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Autonomous Docking for Exploration of Extraterrestrial Lakes*

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The exploration of extraterrestrial lakes and oceans is recent a topic of interest aided by the improvements to autonomous underwater vehicle and rocket technology. Several methods have been proposed, this paper proposes usage of large and small autonomous underwater vehicles (AUVs) in coordination to maximize exploration efficiency. The use of a large submarine presents unique opportunities for a large science payload capable of meteorology, geoscience, and fluid sampling as well as extended endurance. The large platform size limits exploration of hazardous littoral regions due to mobility and risk concerns. To that end, multiple small AUVs can be launched, recovered, and charged by the larger submarine. These small scale crafts can explore at higher speeds and map the region around the large submarine for points-of-interest and hazards that the large submarine can then transit to or avoid. Critical to the functionality of the small scale craft is the docking solution to enable coupling between vehicles and power transfer. This paper presents the docking concept, dynamic modelling and control, simulation results, and preliminary experimental results for the proposed docking system. The proposed system is a small, collapsible design that is integrated within the large submarine and fits within the launch vehicle requirements. The working vehicles and stations are deployed upon splashdown from the stored configuration.

I. Introduction

Extraterrestrial oceans are some of the most interesting areas to explore in the universe as they are promising locations to find evidence of life. While oceans similar to Earth may exist on exoplanets, they are not accessible with today's rocket technology. The moons of Jupiter and Saturn are however accessible with current rockets, and several of these moons are believed to be home to liquid oceans.[1] The exploration of extraterrestrial oceans is highly dependent on the development of autonomous underwater vehicle (AUV) technology on Earth. AUV design has progressed rapidly over the past decade with the miniaturization of computation, actuation, and energy storage technologies. Modern AUVs are able to explore to the depths of Earth's oceans and accurately navigate with the aid of occasional localization fixes from GPS. Despite these advances, one key limitation exist for AUVs: the typical endurance of AUVs is measured in hours.[2]

The small form factor of an AUV limits the space and weight that can be committed to energy storage. Using current battery technology, the longest lasting AUVs are able to operate for up to 6 months with minimal scientific payload.[3,4] More typical endurance is measured in hours to a few days.[2] Upon energy depletion, batteries must be recharged and the vehicle re-tasked. One energy alternative when operating in extraterrestrial lakes is to use a radioisotope power system rather than a more traditional chemical battery. These power systems are able to supply sufficient power for the long transit from Earth to the target as well as support the large power loads associated with AUV operation. They are, however, bulky systems and cannot be installed into small scale craft. A cooperative network of one large scale AUV with a radioisotope

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power system and multiple small scale AUVs with traditional rechargeable batteries would be able to explore an extraterrestrial ocean more efficiently and completely.

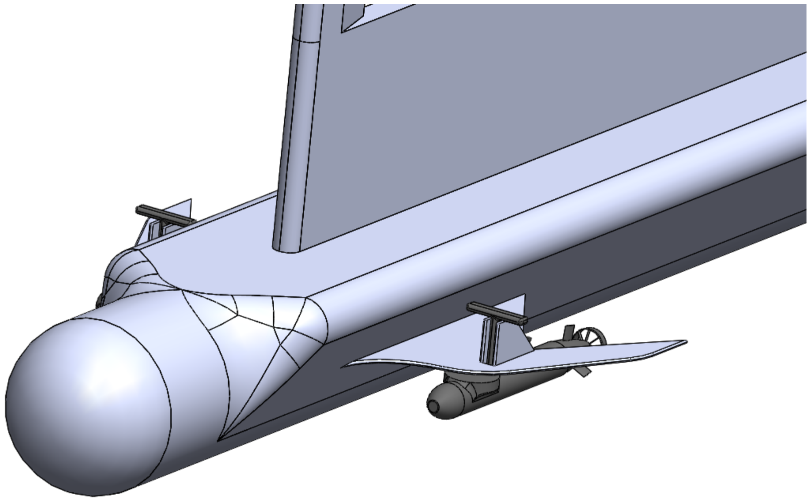


Figure 1: The docked configuration of the AUV attached to the larger Titan Sub. The docking station is a simplified funnel design that is able to be pulled by the Titan Sub with minimal drag and is collapsible and low weight to minimize the impact on launch costs. The docking stations can serve as dive planes for additional control if desired.

