Design of Underwater Coordinate Measuring Machine Using Multi-joint Link

Soji Shimono, Uichi Nishizawa, and Shigeki Toyama

***Abstract*—In this paper, an underwater positioning system that consists of underwater robot and multi-joint serial link. The serial link is connected to the underwater robot from the water surface. The position of the underwater robot is obtained from kinematics of the serial link. The experimental model for evaluation of the proposed system is developed and its detail is explained. Then positioning error due to the joints angle measurement error is evaluated and influence of the underwater environment to the proposed positioning system is also discussed.**

***Index Terms*—Underwater inspection, underwater positioning, multi joint link.**

I. Introduction

In recent times, there has been an increase in the needs for underwater observation, such as ocean resource exploration [1], [2] and dam inspection [2], [3]. High-resolution inspection data are required to identify the target correctly and therefore advanced observation methods are required. The position data of the observation platform, such as a remotely operated vehicle (ROV) or autonomous underwater vehicle, becomes more important for implementing such a method. Therefore, accurate positioning is a major maritime research theme given that the global navigation satellite system (GNSS) is not functional in water. Therefore, acoustic positioning systems and inertial navigation systems (INS) or a hybrid system of these devices are mainly used for maritime work [5], [6]. However, the acoustic positioning system requires a proper sound velocity profile of the area in which the system is deployed to obtain an accurate position. When the inspection platform is near the complex structure, the incorrect position is sometimes obtained due to the multi pass of the sound wave. On the other hands, since INS suffers from inevitable drift, the position needs to be regularly updated by another method. Another positioning method is the KCF Smart Tether which obtains a vehicle's position using a tether cable including several accelerometer. The shape of the cable is estimated from the accelerometer and the position of the vehicle toward the end of the cable is obtained. A Smart Tether was used in the inspection of an ancient waterway, which has a narrow entrance [7].

In positioning equipment used on land, a coordinate measuring machine (CMM) that has a multi-joint serial link has been used for precise object shape measurements. The position of its probe is calculated by the kinematics of the serial link. Because it can perform stable position measurements with high accuracy, it is possible to measure narrow sites and positional drift is not an issue. However, the application of this method for underwater positioning has not yet been confirmed. In this study, the underwater coordinate measuring machine (UWCMM) consisting of a multi-joint serial link and ROV is proposed as a novel method for underwater positioning. This study aims to clarify the feasibility of the proposed method, and to understand the effects of an underwater environment on the accuracy of the method. This paper explains the concept of UWCMM and the detail of developed experimental model. And the influence of the joint angle measurement accuracy and the underwater environment to the positioning accuracy of the UWCMM are discussed.

II. UWCMM

The conceptual diagram of the UWCMM is shown in Fig. 1. The system consists of an underwater robot and multi-joint serial link. The underwater robot performs an inspection and its position from a base point that is defined above the water surface is obtained from the multi-joint serial link. The position of the base point is measured by GNSS. When the base point is set on a ship, some swinging is unavoidable. So, as well as the acoustic positioning method, the orientation of the base point is measured by an attitude sensor to compensate for the calculation of the underwater robot that is at the tip of the serial link. The underwater robot has maneuverability, the probe of the CMM can be manually manipulated or by the CMM itself to measure the target object.

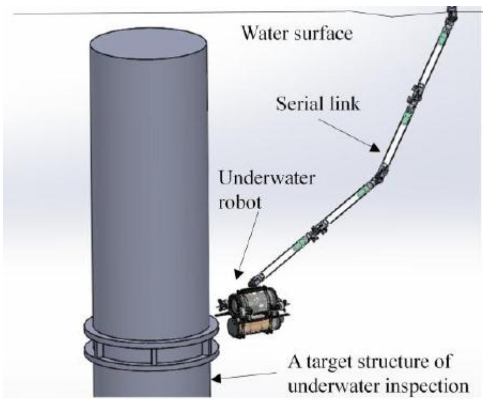

Fig. 1. Concept of the UWCMM.

However, in an underwater environment, the former is impractical and the latter requires a large torque in the root joint when the total length of the serial link becomes longer.

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This increases the cost of the serial link because each joint has a different design. Thus, the underwater robot manipulates its own position to reduce the requirement for increased joint torque. Because of this, each joint can have the same design and suitable number of joints can be selected depending on the inspection task. To summarize, the proposed UWCMM can be defined as a ROV whose tether cable is replaced by a multi-joint serial link.

III. Design of UWCMM

An experimental model of the multi-joint serial link for the UWCMM was developed. The model is used for water tank experiment that evaluate the feasibility of the UWCMM. The appearance of the model is shown in Fig. 2. This chapter explain design of the model.

A. Mechanism

The experimental model has five joint and each joint has single axis. The direction of each joint axis is twisted by 90 ° from the next joint in the axial direction of the link. All joint and link has same design, thus the number of joint is configurable by adding new joint.

