

VISION BASED 3D MEASUREMENT AND GUIDING SYSTEM FOR REMOTELY OPERATED UNDERWATER VEHICLE

Xi ZHANG¹, Laiwei LI² and Junyi YANG³

¹ Shanghai University, Yanchang Rd.149, Zhabei District, xizhang@shu.edu.cn

² Shanghai University, ³ The Second Institute of Oceanography, SOA

Abstract:

Remotely operated underwater vehicles (ROV) equipped with manipulator have been used for underwater operation increasingly. The ROV is usually operated manually with the aid of underwater camera to approach and grasp a target by its manipulator. Due to the low quality of underwater imaging, it is quite difficult for the human operator to determine the accurate distance and orientation between the ROV and the target interested. This paper presents an idea of developing an automatic 3D measurement and guiding system for ROV in an effort to facilitate this process. Based on structure-light triangulation principle, dual laser line and a camera are utilized to calculate the position and orientation of a cylindrical target. The measurement model considering refraction compensation and system calibration method is proposed. A prototype measurement system is designed and tested in a simulated underwater environment by a glass water tank. The experiments show that the proposed system is feasible to determine the position and orientation of the target automatically on an accurate and efficient manner.

Keywords: ROV, Underwater manipulator, 3D measurement, Guiding

1. INTRODUCTION

With the development of deep exploration of ocean, remotely operated underwater vehicle has attracted increasing attention. The ROV is usually equipped with underwater manipulator for operation task for example grasp a handle in order to dock the ROV to an underwater platform. Currently, with the aid of an underwater camera the ROV and manipulator are operated manually to execute this kind of task. Due to the low quality of underwater imaging, it is difficult for the human operator to determine the accurate distance and orientation between the ROV and the target interested. Therefore, it is time-consuming to approach and grasp the target due to the process of trail and error. The underwater 3D measurement method contributes to overcoming these difficulties.

Nowadays, the acoustic detection technology [1-2], laser radar technology [3], monocular vision technology [4] as well as structured-light technology [5-6] are used for underwater 3D measurement. Since the underwater structure-light technology possesses the advantages including high accuracy, low cost, non-contact measurement, suitable for close range measurement and so on [5], it is utilized in the paper. An underwater structure-light system with dual line is presented to measure the distance and orientation between a ROV and a cylindrical target.

2. METHODOLOGY

2.1 Proposed Measurement System

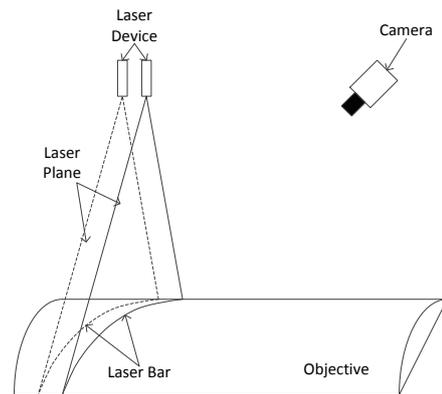


Fig. 1: Automatic 3D measurement and guiding system

An automatic 3D measurement and guiding system for ROV in an effort to facilitate its manipulator to grasp an object was proposed as shown in Fig. 1. Based on line structure-light triangulation principle, the system consists of a camera and two laser diodes. The laser diode projects a light plane onto the target to form a laser line, which is imaged by the camera. The 3D coordinate on the target can be calculated by the intersection of a light ray and the laser plane. With two laser planes, the position and orientation of a target can be determined.

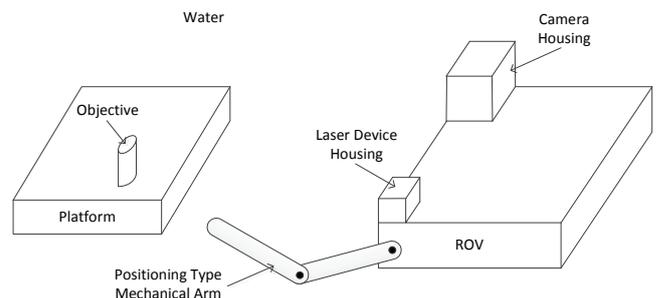


Fig. 2: Function description of the whole system

This system is designed to function as shown in Fig.2. First, ROV is manually operated to approach the target at a distance to make the target appear in the field of view of the proposed measurement system. Then the automatic guiding mode is activated. The position and orientation of the target relative to the coordinate system of the ROV is calculated by the measurement system. This information will be feed back to the control unit of the ROV on a real time basis to

adjust the direction of ROV automatically in order to keep the target within the field of view of the measurement system. In this way, the ROV is guided to approach the target continuously. Finally, when the ROV is close to the target at an appropriate distance, the manipulator on the ROV will grasp the target accurately according to the measurement results. This function description is shown in Fig. 2.

