The Underwater Swimming Manipulator – A Bio-Inspired AUV

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Abstract—**Autonomous underwater vehicles (AUVs) have been used for environmental mapping and surveys of various kinds for some time. More recently, the AUVs have entered the domain of the remotely operated vehicles (ROVs) to tackle some of the lighter subsea operations, such as inspection, maintenance, and repair (IMR) and light intervention tasks. The successful transition to AUVs for inspection of subsea infrastructure has pushed the technology towards AUVs equipped with robotic arms. Some AUVs with attached manipulator arms have demonstrated autonomous light intervention, but the majority of such tasks are still carried out using tethered and expensive ROVs with support vessels. The underwater swimming manipulator (USM) presented in this paper, is a snake-like bio-inspired AUV with exceptional accessibility and flexibility, due to its slender, multi-articulated structure. In this paper, we discuss why the USM is an appropriate system for certain tasks that are normally carried out by conventional ROVs and AUVs. Furthermore, we address the topic of kinematic control of the USM to utilize the inherent redundancy. Finally, we present and make use of a newly developed and versatile simulation environment for USMs to assert the applicability of the USM for performing subsea inspections and light intervention.**

I. INTRODUCTION

As more and more oil and gas operations are performed subsea and at greater depths, the importance of routine inspections and preventive maintenance increases. Furthermore, existing subsea infrastructure is ageing, amplifying the demands for subsea inspection, maintenance, and repair (IMR). Using conventional remotely operated vehicles (ROVs) for such tasks is both time-consuming and expensive, as it requires the support of a surface vessel. The drop in oil prices seen over the last year and a general focus on increased profitability and more efficient subsea operations have turned the interest of the industry towards smaller and more specialized vehicles capable of performing autonomous tasks [1]. The underwater swimming manipulator (USM), which was modelled in [2], is an innovative underwater vehicle that to a large extent can replace the use of expensive support vessels and ROVs for carrying out inspections and light intervention tasks.

A USM is essentially a fusion of an underwater snake robot (USR) and a conventional autonomous underwater vehicle (AUV). It is an articulated mechanism consisting of serially connected modules, equipped with forward thrusters and tunnel thrusters along the body to provide hovering capability. By using the thrusters in combination with the articulated joints, the USM is able to both propel itself forward and serve as a manipulator while hovering in the water. The USM also has the ability to swim like a biological eel using joint motion alone. This can be important in case of thruster failures or if the use of thrusters is not recommended in a particular application. In addition, the combination of a slender and flexible body with long reach makes the USM superior in terms of accessibility and manipulability. With its high number of articulated links, the USM can provide access to confined areas that are difficult to access with other types of underwater vehicles. An illustration of a USM is shown in Figure 1.

Typical jobs where USMs can replace ROVs include visual inspection, cleaning, and adjusting valves and

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chokes. The USM can also provide an extra eye during ROV operations. As a permanently installed janitor on the seabed, the USM can perform both planned and on-demand tasks. Short mobilization time can also help to prevent unscheduled shutdowns by reacting instantly when required. The USM has the potential to significantly reduce costs related to subsea IMR.

In this paper, we explain how the USM can be used for subsea IMR operations, and we provide a feature comparison between the USM and existing technology being used for such tasks. Furthermore, we discuss why the USM has superior properties in terms of accessibility and manipulability due to the long reach and the hyperredundant characteristics. Preliminary results for modeling and simulation of a USM are presented in [2] for the planar 2D case. Due to the complexity of modeling the hydrodynamics, we have chosen to develop the 3D model of the USM using the dynamic simulation tool Vortex, and we have coupled this with Matlab®/Simulink® to create a complete and versatile simulation environment for underwater snake robots with thrusters, i.e. for USMs. To the authors' best knowledge, this has not been done before. The simulation environment can act as a test bed for verification of new and updated algorithms before performing real-life experiments. Control laws and algorithms can easily be implemented in Matlab and executed in closed-loop with the Vortex 3D model. In [3], the authors present various methods for kinematic redundancy resolution for the USM, and a proof of concept is given using simulations based on the 2D model from [2]. This paper extends the results to 3D and presents simulations to show the applicability of the inverse kinematics singularity-robust task priority (SRTP) method [4] for redundancy resolution for the USM. The SRTP method has previously been applied in 2D simulation of a standard ROV/AUV with an externally mounted robotic arm [5], [6]. In [7], some results for the 3D case are presented using a fuzzy logic redundancy resolution approach.

