Automated Recovery of the UUV based on the Towed system by the USV

Hai-tao GU1
1. State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang, China.
ght@sia.cn

Lingshuai MENG1,2
1. State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang, China.
2. University of Chinese Academy of Sciences, Beijing, China.
menglingshuai@sia.cn

Guiqiang Bai1,2
1. State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang, China.
2. University of Chinese Academy of Sciences, Beijing, China.
baiguiqiang@sia.cn

Yang Lin1
1. State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang, China.
liny@sia.cn

Shuang Liu1,2
1. State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang, China.
2. University of Chinese Academy of Sciences, Beijing, China.
luishuang1@sia.cn

Haiting Zhang 1,2
1. State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang, China.
2. University of Chinese Academy of Sciences, Beijing, China.
zhanghaiting@sia.cn

Abstract—With the development of unmanned systems, automated launch and recovery of an Unmanned Underwater Vehicle (UUV) has become a bottleneck technology. Using an Unmanned Surface Vehicle (USV) to recover an UUV has become one of the direction of the future development of marine unmanned systems. At present, some research institutions have proposed the program using an USV recovering an UUV, but the maturity is not good. In order to achieve an USV autonomous recovering an UUV, this paper designs a recovery device for the USV to recover an UUV. The device is connected by rope to a winch fixed to the USV, with a V-shaped wing below for maintaining the stability of the device. By this device, the USV can launch and recovery the UUV autonomously. This paper first introduces the state of the art for the autonomous recovery, and then analyzes the design background, the structure and stability of recovery device was given. Finally, the dynamic process of an UUV underwater docking was simulated by using hydrodynamic software CFX, and the change of resistance when the recovery device was docked under different working conditions was obtained. The numerical simulation shows that when the UUV moves closer to the recovery device, the viscous resistance of the UUV gradually becomes larger. When the UUV approaches the recovery device, the pressure resistance rapidly decreases. However, the total resistance change of the UUV first increases and then decreases. In addition, the recovery device designed in this paper has good stability and has a certain guiding significance for the dynamic recovery of an UUV in the future.

Keywords—USV, Recovery, UUV, Underwater

I. INTRODUCTION

After decades of development in science and technology, underwater robot technology has gradually become mature[1], and the Unmanned Surface Vehicle (USV) technology has also made considerable progress in recent years[2]. At present, the launch and recovery of an UUV basically requires the help of manned ships and manpower. In order to reduce the difficulty of the launch and recovery of an UUV on the manned platform, especially the difficulty of personnel operations and the risk of equipment damage in high-sea state, an urgent demand for unmanned automatic launch and recovery technology is put forward[3][4]. Meanwhile, with the rapid development of unmanned platforms and unmanned systems, the demand for the cooperation between USVs and UUVs is increasing. It becomes one important research direction with great potential and value to use an USV to support and manage an UUV. It has many advantages to use an USV to launch and recovery an UUV, for example, it can reduce the safety risk on the one hand, and on the other hand it can realize the automation and unmanned launch and recovery of an UUV, which can clear technical obstacles for the future development of marine unmanned system.

Florida Atlantic University, Massachusetts Institute of Technology, and Kongsberg Company all conducted a series of researches on the USV to recovery the UUV [5][6][7]. They discussed and analyzed the programs and strategies for USV recovery UUV, but did not thoroughly study the hydrodynamic analysis of the underwater recovery process. The main mechanical factors affecting the recovery success rate can be obtained through hydrodynamic calculation and analysis.

II. RESEARCH ON UUV’S UNDERWATER RECOVERY

Underwater dynamic recovering an UUV by an USV means that the surface platform(USV) towed a recovery device which can move with the surface platform to complete the capture and recovery of an UUV below the surface. Compared to surface recovery, the underwater recovery not only avoids unfavorable load impact caused by the surface wave, but also reduces the impact of the unsteady flow generated by the recovery platform(such as USV) on the UUV. At present,
several institutes have done some new concept designs and researches on dynamic recovering an UUV by an USV.

A. Funnel recovery program

The shape of this recovery device is like a funnel [8]. Kongsberg's Hydroid designed a device for underwater recovery of REMUS 100 UUV[9] that can be mounted on a moving platform, combining a funnel-shaped recovery device with a V-shaped wing, using a Digital Ultra Short Base (USBL) and Long Base Line (LBL) to guide the UUV to dock with the recovery unit. During the eleven successful docking test samples, the number of test samples less than 2 times accounted for 77%, and the impact of depth on the success rate is analyzed. This study shows that it is feasible to use the surface platform to tow a recovery device to recover an UUV below the water surface. However, this recovery device experiment was implemented on a manned vessel and has not been tested on unmanned platforms such as an USV. In addition, funnel recovery device has some restrictions on the size of the recovery device, and high precision requirements for final guidance is also required.

