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Ship Trajectory Control Optimization in Anti-collision Maneuvering

J.F. Zhang, X.P. Yan & D. Zhang
Intelligent Transport Systems Research Center, Wuhan University of Technology, Wuhan, China
Engineering Research Center for Transportation Safety (Ministry of Education), Wuhan University of Technology, Wuhan, China
Research and Development Base on Waterway Transportation Safety and Anti-pollution of CJRDC Ministry of Transport, Wuhan University of Technology, Wuhan, China

S. Haugen
Department of Production and Quality Engineering, Norwegian University of Science and Technology, Trondheim, Norway

ABSTRACT: A lot of attention is being paid to ship's intelligent anti-collision by researchers. Several solutions have been introduced to find an optimum trajectory for ship, such as Game Theory, Genetic or Evolutionary Algorithms and so on. However, ship's maneuverability should be taken into consideration before their real applications. Ship's trajectory control in anti-collision maneuvering is studied in this paper. At first, a simple linear ship maneuverability model is introduced to simulate its movement under different speed and rudder angle. After that, ship's trajectory control is studied by considering the duration of rudder, operation distance to turning points, and maximum angular velocity. The details for algorithm design are also introduced. By giving some restrictions according to the requirements from COLREGs, the intervals for rudder angle in different circumstances can be determined based on the curves. The results can give very meaningful guidance for seafarers when making decisions.

1 INTRODUCTION

Ship's intelligent control and navigation of unmanned marine vehicles has been studied for many years. One of the most important objectives is finding an optimum trajectory and speed for a ship to keep away from both stationary obstacles and moving ships while the distance to its destination is the minimum. Several solutions have been introduced to solve this problem, such as Game Theory, Genetic or Evolutionary Algorithm and so on. Many studies have achieved rather satisfactory results. An evolutionary Planner/Navigator algorithm was proposed by Smierzchalski early in 1999. In the model, the problem was reduced to a dynamic optimization under both dynamic and static constraints. The model can be integrated in Automatic Radar Plotting Aids (ARPA) to make decision support for seafarers. Smierzchalski, et al (2000) extended the work and proposed a novel θEP/N++ model. The main target is trying to reduce calculation and searching for trajectory very quickly. By using the algorithm, a safe and near optimum trajectory for each involved ship can be found within 1 minute. When finding an optimum trajectory for ships, the requirement from International Regulations for Preventing Collision at Sea (COLREGs) should not be neglected. Michael, et al (2006) studied the problem of unmanned marine vehicles autonomous operation by multi-objective optimization and interval programming under COLREGs. An in-field experiment with two crafts was also carried out to validate the model. The work did not consider multi-ship anti-collision problem. Szlapczynski, et al (2011) considered multi-ship trajectory planning problems. Instead of finding optimum trajectory for only one ship, their study can find safe trajectories for all ships involved to avoid all ship domains violation and stationary constraints. In all the above studies, the focuses were trajectory searching. However, ship's

maneuverability should also be taken into consideration, especially in turning points. So the results cannot be used in reality directly.

In term of ship maneuverability, Proportion Integration Differentiation (PID) control is widely used. There are also a lot of ship control methodologies under different kind of desaturations such as wind, wave, and current and so on. Zhang, et al (2002) proposed a trajectory control system called closed-loop gain shaping. Sliding model, including back-stepping (Lin, et al, 2000) and fuzzy sliding-mode (Yuan, et al, 2011) is another course control algorithm. Soda et al (2012) studied numerical simulation of ship's navigation under the influence of wind and wave. In those models, the characteristics of disturbance signals are unknown. A series of fuzzy logic are used to make decision inferences. The models perform well even in nonlinear systems and priori knowledge is not needed. In the above studies, a lot of attentions are paid to course control. But in anti-collision maneuvering, ship should not only alter to its target course, but also should keep close to its planned trajectory. By taking the problem into consideration, a path controlling system was designed by Fossen, et al (2003) by minimizing the difference between designed and actual speeds and the track error simultaneously. The operations are totally on automatic ways.

It must be admitted that most anti-collision operations are still carried on by seafarers. So it is necessary to find some regular patterns when ships are altering their courses by rudder angle operation. By doing so, seafarers decision making could be supported, which would help them make better performance. This paper will focus on ship's trajectory control in turning points during anti-collision maneuvering. At first, a ship maneuverability model is built to simulate its movement under different velocity and rudder angle. After that, an algorithm is introduced to find the relationships between rudder angle and other parameters such as course alteration and time and so on.