II. COMPARISON WITH EXISTING TECHNOLOGY

The USM has some properties in common with mobile robots operating above water, such as wheeled mobile robots, land-based snake robots, spacecraft manipulator systems, and aerial manipulators. Solutions used for such systems are, however, often not directly applicable to a USM. For instance, many solutions for spacecraft manipulators rely on conservation of momentum due to the absence of external forces acting on the system. This is advantageous in terms of energy efficiency, but due to the hydrodynamics this is not a feasible solution for a USM. Land-based mobile robots are often equipped with wheels, and can thus be subject to nonholonomic constraints, unlike the USM which is free to move in all directions as long as it is fully actuated. Despite the differences, the USM may still benefit from lessons learned in areas like kinematic control, path planning, and obstacle avoidance.

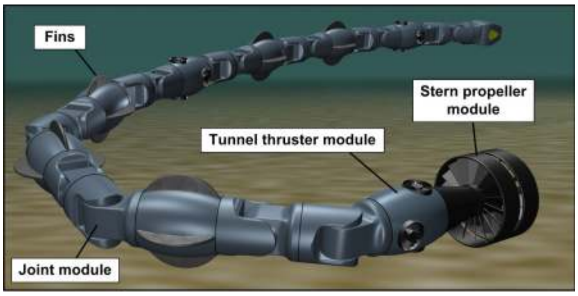


Fig. 1: Concept illustration of an underwater swimming manipulator

In general, the USM has more similarities with conventional ROVs and AUVs with robotic arms. In order to highlight some advantages and disadvantages of the different systems, we present a comparison of the most important features in Table I.

One obvious question is why we need a USM when there are options like inspection class ROVs, small AUVs with various shapes and configurations, and AUVs with robotic arms that are capable of performing intervention tasks. One of the main purposes of the USM is to reduce the operational expenditure associated with subsea inspection, maintenance, and repair. All ROVs are tethered and they are remotely operated from a specialized support vessel. This vessel must be equipped with a tether management system and dynamic positioning equipment. In addition, the ROVs require constant supervision and control by trained operators. All these requirements are associated with high costs. Finally, the time to mobilize and deploy the ROV system are often quite long.

Furthermore, conventional AUVs come in many sizes and can be equipped with a long list of payload and sensors for various subsea operations and activities. Many of them are torpedo shaped and optimized for low longitudinal drag forces to perform long endurance surveys of various kinds. Such AUVs consist of a single rigid body with no robotic arm, and thus, they are not suitable for intervention operations. Lack of hovering capability is also an issue for many conventional AUVs. Restricting the selection of AUVs to systems with hov-

TABLE I: Highlighted differences between a USM and existing technology

Feature	**USM**	**Inspection class ROV**	**Small AUV**	**I-AUV (existing)**
Size and weight	Small, lightweight	Small, lightweight	Small, lightweight	Large, heavy
Supervision and control	Supervised autonomy	Manually controlled	Supervised autonomy	Supervised autonomy
Interchangeable toolkit	Yes	Yes	No	No
Tethered	No	Yes	No	No
Consequence of collisions	Small	Medium	Medium	Severe
Accessibility	Very good	Good	Good	Restricted by large size
Kinematic redundancy of manipulator arm	Very high	Low	–	Intermediate
Intervention capabilities	Yes	Yes	No	Yes

ering capabilities being used for subsea inspections reduces the options significantly. We briefly mention some examples, such as the hovering AUV (HAUV) by Bluefin Robotics [8], the Autonomous Inspection Vehicle (AIV) developed by Subsea 7 [9], SAAB Seaeye Sabertooth [10], and Marlin Mk1 by Lockheed Martin [11]. These are systems capable of performing subsea inspection tasks, while the USM in addition can provide light intervention capabilities, as well as enhanced flexibility and accessibility, due to its slender, articulated structure and small cross-section.