2.2 Measurement Model

Since a camera and two laser diodes respectively are enclosed in the waterproof housing, the refraction effect is inevitable when the whole system is utilized underwater. Considering the refraction influence, the measurement model of the automatic 3D measurement and guiding system is shown in Fig. 3. The model is based on the perspective projection model of a camera. Note that O_1 is the center of the camera image plane, O represents the optical center of camera and z axis is the optical axis of camera lens. The relevant coordinate frames are defined as follows: O_1XY is 2D normalized image coordinate frame, ouv is 2D image plane coordinate frame, $O_wx_wy_wz_w$ is 3D world coordinate frame and $Oxyz$ is 3D camera coordinate frame. Meanwhile, we define some known geometry relations in the model, such as $Ox // O_1X // ou$, $Oy // O_1Y // ov$ and $Oz \perp ouv(\text{plane})$.

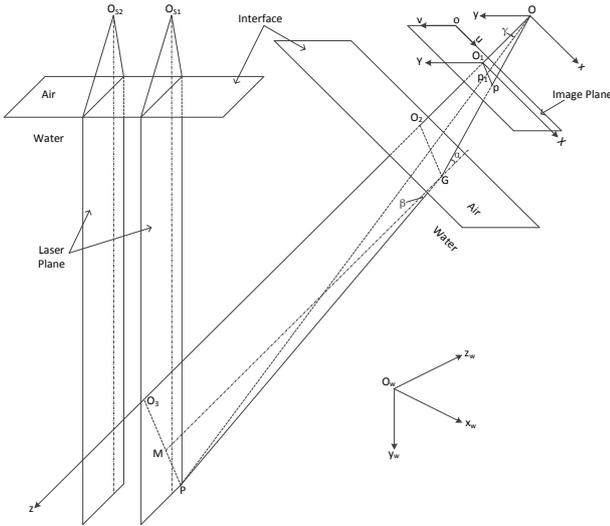


Fig. 3: Measurement model of the system

When the refraction impact is neglected, the light path is described approximately as the dash line in the Fig. 3. Like this, a common perspective projection model is applicable. Given one point P in the 3D camera coordinate frame, its coordinate is denoted as $P = (x, y, z)$ and the coordinate of corresponding perspective projection point in the 2D image plane coordinate frame is denoted as $p_1 = (u_1, v_1)$.

Firstly, the coordinate of point p_1 in the 2D normalized image coordinate frame is solved by

$$X_1 = dX(u_1 - u_0), Y_1 = dY(v_1 - v_0) \quad (1)$$

where (u_0, v_0) is the coordinate of principal point O_1 in the 2D image plane coordinate frame, dX and dY represent the physical size of a pixel along the X and Y axis, respectively.

Secondly, correct the camera lens distortion in the focal length normalized plane. First and foremost, the focal length normalized plane is defined as follows: the optical axis of camera lens is vertical to this plane, the distance of the camera focal point to this plane is 1mm and the coordinate frame in this plane is analogous to the 2D normalized image coordinate frame. Hence, the coordinate of point p_1 in this plane is solved by

$$X_d = (u_1 - u_0)/a_x, Y_d = (v_1 - v_0)/a_y \quad (2)$$

where $a_x = f_x / dX$ is the normalized focal length in the X axis, $a_y = f_y / dY$ is the normalized focal length in the Y axis, f_x and f_y respectively represent the effective focal length in the X and Y direction. Then we utilize the following model to handle lens distortion effects.

$$X_d = X_p + X_p r^2 (k_1 + k_2 r^2) + 2p_1 X_p Y_p + p_2 (r^2 + 2X_p^2)$$

$$Y_d = Y_p + Y_p r^2 (k_1 + k_2 r^2) + p_1 (r^2 + 2Y_p^2) + 2p_2 X_p Y_p$$

$$r^2 = X_p^2 + Y_p^2 \quad (3)$$

where (X_p, Y_p) is the ideal coordinate of point p_1 in the focal length normalized plane, k_1 and k_2 are the coefficients of the radial distortion, p_1 and p_2 are the coefficients of the tangential distortion.

Thirdly, solve the coordinate of point P in the 3D camera coordinate frame. In the 3D camera coordinate frame, point P is located on the line through point O and ideal point $p_1(X_p, Y_p)$ in the focal length normalized plane. Meanwhile, point P is located on the laser plane (see Fig. 3). So utilize the equation of the line and the equation of the laser plane, the coordinate of point P in the 3D camera coordinate frame is solved.

$$x/X_p = y/Y_p = z/1 \quad (4)$$

$$ax + by + cz = 1 \quad (5)$$

In section 2.3, the paper describes how to solve the equation of the laser plane.