The rest of paper is organized as follows: In section 2, a ship maneuverability model is introduced in detail. Section 3 will give algorithm design for rudder control during course alteration. Case studies are carried out in section 4. Conclusions and future works are summarized in section 5 and acknowledgments are given in section 6.

2 SHIP'S MANEUVERABILITY MODEL

A simple linear ship maneuverability model proposed by Nomoto (1957) was used in this paper. The model gives the relationship between rudder angle and angular velocity by using the following equation:

$$T \cdot \dot{r} + r = K\delta \tag{1}$$

where r is ship's yaw rate, δ is rudder angle. T and K are time constant and rudder gain respectively, which should be obtained by field experiment for a typical ship. Solving the above inhomogeneous differential equation, the angular velocity at time t can be obtained by the following equation:

$$r(t) = K\delta_0(1 - e^{-\frac{t}{T}}) \tag{2}$$

where δ_0 is ship's initial rudder angle. Furthermore, the course alteration during the period can be computed by integrating angular velocity during the time as follow:

$$\begin{aligned}\psi(t) &= \int_0^t \int K\delta_0(1 - e^{-\frac{t}{T}})dt \\ &= K\delta_0(t - T + Te^{-\frac{t}{T}})\end{aligned} \tag{3}$$

where $\psi(t)$ is ship's course alteration after period t. During anti-collision operation, the rudder will return to midship after some period, so that the ship could reach the target course gradually under its inertia. Under this situation, ship maneuvering equation changes into the following version:

$$T \cdot \dot{r} + r = 0 \tag{4}$$

By solving the above equation, the course alteration after the rudder returning to midship as follow:

$$\phi(t) = \int_0^t r_0 e^{-\frac{t}{T}} dt = r_0 T(1 - e^{-\frac{t}{T}}) \tag{5}$$

where r_0 is ship's angular velocity when rudder began to return to midship. It can be conveyed that when ship's course became stable ($t \to \infty$), course alteration from returning to midship would be $r_0 T$.

3 ALGORITHM DESIGN AND CASE STUDY

3.1 *Phases for course alteration*

A course alteration operation can be divided into three phases. As can be seen in figure 1, ship can change its course by steering. In the first phase until t_1, the rudder is altered from midship to a certain angle. In the second phase, from t_1 to t_3 the rudder angle remains constant. In the last phase from t_3 to t_4 the rudder angle return to midship.

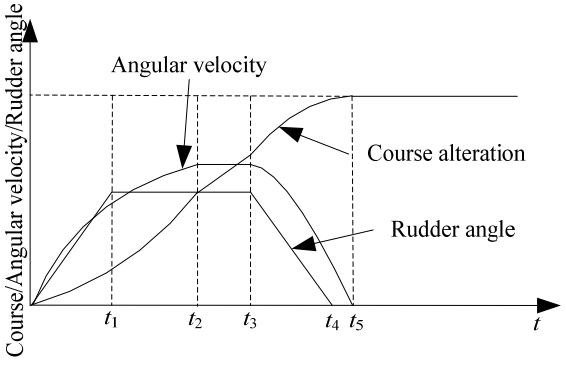

Figure 1. Demonstration for ship's course alteration

During the three phases, ship's course alteration can still be divided into three steps. According to the course alteration curve, the course changes quickly and the curve is concave until t_2. The curve comes to be a straight line between t_2 and t_3, which means there is equilibrium between the torque from rudder and flow resistance. The curve between t_3 and t_4 turn out to be convex, which means that course is altering slowly. The angular velocity curve comes from the differential of the curve course alteration. It is still divided into three steps. It should be mentioned that there is at least a maximum value for angular velocity according to its curve. Of course, the three phases do not absolutely exist simultaneously in reality. It is possible that the rudder may return to midship before ship's angular velocity becomes stable. The curves in figure 1 are just conceptual demonstrations and qualitative study will be carried out in next subsection.

3.2 *Algorithm design*

It can be seen from figure 1 that course alteration curve is a monotonic function with respect to time. So the idea of squeeze rule is used in this section.

Table 1 shows the pseudo code for the calculation of time needed in a typical course alteration. Suppose the rudder angle is δ and the course alteration in a turning point is Ψ, then the time needed for the rudder to keep on this angle can be computed in the following shown procedure.