AUVs equipped with one or more robotic arms are commonly referred to as intervention AUVs (I-AUVs) [12]. The AUVs developed through the research projects ALIVE, SAUVIM, and RAUVI/Trident have all demonstrated autonomous intervention capabilities [12]. Earlier this year, the hybrid ROV/AUV system H-ROV Ariane was officially presented by the ECA Group and Ifremer [13], [14]. However, these vehicles are quite large and heavy compared to a USM. They require a large open space to operate safely and must be deployed by crane. The relatively large mass also increases the potential consequences of a collision with subsea infrastructure.

The USM can be operated as a conventional AUV to perform, for instance, inspection tasks, installation support, and pipeline surveys. However, the most important benefits of the USM are associated with access to narrow spaces, the long reach, and the hyperredundant characteristics. Narrow spaces and passages can be found in conjunction with subsea installations, marine archeological sites, such as shipwrecks, and underwater caves. A typical USM can have a diameter of less than 15 cm and provides unprecedented accessibility. Furthermore, the size of future subsea installations can be reduced if routine ROV inspections and operations can be carried out by the much smaller USM.

The USM can be permanently installed subsea with a docking station to recharge the batteries, upload videos and footage, and receive updated commands. Similar ideas have been presented by the developers of the Saab Seaeye Sabertooth AUV and with the hybrid ROV/AUV concept SWIMMER from the late 90’s. An important difference here is the size of the USM. The USM can dock and be launched from a small tube, which can easily be fitted to existing subsea structures without requiring significant modifications. The long reach and the hyperredundant design enable the USM to attach the rear end to a suitable handle or grab bar, in order to perform tasks such as close-up inspection, cleaning, and opening and closing valves.

For all the reasons mentioned above, we believe that the USM is the most complete and versatile system for small-scale subsea IMR operations. In the next section, we address the challenges associated with modeling and simulation of the USM.

III. SIMULATION ENVIRONMENT

Modeling and simulation of a multi-body system subject to hydrodynamic and hydrostatic forces are complex problems. In order to implement and test various control approaches for the USM, we have set up a complete simulation environment using Matlab/Simulink and the multibody dynamic simulation tool Vortex by CM Labs [15]. This combination gives a powerful and flexible way to experiment with different controllers, control parameters, and physical designs, e.g. number of links and various thruster configurations. The setup enables real-time simulation and testing under realistic and adjustable hydrodynamic conditions including added mass forces, drag forces, hydrostatic forces, and thruster dynamics. At any time, the Vortex simulator can be replaced by the physical system to perform real-life testing and validation. Valuable time can, thus, be saved by doing simulated realistic testing and bug-fixing prior to the real-life experiments.

A functional overview of the simulation environment is shown in Figure 3. The partitioning of the control

