Active manipulator-aided docking of underactuated autonomous underwater vehicles

Christian E. S. Koch* and Miguel Bande Firvida*
* *Robotics Innovation Center*
German Research Center for Artificial Intelligence
Bremen, Germany

***Abstract*—Underwater docking stations (DS) are essential for subsea resident autonomous underwater vehicles (AUV). Commonly, the DS is passive and the AUV is designed with sufficient maneuverability to achieve docking. In this work, we propose an alternative approach for an AUV with low maneuverability by equipping the DS with a robotic manipulator arm to actively catch the approaching vehicle. In particular, we present kinematic analysis tools tailored towards the docking task and a *dockability metric* to determine and evaluate suitable docking poses. By means of this analysis, an optimal approach path can be determined for the AUV to follow during the docking process. To demonstrate the feasibility of active docking, preliminary experiments were conducted in a control environment using a hardware-in-the-loop (HITL) simulator and a simple control architecture. The experimental results are further analyzed to investigate the limitations of the approach.**

***Index Terms*—AUV, docking, autonomy, manipulation, workspace analysis**

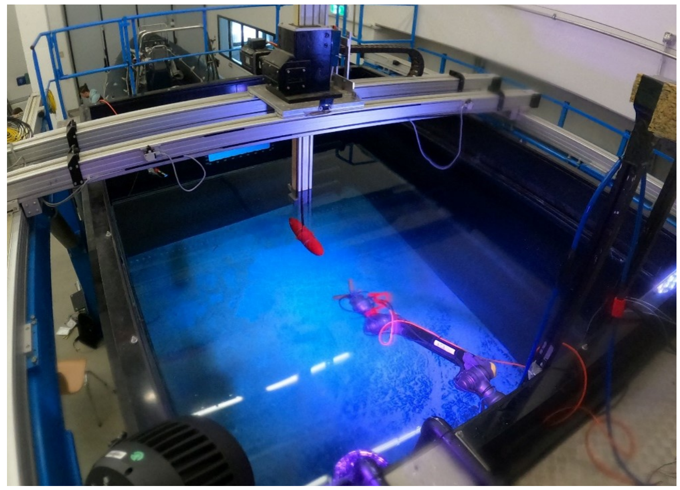

Fig. 1: HITL-simulator for active docking in a small test basin at DFKI RIC in Bremen, Germany. A 3D-printed mockup of the AUV is dynamically positioned by a 3-axis gantry crane. The docking manipulator can be seen mounted to one side of the basin.

I. Introduction

Autonomous underwater vehicles (AUVs) are increasingly demanded from both research and industry for seafloor survey and exploration as well as maintenance, recovery and construction operation of subsea facilities [1]–[3], as currently these activities involve the use of divers and/or remotely operated vehicles (ROVs), which is associated with substantial effort and costs. Subsea resident AUVs are particularly a promising initiative, as they can reduce the current costs while increasing operation intensity and safety [4]. Nevertheless, subsea resident operation implies the entry and/or connection to a docking station (DS) nearby the activity area where the AUV can exchange data and recharge [5].

The most common DSs currently used comprises a funnel-shaped entrance to provide a large cross-section area. Such unidirectional passive DS imposes two main requirements for the AUV: i) the relative pose of the AUV and the DS must be continuously known and ii) have high maneuverability to align the AUV and the DS during the final approach, even under strong disturbances [6]. These capabilities require therefore high level of actuation, sensory and power budget, which implicates larger and more costly AUVs. On the other hand, active DSs, which can actively track and capture the AUV during the approach phase, can reduce significantly the need of such capabilities, thereby enabling for smaller and simpler AUV designs. However, this shifts the complexity of docking from the AUV to the DS, i.e., the DS must instead fulfill the requirements i) and ii). Considering that the primary risk entails the total loss of the AUV, proceeding in such a manner appears to be a rational course of action.

In this work, we focus on active manipulator-aided docking which utilizes a robotic arm to catch the approaching vehicle for docking.

The work is motivated by the requirements of the TRIPLE[1] project, where a miniaturized underactuated AUV is developed for the exploration of subglacial lakes. The AUV is carried through the ice and deployed in the lake by a melting probe which serves as the DS. To facilitate docking despite the limited maneuverability of the AUV, the DS is equipped with a manipulator with 5 degrees of freedom (DOF) for actively catching the AUV.

