# DYNAMICS OF TWO ACTIVE AUTONOMOUS DOCK MECHANISMS FOR AUV RECOVERY

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## ABSTRACT

Autonomous Underwater Vehicles (AUVs) are presenting an ever expanding range of applications that enhance human capabilities and mitigate human risk. Development of a successful subsurface autonomous launch and recovery system would expand the functional use of AUVs in many fields, *e.g.*, year-round Canadian Arctic exploration and sovereignty missions. This paper provides an overview of the design and dynamic modelling of two concept mechanisms being developed to recover AUVs to a slowly moving submerged submarine. Both have a serial R⊥R⊥P architecture while one is mechanically actuated while the second uses an actively pitched wing to indirectly provide motive force for the passive revolute joint. Dynamic models of both manipulators are developed. Although similar in architecture, several extensions are required to accurately predict the non-linear dynamics provided by the wing. High speed actuation of the devices is required to compensate for relative trajectory errors between the submarine and AUV during significant sea states in littoral waters. Hydrodynamic and additional inertial forces present in water cannot be ignored. Alterations to the recursive Newton-Euler derivation of manipulator dynamics are explained, and results of some initial modelling are presented.

**Keywords:** AUV; serial manipulator; passive joint; manipulator dynamics; hydrodynamics.

# DYNAMIQUE DE DEUX SYSTÈMES AUTONOMES DE RÉCUPÉRATION D'AUV

## RÉSUMÉ

Les véhicules sous-marins autonomes (AUV) présentent un éventail toujours croissant d'applications qui améliorent les capacités humaines et aident à atténuer les risques pour les humains. Le développement d'un système autonome pour mettre à l'eau et récupérer les AUVs permettrait d'étendre l'utilisation fonctionnelle de ces véhicules dans des nombreux domaines, *e.g.*, l'exploration de l'Arctique canadien et les missions de souveraineté pendant toute l'année. Ce document donne un aperçu de la modélisation dynamique et la conception de deux systèmes qui permettront de récupérer les AUVs à un sous-marin. Les deux sont des manipulateurs en série R⊥R⊥P, le premier est actionné mécaniquement tandis que le deuxième utilise une aile dont l'angle d'attaque est actionné pour fournir indirectement une force motrice. Les modèles dynamiques des deux manipulateurs sont développés. Bien que similaire en architecture, plusieurs extensions sont nécessaires pour prédire avec précision la dynamique non-linéaire produite par l'aile. L'actionnement à grande vitesse des appareils est nécessaire pour compenser les erreurs de trajectoire entre le sous-marin et l'AUV pendant les états de mer significatives dans les eaux littorales. Les forces hydrodynamiques et autres forces d'inertie présentes dans l'eau ne peuvent pas être ignorées. Les modifications apportées à la méthode récursive de la dynamique des manipulateurs de Newton-Euler sont expliquées. Les résultats d'une modélisation initiale sont aussi présentés.

**Mots-clés :** AUV ; manipulateur en série ; joint passive ; dynamique de manipulateurs ; hydrodynamique.

## 1. INTRODUCTION

Autonomous Underwater Vehicles (AUVs) are presenting an ever expanding range of applications that enhance human capabilities and mitigate human risk. The main limitation of these vehicles is endurance. Oceanographers and scientists envision continuous automated surveying of geology and marine life. Navies and governments desire continual surveillance of territory, and autonomous front line capabilities delivered covertly by submarines [1]. The bottleneck in the adoption of these capabilities is a viable autonomous Launch and Recovery (L&R) system [2].

Watt *et al.* [3] discuss three kinds if AUV L&R systems: passive subsurface stationary docks, surface ships, and torpedo tube L&R for military submarines. The majority of existing AUV docking devices use some form of man-in-the-loop control with the exception of autonomous subsurface stationary docks. Present autonomous AUV docking experiments have yielded marginal success rates, primarily due to limited lateral dexterity of streamlined AUVs. Active control of the dock appears to be necessary for higher success rates.

Defence Research and Development Canada (DRDC) has proposed an innovative project to develop an active automated docking device to be used on slowly moving submarines while maintaining level flight with various AUV designs. Figure 1 illustrates the proposed scenario of recovering an AUV to a submerged submarine. A generic representation of the active docking mechanism is shown. The University of New Brunswick (UNB) is assisting in this multi-year project with the design and development of specific active dock mechanisms along with their dynamic models and motion controllers for multi-body simulations. This paper discusses the formulation of a dynamic model for both a mechanically actuated and a partially hydrodynamically actuated docking device for which physical prototypes are being built.

### 1.1. Related Research

The development of AUVs and AUV supporting systems have been gaining The United States of America's Department of the Navy has compiled an AUV master plan [1], outlining the goals and strategic advantage of implementing and using an AUV program. The plan depicts the use of AUV fleets with a centralized mission control ship, discussing the importance of AUV support systems and infrastructure. The development of an active autonomous L&R docking device is required to progress the functionality of using AUVs.