II. Proposed Mission

In-situ exploration of extraterrestrial oceans is a unique opportunity to improve our understanding of life in the universe, as well as hydrological and atmospheric processes on Earth. In particular, exploration of the hydrocarbon ocean Kraken Mare on Saturn's moon Titan presents the opportunity to find exotic lifeforms. These types of missions have been studied recently including the Moball buoy mission,[5] the Planetary LakeLander,[6] the Titan sub,[7–9] the Titan Mare explorer,[9,10] the SCALARS concept,[11] and the Titan boat.[12]

In a 2015 Phase I study[7,8] the feasibility of launching a large submarine to explore the seas of Titan was explored. In this study, a 6m long, 0.62m diameter vessel was presented, powered by radioisotope generators and capable of exploring the full depth of Kraken Mare. During its primary mission, the submarine is designed to transit 3000km at an average speed of 0.3m/s. With this 3000km transit distance, the submarine will be able to explore a relatively narrow swath of the Mare. Additionally, the large scale and cost of the submarine will restrict it to operation in open, low-risk areas. This group is continuing work on a Phase II study to advance the technology readiness level.

To extend the functionality of this large scale submarine mission we propose multiple small scale vehicles that operate with the submarine to aid exploration, Fig. 1. These small scale vehicles, called working AUVs, would be highly maneuverable, high speed working AUV with a reduced science payload and limited endurance. To recharge between deployments, the vehicles need to be able to autonomously dock with the large submarine and charge from the large vehicle's radioisotope generators. This paper presents a unique docking station design that is light weight, collapsible, and hydrodynamically efficient to tow with a large submarine.

In the proposed mission, a vehicle similar to the 2015 Titan Sub[7] is launched to Titan or any other astronomical body with significant liquid oceans. The large scale submarine features a full scientific payload, sufficient radioisotope generators for a 3 month nominal mission, a direct to earth communication capability, and two small scale autonomous working AUVs with independent docks. The large scale submarine receives global position estimates from Earth accurate to approximately 1 km.[7] The small working AUVs are torpedo shaped and approximately 1 meter long with a 0.12 meter diameter. These small crafts have an endurance on the scale of 12 hours using rechargeable batteries and feature a reduced scientific payload capable of mapping and basic fluid sensing.

During the planned mission, the large scale submarine explores the extraterrestrial ocean at a low speed. To extend sensor range and perform closer inspection of interesting features, the two working AUVs are deployed. The working AUVs can transit at high speeds and closely inspect target features. This enables mapping to be completed closer to shore and in hazardous regions such as Seldon Fretum, or the Throat of Kraken. Additionally, the working AUVs can highlight regions of interest for the larger submarine to survey and identify hazards to avoid. Prior to battery depletion, the working AUVs rendezvous with the large submarine, dock, and charge their batteries. Localization between the vehicles is completed using a combination of Ultra-Short Base Line (USBL) and visual feedback.[13]

This paper presentes early stage development of the docking system. All modelling, simulation, and experimentation is completed for operation in the Earth analog to the seas of Titan, our liquid water lakes and oceans. The docking station concept has recently been developed through exhaustive simulation and optimization presented in.[14,15] Additionally, the docking station has been used for mission planning of long term missions with preliminary experimental docking.[16]

III. Docking System

In order to achieve efficient long term exploration of extraterrestrial lakes, a mobile charging infrastructure must be developed that is capable of combining large crafts with sufficient payload for nuclear power sources and small, highly maneuverable vehicles. This charging infrastructure must be able to 1) charge AUVs at optimal locations along the their trajectories, 2) perform in real-world conditions such as currents, and 3) be light weight and collapsible to minimize launch costs and resource consumption on the host vehicle. The mobile charging concept includes adding two docking receivers to a large nuclear powered submarine and customizing the working AUVs to support docking/charging operation. The proposed docking system is shown in Fig. 1. The two docking stations are positioned on the Titan sub such that they can be actuated as dive planes for additional control while underway as compared to a purely buoyancy based system.

To achieve the first goal of charging the working AUV at optimal locations along the working trajectory, the mobile charger must be able to travel long distances and operate in the range of depths of the working AUV. Further, the two vehicles must be able to localize relative to each other when at close range to complete the docking maneuver. The proposed large scale Titan sub is a good candidate for this operation as it is able to transit long distances and has sufficient energy capacity to support charging. Additionally, the Titan sub receives global position estimates from Earth based measurements and through the addition of a USBL system, relative localization can be achieved accurately.