A. Related work

Manipulator-aided underwater docking by an intervention-AUV has been demonstrated in the projects ALIVE [7] and

[1] https://triple-project.net/

ATLANTIS [8]. The AUV is equipped with a dedicated manipulator to dock to a subsea structure by grasping handling bars or magnetically docking to metallic surfaces. Similar research, commonly referred to as floating-base manipulation, can be found in space robotics, e.g., for catching space debris [9]. The core difference between these approaches an ours is that, in our approach, the docking manipulator is part of a DS with a fixed base that actively tracks and grasps the moving vehicle.

The task of actively catching a thrown object with a manipulator is a common research problem for terrestrial robotics. It has been demonstrated repeatedly using different controllers, e.g., visual servoing [10] [11], model predictive control [12] [13] or learning-based methods [14]. A notable difference to our scenario is that most studies consider objects that allow for multiple or arbitrary grasping orientations, e.g., spherical objects. This is in contrast to docking an approaching AUV, which can only be grasped in one specific attitude. Furthermore, these works focus on the capability of the manipulator in terms of motion planning and dynamic control while the trajectory of the thrown object is considered an external factor. In the context of our work, the AUV is capable of controlling its trajectory to aid docking, and hence, it is necessary to determine a suitable path for the AUV, prior to initiating the docking process.

In this paper, we present an approach to determine the optimal docking pose for an approaching vehicle. For this, the DS workspace is analyzed to reveal valid docking poses and a new metric is introduced that assesses the ability of the DS to track the AUV, when it is diverging from its nominal path. This allows us to not only provide performance guarantees but also to determine the most suitable approach path, and consequentially, an optimal docking pose. Furthermore, the feasibility of active docking is evaluated using a hardware-in-the-loop (HITL) demonstrator.

II. Problem Statement and Definitions

The AUV may approach the DS from different directions (*approach direction*) depending on the mission, environment and disturbances. For instance, since the AUV is underactuated and not hovering-capable, it is very limited in counteracting sideways currents. Thus, the AUV may choose to align itself with the current in order to minimize tracking errors. In this work, we assume that the AUV will attempt to follow a straight path towards the DS, referred to as the *approach path*. Along the approach path, a *docking pose* must be found, where the manipulator is able to grasp the AUV, i.e., a pose inside the *workspace* of the manipulator. If a docking pose exists for a given approach path, we call the path *feasible*, otherwise *infeasible*. This is depicted in Fig. 2.

The workspace and the number of docking poses per approach path depend on the manipulator kinematics. In this work, we are considering a manipulator with 5 DOF. This is sufficient to reach at least one pose along a feasible approach path. With additional DOFs, we would gain more flexibility in selecting a docking pose along a given path. This additional

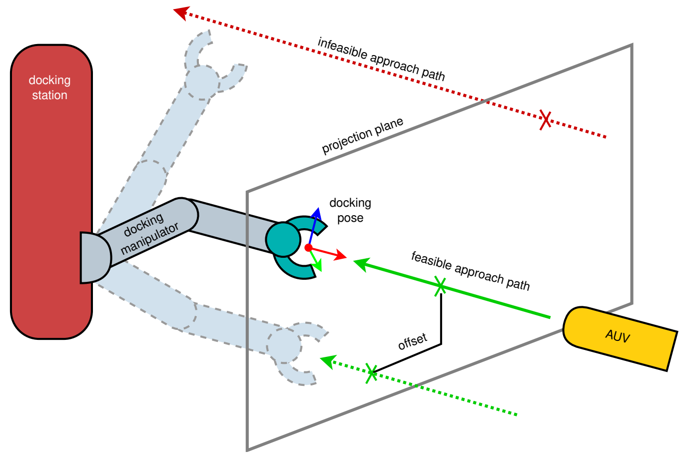

Fig. 2: The AUV is approaching the DS with a certain direction. Three parallel approach paths are shown, one of them is infeasible as it is unreachable by the manipulator. The relationship between approach paths is given by their vertical and horizontal offset on a projection plane. The projection plane is perpendicular to the approach paths.

flexibility could be used, for instance, to match the velocity of the AUV with the gripper for smoother docking. However, more DOFs also results in a increase of the size, weight and complexity of the DS, which leads to less flexibility in the design and higher risk of failure during operation.

In the nominal case, the AUV will attempt to follow a feasible approach path towards a docking pose. However, due to disturbances, the AUV might drift from the reference path. In this case, the manipulator must dynamically *track* the AUV to achieve docking, i.e., dynamically align its end-effector pose with the centerline of the AUV. As the predicted docking pose is updated repeatedly based on the current estimate of the AUV pose, the manipulator must dynamically be controlled to intersect the vehicle.