The current autonomous docking devices have had marginal success rates, too low to merit the risk of using the AUVs in service. Stokey *et al.* [4] achieved a 62% docking rate using a REMUS 100 AUV and a 1 m diameter stationary funnel dock with acoustic homing. Allen *et al.* [5] obtained a similar docking rate of 60% using an updated version of a similar setup with a rectangular funnel dock. Both trials used varying locations and environmental conditions, and were conducted in conjunction with the Woods Hole Oceanographic Institution. Using electromagnetic homing, Feezor *et al.* [6] achieved successful docking in five out of eight attempts. They used a SeaGrant Odyssey IIB AUV and a 1 m diameter stationary funnel dock. The trials were preformed over a two week period in environmental conditions with cross currents upwards of 0.3 m/s. They noted that docking typically failed when the AUV was initially misaligned with the dock by more than 30 degrees. Additional similar stationary docking trials have been performed with various homing and sensing schemes [7–9] but without presenting docking success rates. Surface ships typically use human-controlled L&R systems involving cranes or ramp systems [10, 11]. There are surface L&R systems under development using towed bodies [12], and some are even using Unmanned Surface Vehicles (USVs) to autonomously recover AUVs [13]. Successful recovery of an AUV by any surface system is highly dependant on the sea state [3].

Many countries are interested in an AUV L&R capability for submarines [2, 14–16]. Fedor [14] discusses optimal AUV docking locations along a submarine. To maximize docking feasibility, Fedor suggests docking occur in areas with minimal disturbances, *e.g.*, avoiding local turbulence from obstructions such as the

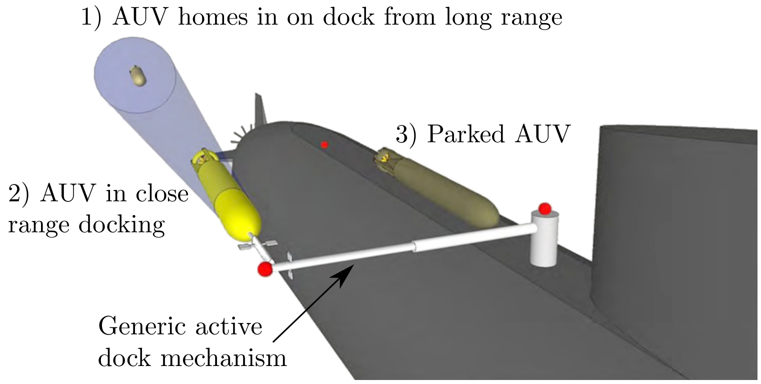



Fig. 1. Generic illustration of the proposed docking scenario.

submarine sail. The current submarine docking systems under development utilize either tethered Remotely Operated Vehicles (ROVs) [2, 15, 16] or a deployed stationary dock [17] for AUV recovery. The current methods also recover to the submarine's torpedo or missile tubes, disabling their traditional use for the submarine.

The majority of these docking devices rely on either the AUV for correctly aligning itself with the dock or man-in-the-loop remote control. As described by the Director of Innovation, of the US Office of Naval Research, AUV recovery must account for the: sea state, operational tempo, autonomy, motion prediction, and AUV maneuvering and control authority to be successful and robust [2]. Seizer [12] notes the absence of ship board autonomous AUV L&R devices. DRDC suggests that the deficiencies apparent with stationary autonomous docking systems might be corrected using active autonomous docking.

A successful active, autonomous AUV docking device will require a mechanism with the control and dexterity to achieve contact with the AUV in the presence of environmental disturbances. Mechanically actuated manipulators are currently in use with submerged ROVs [18]. These are typically used for precision tasks but on a relatively small size scale. Control of ship board robotic manipulators has been explored by From *et al.* [19]. They augment a Proportional-Derivative (PD) controller with a real-time wave prediction model to overcome the non-inertial effects of the manipulator base and optimize joint torques for prescribed trajectories.

There has been significant effort to develop AUV docking systems, all with marginal success rates. The functional use of AUVs is limited by the absence of a robust AUV docking device. An active, autonomous, reliable AUV docking device would allow AUVs to be recovered to naval platforms quickly. The successful implementation of such a device will require the synthesis of sensing information, robust autonomous control, and an actuated mechanism with sufficient dexterity to overcome relative motion between the AUV and submarine imposed by environmental disturbances. This project will contribute to the development of AUV docking by proposing an active autonomous AUV docking solution for submarines.

### 1.2. Project Scope

The AUV underwater docking problem is complex. DRDC states the docking solution should provide for [3]:

- deep water operations,
- littoral operations with minimal sea state limitations,
- automation for reliability and temporal efficiency,
- low risk to the submarine propeller or appendages should something break or let go during docking,

– low risk of AUV/submarine collision in the presence of environmental disturbance,
– a flexible choice of AUV size and shape to maximize endurance and functionality,
– minimal docking infrastructure on the AUV to simplify off-the-shelf use of commercial vehicles,
– and a fail safe design for emergency manoeuvres.

