2024 9th International Conference on Automation, Control and Robotics Engineering (CACRE) | 979-8-3503-5030-2/24/$31.00 ©2024 IEEE | DOI: 10.1109/CACRE62362.2024.10635067

Investigation of Propeller Control Method Focusing on Reverse Force Input for Collision-free Arrival Motion of Ship

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***Abstract*—In this paper, a novel controller design focusing on reverse input using propeller thruster such as air plane taxiing and ship for collision-free arrival motion was proposed and evaluated in mock up model. And ultimately, it is necessary to control the position, attitude and speed at the same time. The operation of docking at a port has not yet been automated by machines, and is known as a special skill that requires the concentration of craftsmen. In our study, to aim at automating accurate docking and berthing operations in ship control, we used an airplane-type model with a propeller, which is relatively easy to test, rather than a test environment using water, where the effects appear three-dimensionally, and the reaching motion characteristics on the ground were investigated. In this process, we focused on the reverse motion often employed when the craftsman controls the ship. We developed two types model devices of ground taxiing airplane and ship, and perform the reaching movement experiment by normal P, PD control and human's visual feedback control also performed. As a result, in order to rapid approach without overshoot, the applied thrust for a constant time period gave relatively good results, and it was possible to control stably even though it was necessary to search for parameters. By comparing with a human control by pressing keyboard button method using a reverse force input, it also relatively good result, and by introducing the human reverse force input way to the thrust for a constant time period method, it could realize rapid and stable controlling. As a basic study, we developed a simple ground taxiing airplane model and U-shaped guided model ship to realize a rapid, non-overshoot and stable reaching movement. The difficulty of the reaching movement would be mainly occurred by propeller / screw type thruster control difficulty, however, by using a human control way of using reverse force input, we found some reaching movement performance improvement even though using a constant time period forward / reverse force input controller.**

***Index Terms*—reverse motion, reaching movement, thruster, basic study, airplane, ship**

I. Introduction

In this paper, a novel controller design focusing on reverse motion using propeller thruster such as air plane taxiing and ship for collision-free arrival motion was proposed and evaluated in mock up model. To realize steering a ship accurately (especially for docking at the port), it is necessary to grasp the motion characteristics of the hull, the fluctuation characteristics due to waves and wind, and the surrounding environment [1] . And ultimately, it is necessary to control the position, attitude and speed at the same time [2]. The operation of docking at a port has not yet been automated by machines, and is known as a special skill that requires the concentration of craftsmen [2], [3], [4].

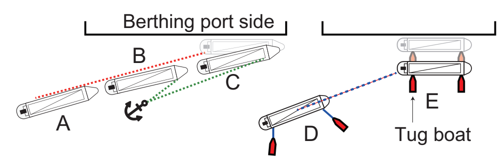

Fig. 1. Background of difficulties of docking operation of ship. Light weight ship dock approaching method (Left). To stable approaching, the anchor is usually used. And it is necessary some tug boats in the case of a heavy weight ship (Right).

Figure 1 left shows the ship approaching basic process to dock case of the left side berthing. First, A of Fig.1 approaches to the dock and in the timing of B, the ship anchors (green dot line and anchor mark)[3], [5]. Next, after the anchoring, while extending the length of the chain appropriately, and the ship decelerates to reach the anchorage position (sign C, using the anchor is the key).

Figure 1 right shows the ship approaching basic process to dock using two tug boats. D of the figure represents that two tug boat closed and connected to the ship by a tug rope, and the ship was moved to the dock horizontally by coordinated operation of the two tug boats (E).

In the above situation, we focused on a reverse force input behavior of the craftsmen's ship control process. It is mainly seen in decelerating period when approaching to the dock (D or E phase in Fig.1(b)), the operator generate a reverse input (negative force input) for rapid deceleration. Figure 2 (a) explains the one x axis simplified concept of the reverse force input for the rapid deceleration and correct approaching. Vertical axis x means the distance from the dock and the ship intended to move to the target dock position x_0, and horizontal axis means the time. To simplify the story, we considered