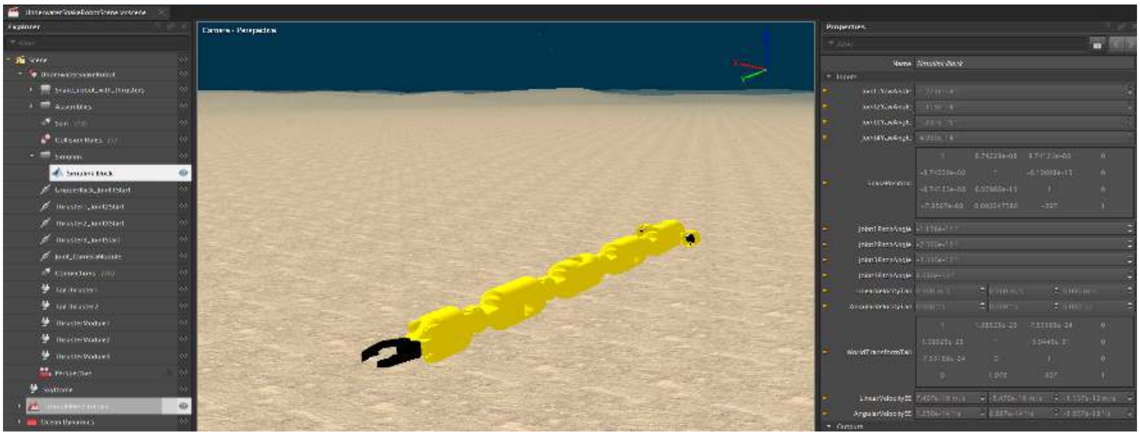


Fig. 2: Vortex simulation environment

approach block is similar to typical guidance, controller, and allocation frameworks for underwater and surface vessels [3]. For USMs, in particular, additional challenges arise because the continuous movement of the joint angles is strongly coupled with the motion of the whole mechanism and also changes the direction of the thruster forces. The main functionality of the subsystems shown in the control approach block in Figure 3 are:

- *Inverse kinematics reference generator* - resolves the kinematic redundancy and determines the reference velocities for the joints and the overall motion of the USM.
- *Dynamic motion controller* - calculates the forces and moments required to follow the reference velocities.
- *Thruster allocation* - performs an optimal distribution of the control efforts.

The control algorithms are implemented in Matlab and communicate with Vortex through a generic Simulink interface. Command signals and simulated position and velocity measurements are exchanged in real-time. The execution of the Vortex model and the Simulink model is synchronized and runs at 60 Hz with a fixed integration step size. In this paper, the Vortex model is set up to accept kinematic control signals, i.e. the joint angles and the position and orientation of the tail module are enforced. This approach disregards the hydrodynamic forces and is used in this paper only to demonstrate the potential of this new technology.

The Vortex model presented in this paper is composed of five modules, also referred to as links. There is one tail module and one gripper module, in addition to three thruster modules in between. The thruster modules are 44 cm in length. All the modules are connected by two articulated joints for rotation in pitch and yaw, giving a total of eight independently actuated joints. In Vortex, these joints are modeled as 1 DOF hinges with applied velocity and deflection constraints. The implemented model is visualized in Figure 2.

IV. MOTION COORDINATION

In order to realize operational USMs for underwater inspection and intervention tasks, several complex problems needs to be addressed. In this paper, we focus on inverse kinematic control, and in particular how to make the head link of the USM follow a desired trajectory. The USM is kinematically redundant with respect to this task as it possesses more independent control inputs than required to carry out the commanded task. Due to the integrated thrusters, the USM can move and turn as a rigid body. At the same time, the USM can use its articulated joints to change the position and attitude of the head link. This redundancy can be exploited by introducing secondary objectives to be fulfilled simultaneously with the primary task.

In this paper, we explain how the inverse kinematics singularity-robust task priority (SRTP) approach [4] can be applied for redundancy resolution for a USM. The SRTP approach is a null-space based method which can handle multiple tasks with strict prioritization. This means that each task will be fulfilled in a strictly prioritized order, if at all possible. Lower-priority tasks will only create internal joint motions that do not interfere with the higher-priority tasks.

We apply the SRTP approach to coordinate the actuation of the articulated joints and the motion of the USM as a rigid body. During execution of a manipulation task, it is preferred to keep the tail link as stationary as possible to replicate the behavior of a fixed-base

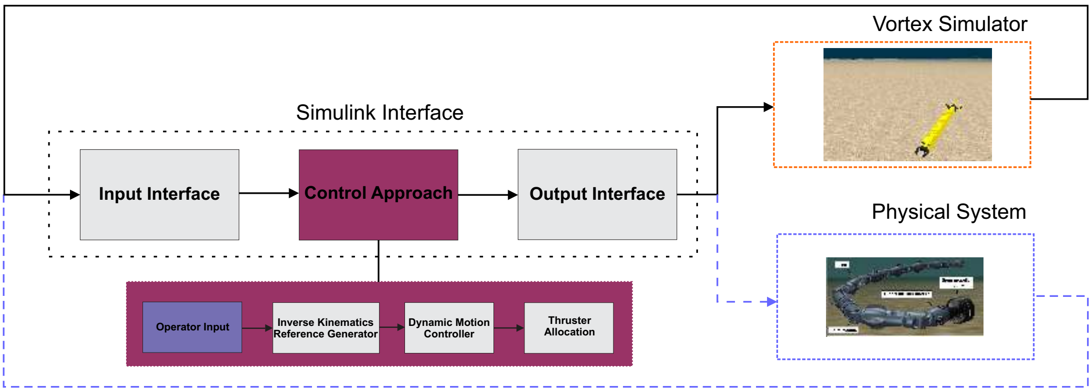


Fig. 3: Simulation environment

manipulator. Thus, we consider as the primary task to follow a 6 DoF trajectory for the head link of the USM and as a secondary task to maintain a stationary position for the tail link.