More specifically, it is convenient to consider docking in three primary stages: making physical contact between the AUV and dock, capture, and parking [3]. Achieving precise contact with the AUV has been identified as the most challenging task of this project, largely because the system has complex nonlinear dynamics and if unsuccessful capture will become infeasible. Thus, designing a dock prototype which is capable of achieving precise contact with the AUV has been established as the first stage of the overall project. UNB will provide a proof-of-concept design, including a dynamic model of the prototype and its controller for initial multi-body simulations. DRDC and other collaborators will provide sensing systems, AUV homing trajectories, and expertise to assist in the development of the initial prototype design for dynamic simulation. AUV capture will occur alongside the submarine, heading into the waves, while the submarine is at depth maintaining level flight in littoral waters. All designs must be made fail safe in operation to mitigate the risk to submariners. The most important of the UNB design objectives are:

– the primary objective of the dock mechanism is to provide transverse trajectory corrections for the AUV during the final stages of achieving contact,
– the submarine will maintain straight and level flight at 2 to 3 knots ($\approx$ 1.5 m/s),
– docking will occur from 4 to 8 m off the side of the submarine's hull, at the midline of the submarine where the flow is most uniform,
– the dock must achieve precise contact with a point on the AUV; given a tolerance of $\pm$0.005 m,
– initially, the orientation of the AUV will be neglected, reducing the task to three Degrees Of Freedom (DOF) and focusing on accurately contacting a point on the AUV,
– the worst case scenario is defined as docking at 15 m depth in littoral waters in sea state 6 (4 to 6 m high waves),
– the worst case AUV motion is assumed to be the fluid particle motion given by unimodal linear wave theory predictions of sea state 6 waves,
– and the dock design must be fail-safe, minimizing risk to submariners.

## 2. CONCEPTS

A large number of actuation concepts were analysed for the docking mechanism. They can be classified as either hydrodynamically actuated or mechanically actuated. Hydrodynamically actuated designs included directed water-jets, ducted fans, and actively controlled hydrofoils on links of arms or towed bodies. Mechanically actuated designs contained more traditional power transformers such as scissor arm linkages, and motor actuated links. Less conventional concepts such as tensioned spring and cable articulated bodies, and adjustable arrestor cables were also investigated [20, 21].

Concept winnowing was a large task accounting for input from a wide variety of sources. Fail-safe design considerations, consultations with submariners, and proof-of-concept analysis were the main drivers of the process. These inputs lead to the avoidance of mechanisms using cables or towed bodies due to the increased risk of fouling the propeller. Eventually the two most promising concept designs were agreed to be a mechanically actuated $R\perp R\perp P$ serial manipulator (or RRP for short), shown in Fig. 2(a), and a hydrodynamically actuated $R\perp \widetilde{R} \perp P$ serial manipulator (or wing dock), as shown in Fig. 2(b). The $R\perp \widetilde{R} \perp P$ architecture uses the forward motion imparted by the submarine and an actively pitched wing to indirectly provide motive force for the passive revolute joint, denoted by $\widetilde{R}$.

The RRP robotic arm, using a 2-DOF shoulder joint at the submarine hull, will be able to move in the longitudinal plane in addition to the transverse plane. Having each joint actively driven with a motor leads to

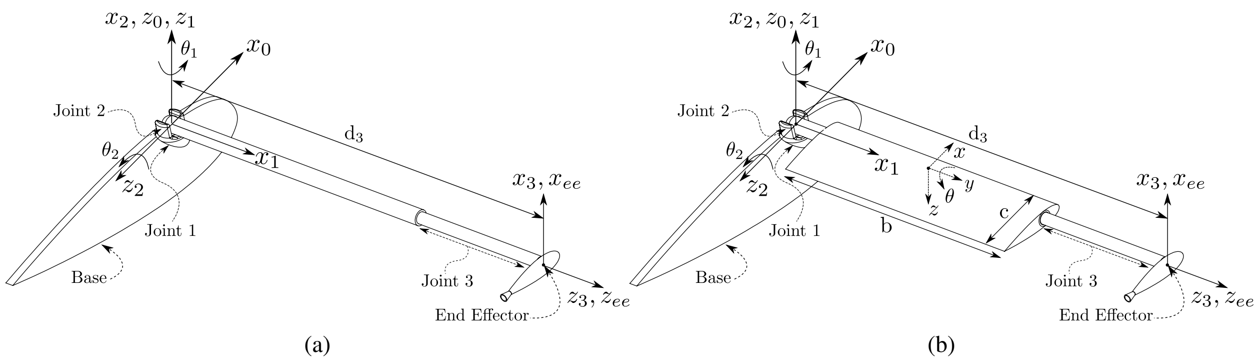



Fig. 2. The two autonomous dock concepts under development, shown with their faired base (submarine absent). (a) Mechanically actuated 3-DOF arm, and (b) Hydrodynamically actuated wing.

the potential benefits of: rapid closed-loop response times, a relatively simple and robust control algorithm, good disturbance rejection characteristics, and the fact that actuation does not require fluid flow. The hydrodynamically actuated concept will derive potential benefits of: low actuation power and noise, inherent streamlining for reduced drag, and passive compliance to compensate for submarine roll.