The second goal of supporting real-world conditions such as currents requires that the mobile charging system concept have a wide effective capture envelope. The docking capture envelope is defined as the 2D region that will result in successful docking. A large capture envelope will enable docking operations to continue even in the presence of large currents and other disturbances. In existing underwater docking stations, a large funnel maximizes capture envelope. However, towing a large funnel through liquid attached to the charging submarine is not feasible, therefore, a simplified funnel design is considered for the docking receiver, Fig. 1. Two docking receivers will unfold from the Titan sub and includes the power transfer and localization hardware to support docking.

The final goal is designed to ensure efficient launch by not significantly impacting the launch vehicle. The docking system is collapsible and light weight enabling it to fit inside of the planned Boeing X37-B launch vehicle without modifications. To achieve this, the simplified funnel design is designed to fold along the Titan sub hull and collapse into a nearly flat plate. This collapsed design then deploys after splashdown.

The functionality of the mobile charging concept is illustrated in Fig. 2. In A) the working AUV approaches the mobile charger from the rear. B) The mast of the docking adapter then slides along the simplified funnel towards the charging location. The docking adapter then slides up the ramps and into the receiver C) where power transfer is completed.

Control of the docking procedure is completed in a multi-stage approach. First, the working AUV navigates to the general vicinity of the Titan sub using dead-reckoning. Once within range, the two vehicles localize relative to one another using a USBL system to drive the AUV near to the dock along a direct approach. During the majority of operation, the working AUV will not leave USBL range. When close to the dock, a visual guidance system is engaged to track an active beacon on the Titan sub similar to.[13] As docking proceeds, localization quality and frequency improves from the dead-reckoned estimate to 1 meter accuracy and 1Hz using USBL to centimeter level accuracy and update rates in the 10s of Hz using vision.

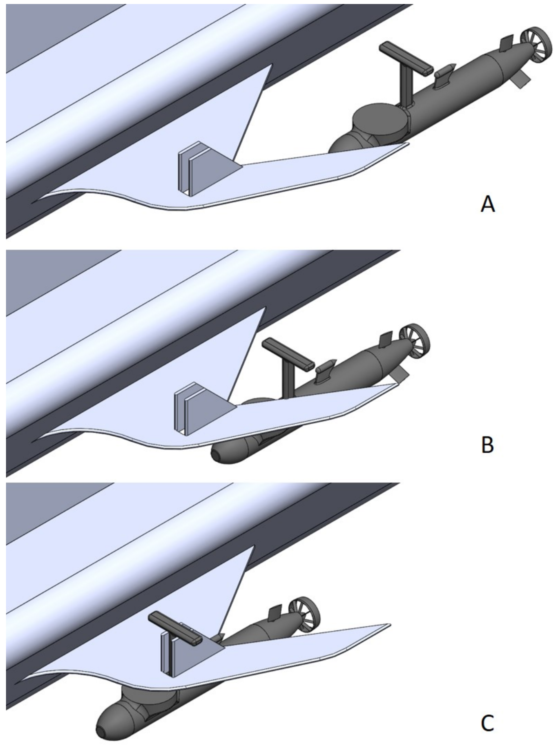


Figure 2: Docking with a free-floating mobile charger. A) The AUV approaches the mobile charger, B) impacts the wings with the docking adapter mast, slides along the wings, then C) slides along the ramp into the receiver where power transfer occurs.

Once docked, the working AUV latches into the Titan sub for power and data transfer and awaits the next mission.

IV. Dynamic Modelling

To evaluate the feasibility of the mobile charging concept, it is critical to model the docking procedure while effected by currents. Due to the relatively unknown currents possible on Titan, the AUV must be able to dock while in the presence of strong disturbances. It is estimated that currents on Titan reach up to 0.5m/s.[17] The mobile docking model involves the hydrodynamics of two vehicles, impact modelling, and controller action. The hydrodynamic and impact models used in this work are based on.[18,19] The controllers used follow a switched PID approach. For the purposes of this paper the working AUV is assumed to be underactuated with just a thruster, elevator, and rudder while the mobile charger is assumed to be unactuated during the docking maneuver.