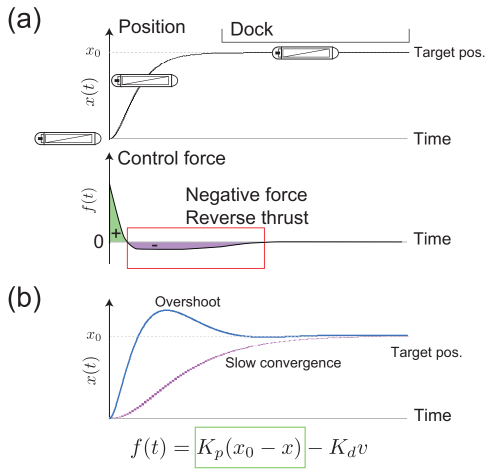

Fig. 2. Backgrounds. (a) Simple model x axis only dock approaching. All the cases, there is a wall at the dock and it must be docked as close as possible. The control force transition have forward and reverse input control by tug boat or craftsman's control process. (b) Only P type controller induces overshoot fashion by the reason of the controller design when the rapid movement. To reduce the overshoot fashion, basically it is necessary to reduce the settling time.

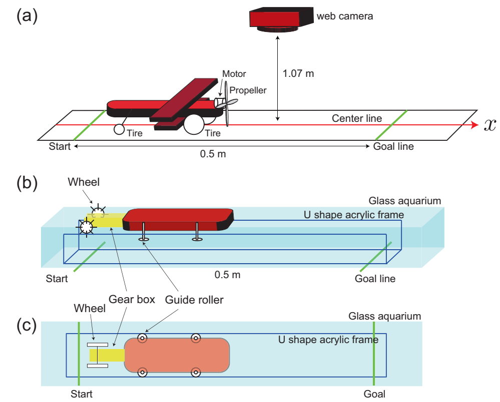

Fig. 3. Experimental setup. (a) Characteristic verification reaching movement experiment of propeller-type propulsion mechanism on the ground. (b) Ship model reaching movement experiment on the water. (c) To reduce the lateral side fluctuation of the ship, a U-shape acrylic frame was placed in the 0.9 m length aquarium. The width of the U-shape frame was fixed to the width of the four corners wheel.

only x axis lateral motion of the ship. First, since the target position x_0 is the physically the motion boundary, the ships have conditions under which they must not "overshoot" [6], [7], [8], [9], [10]. In these situation, the craftsmen's control strategy adopts the reverse force input. $f(t)$ of Fig.2(a) means the control force input transition of rapid and non overshoot movement of $x(t)$. There is a negative force ($f(t) < 0$) value area (the red rectangle, purple filled area) in the $f(t)$, and it generates the rapid speed down by the reverse thrust.

From the viewing of normal proportional (P) and differential (D) control method [9], [10], Fig.2(b) graph represents the basic motion features of the PD control, and though the speed of the approaching to the x_0 mainly depends on the K_p so as P control gain, a large K_p (the blue graph) tends to lead a large overshoot. To suppress this overshoot feature by a physical boundary condition as the dock quay, it is necessary to reduce the K_p, and it would induce the approaching speed down (purple line graph) [11], [12], [13], [14], [15].

If there is a physical boundary condition that x_0 must not be exceeded, the controller output $f(t)$ takes always "positive" value ($f(t) \geq 0$, the green rectangle of the figure), and it means there is "no" negative force generation such the craftsman's using strategy - the reverse force input.

As the force generating module, in the sense that it operates with a propeller, the airplane have the same control difficulties as the ships. To avoid serious equipment / mechanical / environment problems using model ship on water, we firstly used a model plane moving on the ground. Next, we develop a model ship floating on the water in a vertically long water tank, and motion control experiment was performed.

Our aim of this study is to examine the role of a craftsman's reverse force input on the model airplane / ship by developing

.

II. Method

Figure 3(a) shows the experimental setup of the characteristic verification reaching movement of propeller-type propulsion mechanism on the ground. And developed airplane and ship models. The airplane model with one propeller connected to a small DC blush motor (wing is not used, three wheel was attached) and a 4WD car model with same DC blush motor were used. The control axis was only x axis, and the model is to stop accurately at a distance 0.5 m from the starting position (green line to green line) along a straight line. The target position of the airplane and car was measured by the web camera (BUFFALO, BSW20KM11BK, 320 x 240 dots, 30 fps) that was positioned 1.07 m height from the ground.

Figure 3(b) shows a ship model reaching movement experiment on the water. The ship frame is made of styrene plates, and it has a small DC blush motor gear box (yellow) and it is connected to two paddle-wheel propulsors. To reduce the friction between the inside wall of the aquarium and the ship, we added four guide roller wheels to four corners of the ship. In addition, to reduce the lateral side fluctuation of the ship, a U-shape acrylic frame was placed in the 0.9 m length aquarium (Fig.3(c)). The width of the U-shape frame was fixed to the width of the four corners wheels.