Even when diverging from the reference path, it is assumed that the AUV is capable of keeping its heading stable, which results in a parallel approach path. For a given approach direction, all approach paths are therefore parallel. They can be represented by points, which result from projecting the approach paths to a perpendicular *projection plane*. These points are referred to as *projected points*. The relation between two parallel approach paths is specified by the *horizontal and vertical offset* with respect to the projection plane. Furthermore, a *central approach path* is defined for a given approach direction as the approach path that intersects the *DS reference point*, e.g., the origin of the frame at the base of the manipulator (see Fig. 3). All parallel approach paths are uniquely identified by their offset to the central approach path. Note that the central approach path does not have to be feasible and only exists as a reference.

Not all approach paths are feasible and when the offset is too large, the AUV will end up on an infeasible path. The AUV should therefore follow an approach path that allows for

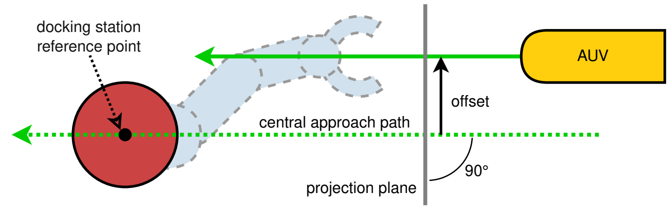

Fig. 3: Central approach path (top view). The central approach path intersects the DS reference point. Parallel approach paths are specified by their offset to the central approach path.

a large deviation, i.e., large offsets. Another important factor is the velocity of the AUV, particularly, the *lateral velocity* with which the AUV deviates from the target straight path. When the lateral velocity of the AUV is too large, the manipulator will not be able to track the vehicle. Due to the kinematics of the manipulator, poses that are close in Cartesian space, may be distant in joint space and thus require a large joint motion. For successful docking, the manipulator must be able to match the lateral velocity of the AUV.

Perfect tracking is, however, infeasible due to external factors, e.g., communication and processing delays, as well as sensor and actuator inaccuracies. To allow for such uncertainties, it is important to consider sufficient tolerances in the the design of the docking gripper. This is outside the scope of this work.

III. Dockability Analysis

The dockability analysis is the process to determine and evaluate all docking poses for the approaching AUV based on the kinematics of the manipulator. Furthermore, it aims to provide an optimal approach path for the AUV.

The analysis is performed per approach direction in heading and pitch. The range of possible approach directions is discretized to form a set of sampled directions to be analyzed by the means of the following steps:

1) For each sampled direction, a corresponding grid of parallel approach paths is determined.
2) For each approach path, feasible docking poses are calculated by solving the constrained inverse kinematics (IK) problem.
3) All feasible approach paths are evaluated by a metric that considers the maximum lateral velocity of the manipulator.
4) Based on the evaluation, the approach paths with an insufficient lateral velocity are discarded.
5) From the remaining approach paths, the optimal one is identified.

In the following, the process is further detailed.

A. Dockability Metric

The ability to react to deviations and track the AUV is one of the advantages of manipulator-based active docking. However, the velocity of the manipulator joints is limited, and hence, the tracking ability depends on the AUV's lateral velocity, as mentioned in section II.

The range of possible motions for a manipulator at a given configuration is commonly characterized by the *manipulability ellipsoid* and associated metrics [15]. These tools are based on the Jacobian matrix and reflect how changes in joint angles affect the pose of the end-effector. While this is useful to assess the abiltiy of a general-purpose manipulator, it can be misleading for specific tasks, e.g., when certain orientations are not required. This applies to the docking scenario, since the orientation of the end-effector must match the orientation of the AUV, which is assumed stable throughout the final approach. Furthermore, these Jacobian-based methods do not consider collisions and joint limits.

In order to incorporate the tracking ability into the dockability analysis, a novel *dockability metric* is introduced in this work, which is a scalar value associated with each docking pose. This value is the basis for identifying the optimal docking pose to be targeted by the AUV during the docking process.

We define the dockability metric $m(P)$ in meters per second for a feasible approach path P as follows: Starting at P, the end-effector can move to an arbitrary neighboring approach path with a lateral velocity of at least $m(P)$. All neighboring approach paths N_P w.r.t. P are those paths, whose projected points are within a safety distance d_{th} on the projected plane. Should the AUV approach the DS along the path P, docking can be guaranteed only if the AUV's lateral velocity does not exceed the value specified by the dockability metric $m(P)$ and its offset deviation remains within the safety distance d_{th}. The higher the dockability metric $m(P)$, the higher the allowed AUV's lateral velocity. Note that d_{th} is the only hyperparameter that must be provided to compute the dockability metric.

