AUV terminal docking experiments based on vision guidance

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***Abstract*— In this paper, we present the terminal docking experiment of an autonomous underwater vehicle (AUV) based on vision guidance. The configuration of this docking system, including the AUV and the docking system, is proposed. The vision guidance system using one camera and one light is described in detail. The vision based guidance algorithm namely the imaging processing can be divided into 4 stages: image acquisition, binarization of the grabbed images, elimination of noisy luminaries, estimation of the relative posture. Based on the vision based guidance algorithm, the control algorithm, which can control the underactuated AUV to track the dock without the distance information, is shown. To validate the proposed guidance and control algorithms, a pool trial was conducted. The results of the pool trial show the effectivity of proposed algorithm. Some improvements to be done in the future are described at last.**

Keywords—Autonomous Underwater Vehicle; terminal docking; vision guidance;

I. Introduction

Autonomous Underwater Vehicles (AUVs) are playing a growing role in oceans because of their vast scientific, commercial and military applications. However, the high-power draw of instrumentation and the low capacity of battery limit AUVs' endurance to roughly one day. Then, underwater docking technology which has the ability of recharging battery, transferring data and safely parking AUV has been proposed in recent decades. Guiding AUV to a docking station is one of the core technologies to realize underwater docking. Robert S. McEwen et al. [1] divide this guiding stage into homing and docking sequence. The homing guidance sequence would lead the AUV to the field near the docking station mostly using some acoustic positioning and inertial navigation sensors, and this has been successfully dealt with by numerous researchers [2-4]. While, several kinds of guidance technologies have been proposed and applied in the docking guidance sequence, that include acoustic guidance [5, 6], electromagnetic guidance [7] and optical guidance [8-11].

As compared with the docking guidance technologies mentioned above, the optical guidance is simple but more effective, especially in the near range of 0–15 m [10] and is most widely used as a result at present. Park JY .et al [8] adopted one charge-coupled device (CCD) camera and five lights as the vision guidance system to guide the AUV to the dock in the docking sequence. While, two CCD cameras and four green LED lights were applied in the vision positioning method by Li Y .et al [9]. Apart from the vision-based scheme, other optical guidance system that replaces the traditional CCD camera with quadrant detector was also proposed and tested [10], which offers a novel idea to realize the underwater docking.

In this paper, we focus on the short range guidance process in the terminal docking sequence. In our scheme, considering the design to be reliable and simple, we only used one CCD camera and one high-power LED light to

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realize the AUV vision based guidance. Both the hardware and the algorithm relevant to the vision guidance are quite simple. The results of trials in pool demonstrate the satisfied guidance accuracy.

This article is organized as follow: Section II shows the system configuration; Section III discusses the vision guidance algorithm and relevant control method; Section IV demonstrates the terminal docking trail in a pool; Lastly, section V as the conclusion part presents the merit and demerit of the terminal docking system and proposes some future improvements.

II. System Configuration

A. Design of AUV

The docking AUV in our project as shown in Fig. 1 is a modified version of *Dolphin II* [12], whose bow part was replaced with new sections and the sequence of some other sections of which was exchanged to be convenient to accomplish the docking task, and to transfer power and data in the contactless method. It is designed to work in vast sea up to 100 m in depth. According to the original design, the speed of the AUV could reach 5 knots, which was verified in previous lake trials. The modified AUV can be divided into five sections: Bow Section, Non-contact Section, Battery & Control Section, Navigation & Communications Section, Tail Section. An ultra-short baseline (USBL) and a CCD camera are installed in the bow section as shown within the blue box in Fig. 1.The USBL is used in the long range guidance process. The fairing in bow section is made of polycarbonate, which has small light and sound attenuation.