The web camera was connected to Windows PC (Win 11) , and PWM signal generating microcomputer Arduino UNO was also connected to the PC via USB cable. A motor was driven by a FET(2SK2936, motor supply voltage is 6.5 V), the motor rotational direction was changed by a transistor (2SC1815) and 5V 2C type mechanical relay, and it were controlled by an Arduino UNO's PWM / digital signal ports. The main power with the PWM modulation was transferred via 0.03 mm diameter light weight twisted urethane wire. It was holed by a wire stand equipped near the web camera.

III. EXPERIMENT

Experiment 1 performs the difference between three basic thrust control methods that was implemented in the airplane model. The device (airplane/ship) position was measured from the red marker area of the web camera by using Processing language environment in the PC. The frame rate of the position detection was about 30 Hz (equal to the control command frequency).

There are three control method was used in this experiment 1:

Method 1:

$$f(t) = K_p(x_0 - x), \tag{1}$$

where $f(t)$ means the PWM output of the Arduino (0 - max 255), x_0=0.5 m, x mean the goal position and the present position of the model, and K_p is a simple proportional gain of the controller.

Method 2:

$$f(t) = K_p(x_0 - x) - K_d v, \tag{2}$$

is the general PD controller (K_d is the differential control term).

As experiment 2, we verified the possibility of accurate arrival control only using the time interval change (Method 3). In the experiment, the time interval t_0 was changed while changing by 20 msec. This experiment is intended to test that the reaching movement could be realized by even if the typical most simple feed forward (such a Method 1) when the friction between the tires and the ground, and the influence of the wind from the air conditioner are almost constant.

Method 3:

$$f(t) = \begin{cases} f_0 & t \leq t_0 \\ 0 & t > t_0 \end{cases}, \tag{3}$$

where f_0, t_0 is a constant power input, a constant power input time width respectively.

Experiment 3 performs that to introducing a craftsman's control strategy of non-overshoot rapid reaching movement for controlling the airplane, a human subject controls the airplane thrust by his hand, Experiment 3 used three keys beginner control - pushing keyboard buttons, G, R, V corresponds to Forward, Reverse, Stop respectively.

Experiment 4 performs that using the parameters estimated from the human reaching movement experiment 3 using a reverse input, the following time intervals t_0. t_1 are controlled as Method 4.

Method 4:

$$f(t) = \begin{cases} f_0 & t \leq t_0 \\ -f_0 & t \leq t_1 \\ 0 & t > t_1 \end{cases} \tag{4}$$

. The parameters of Exp.3 were used for the optimal time t_0, t_1 for this reaching movement as experiment 4.

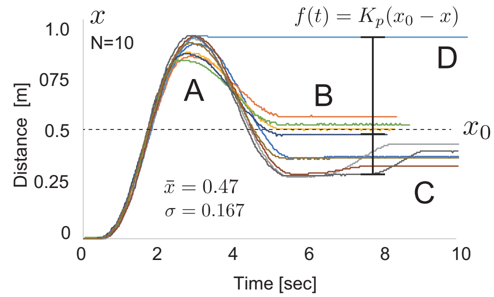

Fig. 4. Result of experiment 1, only P control case.

At last, as experiment 5, the reaching movement trend was confirmed by using the airplane and ship. The control method was used general PD controller in this case.

IV. RESULT

A. Experiment 1

Figure 4 shows the result of experiment 1 (airplane case) and the controller was used Method 1 (P only controller) described in the Experiment section. Vertical axis represents x reaching distance from the start position x=0, and the target position is x_0=0.5 m. Horizontal axis is time [sec]. After over 100 times reaching experiment, we experimentally searched a parameter K_p that has the shortest arrival time and accurately converges to the arrival position x_0=0.5 m. Next, we measured N=10 times airplane model 0.5 m (x_0, the horizontal black line) reaching movement using propeller thruster.