The lateral velocity v_A to move the end effector from the approach path P to the neighboring approach path A, is defined as the offset Euclidean distance d_{AP} of both approach paths P and A, divided by the minium duration t_{AP} required by the manipulator for this movement. We have made two assumptions to simplify the analysis: 1) The joint motions are executed concurrently at constant maximum velocity $\dot{\mathbf{q}}_{\max}$, i.e., acceleration and deceleration are assumed to be infinite. 2) No obstacles are present between neighboring approach paths. Based on these assumptions, the minimum duration t_{AP} for moving between P and A is determined by the joint i that takes longest time to move from an angle $q_{P\,i}$ to $q_{A\,i}$. The lateral velocity v_A is therefore calculated as follows:

$$t_{AP} = \max_i \left(\frac{|q_{A\,i} - q_{P\,i}|}{\dot{q}_{\max\,i}} \right) \tag{1}$$

$$v_A = \frac{d_{AP}}{t_{AP}} \tag{2}$$

Alternatively, the lateral velocity could be calculated by analyzing a trajectory generated by motion planning, that respects both obstacles and acceleration limits at the cost of increased computational complexity.

In case one of the neighboring approach paths is not feasible, v_A is set to zero as the approach path A can never be reached from the approach path P.

After computing all the lateral velocities of all neighboring approach paths N_P, the minimum is taken as the dockability metric $m(P)$ for the approach path P:

$$m(P) = \min_{A \in N_P} v_A \tag{3}$$

where $N_P = \{\forall A \mid d_{AP} < d_{th}\}$.

For the studied use case, all dockability metrics for certain approach directions are presented in Fig. 4. Here, the dockability metrics for each approach direction are depicted not in the resulting docking pose, but in the corresponding projected points.

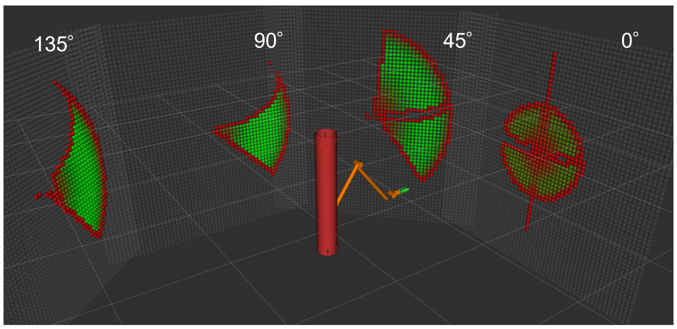

Fig. 4: Result of the dockability analysis for the studied use case. Only selected approach directions are shown. Docking poses are projected to a plane perpendicular to the approach paths. Grey spheres represent approach paths with no possible docking pose. Colored spheres represent approach paths with possible docking poses. The color gradient represents the *dockability metric* from best (green) to worst (red).

As observed in Fig. 4, feasible approach paths are normally grouped together, forming *feasible approach regions*, where d_{th} determines a safety distance to the boarders of these regions, colored as red in the figure.

B. Docking Pose Optimization

Although the dockability metric is used to ensure docking of a single feasible approach path, the formation of feasible approach regions enables to increase the offset deviation within which the docking can still be guaranteed as long as the AUV's lateral velocity does not exceed a certain value v_{th}. We define therefore the *optimal approach path* as the approach path that enables the highest offset deviation that ensures at least a lateral velocity v_{th} specified by the mission and AUV's performance requirements. And consequentially, the *optimal docking pose* is defined as the end effector pose of the optimal approach path.

By definition, the projected point of the optimal approach path is the center C of the minimal-radius circle enclosing the entire set of points $\mathbf{Q}$, which are the projected points of all the feasible approach paths with equal or higher dockability metric than the given v_{th}. This is, in fact, the definition of the Chebyshev center of a bounded set $\mathbf{Q}$. The bounded set $\mathbf{Q}$ forms a subregion of the feasible dockability region, referred as *guaranteed region*.

The results of the docking pose optimization process for one of the approach directions of our studied use case is presented in Fig. 5 as an example.

