RobCutt: A Framework of Underwater Biomimetic Vehicle-Manipulator System for Autonomous Interventions*

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Abstract—This paper presents a general concept framework of the underwater biomimetic vehicle-manipulator system (UVMS) for autonomous interventions in terms of objectives, as well as technologies and methodologies. With full consideration of the autonomous cruise and intervention, the RobCutt system’s configuration and methodology are designed to promote the levels of autonomy of the autonomous underwater vehicle-manipulator system (UVMS). The second generation UBVMS (RobCutt II) is introduced, including the design and principle of the biomimetic propulsion inspired by the cuttlefish and lightweight manipulator, and the advantages are concluded. Moreover, technologies and methodologies of underwater localization, object detection and coordination control are designed and accomplished respectively. Finally, pool tests have been carried out to verify the feasibility and effectiveness of the developed framework and methodology.

I. INTRODUCTION

Underwater Vehicle-Manipulator System (UVMS), as a kind of underwater robot with the capabilities of interacting with the environment for intervention missions, has shown great potentials and promising future in underwater manipulation and scientific study. A multitude of efforts have been committed to the research of the autonomous UVMS, including the mechanical design, system integration, system framework, methodology, mission plan, and control strategy. Nevertheless, the levels of autonomy of the UVMS in underwater survey and intervention tasks have always been perplexing researchers.

Traditionally, underwater operations are mainly undertaken by human occupied vehicles (HOVs), like Alvin developed at Woods Hole Oceanographic Institution (WHOI), or remote operation vehicles (ROVs), such as Jason [1], Victor 6000 [2] and KAIKO. Typically, all underwater vehicles mentioned above are equipped with robotics manipulator of multi-degree of freedom for interacting with environment dexterously. The operator plays an indispensable role in underwater operations through HOVs or ROVs. Though manual operation has the advantages of high efficient and high precision, the operation of long time is a kind of severe challenge for operators. Moreover, professional operation skill is needed for the operators, and this is high demanding for public terminal users. It will endow the vehicles with great intelligence to keep the operator out of the control loop.

The development of the autonomous underwater intervention vehicle was beginning to emerge just from the 1990s. AMADEUS project [3] was conducted to improve the dexterity and sensory abilities of underwater systems for underwater delicate manipulation in cooperative mode on an underwater fixed base with two 7 DOF manipulators [4].

SAUVIM [5] characterized itself the excellent capability of performing autonomous manipulation tasks in the underwater environment. The advanced concepts of this project could be summarized into three aspects and pave the way for successive study and design works. Firstly, completed work methodology was designed, including undocking, platform searching, approaching, hovering, arm preparation, target searching and tagging, and docking. Secondly, only higher-level information, like unplugging the connector, was communicated, which overcame the low bandwidth and significant time delay of the underwater communication to some extent. Thirdly, the UVMS whose manipulator’s mass was much less than the mass of the vehicle was constructed to reduce the complexity of the coupled motion of the vehicle-manipulator system.

RAUVI was developed to perform an intervention mission in underwater environments autonomously, where the methodology is divided into survey and intervention [6]. In survey phase, the I-AUV was firstly launched from the support vessel, then explored the region of interest, collected visual and acoustic data, finally surfaced to send data to base station. Then the operator identified the object of interest and described the task. In intervention phase, the I-AUV robot navigated again to the region of interest, identified the target object and performed the intervention task. Then a new methodology was proposed to provide multipurpose dexterous manipulation capabilities for intervention operations in unstructured underwater environments in TRIDENT [7]. The multipurpose generic intervention was also composed of survey and intervention. GIRONA500 UVMS once succeeded in searching and grasping a black box in the field [8]. And the latest autonomous underwater panel operation was reported in [9]. Latest, MARIS [10] was carried out particularly for interventions by performing manipulation and transportation...
activities in underwater environments in an autonomous way.

Future research in autonomous UVMS technology from present literatures mainly lies in higher levels of autonomy. A full autonomous way in cruising, sensing, detecting and intervening would be a crucial contribution to the development of autonomous UVMS. Full level of autonomy means higher operational efficiency and longer operational duration without resorting to the assistance of the operator. And the communication problems of fast decay and high delay are also avoided.

In this paper, the level of autonomy of underwater robots is promoted remarkably, and the autonomous grasping without assistance of the operator is achieved in laboratory environment after the UBVMS is deployed. A general concept framework of the UBVMS for autonomous interventions is developed to pursue the verification of the methodology and application. The underwater localization and navigation are achieved via a global camera. The target is detected autonomously and pose is estimated through 3D reconstruction. The intervention is performed by the gripper through the coordination of vehicle-manipulator.