Table 1. Pseudo code for the calculation of time needed in a typical course alteration

```
function:        Time = CourseAlteration(Ψ, δ)
Initialization: Tmin, Tmax, Tthre
   while Tmax - Tmin > Tthre
      Ttemp= (Tmax + Tmin)/2
      Find course alteration by keeping rudder
      angle δ for Ttemp: Ψtemp
      if   Ψtemp>Ψ
         Tmax= Ttemp
      else
      Tmin= Ttemp
      endif
   endwhile
return (Tmax + Tmin)/2
```

In the above pseudo code, the parameters T_{min} and T_{max} are determined intuitively to make sure that *Time* is within them. T_{thre} is used to define precision. The smaller the parameter is, the higher the precision will be. Either T_{min} or T_{max} will be updated in each iteration.

After determining the parameter *Time*, another parameter, which is called operation distance, should also be determined. The operation distance is defined as the distance between turning point and the point that the rudder operation begins. As shown in figure 2, if the operation distance is too large, ship's route will not reach its planned route when ship turned to the target course. If operation distance is too small, ship's route will surpass the planned route.

In order to determine the operation distance, another pseudo code is also designed based on squeeze rule, which is shown in table 2. The parameter δ means rudder angle and *Trajectory* includes all parameters that can explain the planned route.

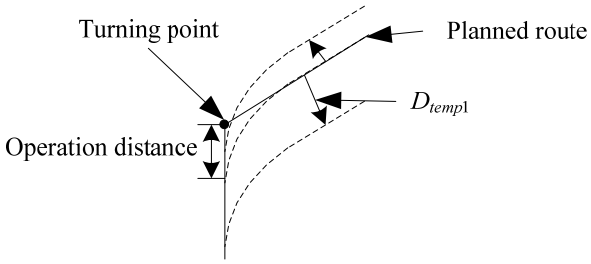

Figure 2. Illustration of operation distance when turning to planned route

The procedure is quite similar with the pseudo code in Table 1. It should be mentioned that the parameter D_{temp1} will be positive if ship's actual route surpass the planned trajectory. Or else it is negative. Either D_{min} or D_{max} will be updated in each iteration.

Table 2. Pseudo code for the calculation of distance needed in a typical course alteration

```
function:   D = Distance (δ, Trajectory)
Initialization: Dmin, Dmax, Dhre
   while Dmax - Dmin > Dthre
      Dtemp= (Dmax + Dmin)/2
      Find the distance between ship's position and
      Trajectory when course alteration is over under the
      circumstance that rudder angle is δ and operation
      distance is Dtemp: Dtemp1
      if   Dtemp1>0
            Dmax= Dtemp
      else
         Dmin= Dtemp
      endif
   endwhile
return (Dmax + Dmin)/2
```

4 CASE STUDIES

In this section, case studies by using the above algorithms are carried out. Without loss of generality, the parameters in Yuan et al (2011) are used. In their studies, the time constant T is set to be 63.69, the rudder gain K is set to be 0.114 and ship's velocity is set to be 7.2m/s. The model proposed in this paper can be extended to other types of vessels by changing relevant parameters. According to COLREGs, the give way ship should make early and substantial actions so that other ship could notice. On the other hand, although COLREGs do not have similar requirements, ship should also try to avoid too large course alteration because it needs to return to target course after anti-collision operation is over. When a large course alteration is inevitable in certain situations, the ship can consider avoiding collision by speed alteration instead. In general, the course alteration for a ship during anti-collision operation is between 30° and 60° at most times.

At first, the duration of rudder needed for different course alteration is obtained, which is shown in figure 3. The rudder angle varies from 2° to 20° with an interval of 2°. The maximum rudder angle is usually 35° for many ships. However, full rudder

should be avoided as far as possible in anti-collision operations. So the maximum rudder angle is supposed to be 20°.

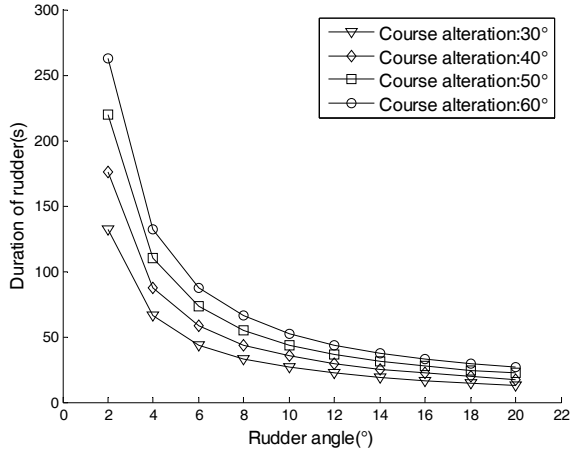

Figure 3. Relationship between rudder angle and the duration for the rudder to keep for course alteration

It can be seen from figure 3 that the duration of rudder is decreasing as rudder angle increases, which is consistent with intuition. In reality, the duration of rudder should be large enough for seafarers to respond. For instance, when course alteration is 30°, the rudder angle should not be larger than 12° if the response time is set to be 30s. That's to say, the curves can provide an upper bound for rudder angle for seafarers in anti-collision operations.