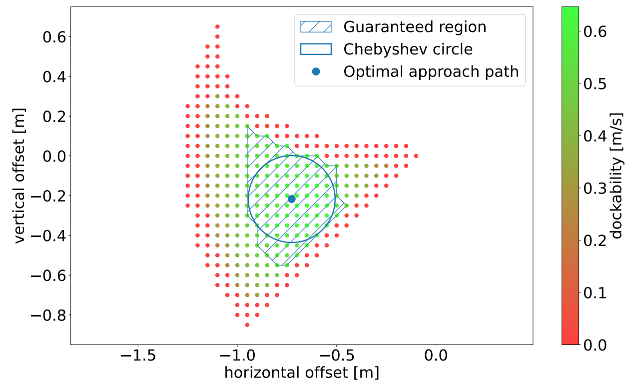

Fig. 5: Resulting docking pose optimization for one of the approach directions of the studied use case. The blue line defines the contour of the region where the dockability is higher than 0.5, i.e., all projected points within the safety distance can be reached faster than 0.5 m/s, and hence, docking is guaranteed. The red point represents the approach path with the largest distance to any of the projected points within the guaranteed approach region, i.e., the Chebyshev center.

IV. Docking Controller

The docking process is initiated when the AUV is on its approach path. It is assumed that, during the docking process, communication exists between the AUV and the DS, and that both are aware of each other's pose. In our studied use case, this is mainly achieved by means of a USBL.

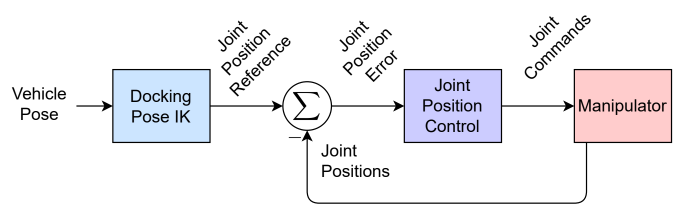

Fig. 6: Simple manipulator controller for the *servoing* phase. Given the AUV pose, the docking pose and corresponding joint configuration is calculated by the *docking pose IK*. Distributed joint controllers are driving the manipulator to the determined docking pose.

The docking process is divided into three phases: 1) *preparation*, driving the manipulator into the nominal docking pose, 2) *servoing*, tracking the AUV when it is diverging from the nominal path, and 3) *docking*, establishing the mechanical connection to the AUV when it is in reach. A fallback strategy is required for the case when the AUV leaves the guaranteed region and safe docking is not possible.

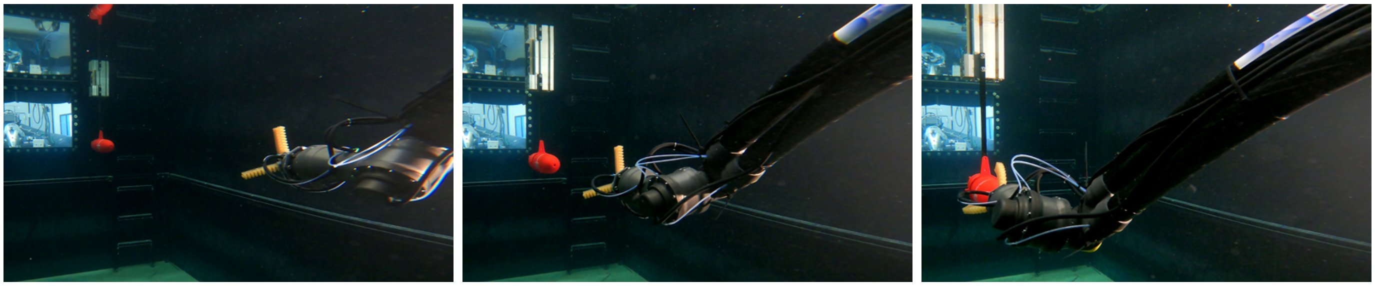

Fig. 7: Active docking experiment for a simple approach scenario. The AUV drifts from its docking path with a constant lateral velocity. The docking manipulator tracks the moving AUV to stay in front of the AUV until the AUV is close enough for grasping.

The *preparation* phase uses a combination of motion planning and dynamic trajectory following to move the manipulator on a collision-free path from the current to a target pose. We use the MoveIt! framework [16] with OMPL [17] for motion planning. For heavy restricted poses, e.g., a home position inside the DS, motion planning might not find a solution. For these cases a predefined trajectory can be provided to the framework.

The *servoing* phase relies on a real-time controller, which is able to minimize the tracking error. A simple servoing controller was implemented as shown in Fig. 6 to validate the concept. Based on the estimated state of the vehicle, the docking pose is predicted repeatedly. Using the inverse kinematics (IK), based on TRAC-IK [18], the corresponding joint values are calculated. A feedback-control loop on joint-level is implemented to command the manipulator and reach the desired joint positions.