## 3. MODEL DEVELOPMENT

A benchmark end effector trajectory is first established based on the docking parameters. Standard manipulator kinematic and dynamic models are employed as much as possible. Kinematic similarities between the two manipulators leads to nearly identical models; since the wing is effectively a non-linear replacement for a motor it simply becomes an extension to the RRP solution rather than a completely divergent derivation.

Section 3.3 describes the general alterations required for both manipulators to account for hydrodynamic effects. Further alterations to analyse motive power provided by the wing are discussed in Section 3.4. The chosen control scheme is introduced in Section 4. Results of initial simulations for both manipulators are presented in Section 5.

### 3.1. Establishing the End Effector Design Trajectory

Unimodal linear wave theory approximates the kinematics of a fluid particle as an ocean surface wave moves past that particle. The worst case AUV kinematics are assumed to match those of a fluid particle at a depth of 15 m within sea state 6 waves in littoral waters. Conservatively assuming the submarine to be unaffected by the waves, results in the benchmark end effector trajectory. Figure 3 shows that this relative motion between the submarine and the AUV can be significant. Maximum displacements can exceed $\pm$ 4 m within a 17 s wave period, while both the velocity and acceleration also have large amplitudes.

### 3.2. Kinematics

Conventional joint frames are assigned to each link of both mechanisms, as shown in Fig. 2, using the Denavit-Hartenberg notation described in Craig [22]. The forward displacement problem is solved using the propagation of homogeneous transformation matrices. Whereas the inverse displacement solution uses a geometric solution. The Jacobian is then derived and used to solve the velocity and acceleration vectors in both Cartesian and joint spaces respectively.

Kinematically, Joint 1 in the wing dock is used for deployment only, it is fixed during the docking procedure. In regards to the specified task of tracking the AUV path error in the transverse plane, the wing dock is a 2-DOF manipulator. Rotation about the shoulder ($\theta_2$), and radial extension of the end effector ($d_3$) fully

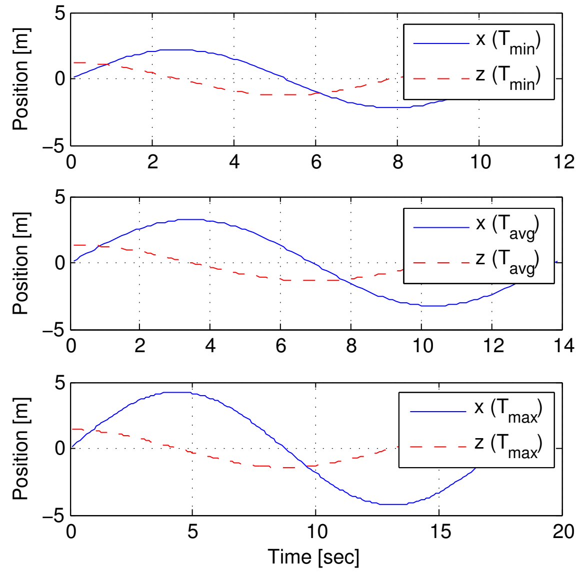



Fig. 3. Relative horizontal ($x - axis$) and vertical ($z - axis$) wave particle displacements as a function of time for sea state 6, given a minimum wave period ($T_{min}$) of 10.5 s (top), an average wave period ($T_{avg}$) of 13.8 s (middle), and a maximum wave period ($T_{max}$) of 17.5 s (bottom).

define the position of the end effector in the transverse plane.

### 3.3. Dynamics

At this point the mechanism links are assumed to be rigid bodies. The development of the equations of motion (EOM) will be completed with the recursive Newton-Euler formulation as opposed to the single body approach common to hydrodynamic analysis. The recursive technique maintains the advantage of having constant moment of inertia tensors for each link. It also provides flexibility for the project to add further DOF to the end effector without re-completing the dynamic analysis of the entire manipulator. Extra DOF could be required to account for orientation between the AUV and end effector.

Inward iterations are performed to propagate accelerations from the end effector to Joint 1 for both manipulators (while completely ignoring the wing as a body at this point). Environmental forces and moments ($\mathbf{f}_n$ and $\mathbf{n}_n$) are considered to be zero until contact with the AUV is made. Motion in a dense fluid like water alters the inertial forces. The driving forces must accelerate the surrounding fluid in addition to the link. Whereas mass is the proportionality constant between the kinetic energy of a link and the square of its velocity, added mass is the proportionality constant between the kinetic energy of the fluid surrounding a link and the square of that link's velocity [23]. For link $i$, added mass ($m_{i_{\text{added}}}$) is linearly summed with the mass of link $i$ to calculate the total inertial force as:

$$\mathbf{F}_i = (m_i + m_{i_{\text{added}}})\dot{\mathbf{v}}_{C_i}, \tag{1}$$

where $\dot{\mathbf{v}}_{C_i}$ is the linear acceleration vector of the centre of gravity of link $i$. In addition to inertial forces, various hydrodynamic forces need to be modelled. Since all of the hydrodynamic forces of interest are superposable vector quantities, Fig. 4(a) represents them as a single equivalent force-moment couple ($\mathbf{f}_{h_i}$ and $\mathbf{n}_{h_i}$) placed at the centre of gravity of each link. The conventional iterative Newton-Euler equations of

