**Fuzzy control system for three-dimensional towing trajectory of trawl gear**

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**Abstract**

In trawling, the trawl gear is connected to a trawler through a warp and towed by the trawler propulsion. The depth of the trawl gear, determined by the warp length, and the trawler direction are the most essential factors for successful trawling. In fact, the position and swimming depth of target fish school should be accurately determined to enable the trawl gear to reach the depth of the fish school by controlling the trawler velocity and direction. Automating this process requires three-dimensional simultaneous control of the trawler direction and trawl-gear depth. In this study, we applied fuzzy logic rules generated from language instructions used by skilled captains, master fishermen, and officers to control the trawl gear depth and trawler direction. We verified the accurate enclosing of a target fish school at the center of the trawl gear through simulations. When applying the proposed three-dimensional position control of the trawl gear, its depth was adjusted with an error up to 7%. Thus, the depth of a trawl gear can be automatically controlled by adjusting the trawler direction and warp length during trawling.

**Highlights**

• Fuzzy control rules based on human instructions were designed to control a trawl system.

• Three-dimensional towing control of a trawl gear regulates trawler direction and warp length.

• These parameters (i.e., trawler direction and warp length) are control inputs subject to fuzzy inference.

• These parameters can be automatically adjusted for trawling through fuzzy control rules.

*Keywords:* Trawl, Trawl gear, Fuzzy logic, Automatic control, Three-dimensional towing control

**1. Introduction**

Trawl systems rely on a trawl gear connected to a trawler through a warp and towed by propulsion. Controlling the depth of the trawl gear is one of the most essential factors for successful fishing. Hence, the position and underwater depth of a target fish school should be accurately determined to then position the trawl gear to catch the fish school by controlling the trawler velocity and direction. In practice, such control and the success of fishing depend on the experience and proficiency of captains, master fishermen, and officers. However, the shortage of executive crews becomes more serious due to staff aging and rising labor costs. Hence, recruiting foreign executive crews is being considered in the fishing industry, along with the automation of executive crew tasks such as fish scouting and fishing gear control.

Automated trawling can be achieved through three-dimensional control to simultaneously adjust the trawler direction and trawl gear depth, which is mainly regulated by the warp length. Several studies on trawling automation have provided the following contributions: simple modeling of trawl system and fuzzy algorithm for gear depth control (Lee, 1994), measurement and analysis of dynamic properties of trawl gear according to warp length and towing speed, which are control inputs of a midwater trawl system (Lee et al., 1998), depth control of a midwater trawl gear using fuzzy control rules (Lee, 1995; Lee et al., 2000; Lee et al., 2001), simulation-based analysis of midwater trawl-gear depth control according to warp length and towing speed (Hu et al., 2001), horizontal control and development of control rules for a trawl system (Johansen et al., 2001), and backtracking controller for three-dimensional trajectory of a midwater trawl system (Zhao et al., 2016).

However, none of the abovementioned models and controllers have achieved the accurate control required to track the complicated and nonlinear towing trajectory of a trawl gear to enclose fish schools. In this study, we designed a controller to predict the trajectory of a trawler net from fuzzy control rules based on language instructions used by skilled captains, master fishermen, and officers. The performance of the proposed controller was analyzed through simulations applied to a trawling multi-mass system. Furthermore, we estimated the controller error in various operating situations from the agreement between the trawl gear center and fish school location, and evaluated the controller applicability to real trawl systems.

**2. Methods**

*2.1. Trawl system modeling*

*2.1.1. Trawler model*

Trawlers have different specifications regarding aspects such as dimension, tonnage, and power depending on the industry, operation type, and target fish species. In this study, we considered a 2,000-ton trawler with the specifications listed in Table 1.

To control the trawler velocity and direction, different kinetic properties can be applied according to a time constant, which quantifies the response speed of a primary control system to an input. Specifically, we consider the time constant to be the time necessary for the system response to reach 63.2% of the target output (Lee, 2009). Hence, larger time constants imply longer time for a trawler to reach a target speed. Equation (1) describes the trawler speed according to propulsion:

 (1)

where  is the mass of the trawler, whereas  and  are the propulsion and resistance of the trawler, respectively. Turning velocity  of the trawler according to its rudder angle can be expressed as

 (2)

where,  is the inertial moment,  is the turning acceleration,  is the rotational torque, and  is the rotational resistance coefficient. From equation (2), the turning velocity per hour can be calculated as

 (3)

The terminal turning speed of the trawler is , and time constant  can be expressed by rewriting equation (2) as (4) and simplifying the expression as equation (5).