This paper extends the typical underwater docking model to allow for disturbances in the form of constant currents and a free-floating mobile charger. The Titan sub will serve as mobile charger in operation. In the standard approach,[18,19] two coordinate frames are used. One body-fixed on the AUV and the other Titan-fixed on the docking station. To support the two extensions presented here, we use four coordinate frames. One body-fixed in both the AUV and the free-floating mobile charger, one Titan-fixed at the free-floating mobile chargers starting coordinate, and one flow-fixed that drifts with the current. All coordinate frames follow SNAME conventions.[20]

The additional frames enables our model to support disturbances in the form of currents with the support of the flow frame. The flow frame moves at a constant, pre-determined velocity dictated by the simulation environment. Time and spatially varying currents are not considered. All hydrodynamic terms are calculated based on the relative velocity and acceleration between the evaluated frame and the flow frame according to:

$$\begin{bmatrix}\dot{\mathbf{v}}_1\end{bmatrix} = \begin{bmatrix}\dot{X}_{body} - \dot{X}_{flow} \\ \dot{Y}_{body} - \dot{Y}_{flow} \\ \dot{Z}_{body} - \dot{Z}_{flow}\end{bmatrix} \tag{1}$$

Where $\dot{X}, \dot{Y}, \dot{Z}_{body}$ are the X, Y, and Z velocities of the AUV or mobile charger frame, $\dot{X}, \dot{Y}, \dot{Z}_{flow}$ are the X, Y, and Z velocities of flow frame, and $\dot{\mathbf{v}}_1$ is the linear velocity vector used in the hydrodynamic model. Similar calculations are completed for acceleration. The relative velocity and acceleration terms are calculated for both the AUV and free-floating mobile charger.

Using the four frames, hydrodynamic forces can be modelled as viscous and inviscid components. All velocities and accelerations used in this model are relative between the AUV (or mobile charger) and the flow frame. Presented here is the AUV model, calculations are repeated for the mobile charger.

The viscous terms are:

$$\begin{aligned} \boldsymbol{f}_v &= \begin{pmatrix} X_v \\ Y_v \\ Z_v \end{pmatrix} \\ \boldsymbol{m}_v &= \begin{pmatrix} K_v \\ M_v \\ N_v \end{pmatrix} \end{aligned} \tag{2}$$

Where f_v and m_v are viscous forces and moments respectively. These forces and moments are then non-dimensionalized (Eqn. 3) and calculated (Eqn. 4).[21,22] Where V is the magnitude of vehicle velocity relative to the flow frame, ρ is the density of the fluid, L is characteristic length, α and β are angle of attack and sideslip angles, δ_r and δ_e are rudder and elevator angles, and AUV angular velocities are non-dimensionalized according to $\bar{p} = \frac{pL}{V}$, $\bar{q} = \frac{qL}{V}$, and $\bar{r} = \frac{rL}{V}$.

$$\begin{aligned} X'_v &= \frac{X_v}{0.5\rho V^2 L^2}, \quad Y'_v = \frac{Y_v}{0.5\rho V^2 L^2}, \quad Z'_v = \frac{Z_v}{0.5\rho V^2 L^2} \\ K'_v &= \frac{K_v}{0.5\rho V^2 L^3}, \quad M'_v = \frac{M_v}{0.5\rho V^2 L^3}, \quad N'_v = \frac{N_v}{0.5\rho V^2 L^3} \end{aligned} \tag{3}$$

$$\begin{aligned} X'_v &= C_X(\alpha) = C_X^0 + C_X^{\alpha_1}\alpha + C_X^{\alpha_2}\alpha^2 + C_X^{\alpha_3}\alpha^3 + C_X^{\alpha_4}\alpha^4 \\ K'_v &= C_K(\beta, \bar{p}, \bar{r}, \delta_r) = C_K^{\beta}\beta + C_K^{\bar{p}}\bar{p} + C_K^{\bar{r}}\bar{r} + C_K^{\delta_r}\delta_r \\ Y'_v &= C_Y(\beta, \bar{p}, \bar{r}, \delta_r) = C_Y^{\beta}\beta + C_Y^{\bar{p}}\bar{p} + C_Y^{\bar{r}}\bar{r} + C_Y^{\delta_r}\delta_r \\ M'_v &= C_M(\alpha, \bar{q}, \delta_e) = C_M^{\alpha}\alpha + C_Z^{\bar{q}}\bar{q} + C_M^{\delta_e}\delta_e \\ Z'_v &= C_Z(\alpha, \bar{q}, \delta_e) = C_Z^{\alpha}\alpha + C_Z^{\bar{q}}\bar{q} + C_Z^{\delta_e}\delta_e \\ N'_v &= C_N(\beta, \bar{p}, \bar{r}, \delta_r) = C_N^{\beta}\beta + C_N^{\bar{p}}\bar{p} + C_N^{\bar{r}}\bar{r} + C_N^{\delta_r}\delta_r \end{aligned} \tag{4}$$