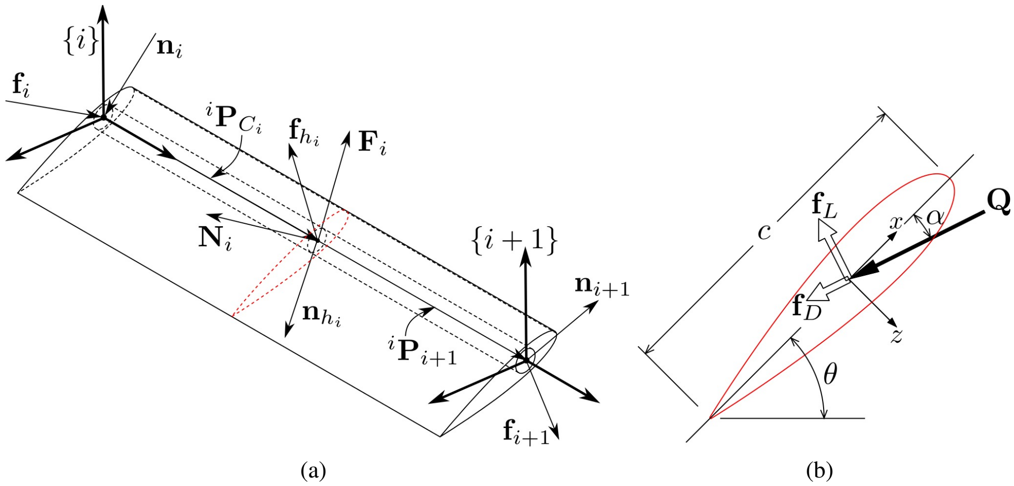



Fig. 4. (a) Free-body-diagram of general submerged link *i*. (b) Nomenclature and forces acting on an airfoil.

motion are then revised as:

$$ {}^i\mathbf{f}_i = {}^{\;\;\,i}_{i+1}\mathbf{R}\ {}^{i+1}\mathbf{f}_{i+1} + {}^i\mathbf{F}_i - {}^i\mathbf{f}_{h_i} \tag{2} $$

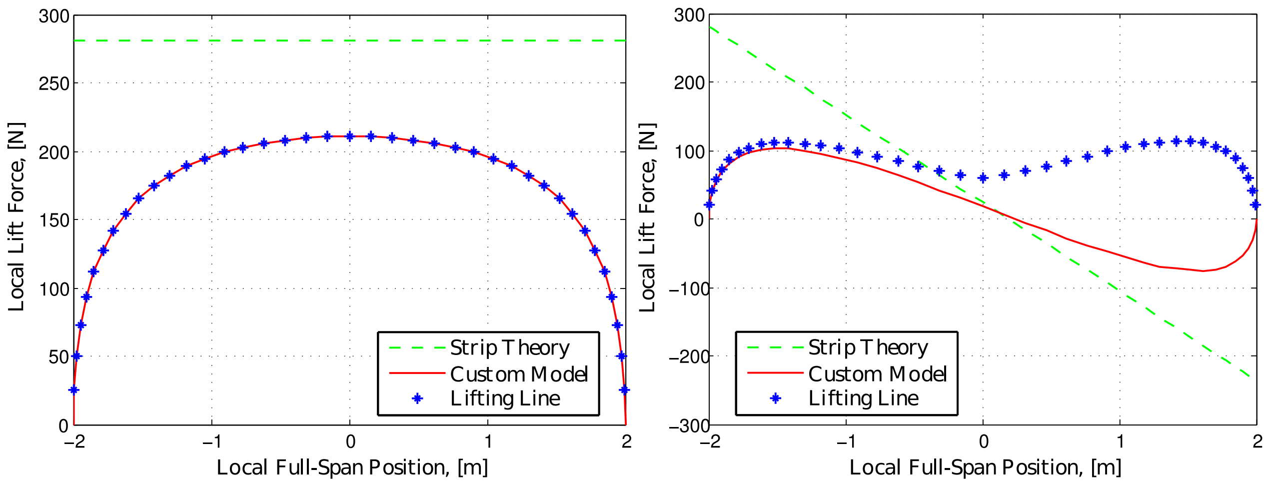
$$ {}^i\mathbf{n}_i = {}^i\mathbf{N}_i - {}^i\mathbf{n}_{h_i} + {}^{\;\;\,i}_{i+1}\mathbf{R}\ {}^{i+1}\mathbf{n}_{i+1} + {}^i\mathbf{P}_{C_i} \times {}^i\mathbf{F}_i - {}^i\mathbf{P}_{C_i} \times {}^i\mathbf{f}_{h_i} + {}^i\mathbf{P}_{i+1} \times {}^{\;\;\,i}_{i+1}\mathbf{R}\ {}^{i+1}\mathbf{f}_{i+1}, \tag{3} $$