 (4)

 (5)

*2.1.2. Trawl gear model*

For depth control of the trawl gear, we model a midwater trawl gear as a mass–spring model. The trawl gear used in this study is illustrated in Fig. 1, and its specifications are listed in Table 2. From the specifications, we designed the gear on the SimuTrawl software (Ver. 1.025, MPSL, Korea) for simulations. In addition, we apply the material point method to minimize the number of simulated points to 136 for improved computation time (Cha, 2003; Lee et al., 2008; Kim et al., 2007; Hosseini et al., 2011).

*2.1.3. Models of coupling system, trawler and trawl gear*

A trawl system consists of coupling of the trawler, which is considered as a rigid body, and the trawl gear, which is considered as flexible. We use a mass–spring model to describe the system comprising the flexible trawl gear connected to the rigid trawler. In fact, while a large fishing net can be towed through the seabed or midwater, the trawler motion is restricted, whereas the shape and behavior of the trawl gear are influenced by the waves and varying ship direction and velocity. Furthermore, as the trawler operates under the influence of the marine environment, both the trawler and trawl gear cannot be modeled as independent systems but as an interdependent system (Fig. 2). The above mass–spring model can be applied to analyze various flexible structures including trawls (Cha, 2003), fish cages (Lee et al., 2008), longlines (Lee et al., 2005) and purse seines (Kim et al., 2007; Hosseini et al., 2011). We provide a brief description of the model in the sequel.

The general equation of motion for every material point of the trawler and trawl gear can be derived from the Newton’s second law of motion and expressed as

 (6)

where  is the mass of the material point,  is the additional mass,  is the acceleration of the material point,  is the internal force between material points, and  is the external force acting on the material point. The internal force acts among material points, whereas the external force acts on each material point. For instance, buoyancy, sinking force, drag, and lift are internal forces acting on the trawlers and trawl gears.

The specific equation of motion for a trawler, a trawl gear, and the coupling system can be expressed as equation (7), i.e., a second-order nonlinear ordinary differential equation with respect to time  and obtained from specifying the internal and external forces in equation (1):

 (7)

where , , and  are the position, velocity, and acceleration of the material point over time,  is the mass of the material point,  is an attenuation coefficient,  is the modulus of elasticity of a spring, and  represents any external forces excluding drag.

*2.2. Controller design of trawl system*

*2.2.1. Direction controller for trawler*

During trawling, the success of fishing depends on the accuracy of trawl-gear shooting on the target fish school identified by sonar and fish finders. In this study, we analyzed the target accuracy of the trawler by adopting fuzzy control rules.

To control the trawler direction, motion of the trawler and fish school are modeled by using the right-handed scheme from first-person shooter games, in which the trawler location is set as the origin, and the target (i.e., fish school) is located at an arbitrary point. The size of the fish school depends on the species, water depth of habitat, and marine environment. In this study, we considered the target trajectory, which represents a fish school, as a straight line along 500 m.

The proposed fuzzy controller calculates the control input by using error  between the current trawler direction and target, and error variation :

 (8)

 (9)

 (10)

where subscript  denotes the directional control of the trawler,  is the current trawler direction,  is the target direction set at the *r*-th sampling time,  is the control input variation, representing the variation in rudder angle of the trawler. This process is expressed as a fuzzy set with integral structure, and the control input is determined at each sampling time (Lee et al., 2001).

When the fish school direction and the current trawler direction are input into the fuzzy controller, the corresponding membership function is determined for the fuzzy set of input values. The membership function for controlling the direction of the trawler is constructed by using five linguistic evaluations, namely, positive big (PB), positive small (PS), Zero (ZO), negative small (NS), and negative big (NB). Fig. 3 shows that error  between the current trawler and target directions, error variation , and control input variation  can be expressed as continuous triangular membership functions.

Control input  is the rudder angle of the trawler determined at each sampling time. The rudder angle is set according to the experience of a captain or another skilled officer, who adjusts the rudder angle to catch the target fish school during trawling. To control the trawler direction, we established 25 control rules as the fuzzy associative memory detailed in Table 3. Once the directional error between the current coordinates of the trawler and fish school and the error variation are given, the control input variation is determined from inference using the control rules.