According to the SRTP approach and our selection of primary and secondary tasks, the reference velocities can be resolved by

$$\begin{aligned}\zeta_r &= J_P^{\dagger}(\eta_e,q)(\dot{\eta}_{e,d}+k_p\tilde{\eta}_e)\\ &\quad + (I - J_P^{\dagger}(\eta_e,q)J_P(\eta_e,q))J_S^{\dagger}(\eta_b)(\dot{\eta}_{b,d}+k_s\tilde{\eta}_b),\end{aligned} \quad (1)$$

where $\zeta_r = \begin{bmatrix} v_{b,r}^T & \omega_{b,r}^T & \dot{q}_r^T \end{bmatrix}^T \in \mathbb{R}^{14}$ is the calculated reference velocity vector for the joint angles and the tail link of the USM, $\dot{\eta}_{e,d} = \begin{bmatrix} \dot{p}_{e,d} \\ \dot{\Theta}_{e,d} \end{bmatrix}$ and $\dot{\eta}_{b,d} = \begin{bmatrix} \dot{p}_{b,d} \\ \dot{\Theta}_{b,d} \end{bmatrix}$ represent the desired velocities of the head link and the tail link of the USM in the inertial frame, respectively, and $\tilde{\eta}_e = \eta_{e,d} - \eta_e$ and $\tilde{\eta}_b = \eta_{b,d} - \eta_b$ are the corresponding position and attitude error vectors. Furthermore, J_P and J_S are the Jacobian matrices for the primary and secondary tasks, respectively.

The † operator in (1) denotes the Moore-Penrose pseudo-inverse. In order to account for the joint angle constraints, the pseudo-inverse of the primary Jacobian can be replaced by a weighted pseudo-inverse with a properly selected weighting matrix as described in [16]. In (1), the error vectors are fed back in a closed-loop manner to avoid end-effector drift due to numeric inaccuracies when integrating the reference velocities, ζ_r, to obtain the required joint angles and the tail link position and orientation. The Jacobians specify the velocity mapping between configuration spaces. In this case, the primary Jacobian, J_P, maps the tail link and joint velocities to the inertial frame velocities of the head link according to

$$\dot{\eta}_e = J_P(\eta_e,q)\zeta. \quad (2)$$

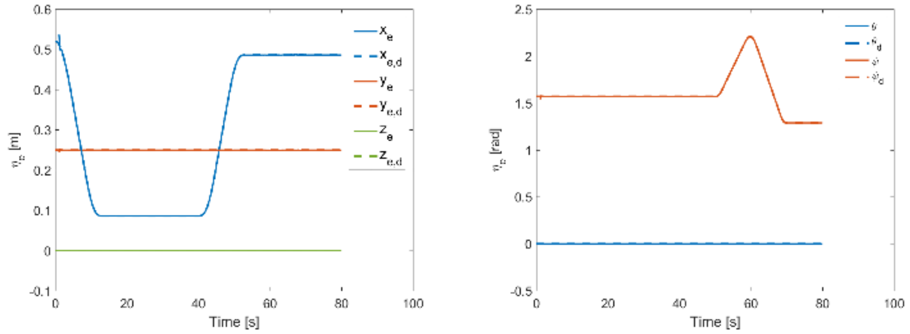
In this paper, the primary Jacobian has been derived and implemented by following the approach outlined in [3]. Simulation results showing the applicability of the SRTP method for controlling the motion of the head link of the USM is presented in Section V.