Considering the refraction effect, the optical path becomes the full line from the dash line (see Fig. 3). At the same time, the perspective projection point of point P in the 2D image plane coordinate frame becomes point p . Hence, point p should be changed back to point p_1 in order to calculate the coordinate of point P in the 3D camera coordinate frame. The process is defined as refraction compensation. Utilize Equation (1) to solve the coordinate of point p in the 2D normalized image coordinate frame. Then based on the geometric relation, the coordinate relation between point p_1 and point p in the 2D normalized image coordinate frame is described as $(X_1, Y_1) = k(X, Y)$. From the geometric relation, the compensation coefficient k is solved by

$$k = \tan\gamma / \tan\alpha = ((O_2O_3 \tan\beta + O_3M) / OO_3) / (O_1p / OO_1)$$

When $OO_3 \gg OO_2$, utilize following equations, then the coefficient k can be obtained:

$$k \approx \tan\beta / (\sqrt{X^2 + Y^2} / f_a), f_a = (f_x + f_y) / 2, n_w = \sin\alpha / \sin\beta \quad (6)$$

where (X, Y) is the coordinate of point p in the 2D normalized image coordinate frame, n_w is the refractive

index of water, α and β represent refraction angle and incidence angle respectively.

After finishing the refraction compensation of point p, the coordinate of point p_1 in 2D normalized image coordinate frame is obtained, then Equation (2) ~ (5) are utilized to calculate the coordinate of point P in 3D camera coordinate frame.

2.3 System Calibration

In order to realize the function of the automatic 3D measurement and guiding system, first and foremost, calibrate the sealed system that a camera and two laser devices respectively enclosed in the waterproof housing in air is essential. In the paper, with water-tank simulating the sealed environment, collect a kind of calibration pictures as shown in Fig. 4. During collecting calibration pictures, obtain pictures of the target in different positions and guarantee the laser bar is projected on the black portion of the target in every picture.

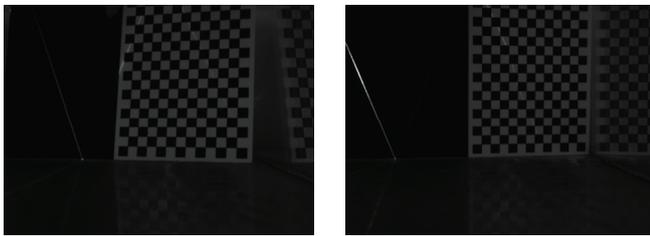


Fig. 4: Images for system calibration

Firstly, finish the camera calibration. In the paper, the method of camera calibration refer to Ref. [7] is utilized to calibrate the camera with checkerboard as calibration target. So obtain camera intrinsic parameters, lens distortion coefficients and external parameters of the target in 3D camera coordinate frame in every picture.

Secondly, the laser plane equation in the 3D camera coordinate frame is calibrated. In the paper, utilize the centroid method to extract the coordinate of every central point on the laser line in the 2D image plane coordinate frame. Then based on Equation (1) ~ (5), the coordinate of every central point in the 3D camera coordinate frame is solved. However, the equation of the laser plane need replace with the equation of the target plane. In every picture, obtain the equation of the target plane through utilizing external parameters of the target in 3D camera coordinate frame. Finally, utilize the coordinate of every central point in the 3D camera coordinate frame to fit the laser plane equation with the least square method.

3. EXPERIMENTAL STUDY

3.1 Prototype System Design

In this paper, a prototype system is designed in order to investigate whether the proposed method is applicable in the simulated environment. Based on actual application requirements, a CCD camera with a 6mm lens and two 50mW laser diodes whose wavelength is 650nm and 532nm respectively are chosen. Fig. 5 shows the prototype system. A camera and two laser devices are fixed on an aluminum

alloy plate. In addition, a water-tank is utilized to simulate the waterproof housing and underwater application environment (Fig. 6).

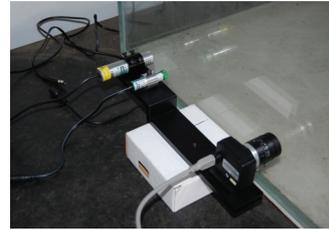


Fig. 5: Prototype system



Fig. 6: Simulated underwater environment

3.2 Refraction Compensation Experiment

In order to verify whether the refraction compensation method is feasible, the experiment is designed as follows. First, take images for system calibration. Utilize the prototype system and the empty water-tank to collect calibration pictures in air. Then, inject an appropriate volume of clear water into the water-tank and immerse the calibration target in the water to collect calibration images. Second, respectively calibrate the system parameters in air and underwater. Third, verify whether the proposed method is feasible. Utilize the refraction compensation method to measure every square side length along the row direction on the checkerboard of underwater calibration images (Fig. 7), where the real value of square side length is 15mm. The result of experiment is shown in Table 1. By the experiment, feasibility of the proposed refraction compensation method is proved.