The inviscid hydrodynamic forces and moments can be represented by the generalized added inertia matrix.[20] In the case of the most torpedo shaped AUVs, this can be simplified due to vehicle symmetry and effective terms (Eqn. 5). Where $\mathbf{M}_f$, $\mathbf{C}_f$, and $\mathbf{J}_f$ represent the added mass, hydrodynamic coupling, and added inertia. The terms in the added inertia matrix are calculated following Eqn. 6.

$$\mathbf{M}_f = \begin{pmatrix} \mathbf{M}_f & \mathbf{C}_f^T \\ \mathbf{C}_f & \mathbf{J}_f \end{pmatrix} = -\begin{pmatrix} X_{\dot{u}} & 0 & 0 & 0 & 0 & 0 \\ 0 & Y_{\dot{v}} & 0 & 0 & 0 & Y_{\dot{r}} \\ 0 & 0 & Z_{\dot{w}} & 0 & Z_{\dot{q}} & 0 \\ 0 & 0 & 0 & K_{\dot{p}} & 0 & 0 \\ 0 & 0 & M_{\dot{w}} & 0 & M_{\dot{q}} & 0 \\ 0 & N_{\dot{v}} & 0 & 0 & 0 & N_{\dot{r}} \end{pmatrix} \tag{5}$$

$$
\begin{aligned}
X'_{\dot{u}} &= \frac{X_{\dot{u}}}{0.5\rho L^3} & K'_{\dot{p}} &= \frac{K_{\dot{p}}}{0.5\rho L^5} \\
Y'_{\dot{v}} &= \frac{Y_{\dot{v}}}{0.5\rho L^3} & M'_{\dot{q}} &= \frac{M_{\dot{q}}}{0.5\rho L^5} \\
Z'_{\dot{w}} &= \frac{Z_{\dot{w}}}{0.5\rho L^3} & N'_{\dot{r}} &= \frac{N_{\dot{r}}}{0.5\rho L^5} \\
Y'_{\dot{r}} = N'_{\dot{v}} &= \frac{Y_{\dot{r}}}{0.5\rho L^4} & Z'_{\dot{q}} = M'_{\dot{w}} &= \frac{Z_{\dot{q}}}{0.5\rho L^4}
\end{aligned}
\tag{6}
$$

The added inertia matrix can then be used to calculate resulting forces per Eqn. 7[23] where $\mathbf{v}_1$ and $\mathbf{v}_2$ are linear and angular velocities respectively.

$$
\begin{bmatrix} \mathbf{f}_i \\ \mathbf{m}_i \end{bmatrix} = -\mathbf{M}_f \begin{bmatrix} \dot{\mathbf{v}}_1 \\ \dot{\mathbf{v}}_2 \end{bmatrix} \tag{7}
$$

This hydrodynamic model is independently calculated for both the AUV and the free-floating mobile charger. Hydrodynamic terms for a comparable AUV are available in[18] for liquid water. Hydrodynamic terms for the mobile charger are scaled versions of the AUV terms based on the geometry of the charger.

The impact between AUV and mobile charger is modelled following the approach in[18] using a force-indentation model, Eqn. 8.[24]

$$
F = F_c(\delta) + F_v(\delta, \dot{\delta}) + F_p(\delta, \dot{\delta}) \tag{8}
$$

In the force-indentation model, F_c, F_v, and F_p are the elastic, viscous damping, and dissipative parts of the impact force and δ, $\dot{\delta}$ are the penetration and penetration rate. Based on the key assumptions at the start of this section, no plastic deformation can be assumed simplifying the model to a spring-damper with k stiffness, e force exponent, and c damping coefficient. In the model, friction is approximated using a Coulomb approach.