V. SIMULATION RESULTS

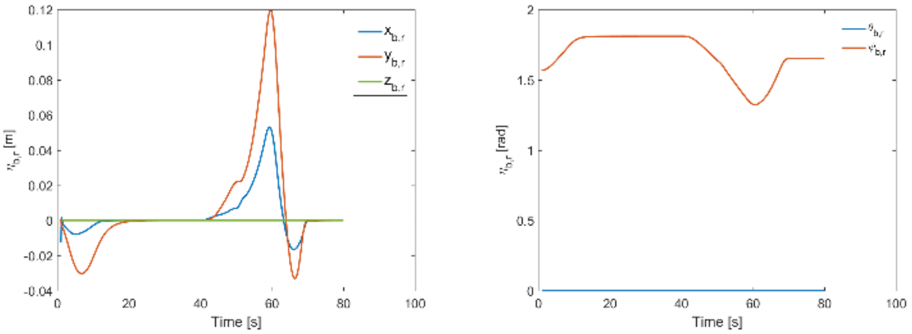
In this section, we present two case studies with the SRTP approach carried out using the newly developed simulation environment described in Section III. The first study restricts the desired motion of the end-effector to a 2D horizontal plane. The motion pattern consists of a sideways motion back and forth along the x-axis followed by a rotation in yaw starting at simulation time 50 seconds. The desired position of the end-effector along all the other axes are kept at their initial values. The second case study presents a full 3D motion of the end-effector moving the head link in all three translational directions in parallel with the same yaw motion as in case study 1.

We want to utilize also the pitch and yaw motion of the tail link to gain two more controllable degrees of freedom to obtain the desired end-effector posture. Therefore, we include only the stationary position of the tail link in the secondary objective. In this particular case, the secondary Jacobian becomes $J_S(\eta_b) = \begin{bmatrix} R_b^i(\eta_b) & 0_{3x11} \end{bmatrix}$, since $\dot{\eta}_b = J_S(\eta_b)\zeta$.

Figures 4a and 4c show that from time 0 to 20 seconds the head link moves 40 cm along the x-axis, while the tail link maintains its position within 3 cm. In the time interval 20 to 40 seconds, the tail link quickly converges back to its desired stationary position, in agreement with the priorities defined by the SRTP Equation (1). During



(a) Position of the head link (b) Pitch and yaw angle for the head link



(c) Position of the tail link (d) Pitch and yaw angle for the tail link

Fig. 4: Actual and desired position and orientation for the 2D motion pattern

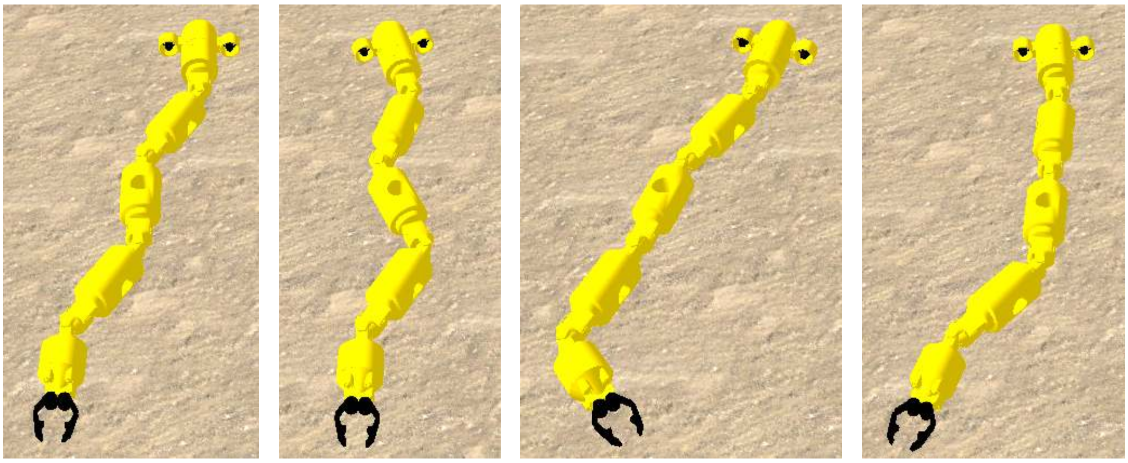
the yawing motion of the head link (see Figure 4b), we observe that the tail link undergoes a change of yaw angle in the opposite direction and moves forward along the y-axis to allow the head link to perfectly track the desired angular motion. Figure 5 shows a sequence of snapshots from Vortex illustrating the shape of the USM throughout the whole motion. The development of the joint angles are displayed in Figure 6a.

