can imagine how the drift could cause some maneuvering issues inside the tight turn of a complex piping system. Even more noticeable is the functionality of the high speed 180 degree turn 4-7. Significantly less drifting issues occur, making the ease of vehicle reversal less problematic in environments that don't allow for wide sweeping turns. Sacrificing the vertical jet for better planar mobility seems worthwhile, and potential dive capability in this robot are possible through buoyancy chamber inclusion. These improvements upon the planar mobility as compared to the multi-planar robot are significant and greatly improve the mobility attributes.



a) Vehicle path with robot at final destination   b) Time Trajectory

Figure 4-6: Visual and numerical data for the trajectory of a 90 degree turn.



a) Vehicle path with robot at final destination   b) Time Trajectory

Figure 4-7: Visual and numerical data for the trajectory of a 180 degree turn.

Chapter 5

Conclusion

5.1 Overview

This thesis addressed new designs of small, highly maneuverable underwater ROVs that implemented some key new design features from previous designs for robots similar to these. While maintaining their completely smooth external shell internalizing all of the mechanical propulsion systems, the new designs revisited some of the actuator designs that have been successful with other robots of this type. This new design attempted to make these robots even smaller, using only one pump and valve system while implementing a spherical shape instead of an elongated ellipsoid. This redesign revealed some benefits over the previous designs that could be useful for a range of underwater applications. Achieving a working prototype and successfully testing some of the key features confirmed the desirability of robots like these for future industry use.

5.2 Application

The work of this thesis and the similar work done before it was inspired by the shortcomings of the current available technology used to inspect the piping systems of nuclear reactors. Hazardous environments make it impossible for humans to inspect the inside of the pipes themselves. For human inspection, the reactor must be shut down, drained and taken apart in order to inspect the inside of the pipes, which is a long and laborious process that costs a lot of down time for the reactor. Other methods have attempted the use of tethered ROVs that could travel and inspect the piping systems, but the shortcomings of these robots that make them very hard to navigate in such environments don't significantly improve on the inspection process, especially when the robots fail and the reactor must be shut down anyways. This application is definitely on the forefront for how robots like these will be used, but there may also be many other applications for these underwater ROVs.

Other applications may occur in the realm of testing the chemical properties of water sources. Implementing an array of small sensing and testing equipment to test the quality of water may help detect certain undesired or problematic properties that a source of water might contain. Small robots like these could easily travel through small bodies of water, continuously sampling and sending data about the water properties to an operator. This potential application could also be expanded upon for larger bodies of water that made use of arrays of these robot. Because communication of radio signals through large distances of water is a problematic task, dispatching a large series of these robots to communicate with another robot in close proximity to itself could essentially overcome this issue as each robot acts as a signal beacon extending to a final destination. Cooperative control of underwater robots would be extremely helpful for the use of arrays of these robots [19].

Some work has been done in regards to scaling systems like these. CAD modeling and CFD analysis suggests that systems like these can be efficiently scaled which presents some more potential applications. Manned submersible vehicles that need precise maneuvering capabilities and lower power consumption may be able to implement systems like these. Many vehicles implement jet propulsion instead of propeller derived propulsion [20] and implementing systems like these to those jet propelled vehicles may help to improve their mobility.

5.3 Future Work

With a significant amount of progress made in the design of this new breed of underwater ROV that internalizes all propulsion components to maintain a completely smooth exterior shell, there is still a lot of features that are being researched to make these robots even more useful. One area of improvement is focusing on the implementation of even more sensing capabilities to make the controls of the robot more robust. Proximity sensors that can pinpoint the location of the robot with respect to a certain destination or visual goal will help control the robot and make inspection processes more useful. For example, being able to follow along the edge of a wall while maintaining a set distance can be very useful for video inspection. Knowing exactly where the video data was recorded with respect to environmental features will allow a better understanding of what the issue at hand might be.

Other work is being done on the communication system for underwater ROVs like these because the transmission of radio signals through water is very limited when the distance the signal has to travel through the water becomes significantly greater than a couple meters. New research in designing an acoustic communication system shows some potential to help these issues.

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