$$
F = k\delta^e + c\dot{\delta} \tag{9}
$$

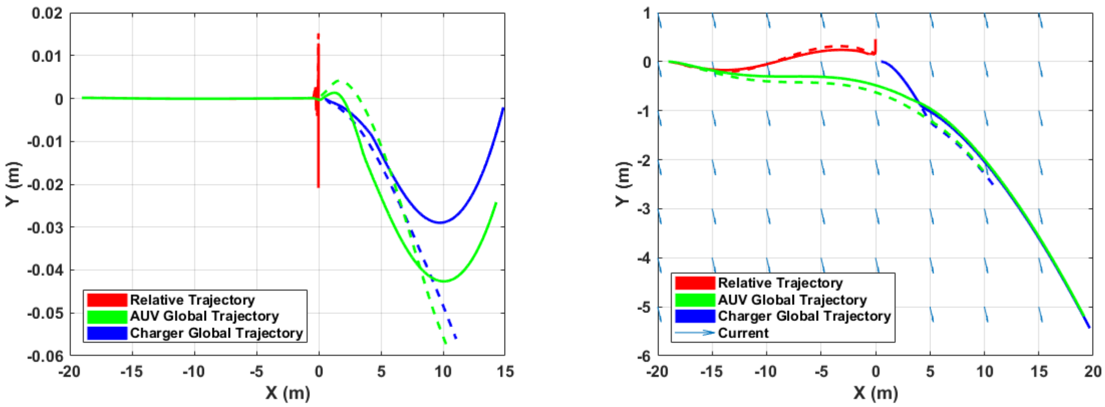
The presented hydrodynamic model is implemented in Simulink for both the mobile charger and the working AUV. Multi-body physics including impact dynamics is modelled in ADAMS. The co-simulation effectively models the mobile docking process. The docking model is run in a batch mode to evaluate a wide range of potential current fields.

The results presented here in simulation and experiment are based on operation in liquid water on Earth. These results are used to perform preliminary validation of the simulation approach, docking station design, and controllers. Prior to final design, the hydrodynamic parameters for operation of the working AUV and the Titan sub in the specific environment of the target extraterrestrial lake can be calculated using a computational fluid analysis software such as ANSYS Fluent using fluid parameters from[25] .

V. Simulation and Experimental Test Results

Two simulation runs based on Sec. IV are completed to compare two different thrust control strategies. The first strategy involves controlling the relative approach velocity based on feedback from the USBL and vision systems. The second strategy uses a downward looking doppler velocity log to maintain a constant forward velocity of the AUV in the current. Each simulation run included 4851 permutations of the current field to evaluate performance. The range of currents explored is from -1m/s to 1/ms along X, 0m/s to 1m/s along Y, and -1.5m/s to +0.5m/s along Z. Due to symmetry along the XZ plane, the results can be mirrored to support the -1m/s to 0m/s range along Y. The full space is explored at 0.1m/s linear spacing for an effective 9261 point exploration. Each control strategy took 309 hours to evaluate for a total of 619 hours of compute time.

In the simulation, the mobile charger starts at (0,0,0) with zero velocity in the global frame. The working AUV begins at (-20,0,0) with a small initial forward velocity. When the simulation begins, both platforms



(a) No currents

(b) Current field of $(+0.1m/s, -0.1m/s, -0.1m/s)$.

Figure 3: In the zero current case (a) both controller variants perform the same. In (b) the controller maintains the relative trajectory without regard for the global trajectory. Upon docking, both the AUV and charger drift together with the current.

begin drifting based on the current. Starting the working AUV 20 meters away from the mobile charger simulates the limited expected localization range from vision sensors.

Each of the 9261 simulations created trajectories for a working AUV, mobile charger, and relative position during the docking maneuver. These trajectories are then grouped according to control strategy (global velocity thrust control or relative velocity thrust control) and current field. For the zero current case, the trajectories are shown in Fig. 3a. In this case, all three trajectories overlay during the approach phase from -20m to 0m along X. The relative trajectory (red) then has a small amount of motion during the rest of the simulation as the docking adapter allows a degree of misalignment in the docking receiver. The thruster remains on for the remainder of the simulation with the control surfaces attempting to maintain alignment with the mobile charger. This causes the two vehicles to continue to move together after docking.