Until point A of the figure, the x was increasing stably although there are large overshoot (max is 1.0 m). And after the point A, the convergence features showed mainly three various characteristics. Three / N=10 cases were converged relatively correct target position x_0=0.5 m in the form of one reverse movement after the overshoot. Most common reaching movement was four / N=10 cases (the area C) that converged to a non-overshoot $x < x_0$ area with a large noise in the form of one reverse and one forward movement after the overshoot. And in non-zero cases, one or two out of N=10 cases (the area D) was sticked somewhere mainly the speed v is relatively low area such the area A. The serious problem in this case D that after a large overshoot, the airplane stopped on the spot, even though it was in a state where it was able to obtain a large amount of reverse thrust (because $f(t) = K_p(x_0 - x)$).

Next,the controller was used Method 2 (PD controller). Vertical axis represents x and the horizontal axis is time [sec]. After over 100 times reaching experiment, we experimentally searched the parameters K_p and K_d that has the shortest arrival time and accurately converges to the arrival position x_0=0.5 m. Next, we measured N=10 times airplane model 0.5 m reaching movement using propeller thruster.

The x was stably increasing and there was almost no fluctuations out of N=10 cases. This stable feature, which was not seen in Fig.4, was generated from the differential term K_d and it caused the speed down and suppress the oscillatory behavior of $f(t)$. Next point is the convergence point (it was

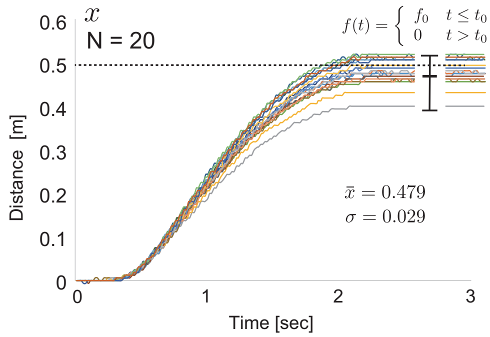

Fig. 5. Result of experiment 2 using Method 3. t_0=405 msec case was plotted. N=20 times experiment was performed.

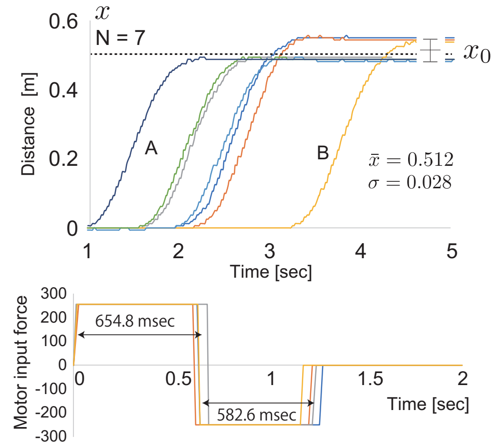

Fig. 6. Result of N=7 times good control case selection from Experiment 3-1 (top). The force input transition of N=5 cases in the case of around 2 sec starting (bottom).

calculated x=0.669±0.0094 m (standard deviation S.D.). It means there is $(0. \quad - 0.5)/0.5$=33.4% deviation from the x_0, and it is also important that overshooting always occurs in all cases N=10 times.

In the real engineering situation such product development, since the optimal parameter set of K_p and K_d could not be found in advance, experiments were actually performed, and the process of finding the optimal parameter relationship (such as ratio of K_p and K_d for example) is carried out. After the process, it is necessary to work to find coefficients that get as close to the target position as accurately as possible while fine-tuning the values of all parameters.

About the result of PD controller , to increase the target position approaching precision, most simple way is to reduce the K_p and K_d values. Since the settling time (convergence time, about 3 sec in this case) was closed to the result of Fig.4 only P controller case, by reducing the two parameters K_p and K_d it clearly reduce the settling time (we found it was about 5 or 6 sec over), and the small value of K_p induced the instability of the reaching movement.

B. Experiment 2

During this experiment, the input power was f_0=255 (max of Arduino's PWM), it means that the input voltage to the motor maintains 6.5 V.

Even if the t_0 is 400 msec appropriately set by the experimenter, the convergence position x was 0.482±0.0314 m. A good result was obtained comparing with P only control stability and PD control reaching position. As another features, the stability of position increasing transition (A of the figure) would be worse than the PD control fashion and the settling time (B of the figure) was about 3 sec same with another control conditions.

As next experiment, to increase the positional control precision, we changed the t_0 from 0.3 to 0.42 sec with 20 msec steps and measure the reaching movement of the Method 3. The calculated linear fitting was $x_t = 0.002t_0 - 0.33(R^2 = 0. \quad)$, and the t_0 could be estimated by using x_t as a target position,

$$t_0 = \frac{x_t + 0.33}{0.002}. \tag{5}$$

From the Eq.5, t_0=405 msec was calculated using x_t=0.5 m.