In fuzzy inference, if the directional error is –17° and its variation is 0.3° over consecutive sampling times, the following four control rules are adopted (see Table 3):

- If (= NB and = PS) then (= NS)

- If (= NB and = PB) then (= PS)

- If (= NS and = PS) then (= ZO)

- If (= NS and = PB) then (= PS)

The final value of  can be obtained from inference based on these four rules.

*2.2.2. Depth controller for trawl gear*

The trawl-gear depth can be controlled through the warp length and operation speed of the fishing winch. Like for the trawler direction controller, we designed a fuzzy depth controller that calculates the control input using error  between the depths of the target (i.e., fish school) and net center of the trawl gear, and error variation :

 (11)

 (12)

 (13)

where subscript  denotes the depth control of trawl gear,  is the current depth of the net center,  is the target depth set at the -th sampling time, and  is the control input variation, representing the variation in warp length. This process is expressed as a fuzzy set with integral structure, and the control input is determined at each sampling time (Lee et al., 2001).

When the target and current depths of the net center are input into the fuzzy controller, a corresponding membership function is determined for the fuzzy set of input values. The membership function for controlling the trawl-gear depth is constructed by using the same linguistic evaluations for the trawler direction controller. Fig. 4 shows that error  between the current net-center and target depths, error variation , and control input variation  can be expressed as continuous triangular membership functions.

The following example illustrates the control instructions that a skilled crew uses during trawling. If the net depth is considerably deeper than the fish school depth and the depth of the fish school slightly varies, the warp length should be reduced. This instruction can be formally expressed as the following control rule: If (= PB and = PS) then (= NB). Specifically, if  and  are 20 m and 0.1 m/s over consecutive sampling times, respectively, the following four control rules are adopted (see Table 4):

- If (= PS and = ZO) then (= NS)

- If ( = PS and = PS) then (= NB)

- If ( = PB and = ZO) then (= NS)

- If ( = PB and = PS) then (= PB)

The final value of  can be obtained from inference based on these four rules.

Control input value  is the warp length determined by fuzzy inference at each sampling time. If the error between the net center and fish school depths and the error variation are given, then the control input variation is determined from inference using the control rules.

*2.2.3. Three-dimensional towing trajectory controller for trawl gear*

To control the towing trajectory of the trawl gear, we devised the simultaneous trawler direction and trawl gear depth control. This control strategy aims to accurately locate the trawl gear at the depth of the target location to catch the fish school. In the towing trajectory controller, the direction control input for the trawler is calculated from direction error  and error variation  between the current trawl-gear and fish school (i.e., target) directions. In addition, the depth control input of the trawl gear is calculated from error  and error variation  between the net center and fish school depths. Fig. 5 shows the block diagram of the proposed control system for three-dimensional towing trajectory control of the trawl gear.

For the three-dimensional towing trajectory control of trawl gear illustrated in Fig. 6, the target trajectory represents the fish school, which is at distance  from the trawler in direction . The length of the target trajectory, , is fixed to 500 m, and distance  from the target trajectory to the cast net point, , can be calculated using equation (14), which considers the time for the trawl to reach a steady position:

 (14)

where  is the steady-state settlement coefficient of the trawl gear, which depends on the size of the gear (set to 3 in this study),  is the trawler velocity,  is the depth of the target, and  is the sinking speed of the trawl gear.

After the primary target point of the trawler, , is set to be the cast net point, , and the trawler direction is controlled accordingly, net cast is performed when the angle between the direction angle and target trajectory () is below 5° (i.e.,  ≤ 5°). After net casting, the three-dimensional towing trajectory control of the trawl gear is conducted by the trawler towards the second target point, , to estimate the target trajectory. When the distance between the trawler and secondary target  is below 20 m (i.e.,  ≤ 20 m), the three-dimensional towing trajectory of the trawl gear is controlled to target point . Then, if the distance between the trawler and third target point  is below 20 m (i.e.,  ≤ 20 m) and thus passes the third target point, the control terminates (Fig. 7).

**3. Results and discussion**

*3.1. Trawler direction control*

Fig. 8 illustrates the fuzzy inference for the control input when the fish school (i.e., target) is located at 2,000 m from the trawler and at 17° from the portside, the trawler velocity is 4.0 knots, and the error variation is 0.3°/s. Error  between the current trawler direction and the fish school position is –17°, and error variation  is 0.3°/s. Based on the membership functions in Fig. 3 and the fuzzy associative memory detailed in Table 3, the following control rules were adopted:

- If (= NB and = PS) then (= NS)

- If (= NB and = PB) then (= PS)

- If (= NS and = PS) then (= ZO)

- If (= NS and = PB) then (= PS)

From these control rules, the rudder angle, which is a control input, was determined as 31.6° using the center-of-gravity method for fuzzy inference (Mizumoto, 1988).