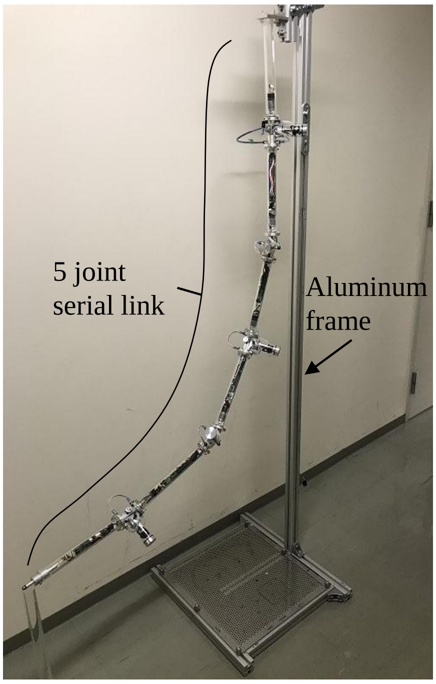

Fig. 2. Appearance of experimental model.

The mechanism of a joint is shown Fig. 3. The joint has absolute rotary encoder for joint angle measurement. Although high resolution encoder is required to obtain higher accuracy of the position measured by UWCMM, such encoder makes joint larger because its diameter is large. Such larger structure takes more drag force of water current, and it is disadvantages to endure water pressure. Thus, small size encoder whose resolution is as higher as possible was selected for experimental model of the UWCMM. Its diameter is 21 mm and resolution is 18-bit. The encoder is directly connected to the joint axis using coupling. The encoder is housed in the pressure vessel and the joint shaft throw into the vessel. The shaft is sealed by O-ring. Although the magnet coupling is a reliable method for waterproof rotation transmission, it has angle gap between input side and output side. The gap produce positioning error of the UWCMM. So the O-ring seal is selected for the experimental model. The joint also has a geared motor, which transmits torque to the joint using a miter gear.

Each joint are connected with link which is pipe structure. The pipe is flanged acrylic pipe. The connection between joint structure and pipe is sealed with O-ring. The pipe house the electronics of the UWCMM.

B. Electronics

Each link include electronics that performs reading joint angle obtained from encoder, controlling motor, and communication to the water surface. A link include all electronics required to one joint. The system diagram is shown in Fig. 4. The microcontroller read joint angle, then transmit angle information to the water surface equipment though the controller area network (CAN) communication. The architecture of the CAN communication is bus type and the electronics can be connected serial.

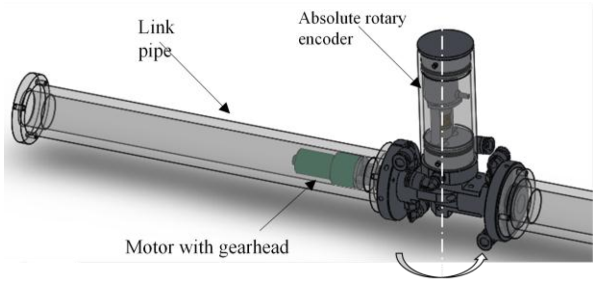

Fig. 3. Joint mechanism.

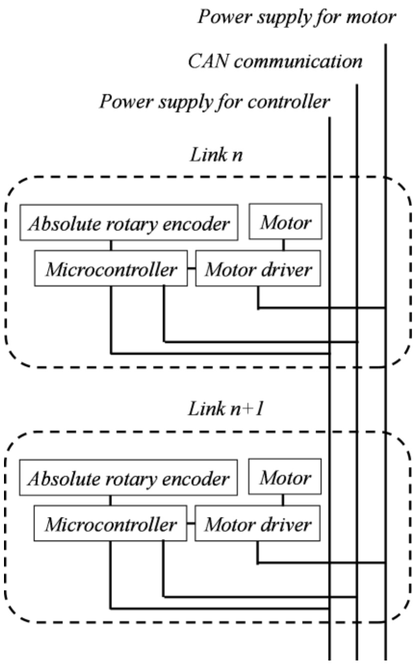

Fig. 4. System diagram of electronics.

IV. Measurement Accuracy

This chapter discus about accuracy of the UWCMM. As factor effect to the accuracy, resolution of the encoder and kinematics parameter error are considered. The kinematics parameter error can be reduced by calibration as well as industrial manipulator. Here, the effect of encoder resolution is discussed, and external influence by underwater environment is also discussed.

A. Joint Angle Measurement Error

Joint angles are measured by encoder, its maximum measurement error is 0.5 LSB. This error produce positioning error of the UWCMM and the error of each joints are accumulated to the tip. Thus the error increase with number of the Joint of UWCMM. Here try to evaluate the effect of the joint angle error. The rotation matrix around the axial direction of the link and the rotation matrix around the joint axis are expressed in equation (1), (2), respectively. And the position vector of the tip of the multi-joint link from the root link is obtained from equation (3).