When the t_0=405 msec, the convergence position x was 0.479±0.0292 m Fig.5, and it was almost same with the t_0=400 msec .

The meanings of the experiment 2 (feed forward type t_0 change control method) is that the conclusion is not simply to introduce the PD control even if a control is introduced. For example, it can be shown that it is possible to reach the target position properly even by a method of manipulating t_0.

C. Experiment 3

Beginners performed the reaching exercise (Experiment 3-1) with three keystrokes (forward, backward, stop) and N = 7 good control results were extracted (Experiment 3-2) Fig.6 top. Except for the A and B cases in the figure, the settling time were relatively small (about 2.5 sec) against another 3 sec settling result And Fig.6 bottom shows the forward / reverse force input transitions in the case of around 2 sec stating time case N=5. The control input $f(t)$ is re-plotted with the time when "G" key is pressed as 0 in the successful reaching motion with the case N=5. It was clearly seen that there were firstly a forward movement phase C and a reverse input phase D until the reaching x_0. (pointed out again, with only P control, no reverse force input does not occurs until x_0). From this bottom figure, the forward input time was calculated as t_0=654.8 msec and the reverse input was t_1=582.6 msec.

D. Experiment 4

Figure 7 shows the result of switching a forward and reverse input using the parameters estimated from the human control (Ex.3, Fig.6 bottom). By using a switching forward and reverse input, the settling time was reduced about 1.3 sec (comparing with another results such Experiment 1, and it was stable result comparing with the only t_0 forward input result as Fig.5.

By using the reverse force input, even if the input features would be digitally changed, it was clear that the reverse force input significantly improved the steering performance.

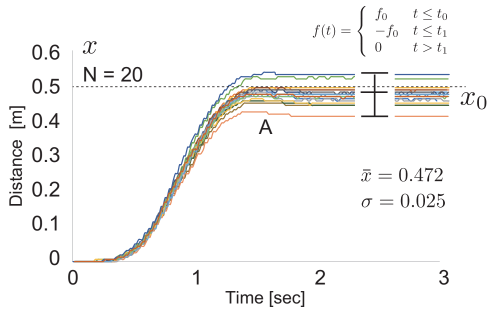

Fig. 7. Result of the experiment 4. Method 4 controller was used. t_0=658.4 msec and t_1=582.6 msec were used same with the result of Exp. 3 bottom case.

E. Experiment 5

In this experiment, we used a simple PD controller (Method 2). The control parameters K_p and K_d were determined over 100 times repeated reaching movement same with the experiment 1 airplane case.

Two features were found comparing with the airplane PD control result. First is that there is some fluctuations while the speed-up phase of the ship , and it is mainly because the wave fluctuations and friction between the ship and the U-shape frame. Next is that there is some difficulties of the slow down process , and since the slope of any graph is not zero, it can be seen that the inertial motion continues while sliding on the water.

Above experimental result, there is almost no reverse force effect by the reason of using simple PD control without overshoot fashion movement. By introducing the reverse force input, it could be expected that there will be some influence on the movement behavior of the ship.

V. Conclusion

In this paper, a novel controller design focusing on reverse input using propeller thruster such as air plane taxiing and ship for collision-free arrival motion was proposed and evaluated in mock up model. In our study, to aim at automating accurate docking and berthing operations in ship control, we used an airplane-type model with a propeller, which is relatively easy to test, rather than a test environment using water. In this process, we focused on the reverse motion often employed when the craftsman controls the ship. As a result, a ground taxiing airplane control by simple PD controller with a condition of minimum settling time high speed movement represents that although the movement was consistently stable, the movement is always accompanied by a large overshoot, and if there is a wall at the target position, it will be accompanied by a collision. In order to rapid approach without overshoot, the applied thrust for a constant time period gave relatively good results, and it was possible to control stably even though it was necessary to search for parameters. By comparing with a human control by pressing keyboard button method using a reverse force input, it also relatively good result, and by introducing the human reverse force input way to the thrust for a constant time period method, it could realize rapid and stable controlling. As a basic study, we developed a simple ground taxiing airplane model and U-shaped guided model ship to realize a rapid, non-overshoot and stable reaching movement. We found some reaching movement performance improvement even though using a constant time period forward / reverse force input controller.

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