to determine the force and moment exerted on link $i$ by link $i-1$ ($\mathbf{f}_i$ and $\mathbf{n}_i$ respectively). Here, ${}^{\;\;\,i}_{i+1}\mathbf{R}$ represents the rotation matrix from frame $i+1$ to frame $i$, ${}^i\mathbf{P}_{i+1}$ is the distance vector describing the origin of frame $i+1$ as seen by frame $i$, and ${}^i\mathbf{P}_{C_i}$ describes the location of the centre of gravity of link $i$ with respect to the origin of frame $i$. To be clear, Eq. (1) is only applied in Eqs. (2–3) to portions of links which are exposed to fluid. Therefore, portions of the prismatic links which are retracted within their housing will not experience additional inertial forces resulting from hydrodynamic effects.

The main contributions to hydrodynamic force come from buoyancy, lift, and drag. All links are assumed to be neutrally buoyant with uniform mass distribution in order to remove unknown buoyancy forces within $\mathbf{f}_{h_i}$ and $\mathbf{n}_{h_i}$. Lift and drag ($\mathbf{f}_L$ and $\mathbf{f}_D$) are the components of hydrodynamic force perpendicular and parallel to the relative fluid flow vector $\mathbf{Q}$. The vector $\mathbf{Q}$ represents the net inertial velocity and orientation between the fluid and link of interest as seen from a link-fixed frame. In general, bodies which are symmetric about $\mathbf{Q}$ can only produce lift under special circumstances. This means that under expected operating conditions the cylindrical links of the RRP dock will produce drag, but never lift.

Wings, however, do produce $\mathbf{f}_L$ dependant on the angle of attack ($\alpha$), which is the orientation of $\mathbf{Q}$ relative to the chord (body-fixed line, $c$, between leading and trailing edge shown in Fig. 4(b)). The magnitude of $\mathbf{f}_L$ varies linearly with $\alpha$ to the point of stall – at which point fluid can no longer remain attached to the wing and $\mathbf{f}_L$ drops rapidly with increasing angle of attack while $\mathbf{f}_D$ increases rapidly. Control of $\alpha$ within variable flow vector $\mathbf{Q}$ is achieved by pitching (rotating) the wing about the $z$ (or equivalently $z_3$) axis, and is tracked by the angle $\theta$ between $c$ and the $y_3$ axis.

Non-planar motions propagated by revolute joints cause variations in $\mathbf{Q}$ along manipulator links. Strip theory is an analysis technique that accounts for these variations in local onset fluid flow. It independently examines cross sectional areas of a body and determines the local forces for each of these “strips” of unit depth. The local 2D forces are then integrated along the link and summed about the centre of gravity to calculate $\mathbf{f}_{h_i}$ and $\mathbf{n}_{h_i}$.




(a) (b)

Fig. 5. Results from the lift distribution model for a rectangular wing with $Æ = 4$ in (a) level flight conditions, and (b) pinned rotation.

The required joint torques are extracted as normal from both manipulators. At this point, the RRP solution is complete. However, the wing dock solution now needs to determine the required pitch alteration to produce the required torque at Joint 2. The complete set of inertial and hydrodynamic forces produced by any change in pitch must be factored in at this time. Calculating $\mathbf{f}_{h_w}$ and $\mathbf{n}_{h_w}$ for the wing also requires compensating for additional complications in the hydrodynamic analysis, which are discussed in more detail in the following section.

### 3.4. Model Extension for Wing Dynamics

Strip theory's 2D flow approximation is only valid for a wing if its span, $b$, is significantly longer than the chord length, $c$ (see Fig 2(b)). Such a wing has a high aspect ratio, Æ. Otherwise, the disturbances from the 3D flow pattern surrounding the geometric boundaries would have an effect over a large portion of the flow over the body. By comparing lift predictions of strip theory to lifting line theory [24] for the wing under consideration, Fig. 5(a) demonstrates that strip theory does not model end effects very well. The finite geometry of the wing must therefore be accounted for separately.

Unfortunately, due to the inherent complexity of fluid behaviour, analytical hydrodynamic models (such as lifting line theory shown in Fig. 5) only apply to very specific conditions. Though perfectly ordinary for a robotic manipulator, the benchmark trajectory is unconventional for a wing. The two main factors which are atypical in hydrodynamics are: the spanwise variations in $\mathbf{Q}$ imposed by varying tangential velocity, $\boldsymbol{\omega}_2 \times \mathbf{r}$ (where $\mathbf{r}$ describes the radial location of the wing strip of interest relative to frame 2); and the formation of streamline curvature lift (a force independent of $\mathbf{f}_L$) produced by wing pitch alterations and corresponding $\boldsymbol{\omega}_2$ occurring while constrained to the forward velocity of the submarine.