B. "Scissors" and rope capture recovery program

The program relies on an USV to suspend single UUV. A flexible rope is suspended from the USV, and a V-shaped stabilizing wing is hinged at the end of the rope [10]. At the same time, the UUV's crotch section was modified. The "scissors" were used to grip the rope to complete the capture. Fig.2 shows the recovery program designed by Florida Atlantic University, using the WAM-V catamaran USV and the REMUS 100 UUV. The advantage of this solution is that the UUV can approach the rope from any direction. It can also be clamped between the stabilizers and the cable range between the USVs. The disadvantage is that there is a need to design a clamping mechanism on the UUV, which increases the complexity of the system.

C. "Wings" and rope capture recovery program

The program uses clips to install "wing"-shaped clips outside the UUV, and captures the ropes with clips on both sides[11]. Fig. 3 shows the underwater moving base recovery scheme designed by Florida Atlantic University. The WAM-V USV was used to suspend the double ropes. The wings on the REMUS 100 hook the ropes to complete the recovery. This solution allows UUV to dock in a wide range, but the docking angle is limited, while increasing the UUV's navigational resistance.

III. DESIGN OF RECOVERY DEVICE

In order to recover an UUV from an USV, a variety of recovery schemes are designed, and a feasible recovery scheme was introduced in the following detail.

A. Design background

In this article, a portable UUV was used, and the main technical details of this UUV are shown in Tab. 1. This UUV uses a Doppler Velocity Log and an electronic compass for underwater navigation, and the USV uses GPS and electronic compass to navigate on the surface. The USV and the UUV communicate with each other in real time through their underwater acoustic communication sensor. They can get information about positions, directions and speed from each other. The two platform can know each other's location and motion information at any time, and calculate the location for autonomous rendezvous, and guide UUV to navigate to the capture device. The bow section of UUV is equipped with a binocular vision sensor, and the final guidance algorithm based
on optical array can provide a higher precision guidance for the UUV’s capture device at short distance.

| Tab. 1 | TECHNICAL SPECIFICATIONS FOR PORTABLE UUV |
|--------|-----------------------------------------|
| Weight | 75kg                                    |
| Length | 1776mm                                  |
| Diameter | 250mm                                  |

The process of an USV dynamic recovery of an UUV can be divided into three parts: long distance, medium distance and close distance docking. The recovery process is shown in Fig. 5.

**B. Structural design**

After installing a small automatic winch on an USV, two cables of the winch limits the horizontal plane rotary motion of recovery device. There is an “V” shape wing under the recovery device, such as its structure shown in Fig. 6, the process for the USV autonomous recovery the UUV was shown in Fig. 7.

The head of the recovery device uses an electromagnet, which can lock the portable UUV after the docking is completed. A stroke switch is installed at the head of the recovery unit to confirm whether the docking is successful. The use of electromagnets as a locking device simplifies the overall structure. Compared with the common hydraulic locking device, the electromagnet is easily manipulated and simple in structure.

The seven LED lamps are installed outside the horn to provide close range optical vision guidance for UUV. A depth meter is installed on the recovery device to be informed of the depth information of the recovery device.

The V shaped wing used in this recovery device is the Rolls Royce V-WING 460 of Rolls-Royce company. The maximum length of V shaped wing is 460mm, the maximum width is 510mm, the maximum height is 185mm, and the weight is 8kg. According to the description in the instructions, the resistance R and the lower pressure L of the V wing are shown in Tab. II.

**Tab. II** | THE RELATIONSHIP BETWEEN THE VELOCITY AND THE FORCE OF ROLLS ROYCE V-WING |
|------------|-----------------------------|
| velocity/(m/s) | 1  | 1.5 | 2  | 2.5 |
| Pressure force/N  | 99.9 | 164.6 | 231.3 | 280.2 |
| drag/N          | 16.6 | 26.7 | 33.4 | 48.9 |

A vertical wing is designed in the rear of the V wing to ensure that the left and right deflections are not occurred when it moves at different speeds. The water drag experiments show that in a certain towing speed range, V wing can maintain depth stability. Adjusting the V wing’s drag can let V wing keep...
stable attitude. The V wing will provide a stable downward pressure for the recovery device.

In order to increase the probability of successful capturing an UUV, the recovery device needs to maintain a steady motion when moves with the USV, so it is necessary to satisfy the balance of the space force system. Recovery device is in a stable state, recovery device is a symmetrical structure. Rope drag force, fluid resistance, gravity, buoyancy, V wing tension can be equivalent to the recovery device of the center of gravity, they focus on the moment can balance each other, so the force can be simplified to a flat plane.