The remainder of this paper is organized as follows. Section II gives the objectives. The underwater biomimetic vehicle-manipulator system is introduced in Section III. Section IV lays out the core technologies and methodologies in autonomous grasping. The experiment results are provided briefly in Sections V. Finally, Section VI concludes this paper with an outline of future work.

II. OBJECTIVES

The UBVMS, named as RobCutt, aims to achieve the autonomous underwater intervention for certain scientific missions. While keeping the operator out of the control loop, the system has to have the capacity to accomplish a series of sub-missions. The technical framework is depicted in Fig. 1 for autonomous underwater interventions. Target recognition and localization, underwater localization, status estimation of the UBVMS and environment are the bases of the mission planning. Mission planning generates all control and decision instructions for the motions of the vehicle and the manipulator. The status of the UBVMS and the environment could be estimated through information fusion based on the rich data of sensors. Meanwhile, the motion of the vehicle and manipulator would also change the position and statuses of the UBVMS in turn.

A. Underwater localization and navigation

During cruising of large range, real-time localization of the UVMS is essential for high accuracy navigation, which contributes to the planning of optimal path.

B. Target recognition and localization

Autonomous target detection and localization is one of the most crucial objectives. In this process, the position and orientation of the object with respect to the UBVMS are estimated. Those are the key information for autonomous plan and decision. So it is necessary to develop underwater 3D computer vision methods for specific object recognition and tracking, as well as pose estimation.

C. Coordinate control of vehicle-manipulator

Another objective is to develop effective coordinate and redundant control algorithm of the vehicle-manipulator to perform specific intervention missions. Generally, it is unattainable to completely eliminate the coupling function between vehicle and manipulator through mechanical design, but that could be reduced by innovative control strategies as much as possible.

D. Mission planning

In this paper, mission planning includes motion planning and decision. Given the grasping mission, the process from the initial configuration of the UVMS to the final grasping must be designed subtly. Because different performances in every phase are requested. For example, high stability and high precision are demanded for executing the grasping when the vehicle is close to the region of interest, while high speed and high maneuverability are required in other cases.

III. OVERVIEW OF THE UBVMS

Inspired by cuttlefish’s swimming mode, a novel kind of UVMS is designed and constructed. At present, RobCutt II, as depicted in Fig. 2, is developed modularly and integrated together as a test bed to verify developed technologies and methodologies. The RobCutt II is composed of main body, underwater manipulator, and symmetrical biomimetic propulsors. And the main vehicle specifications are listed in Table I. The RobCutt belongs to lightweight underwater robots with only 51.9 kg weight. Moreover, the UBVMS

![Fig. 1. Technical framework.](image-url)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Parameters</th>
<th>Values</th>
</tr>
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<tbody>
<tr>
<td>Length</td>
<td>1323 mm</td>
<td>Weight</td>
<td>51.9 kg</td>
</tr>
<tr>
<td>Width</td>
<td>884 mm</td>
<td>Buoyancy</td>
<td>52.1 kg</td>
</tr>
<tr>
<td>Height</td>
<td>381 mm</td>
<td>Max speed</td>
<td>0.33 m/s</td>
</tr>
<tr>
<td>Main Diameter</td>
<td>260 mm</td>
<td>Max rotation speed</td>
<td>55 °/s</td>
</tr>
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</table>
A. Biomimetic propulsor

Instead of traditional propellers, the RobCut II is propelled through two symmetrical biomimetic propulsors, as depicted in Fig. 2. The motion of the undulatory fin will interact with the water to generate corresponding force and/or moment. The undulatory modal can be formulated as

\[
\begin{align*}
\theta_l(i, t) &= A_l \sin(2\pi F_l t - \frac{\pi}{2}(i - 1) P_l \pi) + B_l \\
\theta_r(j, t) &= A_r \sin(2\pi F_r t - \frac{\pi}{2}(j - 1) P_r \pi) + B_r \\
i, j &= 1, 2, \ldots, 12
\end{align*}
\]

where \( \theta_l(i, t) \) is the deflection angle of the \( i \)th fin ray at time \( t \), and \( A, F, B, P \) are the amplitude, frequency, bias and phase of the undulatory fin respectively. The subscript \( r, l \) denote the right and left, and \( i, j \) are the index of fin ray. The direction and magnitude of all forces or moments are determined by the parameters of the propagating wave on both sides. The symmetrical biomimetic propulsors by working together could satisfy all basic motion demands [11], [12].

Compared to artificial propellers, the biomimetic propulsor is endowed with strong stability, low noise and fine adjustment for natural biological propulsion pattern. Those advantages provide distinctive vantage for underwater autonomous intervention.