$$\boldsymbol{R}^i(\theta)= \begin{pmatrix} 1 & 0 & 0 \\ 0 & Cos(\theta) & -Sin(\theta) \\ 0 & Sin(\theta) & Cos(\theta) \end{pmatrix} \quad (1)$$

$$\boldsymbol{R}^k(\theta)= \begin{pmatrix} Cos(\theta) & -Sin(\theta) & 0 \\ Sin(\theta) & Cos(\theta) & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (2)$$

$$\boldsymbol{r}(\theta) = \boldsymbol{R}^i\left(\frac{\pi}{2}\right).\boldsymbol{R}^k(\theta_1).\boldsymbol{l}_1 + \sum_{m=2}^{n}(\boldsymbol{R}^i\left(\frac{\pi}{2}\right).\boldsymbol{R}^k(\theta_1).\cdot \cdot \cdot \cdot .\boldsymbol{R}^i\left(-\frac{\pi}{2}\times -1^m\right).\boldsymbol{R}^k(\theta_m)).\boldsymbol{l}_m \quad (3)$$

$$\boldsymbol{\theta} = (\theta_1, \theta_2, \cdot \cdot \cdot \theta_n) \quad (4)$$

$\boldsymbol{l}$ is the link length vector, and it is defined as $\boldsymbol{l}^T=(l,0,0)$. l is the length between joint to joint. θ is joint angle. Here the position error that defined as the difference between $\boldsymbol{r}$ $(\theta_{1\sim n} = 0)$ and $\boldsymbol{r}$ ($\theta_{1\sim n}$ = 0.5 LSB of 18-bit resolution) is evaluated.

Fig. 5 shows the percentage of the position error to total length of the multi-joint link and the percentage of length of link to length of multi-joint link against the number of joint. It indicate that the position error is proportional to the number of joint. Although small number of joint has small error, it require long length to the link. Such longer link is cumbersome to operate. The number of joint have to decide with consideration about positioning error and operation situation. The experimental model has five joint and its length of a link is 0.33 m, the total length is approximately 1.9 m. Thus its positon error by encoder resolution is 0.043 mm.

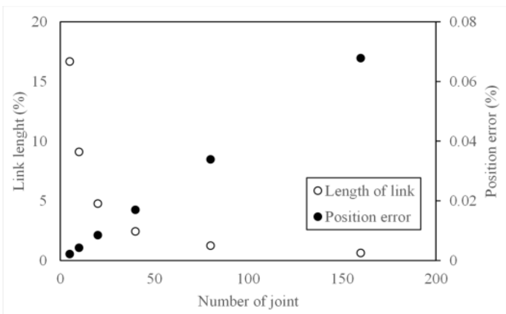

Fig. 5. position error produced by joint angle error vs number of joint.

B. Influence of Underwater Environment

As the factor effect to the positioning accuracy by underwater environment, water pressure, temperature changing, and water current are considered. These factor produce displacement of the structure of the multi-joint link, and parameter of the kinematics is changed.

The temperature of the ocean is decrease with depth, and it smaller than 5 ℃ at the over 1000 m of depth. Here we assume that the UWCMM is inserted from a water surface whose atmospheric temperature is 27 ℃ to a water depth of 1000 m or more, and the deformation in the case where the temperature of the multi-joint link has changed to 22 ℃ is considered. The major materials that used for underwater pressure vessel, is aluminum-alloy, stainless-steel, and titanium-alloy. Table I shows the length displacement percentage due to the temperature changing of the multi-joint link that is regarded as one straight rod. Used coefficient of thermal expansion is also shown the table. As is clear from coefficient of thermal expansion, titanium has most small displacement in the three materials, if the total length of multi-joint link is 1000 m, the displacement is 0.19 m. To compensate positioning error due to this displacement, it is considered that estimate the displacement by adding temperature sensor in the link and calibrate geometric parameter error of the kinematics.

TABLE I: PERCENTAGE OF THE DISPLACEMENT WITH TEMPERATURE CHANGE IS 22°C

	coefficient of thermal expansion (1/k x 10^{-6})	Length of expansion (%)
A6061	23.6	0.052
SUS304	17.0	0.037
Ti-6Al-4V	8.8	0.019

The water pressure produce displacement of the structure of the UWCMM. The displacement proportional to the depth and the positioning error due to the kinematics is increase at the deeper water. To reduce this error, to compensate the displacement of each link and joint is considered. The depth of each element of the multi-joint link can be calculated by the kinematics and displacement can be calculated by the water pressure estimated from the depth.

When water current exist at the operation area or ROV of the UWCMM is cruising, multi-joint link subjected the drag force from the water current. The force produce deflection of the structure of the multi-joint link. It occur positioning error. In addition, the drag force that too large will restrict the maneuverability of the ROV.

V. SUMMARY AND FUTURE WORKS

A novel underwater positioning system that consists of underwater robot and multi-joint link is proposed. And experimental model of the multi-joint link for evaluation experiment in water tank is developed. Then the positioning error that produced by joint angle measurement error due to the encoder resolution is discussed. And the positioning error due to the encoder of the experimental model is 0.043 mm is obtained. The influence of the underwater environment to the positioning accuracy of the UWCMM is also discussed.

For the future works, study about the positioning accuracy when water pressure and water current are effecting to the UWCMM is considered.

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