![Fig.8. Force analysis for the recovery device](image)

Fig.8. Force analysis for the recovery device

O is the center of gravity, coordinates is established as shown in Fig. 8, T1 is the drag force on the equivalent recovery device, T2 is equivalent force on the recovery device for the V-wing, F is recovery device of horizontal fluid resistance, G is gravity, the buoyancy of the recovery device is B, 1 and 0 is the angle between T1 and the vertical direction, is the angle between the T2 and the vertical direction. Expressed as:

\[
\begin{align*}
F_{\text{fluid}} + T_1 \cos \varphi &= T_1 \cos \theta \\
G + T_1 \sin \varphi &= T_1 \sin \theta
\end{align*}
\]

where 0 and can be expressed as

\[
\begin{align*}
\theta &= \arctan \frac{F_{\text{fluid}} + R}{G + L - B} \\
\varphi &= \arctan \frac{R}{L}
\end{align*}
\]

C. Stability analysis

During the design process of the recovery device, we need to analyze its dynamic stability when it is towed in water, and ensure that the recovery device does not have large sloshing in the process of docking recovery and improve the success rate of docking acquisition. Therefore, the following specific measures have been taken in the design.

(1) The use of double cable suspension recovery device restricts the movement of the recovery device in the water, and transfers the double cable to three cable through the transfer plate, so as to prevent the recovery device from rotating in the horizontal plane. To a certain extent, the design ensures the stability of the recovery device during docking.

(2) The recovery device is a hollow structure, which reduces the fluid resistance and reduces the influence of water flow on the recovery device and increases the stability. The simplified structure is used to increase the feasibility and reliability of the scheme.

IV. HYDRODYNAMIC SIMULATION ANALYSIS

the mature Computation Fluid Dynamics (CFD) software named “CFX” was selected to carry out the resistance computational simulations.

A. Drag calculation of recovery device

1) Mesh Generation

The CFD software CFX is used to calculate the resistance of the recovery unit to the water. The resistances under six

| Velocity /(kn) | Mesh grid scale /mm | Encrypted area grid scale /mm | Calculated domain grid scale /mm | Growth Factor | First layer Boundary layer height /mm |
|----------------|---------------------|-----------------------------|---------------------------------|--------------|-----------------------------------|
| 0.5            | 10.7                | 21                          | 160                             | 1.15         | 0.17                              |
| 1              | 9.6                 | 20                          | 145                             | 1.20         | 0.09                              |
| 1.5            | 9.1                 | 18                          | 136                             | 1.25         | 0.06                              |
| 2              | 8.7                 | 17                          | 131                             | 1.28         | 0.05                              |

![Fig.9. The mesh for the recovery device](image)
conditions of 0.25m / s, 0.5m / s, 0.75m / s, 1m / s, 1.25m / s and 2m / s were calculated.

k-\(\omega\) model is a turbulence model commonly used in engineering. It is suitable for most occasions. After repeated analysis, the model can meet the requirements of this paper. The calculation uses k-\(\omega\) model, the final calculation results steady-state error converges to less than 2%.

The recovery unit moves in water, creating a flow field as shown in Figure 11 with a turbulent flow around and behind it, which may affect the proximity of the UUV. The resistance that is experienced increases with the speed of the quadratic curve. Take part of the simulation data into Equation (1) to obtain the value of \(\theta\) as shown in Tab. IV.

\[\text{Resistence} \propto \text{Velocity}^2\]

| Velocity (kn) | Mesh grid scale /mm | Body grid size /mm | Calculated domain grid scale /mm | Growth factor | First layer Boundary layer height /mm |
|---------------|---------------------|--------------------|---------------------------------|--------------|-----------------------------------|
| 1             | 21.4                | 46                 | 342                             | 1.3          | 0.096                             |
| 2             | 19.4                | 41                 | 310                             | 1.365        | 0.05                              |
| 3             | 18.3                | 39                 | 293                             | 1.4          | 0.03                              |

\(\theta\) represents the angle between the recovery device and the rope when the recovery device is towed by the USV, and the change of \(\theta\) will affect the depth variation and depth stability of the recovery device, which will directly affect the position and success rate of the intersection capture. When designing the recovery device, the \(\theta\) value should be as small as possible to ensure that the depth of the recovery device does not vary by more than 20% and the \(\theta\) value does not exceed 37°. In this paper, \(\theta\) is 27.7° and the rate of change of depth is 11.5% when the recovery device is moving at 4kn. The change is within the acceptable range.

### B. Drag calculation of docking process

#### 1) Mesh Generation

When the UUV docks with the recovery device, the size of the encryption area is 7600×1150×1150 mm, the size of the calculation domain is 21200×7000×7000 mm, and the number of boundary layers is 10. Pointwise grid parameter settings shown in Tab. V, Recovery device’s mesh was shown in Fig. 12.