To describe these challenging motions, several conventional methods have been altered and superimposed to solve the complete lift and drag distribution on the wing. This unique model accounts for local variation in the vector $\mathbf{Q}$ at discrete locations in the same manner as strip theory. Forces, however, are calculated using a modified solution to twisted wings in order to account for the overall alterations of the force distribution imposed by finite geometry. The pre-determined variations in $\alpha$ are treated as physical twist in a wing under planar motion, and the typical Fourier expansion used in lifting line theory to solve for circulation is extended

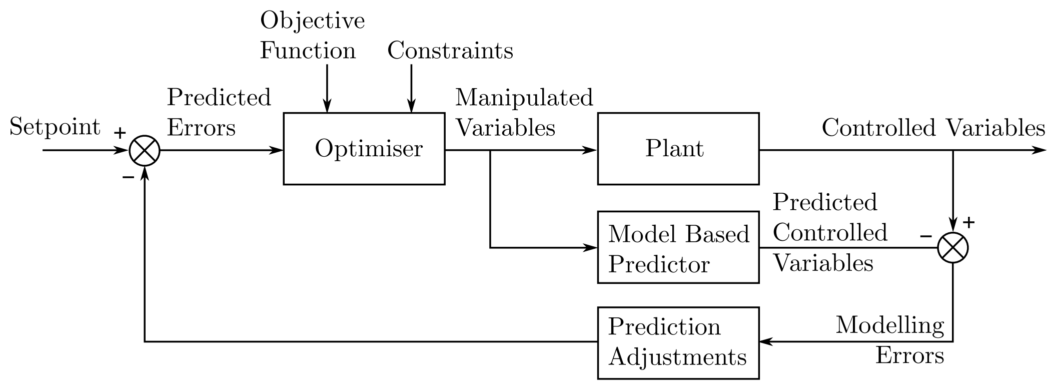



Fig. 6. A generic model predictive controller schematic [26].

across the entire span. Streamline curvature lift is also examined at each point of interest and treated as local physical cambre in a wing under planar motion. Changes in local flow variations are evaluated each time step in order to provide an accurate measure of the total moments produced at Joint 2 by $\mathbf{f}_{h_w}$ and $\mathbf{n}_{h_w}$.

## 4. MECHANISM CONTROLLER

The UNB research team will develop a controller for each mechanism to facilitate multi-body simulations of the docking process. These controllers will provide the mechanisms with the ability to accurately follow commanded setpoint trajectories. However, strategic intelligence used to develop these trajectories during the docking process will be provided by other project collaborators.

Dependencies on link lengths for hydrodynamic effects, and indirect coupling between pitch and end effector motion present a difficult non-linear control problem for conventional gain-driven controllers such as Proportional-Integral (PI) and Proportional-Integral-Derivative (PID). A more advanced control scheme such as Model Predictive Control (MPC) is required. As demonstrated by the basic schematic of MPC (Fig. 6), these controllers are able to monitor multiple inputs and state variables, and use compensated predictions of plant responses to optimise the command signal sent to the plant based on minimising future errors [25].

## 5. MODEL RESULTS

The 3D model of the RRP fully mechanically actuated mechanism is theoretically compared to known analytical test cases. The model is used to evaluate the actuator loads numerically in both pure planar rotation and pure linear translation motions. These results are then compared analytically using strip theory approximation for each test case. This ensures the model is capable of evaluating the general plane motion of a given link for generic trajectories. The numerical test cases correlate with the expected analytical values. The actuator loads are estimated by evaluating the model using the established benchmark trajectory. The torque requirements of the mechanically actuated dock device are significant, as shown in Table 1. The primary contributor to the large torque requirements for the device is due to the drag which the bluff submerged body must overcome. The estimated loads of the RRP dock device suggests the mechanism must be well streamlined in order to be a feasible solution. A well streamlined body can potentially reduce the drag experienced by an identical cylindrical body by up to 10 times its original magnitude [27]. Self-aligning fairings, unactuated fairings which align freely with the flow, could be incorporated into the RRP dock design to improve streamlining. Alternatively, a faired section could be used to both actuate and reduce the drag experienced by the device; such as with the wing dock.

Testing of the hydrodynamic model for the wing is being completed in stages in order to help validate sub

| Joint | Wave Period | Drag [kNm] | Added Mass [kNm] | Mass [kNm] | Net [kNm] |
|---|---|---|---|---|---|
| | $T_{min}$ | 20.95 | 1.31 | 1.31 | 21.26 |
| $\tau_1$ | $T_{avg}$ | 22.02 | 1.12 | 1.12 | 22.29 |
| | $T_{max}$ | 22.23 | 0.91 | 0.91 | 22.40 |
| | $T_{min}$ | 1.74 | 0.74 | 0.74 | 2.05 |
| $\tau_2$ | $T_{avg}$ | 1.22 | 0.47 | 0.47 | 1.40 |
| | $T_{max}$ | 0.82 | 0.30 | 0.30 | 0.93 |

Table 1. Maximum potential actuator torques required in the horizontal (Joint 1) and vertical (Joint 2) planes due to drag, added mass, and mass effects as well as net resultant load; given a minimum wave period ($T_{min}$) of 10.5 s, an average wave period ($T_{avg}$) of 13.8 s, and a maximum wave period ($T_{max}$) of 17.5 s.