The results from the second case study shown in Figure 7 clearly show that the head link position and orientation has the highest priority. The desired motion of the head link is followed exactly, while the tail link has a larger deviation from its desired zero position. The snapshot time sequence and the joint angles are shown in Figures 8 and 6b, respectively. In Figure 8, we see that the USM utilizes the pitch and the yaw axes of the tail link to achieve the desired position and orientation of the head link.

The two simulations demonstrate the use of the simulation environment for kinematic motion of the USM. Strict prioritization between the primary and secondary objectives is achieved using the SRTP approach, and the results show that the tail link remains stationary only when this objective does not interfere with the primary objective. The desired position and orientation of the head link is preferably obtained using the joint motion. However, the ability to also move the tail link if necessary enables the USM to avoid internal and external kinematic singularities, which otherwise would be associated with very high joint velocity commands.

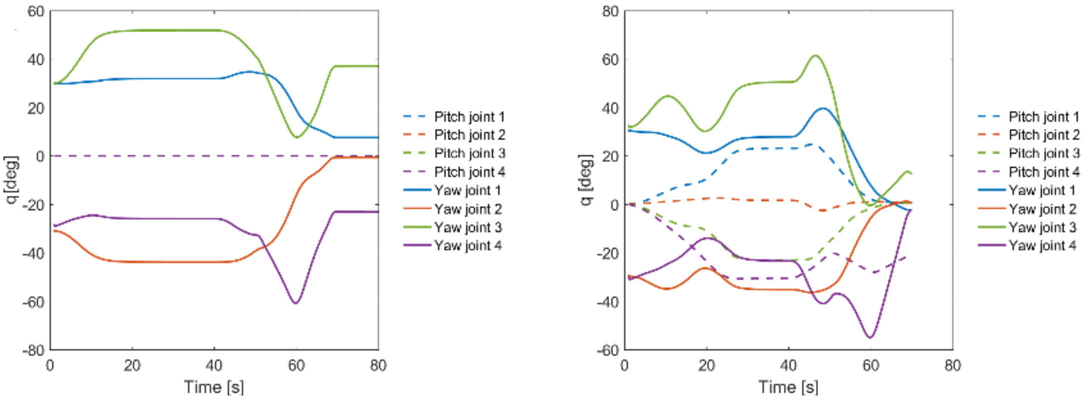
VI. CONCLUSIONS

This paper has presented the concept of the underwater swimming manipulator and discussed how the USM can be used for inspection and intervention operations on subsea infrastructure. In particular, we have highlighted the potential for significant cost savings and increased accessibility and manipulability compared to existing technology. One of the many interesting control problems to solve before such operations are feasible is the motion coordination between the USM as a rigid body, i.e. the motion of the tail link, and the articulated joints. In this paper, we have implemented a model of the USM in Vortex and applied the SRTP approach using the Vortex/Simulink simulation environment to show how the kinematic redundancy can be resolved.



(a) Time = 0 sec (b) Time = 30 sec (c) Time = 60 sec (d) Time = 80 sec

Fig. 5: Vortex snapshots for the 2D motion pattern



(a) Joint angles, 2D motion pattern (b) Joint angles, 3D motion pattern

Fig. 6: Joint angles

Through simulations we have successfully demonstrated the potential of this simulation environment, and the results show that the SRTP approach is well suited for a USM for tracking a desired head link position and orientation.