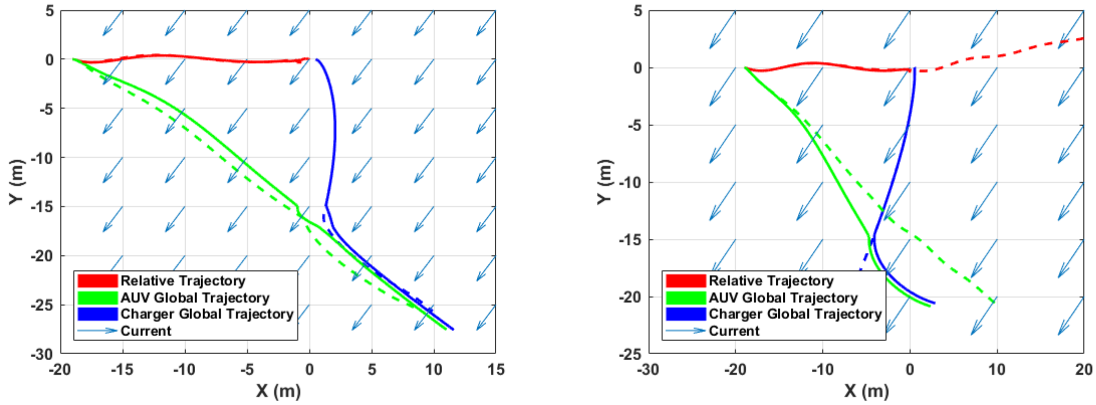
With a slightly increased current ($+0.1m/s$, $-0.1m/s$, $-0.1m/s$), the relative velocity thrust controller (solid lines) approaches the mobile charger while maintaining a constant closing velocity while the global velocity thrust controller (dashed lines) approaches with a known bottom referenced velocity, Fig. 3b. This causes both to dock at slightly different locations in the earth-fixed frame with the global controller impacting the mobile charger slightly sooner due to its increased velocity over the relative controller in this current field.

The mobile docking system is able to perform in some truly strong currents. With a very strong current $(-0.6m/s, -1.0m/s, -1.3m/s)$ both control strategies are able to successfully dock, Fig. 4a. In other strong current cases such as the $(-0.8m/s, -0.9m/s, -0.9m/s)$ case shown in Fig. 4b, only the relative velocity thrust control strategy can successfully dock. The failure of the global velocity thrust controller is due to the global controller approaching the docking platform too quickly with an effective relative velocity of $2.0m/s$, missing the platform.

To evaluate the performance over all the explored currents, each trial is classified as a success if the final relative position and final relative attitude are near zero. Based on this classification, out of 4851 cases the global velocity thrust control strategy successfully docked in 1070 cases while the relative velocity thrust control strategy docked in 1881 cases. The relatively low success rate was expected because the tested range of currents well exceeds the expected currents in operation. The extended testing range is however useful for controller development as it helps amplify any issues with controller performance. In real-world operation the typical current encountered is estimated not to exceed 0.5m/s in the narrowest part of the Throat of Kraken.[26]

Visualization of the range of acceptable currents is achieved by overlaying the 3D shape of each control strategy as in Fig. 5. The range of currents that the global velocity thrust controller can overcome (red) is much smaller than that of the relative velocity thrust control strategy (blue). The relative control strategy is particularly beneficial with any sort of tail current pushing the AUV.

Focusing on the XY plane performance in Fig. 6a, the global velocity thrust controller suffers dramati-



(a) Current field of $(-0.6m/s, -1.0m/s, -1.3m/s)$ (b) Current field of $(-0.8m/s, -0.9m/s, -0.9m/s)$

Figure 4: (a) Docking is successful with both controllers with quite strong currents. (b) The global velocity based thrust controller fails to successfully dock while the relative velocity controller successfully docks.

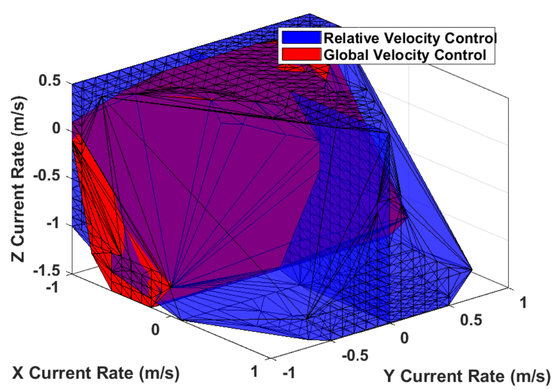
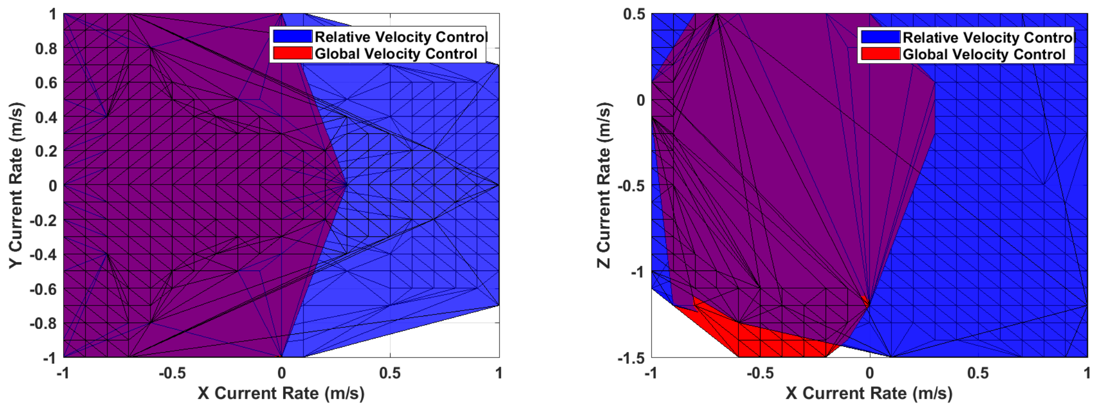