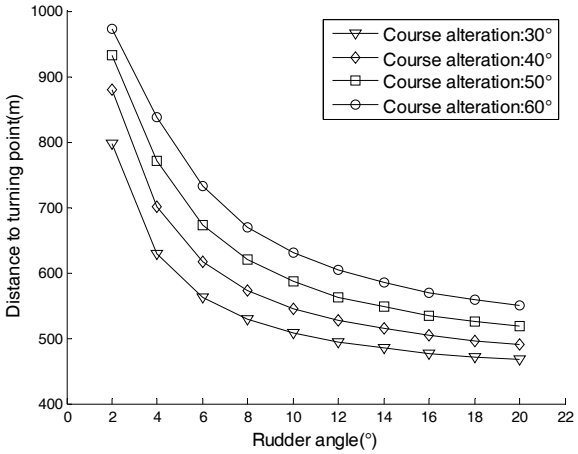

Figure 4. Relationship between rudder angle and the distance between operation start point and turning point

Figure 4 shows the relationship between operation distance and rudder angle when course alteration varies from 30° to 60° with an interval of 10°.

The curves also share a declining trend as well. COLREGs require that early action is desirable in anti-collision operations, which means that operation distance should not be too small. Take course alteration of 30° as an illustration, the rudder angle should not be larger than 10° if the operation distance is set to be 500m. Consequently, the above curves can also provide an upper bound for rudder angle for seafarers in anti-collision operations.

COLREGs also require that ship should take substantial action to make other ships to be able to notice its intension. The maximum angular velocity can reflect ship's action to a large extend. Figure 5 gives the curves of maximum angular velocity for different course alteration.

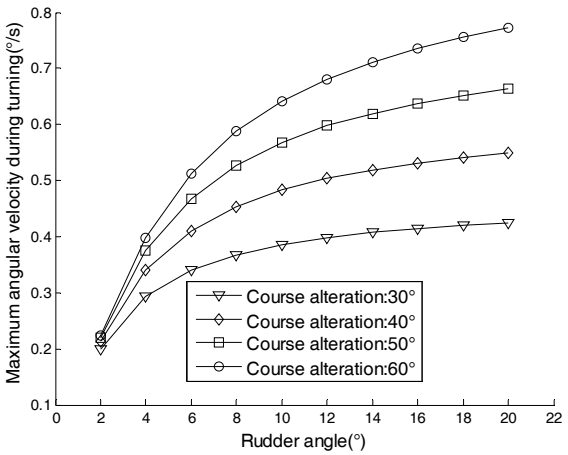

Figure 5. Relationship between rudder angle and the maximum angular velocity during course alteration

It can be seen from the figure 5 that the curves share a rising trend. In reality, ship's angular velocity should be large enough for other ships to notice. The course alteration is also supposed to be 30°. The rudder angle should be at least 8° if the maximum angular velocity is no smaller than 0.35°/s. Consequently the above curves give a lower bound for rudder angle. By combining the above evidences, ship's rudder angle should be between 8° and 10° when course alteration is 30°. This is just an example. Rudder angle decision making under other circumstances can be made in similar ways.

5 CONCLUSIONS AND FUTURE WORK

In this paper, ship's trajectory control in anti-collision operation is studied. Due to the fact that most operations during anti-collision are carried out by seafarers in most time, rather than totally automatically, this paper tries to make a decision support system for anti-collision operations. Not only course alteration is considered, but also the trajectory deviation is taken into consideration. What's more, notice that COLREGs require that ship should take early and substantial actions, the maximum angular velocity is also considered to decide the rudder angle. Finally, an interval for rudder angle in course alteration can be obtained, which can give guidance for seafarers.

Ship's movement is influenced by wind, current and wave. In the future, we will further study ship's trajectory control decision making support system under uncertainty. What's more, ship's trajectory control is usually done by making rudder rectification gradually and small rudder operations are needed to make course and route calibrations. Consequently, further studies are still needed before its real application.

ACKNOWLEDGMENTS

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