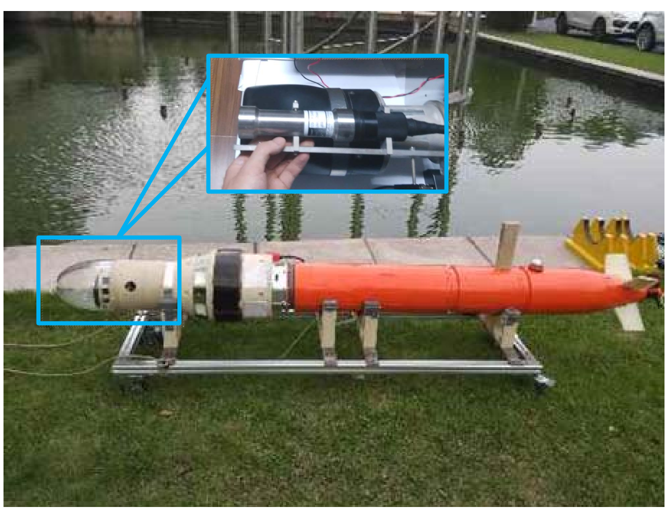

Fig. 1 Configuration of the AUV Dolphin II

B. Docking station

The docking station is mainly composed of a dock, a housing and a base. To prevent the AUV from touching the bottom of the sea, a 3 m-high pyramid base was designed. While for convenience in the preliminary trial, the base and housing was not used. The dock, consisting of a cone, a tube, an initial guidance light, a terminal guidance light and a monitoring camera, is mounted on the base and shown in Fig. 2. The cone is conically shaped and made up of some staves held in place by two stainless steel rings. The entry diameter of the cone is as large as 1.2 m, which is 6 times equal to the diameter of the AUV; the taper angle of the cone is chosen as 76 degrees. The tube can lock and park the AUV after a successful docking. Initial guidance light mounted on the tube and terminal guidance light fixed at the center of the tube end are the key device to lead the AUV to the dock in the terminal docking sequence. The monitoring camera can monitor the AUV's docking process, which is helpful to switch the initial and terminal guidance light.

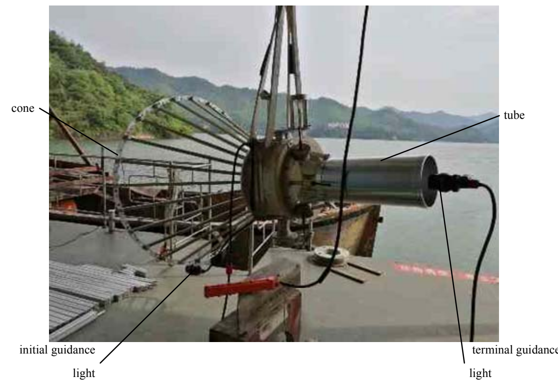

Fig. 2 structure of the dock

C. Hardware of the vision guidance system

As Fig. 3 shows, four components, including two guidance lights, underwater CCD camera, visual processing unit and navigation computer, constitute the vision guidance system. There are two guidance lights (i.e. initial guidance light and terminal guidance light) in the system. The viewing angle of underwater CCD camera can be up to 70 degrees. The layout of LEDs of the guidance light is demonstrated in Fig. 4. The maximum power of the guidance light can be up to 80 W, at which the guidance distance can reach 30 m. During the terminal docking process, ether the initial guidance light or the terminal guidance light would be switched on, but not both. When the AUV is far away from the docking station, the initial guidance light would be turned on firstly. At that time, the initial guidance light can not only guide the AUV as a beacon, but also illuminate the surrounding for the monitoring camera as a light source. After the AUV appears in the monitoring camera view, the initial guidance light would be turned off, and the terminal guidance light turned on instead. Then the AUV follows the terminal guidance light to complete the docking mission.

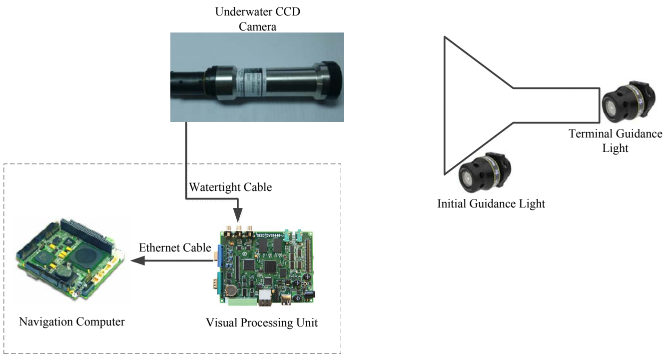

Fig. 3 components of the vision guidance system

Fig . 4 Layout of LEDs

III. THE VISION BASED GUIDANCE AND CONTROL ALGORITHM

In this paper, only one camera and one light are used to guide the AUV. Then it is impossible to acquire the distance information between the AUV and the docking station. Instead, we only used the relative posture to guide and control the AUV.

The vision guidance algorithm, namely the image processing, consists of four stages: (1) image acquisition, (2) binarization of the grabbed images, (3) elimination of noisy luminaries, (4) estimation of the relative posture between the AUV and the dock.

Stage (1): Raw image was grabbed through the underwater CCD camera in PAL format. Generally, the grabbing rate can be up to 25 Hz. But light was scattered, it was difficult to estimate the position of the light in image coordinate.