Table 1: Measurement error of square side length(mm)

	Min	Max	Mean	Standard deviation
1	0.0045	0.2809	0.0840	0.0756
2	0.0002	0.1729	0.0509	0.0406
3	0.0028	0.1463	0.0481	0.0355
4	0.0019	0.2435	0.0950	0.0707
5	0.0042	0.3424	0.1111	0.0758
6	0.00008	0.1504	0.0531	0.0398
7	0.0002	0.1313	0.0381	0.0279
8	0.00008	0.1572	0.0496	0.0387
9	0.0021	0.1161	0.0383	0.0269
10	0.0008	0.1511	0.0404	0.0331
11	0.0053	0.1862	0.0609	0.0410
12	0.0011	0.3581	0.0421	0.0477
13	0.0075	0.3109	0.1708	0.0711
14	0.0093	0.3393	0.1697	0.0654
15	0.0611	0.3495	0.1894	0.0666
16	0.0260	0.3306	0.1778	0.0610
17	0.0366	0.4188	0.2243	0.0646
18	0.0203	0.3275	0.1720	0.0597
19	0.0401	0.3423	0.1696	0.0654
20	0.0078	0.3413	0.1606	0.0692
21	0.0037	0.2698	0.1110	0.0692
22	0.0163	0.2808	0.1449	0.0704
23	0.0101	0.2542	0.1285	0.0636
24	0.0095	0.3081	0.1484	0.0701

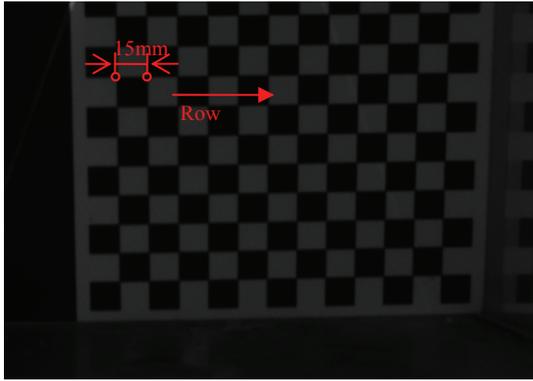


Fig. 7: Measured square side length underwater image

3.3 System Function Simulation Experiment

In the practical application, the position and orientation of a cylindrical target need be determined with this system. Therefore utilize this method to respectively detect 3D center points on two laser lines. Then use two sets of points to fit an ellipse respectively and calculate the coordinate of ellipse center point in the 3D camera coordinate frame. So the position and orientation of a cylindrical target can be determined using the coordinate of two ellipse center. Then this information will be feed back to the control unit of the ROV. Finally, the target can be grabbed. So design the experiment as follows. Detect the direction cosine of a cylindrical target (Fig. 8) in three positions. And calculate the distance between the optical center of camera and the midpoint of the line that is between two ellipse center points in the initial position. The result of experiment is shown in Table 2. The experimental results is in the 3D camera coordinate frame. Define the center point of ellipse on the 650nm laser plane as C_1 , while another center point is C_2 . With the vector quantity C_2C_1 , calculate the direction cosine.



Fig. 8: Utilize a cylindrical target in the experiment

The results show that the proposed method and the measurement system can complete the required function in the practical application accurately.

Table 2: Experimental results

Position		1	2	3
C1(mm)	x	-153.4537	-153.3718	-151.2845
	y	-63.6602	-59.2456	-45.5995
	z	911.0508	872.2841	797.4018
C2(mm)	x	-203.2136	-203.0872	-196.4807
	y	-34.5751	-32.3290	-11.6193
	z	956.0498	909.0484	829.7648
Direction cosine	x	0.6805	0.7372	0.6937
	y	-0.3978	-0.3991	-0.5216
	z	-0.6154	-0.5452	-0.4967
Distance(mm)		951.6993	909.4771	832.4491

4. SUMMARY

This paper presents an automatic 3D measurement and guiding system, which consists of a camera and two laser diodes. And the measurement system is enclosed in the waterproof housing. Hence, the refraction effect is inevitable. The paper proposes to utilize the overall system calibration parameters in air and the refraction compensation to calculate the coordinate of a point on the laser line in the 3D camera coordinate frame. By the refraction compensation experiment, feasibility of this method is proved. Meanwhile, the system function simulation experiment proves that the proposed system in the paper can accomplish the requested function.

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