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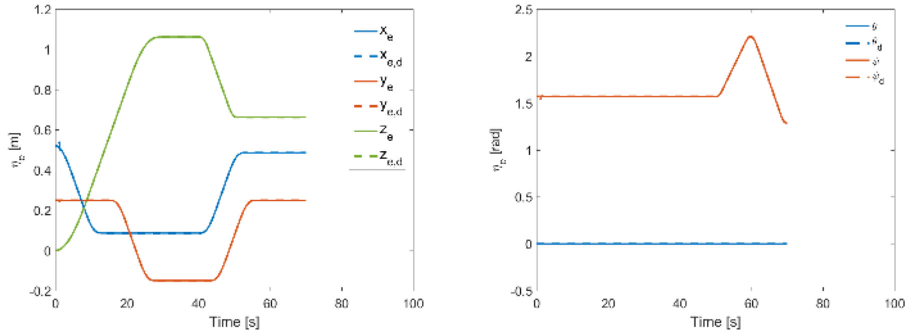
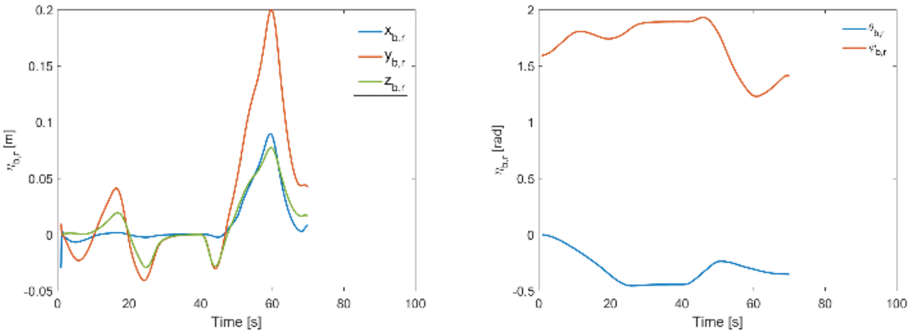
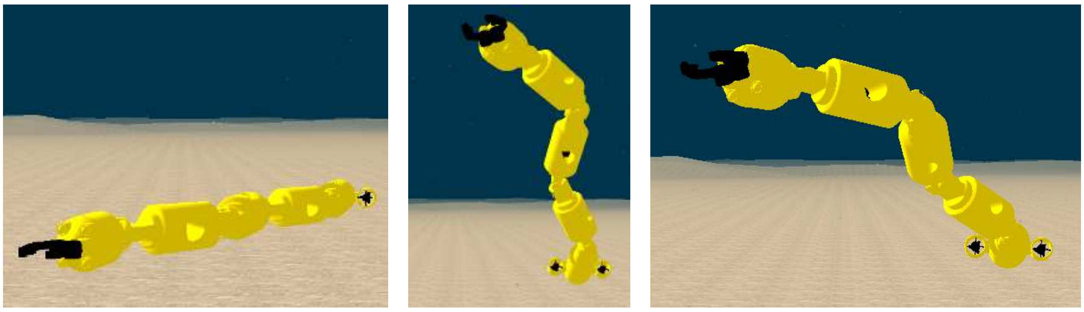


(a) Position of the head link (b) Pitch and yaw angle for the head link

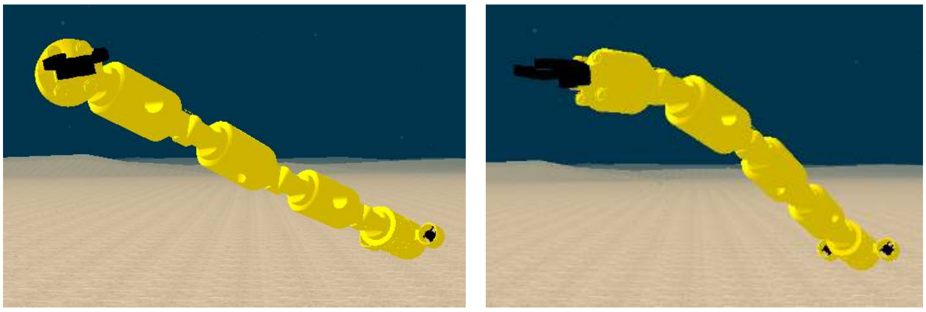


(c) Position of the tail link (d) Pitch and yaw angle for the tail link

Fig. 7: Actual and desired position and orientation for the 3D motion pattern



(a) Time = 0 sec (b) Time = 30 sec (c) Time = 50 sec



(d) Time = 60 sec (e) Time = 70 sec

Fig. 8: Vortex snapshots for the 3D motion pattern

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