Stage (2): To acquire the position of the light in image coordinate, the visual processing unit classified the raw image into two groups, namely the bright group and the dark group, using the method of Otsu. The adaptive threshold value t was adopted as the average value of all the elements of set A . Set A can be chosen as

$$A=\left\{k^* \mid \delta_B^{\,2}\left(k^*\right)=\max_{0\le k\le L-1} \delta_B^{\,2}\left(k\right), k^*\in\left[0,L-1\right]\right\}$$

Where, L is the number of intensity levels; and $\delta_B^{\,2}$ denotes the between-class variance. Then, the result of the binarization is

$$p_{ij}=\begin{cases} a & p_{ij}>t \\ b & p_{ij}<t \end{cases}$$

Generally, a and b are chosen as 1 and 0 respectively.

Stage (3): The binary image with some noises brought adverse effect to estimate the position of the light. The area of the noisy zone is much smaller than that of the target zone. Then the pixels with small connected region area were removed to eliminate the noisy influence. The threshold value of the connected region area was chosen by trial-and-error.

Stage (4): After above processing, the position of the light in image coordinate can be acquired easily. The center of mass of the target zone was chosen as the position of the light and expressed in the image coordinate as

$$\begin{pmatrix}\bar{u} & \bar{v}\end{pmatrix}=\begin{pmatrix}\dfrac{\sum\sum_D u\times\mu(u,v)}{\sum\sum_D \mu(u,v)} & \dfrac{\sum\sum_D v\times\mu(u,v)}{\sum\sum_D \mu(u,v)}\end{pmatrix}$$

Where, u and v are the abscissa and ordinate of the processed pixel in image coordinate; $\mu(u,v)$ is the pixel value of the processed image. Hence $\bar{u}\in\left[-m/2, m/2\right]$ and $\bar{v}\in\left[-n/2, n/2\right]$.

Because of only one light, we can get the relative posture information here. Also we can only control heading of the AUV to eliminate the cross-distance error as a result of the AUV's underactuated characteristic. Following [13], we transform the cross-distance error to relative angles between the AUV and the dock axis in this paper. We assume the viewing angle of the underwater CCD camera is 2α. Then, if the light is within the viewing angle of the camera, the relative angles of the AUV's heading and the dock's axis are β in horizontal plane and ϑ in vertical plane, shown as

$$\beta=\arctan(2\bar{u}/m\times\tan\alpha)$$
$$\vartheta=\arctan(2\bar{v}/n\times\tan\alpha)$$

Here, through the vision guidance algorithm mentioned above, we got the vision based relative angle information whose processing rate could reach 10 Hz. Then, combined with the relative angle information, we can control the underactuated AUV more accurately.

Actually, though some navigation device such as Ultra Short Base Line (USBL) and Doppler Velocity Log (DVL) are used in the long range, the slow updating rate and low precision limit their use in close range. We choose the compass and combine with the vision based relative angle information to control the AUV in the terminal docking sequence. The simple and reliable controller, i.e., the PID controller, was chosen. Fig. 5 shows the control scheme for steering motion in the horizontal plane. In the scheme, ψ_{ref} and ψ indicate the yaw angle of the dock and the AUV in the inertial frame (i.e., the dock coordinate) respectively. ψ_{ref} is measured by the compass in the dock and transmitted to the AUV through the USBL. ψ is the processed output of the compass in the AUV. β_{ref} represents the expected relative angle between the AUV's heading and the dock's axis in horizontal plane and is often set as 0 degree. Through the scaled and summed transformation, the input of the PID controller can be shown as

$$e = \left(\psi_{ref} - \psi\right) + k\left(\beta_{ref} - \beta\right)$$

Where, k is a proportional factor indicating the P Controller in Fig. 5.

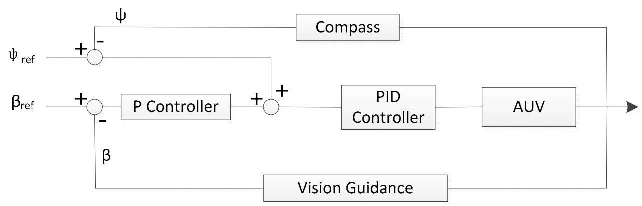

Fig. 5 Control scheme for steering motion

Similar with the control scheme in horizontal plane, replacing ψ with θ and β with ϑ and exerting the homogeneous replacement to the expected angles, we can easily get the control scheme for diving motion in vertical plane. θ_{ref} and θ indicate the pitch angle of the dock and the AUV in the inertial frame (i.e., the dock coordinate) respectively. ϑ_{ref} is also set as 0 degree generally. So far, the control algorithm has been acquired in the terminal docking sequence.