B. Underwater manipulator

Benefitting from the experience and lessons learned in project of SAUVIM, the concept of the low ratio of mass of the manipulator and the vehicle body has reached its full potential in the design of this manipulator to reduce coupling effects. The specific mechanical design is detailed in [13], as depicted in Fig. 3. The total mass of the manipulator is 11.929 kg, and the waterproof base’s mass is 11.04 kg, occupying a large fraction of weight of the manipulator. And the mass of the links and gripper is 0.889 kg, only sharing 7.5% of the manipulator’s weight (11.929 kg) and 1.7% of the UBVMS’ weight (51.9 kg) respectively. Particularly, for keeping inherent stable, the rotation range of the base is confined from -10 to 10 degrees. Otherwise, the vehicle would lose its original balance. So a larger direction deflection is preferentially adjusted by the biomimetic propulsors instead of the manipulator.

IV. TECHNOLOGIES AND METHODOLOGIES

The RobCut system is designed to seek the implement of above objectives, and the sketch of the system is depicted in Fig. 4, which consists of the docking support platform, the UBVMS, global visual system, experimental pool, remote console and communication devices. The docking support platform serves for the launch and recovery of the UBVMS. During cruising and intervening, the global vision system detects the location and yaw angel of the UBVMS in real time, then the information is sent to the processor of the UBVMS via communication equipment. Then the pose of the UBVMS could be estimated together with the depth information measured by a water pressure sensor. After the UBVMS arrives in the region of interest, the binocular camera detects the object of interest continuously. In addition, the relative position and orientation expressed in vehicle-fix frame are computed by stereoscopic vision processing. The motion of the UBVMS is planned by mission planning. And, intervening decision is also made by mission planning, which composes of whether performing grasping, whether grasping successfully, whether grasping again or giving up.

A. Underwater localization

The global vision system plays a vital role in the localization and navigation of the UBVMS, as well as the measurement of yaw. Fig. 5 illustrates the schema of the underwater localization. In practical application, this would be replaced by the GPS and LBL or USBL system. The UBVMS is marked with the red and blue label, as shown in Fig. 2. The red color label is firstly segmented by image processing. Then for improving processing speed, the blue color label is detected only in the region around the red label. The central point \( C_b, C_r \) of the blue and red label are calculated respectively. The the midpoint \( C_v \) of \( C_bC_r \) is
regarded as the plane position of the UBVMS. The arrow direction of the line connecting \( C_b \) and \( C_r \) is the yaw angle of the vehicle.

particularly, the influence of the refraction of the light from water to air is eliminated intensively to assure the precision of localization. The geometrical relationship is expressed in Fig. 4. \( I \) is the point of incidence. \( O_w \) is the cross point of light axis of global camera and water surface. \( \theta_w, \theta_A \) are the angle of incidence and angle of emergence respectively. By the refraction law, the following relationship holds

\[
\frac{n_W}{n_A} = \frac{\sin(\theta_A)}{\sin(\theta_W)} = \frac{|IO_W|\sqrt{|C_vH|^2 + |HI|^2}}{|C_vH|\sqrt{|IO_W|^2 + |OC_wO|^2}},
\]

(2)

where \( n_W \) and \( n_A \) are the refractive index of light in water and air respectively.

Define \( [x_I, y_I, z_I]^T, [x_w, y_w, z_w]^T, [x_v, y_v, z_v]^T \) are the position vector of \( I, W, C_v \) respectively, and \( |OC_wO| = z_c \). The geometrical relationships are expressed as

\[
\begin{align*}
|IO_W| &= \sqrt{(x_I - x_W)^2 + (y_I - y_W)^2} \\
x_v - x_I &= \frac{|C_vH|}{|C_vH| + |IO_W|} x_w - x_I \\
y_v - y_I &= \frac{|C_vH|}{|C_vH| + |IO_W|} y_w - y_I
\end{align*}
\]

(3)

Then the revised position can be calculated by following equations

\[
\begin{cases}
x_v = x_I + \frac{|C_vH|}{|IO_W|} (x_I - x_W) \\
y_v = y_I + \frac{|C_vH|}{|IO_W|} (y_I - y_W)
\end{cases}
\]

(4)

Finally, an Extended Kalman Filter (EKF) is adopted to generate smooth status trajectory. Here \( S = [x_v, y_v, z_v, yaw]^T \) is the status vector of the vehicle.

B. Object detection

Binocular camera system is mainly used for object detection and tracking in close range after the vehicle is navigated to the predetermined region of interest.