*3.2. Trawl-gear depth control*

Table 5 lists the distance between the trawler and fish school, and the distance deviation between the trawl net depth and fish school trajectory according to the depth of the fish school. The velocity of the trawler was set to 4.0 knots, and the net cast velocity of the trawler was set to 2.0 m/s. The depth control performance can be evaluated by calculating the distance deviation between the center of the trawl net and target points  and  (Fig. 6).

As the target depth increases, the distance variation between the net center depth and the fish school also increases. This is possibly because, when the depth of the target increases, the warp length should increase, thus amplifying the vibration on the warp, trawl door, float, and sinker, which notably increase the deviation. In addition, regardless of the target depth, as the trawler approaches the target, the distance deviation between the net depth and the target trajectory tends to increase. This is possibly due to the insufficient time for the trawl gear to reach a steady position after the fishing net was cast and the warp released. To solve this problem, it is necessary to cast the net considering the time required for the trawl gear to settle. For example, consider that the distance between a trawler and a fish school is 2,000 m, whereas the trawler travels at a constant speed of 4.0 knots, and the trawler gear is cast at sinking speed of 2.0 m/s to catch the target located at the depths of 100, 200 and 300 m. The respective times for the trawl gear to reach its steady position are 150, 340 and 430 s. Comparing the distances between the net center depth and target trajectory according to the fish school depths, we found that the depth of the trawl gear can be controlled within 1% deviation irrespective of the fish school depths (Table 5).

*3.3. Three-dimensional towing trajectory control of trawl gear*

We conducted the trajectory control for towing the trawl gear using the fuzzy inference shown in Fig. 8 to simultaneously determine the trawler direction and warp length. Tables 6–8 show the deviation and its rate according to the direction deviation between the trawler and target (i.e., fish school) when the depth of the target is 100, 200, and 300 m, respectively. We set the trawler speed to 4.0 knots and the sinking speed of the trawl gear to 2.0 m/s. Therefore, the trajectory control performance for the trawl gear can be determined from the distance deviation between the trawl net center and target points  and  (Fig. 6).

Regardless of the directional deviation between trawler and target, as their distance decreases, the deviation of the distance between the net depth and target trajectory tends to increase. Again, this is possibly due to the insufficient time for the trawl gear to reach a steady position when the trawler approaches the target, and the fishing net is cast and the warp released. In addition, regardless of the distance between trawler and target, as the direction deviation between them increased, the distance deviation between the net depth and target trajectory tends to increase. This is possibly caused by the large rudder angle of the trawler to control its direction that notably distorts the trawl-gear shape, and thus there was sufficient time for the trawl gear to settle.

We compared the distance deviations between the net depth and target trajectory according to the target depth from the three-dimensional trajectory of the trawl gear. When the depths of the target were 100, 200, and 300 m, the three-dimensional trajectory controller adjusted the distance between the center point of the trawl gear and the target trajectory within 6.7%, 5.5%, and 3.7%, respectively, regardless of the direction deviation between the trawler and fish school.

**4. Conclusion**

For successful trawl operation, the appropriate type and suitable trawl gear considering the habitat layers of target species, distribution, water depth, and other conditions should be determined. In addition, it is necessary to cast the trawl gear considering its time to reach a steady position after releasing the warp. In this study, we designed fuzzy control rules for the simultaneous and automatic control of the trawler direction and warp length. The rules were constructed from linguistic instructions delivered by skilled captains or officers during trawling. The distance deviations between the center point of the trawl gear and the target (i.e., fish school) trajectory were successfully controlled within 7% with respect to the target depth through the proposed three-dimensional towing trajectory control of the trawl gear. The designed control rules provide automatic adjustment of the trawler direction and warp length, resembling the outcomes from trawling under the guidance skilled captains or officers. In fact, when the trawl gear was cast as recommended, the three-dimensional towing trajectory control of the trawl gear was realized with small error. In future research, we will apply learning techniques from artificial intelligence to determine the optimal navigation distance and direction for securing the appropriate distance from a target and casting point. In addition, we will explore the implementation of the designed fuzzy control rules to other trawler components, such as sonar, fish finder, steering gear, and fishing winch system, to further automate trawling.

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