Figure 5: Overlay of the viable current fields. In most cases the relative velocity control strategy (blue) performs better than the global velocity control strategy (red).

cally with positive X currents. The relative velocity control strategy is able to handle strong tail currents, although the strongest tail currents do effect the ability to handle cross-currents.

In the XZ plane (Fig. 6b), the benefit of the relative control strategy is also apparent. Similar to the XY plane, both controllers are able to handle a wide range of currents when in the presence of a head current that slows down the AUV. With a tail current however, the ability of the global velocity controller to handle vertical currents disappears while the relative velocity controller is still able to manage quite strong vertical currents.



(a) (b)

Figure 6: The relative velocity thrust controller is capable of successfully docking over a much wider range of X current velocities than the global velocity thrust controller. Of particular note is the linear relationship between X currents and acceptable Y currents.

The relative velocity thrust controller is able to operate in the $+X$ current range due to its ability to adapt to the motion of the mobile charger. During the docking maneuver, the mobile charger is free-floating along with the current. Therefore, the global velocity controller approaching and impacting the mobile charger at a wide range of velocities, while the relative controller impacts at a consistent $1.0m/s$.

Preliminary experimental validation of the docking procedure was completed using a Bluefin SandShark operating in a swimming pool, Fig. 7. These docking tests were completed with a wide range of initial cross track errors and initial headings for the final docking stage using visual feedback. In the experiment, the AUV approaches a beacon light using a hybrid pursuit algorithm based on known relative yaw angle between the AUV and the station. The tested initial cross track errors exceed the expected error following the USBL approach.

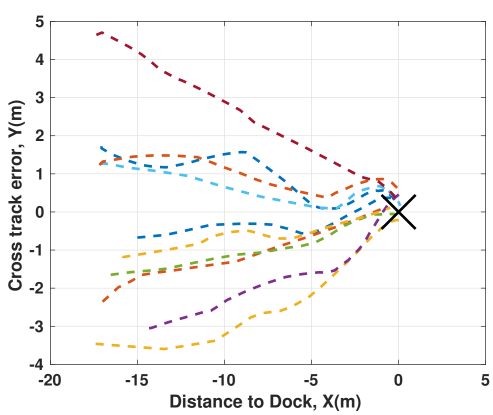


Figure 7: Trajectories followed during soft docking experiment.

VI. Conclusion

In this paper we proposed the combination of large and small scale vehicles to aid exploration of Titan through the addition of two small docking stations and accompanying autonomous vehicles. The two small underwater vehicles would be used to help explore near shore and in hazardous areas while the large vehicle serves as power source and features a full scientific payload for a detailed planetary survey. This paper presented a docking concept to allow the AUVs to charge from the Titan sub's radioisotope power source while not significantly impacting the submarines overall mission performance. This work has been completed for operation in the Earth analog to Titan's lakes, liquid water. Simulation results indicate that the AUVs are able to successfully dock with the Titan sub in the expected currents encountered on Titan using a relative velocity control strategy. Experimental results also demonstrate that the AUV is able to overcome a large initial error and successfully dock. Significant work is required to further evaluate this concept for operation in the specific conditions of Titan. The hydrodynamic model of both the Titan sub with docking stations and the working AUVs needs to be calculated and simulated for the liquid hydrocarbon lakes of Titan to compare to the Earth analog presented in this paper. Additionally, the experimental implementation needs to be extensively tested in liquid water with varying water clarity and conditions. Finally, trajectories for the working AUV and the Titan sub must be planned to optimize the overall mission performance of the Titan sub.

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