1) Object segmentation and recognition: Object segmentation is to divide the image into meaningful components based on color, texture, motion, depth, etc.; and object recognition contributes to identifying a specific object in a digital image or video. For simplicity, a red object is chosen as the target. Due to the special light propagation in water, the image is preprocessed to enhance the contrast. In addition, in order to reduce the effect of the light intensity, the threshold is set in the Hue-Saturation-Value (HSV) color space. In Red-Green-Blue (RGB) color space, as depicted in Fig. 6(a). Therefore, the target area can be defined as

\[
S_1 = \{ (i,j) | H(i,j) < T_h \} \quad S_2 = \{ (i,j) | S(i,j) > T_s \} \quad S_o = S_1 \cap S_2
\]

(5)

where \( H, S \) are the magnitude of Hue, Saturation components of pixel point \( (i,j) \) and \( T_h, T_s \) are the thresholds of the Hue, Saturation components in red color feature. Then the contour of the target is depicted, and the geometry center of the region of red is regarded as the center of target roughly.

2) 3D reconstruction: In the above process, the target’s positions in left and right camera image are calculated respectively in real time, as shown in Fig. 6(b) and (c). The intervention is performed in 3D space, and an effective 3D reconstruction method is provided in [14] to obtain the target’s position.

C. Coordinated Control

Broadly, the UVMS is usually kinematically redundant due to the degrees of freedom provided by the UVMS...
itself including the vehicle and manipulator for multiple interventions. The task-priority method provides a flexible, reconfigurable and extensible framework to solve the redundancy control problem. Inspired by active disturbance rejection control (ADRC), a robust iterative task-priority algorithm with tracking differentiator (TD) and state observer (SO) is developed to solve concerted redundancy control of the vehicle and manipulator [15], as illustrated in Fig. 7.

![Fig. 7. The architecture of the robust iterative task-priority algorithm with tracking differentiator and state observer.](image)

Given the settled tasks, the tracking differentiators are performed firstly to calculate the corresponding desired speed and state based on the current configuration of the UBVMS. Actually, tracking differentiators play the roles of motion planning. Then the robust iterative task-priority algorithm is applied to generate the desired velocity of vehicle and joint. Finally, actuation control is executed to make the UVMS move to achieve desired trajectories. And the state observers are used to observe the corresponding states of the UBVMS, further feed them back to the input of the algorithm. This control frame endows the UBVMS with strong stability and high precision in the phase of intervention, which is crucial for the successful intervention under various disturbances.

V. EXPERIMENTS AND RESULTS

To verify the feasibility and effectiveness of the developed framework and methodology, the actual autonomous grasping experiments have been conducted in pool environment. This can be further applied in the autonomous manipulation in outdoor lakes, such as hooking, grasping, and recovering.

A. Experiment on autonomous grasping

Fig. 8 shows the whole process of the autonomous grasping. After the UBVMS is deployed, it starts to adjust the direction firstly from any initial status, and then swims to the region of interest at a relative faster speed at the beginning. Thereafter the binocular camera guides the manipulator’s end gripper to reach the target. Finally, autonomous grasping motion is performed at ripe time. The trajectory of the UBVMS is depicted in Fig. 9 from global camera and in

![Fig. 8. Images of the autonomous grasping. (1)-(4) are the phase of heading direction adjustment, (5)-(8) are the phase of fast approaching to the target, and (9)-(12) are the phase of autonomous grasping.](image)

![Fig. 9. The trajectory of the UBVMS.](image)

![Fig. 10. The trajectory of the UBVMS and the end effector. To the end, the Robx, Roby, Robyaw denote the trajectories in XY plane and the yaw angle of the vehicle body. EEx, EEy are the trajectories in XY plane of the end effector.](image)

![Fig. 10 from history records. In Fig. 10, the yaw has a](image)
sharp change before 10s, which means that the UBVMS first adjusts its direction. The grasping motion is performed at about 67s successfully. Those trajectories demonstrate that the UBVMS arrives at the target and can keep itself stable.

B. Experiment on autonomous grasping with disturbance

In this experiment, we explore the robustness of the developed control strategy by imposing additional disturbance. Specifically, when the UBVMS is ready to perform the manipulation, the UBVMS is pushed away with a tool for several seconds at about 46s, as shown in Fig. 11. Then under the control, the UBVMS gets back to balance, and the autonomous operation is resumed. Fig. 12 describes the process of the imposing disturbance, back in balance and continuing grasping. Finally, the autonomous grasping is achieved.

This provides an ideal experimental platform for successive research in advanced methodologies and applications.

Currently, the experiments are only performed in lab-environment. So further efforts need to devote to autonomous control in the 3D space in the natural environment in the future. The future work will also focus on the higher levels of intelligence by investigating advanced image processing techniques and decision scheme. In addition, further promotion of the levels of autonomy by modified mechanical design and optimized control approaches is another ongoing endeavor.

REFERENCES