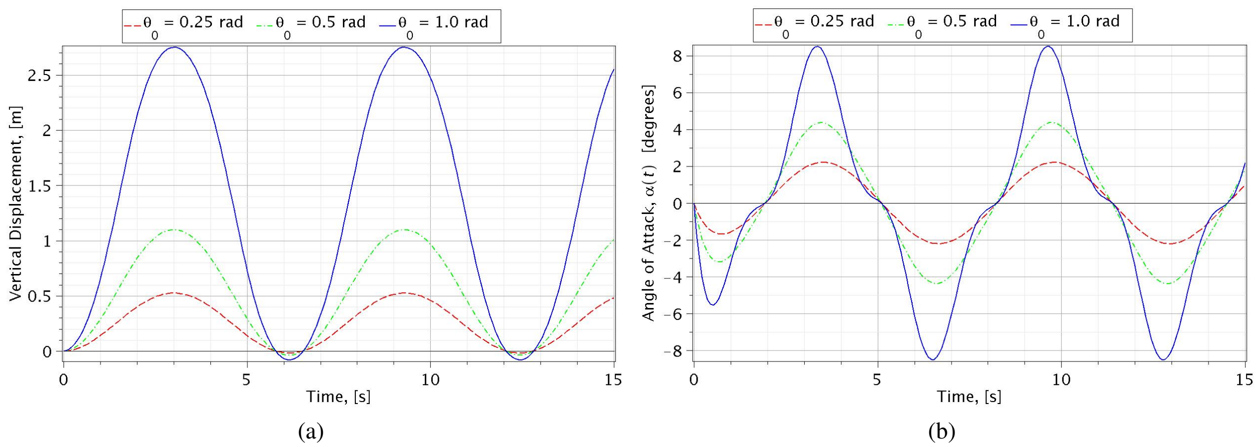



Fig. 7. Resultant vertical motions for wing in water subjected to sinusoidal pitch inputs. (a) Vertical displacements, and (b) corresponding angle of attack resulting from different pitch amplitudes, $\theta_0$ in rad, given a frequency $\omega = 1$ rad/s.

portions of the model. The first stage ignores dynamics and develops a model capable of calculating non-symmetric distributions of $\mathbf{f}_L$ and $\mathbf{f}_D$ caused by $\boldsymbol{\omega}_2 \times \mathbf{r}$. Figure 5(b) shows predictions of the lift distribution produced at the point of maximum $\boldsymbol{\omega}_2$ for the benchmark trajectory combined with a forward submarine velocity of 1 m/s. As expected, strip theory does not account for the finite geometry effects. Whereas the solution to lifting line theory for finite wings cannot properly reflect the variations in $\mathbf{Q}$. The custom model presents a blend of both factors. Figure 5(a) confirms the custom model successfully collapses to the standard symmetric distribution during planar motions.

The second model stage constrains the wing to the forward motion of the submarine, but allows it to freely translate along the vertical axis of the submarine in response to prescribed pitch inputs. The model ignores spanwise variability in $\mathbf{Q}$, but accounts for both forms of lift, inertial forces due to pitching, added mass, and the affects of finite geometry. Figure 7(a) shows the vertical displacement resulting from a sinusoidal pitch input. The non-rotational wing achieves more than the required displacement of 1.2 m in 2.5 s for the fastest expected wave period of 10 s. The corresponding angle of attack in Fig. 7(b) predicts the wing will remain below stall which can occur at angles of attack as low as 10 or 12 degrees.

## 6. FUTURE WORK

Further work is being completed to combine the initial two hydrodynamic model stages for the wing. Results collected from a physical prototype of a pitching and rotating wing section will be used to validate this complete hydrodynamic model. Following validation, the hydrodynamic model will be integrated into the recursive EOM to combine with the remainder of the manipulator model. Controllers will then be developed for both the mechanically and hydrodynamically actuated mechanisms. This will allow closed-loop simulations to to be performed in order to evaluate tracking errors when the devices are subject to disturbances. Measured errors and required actuator loads of the two concepts will be compared to determine the optimal solution for recommendation to DRDC.

## 7. CONCLUSIONS

The dynamic models of two active autonomous dock mechanisms used for recovering AUVs to submerged submarines has been examined. Both serial manipulators are in an R⊥R⊥P configuration, with their base attached to the midline of the submarine hull. While all the joints of one manipulator are directly driven by motors, the second dock uses an actively pitched wing to indirectly drive its passive revolute joint, Joint 2. Necessary modifications to the recursive Newton-Euler dynamics have been introduced to address additional fluid dynamics present in this submerged AUV recovery scenario. Standard lift distribution solutions have also been modified to address rotational motions not typically present with fixed wings. Initial simulations of both dock concepts suggest the benchmark trajectory is feasible, though analysis of joint torques suggests that the mechanically actuated manipulator will need to be adequately streamlined to reduce drag. Prototypes of both concepts will be tested in the future to validate these results.

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