IV. Pool Trial

To validate the vision based guidance and control algorithm in the terminal docking sequence, a terminal docking trial shown in Fig. 6 was conducted in Yuquan Campus of Zhejiang University. The pool is about 50m × 25m × 1.4m , and the walls and the bottom of the pool are all smooth. Because of the insufficient depth, only the motion in horizontal plane was tested. To emulate the dark environment in the deep ocean and eliminate the disturbance of false light, the pool trial was done at night. Also at that time, the pool surface was quite calm with little disturbance of the current. In the final use, two LED lights, i.e. the initial guidance light and the terminal guidance light, are to be adopted and switched according to the distance between the AUV and the dock. While because of no diving motion conducted here, only one LED light was employed and placed in the same location with the terminal guidance light described in section II.

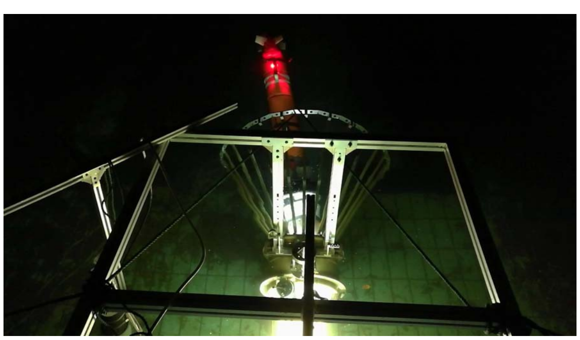

Fig. 6 Terminal docking trial in Yuquan Campus

Fig. 7 demonstrates the AUV's tracking trajectory within horizontal plane in the dock coordinate under diverse initial cross-distance errors (i.e., 5 m, 2 m, 0 m, -4 m and -8 m) but with no heading errors. The AUV at the starting point indicated with black rhombuses was about 45 m far away from the dock in the x_d direction. Under these initial configuration, the AUV followed its incipient heading and made some turning after capturing the effective vision signal when the axial distance was about 20 m. The AUV conducted the terminal docking missions successfully under above configuration though the maximum initial cross-distance error reached up to 8 m in the experiment.

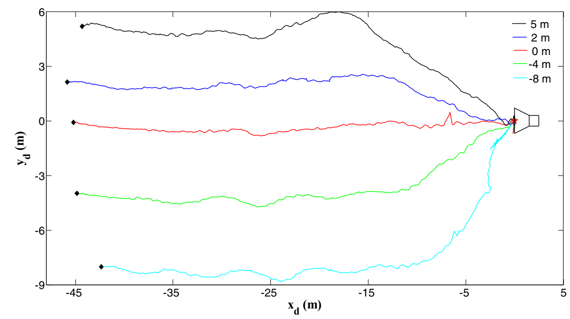

Fig. 7 AUV's tracking trajectory in the dock coordinate

When the initial cross-distance error was -8 m, Fig. 8 depicts the AUV's velocities in the camera coordinate. It took the AUV about 110 s to complete the terminal docking mission with a speed of 0.4 m/s, although approximately 20 s was used during the acceleration phase. During this process, AUV's position in the y_i direction tended to zero especially after 55 s when the AUV caught the beacon (i.e., the navigation light). While because of the sharp impact between the AUV and the dock, AUV's position in the y_i direction suffered large vibration between 112 s and 122 s. The position value returned back to zero after completing the docking mission.

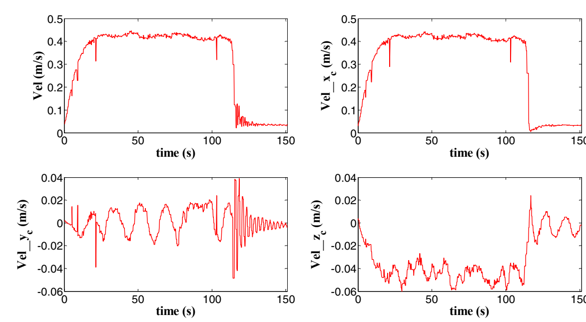

Fig. 8 AUV's velocities in the camera coordinate when initial cross-distance error was -8 m.

V. Conclusion and Future Work

This paper presents a terminal docking process based on one camera and one light. The configuration of this docking system, including the overview of the AUV and the docking station and the detailed description of the optical guidance system, is proposed. Through the analysis of the vision based guidance algorithm, we can control the underactuated AUV to track the dock without the distance information. To validate the proposed guidance and control algorithm, a pool trial was conducted. The results of the trial show the validity of the proposed algorithm.

The proposed algorithm in this paper is simple, convenient and also efficient owing to the straightforward algorithm and limited optical hardware. On the other hand, the anti-interference capability of the vision based docking system is a bit bad. Some other lights with the tantamount intensity to the navigation lights may guide the AUV to false directions. Improving the anti-interference capability is to be done. Also the pool trial only validated the steering motion of the terminal docking in horizontal plane. The performance of the terminal docking in vertical plane is examined in the ongoing lake or shallow sea trial.

VI. Acknolledgement

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