V. Hardware-in-the-Loop Experiments

To validate the active docking dynamic concept, preliminary experiments were conducted. For these experiments a HITL-simulator was developed at DFKI RIC in Bremen, Germany (see Fig. 1).

An AUV mock-up is positioned using a computer-controlled 3-axis gantry crane, which provided the AUV position ground truth. The docking manipulator is mounted to one side of the basin as shown in Fig. 1. Since the target docking manipulator is still under development, an available 4-DOF underwater manipulator [19], developed for the AUV Cuttlefish [20], was used instead. The missing DOF was compensated for by the fact that the AUV-mockup has a fixed heading, as it cannot be rotated by the gantry crane. The HITL-simulator allows us to precisely specify the linear motion of the AUV and repeatedly test the active docking and tracking behavior in a controlled environment.

In a simple approach scenario, we assumed the AUV moves with a constant velocity towards the DS but drifts sideways due to linear currents. The docking pose is calculated based on the heading of the AUV and changes with the lateral movement of the AUV. Using the control chain described above, the docking manipulator attempts to track the docking pose until the AUV is close enough for grasping (see Fig. 7).

Besides validating the behavior and software integration, the HITL-simulator was used for experimenting with edge cases, comparing methods and tuning parameters. An useful metric in this context is the tracking error, i.e., the distance between the gripper and the predicted docking pose. Since the manipulator cannot adapt instantaneously to changes in the predicted docking pose, a tracking error dependent on the variability of the docking pose is to be expected. This tracking error is influenced by the manipulator controllers, communication delays, control rates and joint limits.

As part of the preliminary experiments, the tracking error was assessed for identical paths at varying speeds. The results in Fig. 8 show that the tracking error increases with the lateral velocity of the AUV, as is expected. In this case, the tracking error is predominantly caused by a conservative tuning of the joint-level PID controllers for safety and stability.

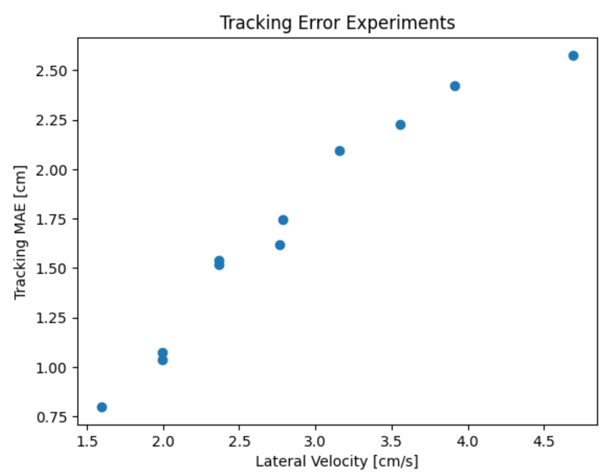

Fig. 8: Mean absolute tracking error (MAE) over the AUV's lateral velocity. Each point represents an experiment performed using the HITL-simulator and identical AUV paths at varying speeds.

These preliminary experiments show the feasibility of the active docking and dynamic tracking of the AUV. However, the current setup indicates high tracking errors that need to be addressed. There are a number of possible strategies to be examined in the future, e.g., i) aggressive tuning of the joint-level controllers, ii) improving the docking pose prediction by using the AUV's velocity, and iii) increase control rates and optimize for time delays.

VI. Conclusion

In this work, we proposed an active manipulator-aided docking method for underactuated AUVs. A process for analyzing the workspace tailored towards the docking task was presented. A dockability metric was introduced to evaluate individual docking poses, provide guarantees and determine an optimal approach path for the AUV. Furthermore, we showed results from preliminary laboratory experiments using a hardware-in-the-loop demonstrator and a simple control architecture. While the results showed the feasibility of active docking, they also indicate necessary enhancements concerning the tracking error, e.g., by improving the predictive abilities and the joint-level controllers.

To extend this work, we plan to further investigate the dockability analysis, e.g., in terms of the applicability to a 6 DOF docking manipulator. In this context, two questions appear especially interesting: i) How does the dockability metric compare to jacobian-based manipulability metrics? ii) How can we extend the dockability metric to find the optimal docking pose for approach paths with a range of feasible docking poses? Additionally, we plan to conduct more experiments with the target systems and optimized controllers.

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