![Mesh for docking scene](image)

#### 2) CFD

The capture of UUV and recovery device belongs to the process of dynamic rendezvous. In this paper, CFX simulation is used to calculate the flow field and the drag characteristics in this process. UUV rendezvous and docking process, at different locations, with different speeds, angles of attack and recovery device docking, use k-\(\omega\) model, get the UUV by the resistance data shown in Fig.12.
In Fig. 13 to Fig. 15, A indicates that the angle of attack is 0 degree and the speed is 1kn; B indicates that the angle of attack is 5 degrees and the speed is 1kn; C indicates that the angle of attack is 10 degrees and the speed is 1kn; D indicates that the angle of attack is 0 degree and the speed is 2kn; E means the angle of attack is 5 degrees and the speed is 2kn; F means the angle of attack is 10 degrees and the speed is 2kn; G means the angle of attack is 0 degree and the speed is 3kn; H means the angle of attack is 5 degrees and the speed is 3kn; A That angle of attack is 10 degrees, the speed of 3kn.

According to Fig. 13, the resistance received by the UUV during its approach to the recovery device first increases and then decreases. UUV by the resistance is divided into viscous resistance and pressure resistance, as shown in Fig. 14 and Fig. 15. the flow field and pressure profile of the UUV as it approaches the recovery unit was shown in Fig. 16 and Fig. 17.

When the UUV comes close to the recovery device from a long distance, the frictional resistance it receives increases. After the water passes through the recovery device, a turbulent zone will be formed on the back side, which will cause the relative velocity of the fluid in the zone to increase, so the Reynolds number Re increases.

\[
Re = \frac{\rho v l}{\mu}
\]

In the formula, \( \rho \), \( v \) and \( l \) respectively the density of the fluid, relative flow rate and a characteristic length. According to the Prandtl-Schishler formula:

\[
C_{DF} = \frac{0.445}{(\lg Re)^{3.8}}
\]

Frictional resistance \( C_{DF} \) will be reduced.

\[
F_0 = C_{DF} \rho v^2 A
\]

Equation (3), (4) and (5) show that when the UUV close to this area, the viscous resistance will be gradually increased. When the UUV reaches the vicinity of the recovery unit, the pressure differential resistance received by the UUV rapidly decreases. Affected by the recovery unit, a low-pressure flow area is formed thereafter, and the UUV’s resistance to pressure differential decreases rapidly as it reaches this area.

For funnel recovery units, UUVs will experience a drastic reduction in resistance as they approach the recovery unit, and once the UUV arrives in the area, it will help to increase the capture success rate for rendezvous and docking.

On the basis of the above research work, we have proposed a new recovery scheme, as shown in Fig. 18, and will carry out the lake test in this summer.
V. CONCLUSION

This paper summarizes the current underwater docking and recovery devices abroad based on mobile platforms, and analyzes their advantages and disadvantages. We propose a recovery scheme and device design scheme can be used for an USV dynamic recovery of an UUV, and introduce the design idea and mechanical structure of the device, make the analysis to the flow field changes and the attitude stability of the device during the dynamic rendezvous, and obtain effective data.

The hydrodynamic calculation and force analysis were carried out for the recovery device, and its navigation resistance change curve and attitude change trend were obtained. We analyze the docking process between the portable UUV and the recovery device, and obtain the change of navigation resistance at different speeds and angles of attack. The following conclusions were obtained:

(1) The recovery device in this paper uses the design of double-cable to triple-cable suspension towing, hollow structure, stable towing and hinged stabilizing wing, and has sufficient dynamic stability to meet the stability requirements during docking.

(2) The angle between the towing rope and the vertical direction of the earth coordinate system is within 0 to 37° to ensure that the depth of the recovery device during the towing process is within a controllable range.

(3) When the UUV approaching the recovery device, the recovery device will form a turbulent flow behind, will UUV by the viscous resistance gradually increased. When the recovery unit is about to be contacted, the low-pressure zone created after the recovery of the unit will rapidly reduce the pressure drop resistance. During the UUV approaching the recovery device, the resistance received increases first and then decreases.

At present, the technical maturity of an USV dynamic recovery of an UUV is still relatively low, which has great research space and development potential. In view of the proposed scheme, the theoretical analysis and simulation research are mainly carried out in the early stage of this paper. At present, the research on experimental verification methods is being gradually carried out. In the follow-up test verification work, it is planned to add a posture sensor to the recovery device to monitor the posture of the recovery device to further verify or modify theoretical research results.

ACKNOWLEDGMENT

This work was supported by The Innovation Fund from Chinese Academy of Sciences(Grant No. CXJJ-17-M130); The Advance Research Fund of Science and Technology(Grant No. 3020605040302); The Joint Fund for Advance Research from Chinese Academy of Sciences(Grant No. 6141A01061601).

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