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DESIGN OPTIMAL CONTROL OF SHIP MANEUVER PATTERNS FOR COLLISION AVOIDANCE: A REVIEW

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Key words: optimal turning maneuver, control model, ship transportation.

ABSTRACT

Although there have been lots studies about vehicular maneuvers on land or sea, maneuvers within a small area that require direction changes have rarely been discussed. Many reports on the arrival or departure of ships from ports have revealed more about what are safe and effective turning maneuvers within a narrow area. Convenient navigation systems for ship maneuvering should allow quick avoidance of obstacle to find the shortest distance in the whole seaway is important. This study proposes a review model that will satisfy optimal turning maneuvering anywhere and be applicable to any type of ship. However, the water-based environment is more complex and there are many factors that will affect the formula. By using a nonlinear unified state-space model to discuss another model we can divide and conquer the problem. In recent studies some categories have been evaluated to determine where the main attention should be directed. In this review study we look at how to construct the optimal turning maneuver within a limited sea area.

I. INTRODUCTION

Water-based transportation is more complex than land-based transportation and there are various environmental factors and vessel characteristics that should be considered in the control of ships for maneuvers. There have been lots studies about structure control in the natural physics [2, 4, 13-67, 68-83, 97-103, 105, 108-111, 113-134, 136, 137]. Nevertheless, a unified numerical model for ship maneuvers is difficult to establish, because the factors affecting it (as described above) are normally nonlinear [157, 158, 197-231].

Ships are of various types designed according to their purpose. The ship's length, weight and even appearance, and the power of its rudders and thrusters, all have a significant effect on the characteristics of its maneuverability [159, 163-177, 179-187, 192, 193]. Due to these conditions, even if a numerical model can be established, it would be difficult to apply to all types of ships. In previous research studies it is common to give restrictions when discussing particular issues about a specific ship. However, it is still necessary to define the basic conditions of an objective ship type. Most models cannot be applied to all types of ships.

In this paper we will discuss several different levels that are related to the behavior of ships. These three levels introduce optimal ship maneuvering, for instance ship positioning, optimal path of ship maneuvering and inland ship maneuvering.

II. LITERATURE REVIEW

1. Ship Positioning

There are different ways to control a ship's yaw. The basic system uses a single rudder or twin rudders at the stern, operating in conjunction. Of course, there are more advanced system, for example, to use twin tunnel thrusters, one installed on the bow section and on the stern, which offers transversal thrust. A contemporary ship might use one or several systems operating in conjunction, for instance, the Glomar Explorer deep-sea mining ship in 1974 and the Glomar C. R. built Luigs drillship in 1999.

Obviously, from prior definition, the control system finds optimal control of ship maneuvers. Therefore, we focus on the basic system which is based on having a single rudder located at the stern to control the ship [140, 147, 148, 150]. Various methods for the study of ship maneuvering have been studied [5, 68, 107, 194]. For more details about ship control modeling see: Inoue, Hirano, Kijima and Takashina [104]; Barr

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Table 1. Four sub problems of the Mayer problem.

	Problem description	Quasi-steady state
P1	Change the yaw angle by a given amount	Not required
P2		Required
P3	Bring the ship from a given initial course to a parallel course	Not required
P4		Required

[9], Fossen [86] and Mandel [135]. For more on the theme of optimal ship maneuvering see: Amerongen and Lemke [3]; Miloh and Pachter [153]; Teo and Lim [178]; Tzeng [189]; Yavin, Francos, Miloh and Zilman [196]; Yavin, Francos and Miloh [195]. In particular, see Tseng [189] and the work of Yavin *et al*. for discussion in either a deterministic setting or a stochastic setting with the boundary conditions handled via penalty function techniques [194-196].

In this type of problem, when describing the ship's movement, we calculate the center of ship which is a fixed point ship, rather than the center of gravity, because this is a variable point. A more complete set of equations is needed to describe the motion of the ship, so as to enable one to consider the restriction of complex boundary conditions without adapting to penalty function techniques. Actually, having a new transformation technique allows one to avoid singularities at the upper and lower bounds of the rudder angle when it and its time derivative incur symmetric upper and lower bounds. Hence, two problems are considered that is course change maneuvers and sidestep maneuvers. The restriction is that the ship must initially be in a quasi-steady state. The criteria for optimization of course change maneuvers and sidestep maneuvers are studied as Mayer problems of optimal control. There are a total of four problems that need to be solved in Table 1.

Constraint: the yaw angle time rate vanishes at the final point.

The sequential gradient-restoration algorithm (SGRA) developed by Miele *et al*. during the years 1968 to 1986 is used to solve the above problems [91, 138, 139, 144, 145, 146]. This first-order algorithm has proven to be a powerful method to improve trajectory tracking problems in the following situations:

- Flight in windshear [149]
- National aerospace plane [145]
- Aeroassisted orbital transfer [152]
- Interplanetary flight [161]
- Next-generation orbital spacecraft [141]

SGRA has been used to calculate variations/optimal control in the Bolza problem. The Lagrange and Mayer problems are special cases of the Bolza problem. Since they are Mayer-type problems, the SGRA can deal with Problems P1 to P4 (in a minimum time).

In 1999, Miele, Wang, Chao and Dabney used the sequential gradient-restoration algorithm to formulate and solve Mayer problems of optimal control [151]. They assumed the criterion of optimization to be the minimum time. The final goal of this method is correctly calculate the module which is significant for improving control of ship maneuvers in a particular situation.

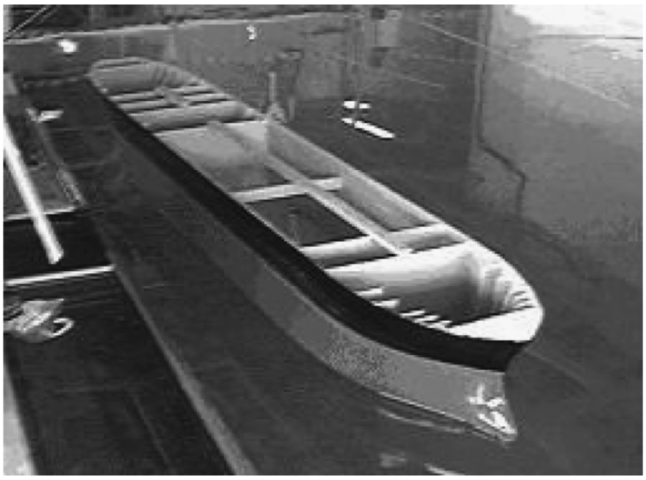

Fig. 1. The "Esso Osaka" model ship [156].

2. Optimal Path of Ship Maneuvers

Both surface and underwater ships are used for monitoring of coastal and inland waters monitoring. Especially, the use of autonomous marine vehicles has grown significantly in recent years, partly due to their low cost, and partly due to their application of autonomous guidance and control technologies that can accomplish tasks by themselves.

There is a scale model of a tanker, the "Esso Osaka" (Fig. 1), which allows different guidance and control strategies to be tested in a natural environment, but it is not have the same type of hull as surface autonomous vehicles do.

The application of autonomous guidance and control technologies to marine vehicles is an important goal because of their lower cost and being able to navigate in multiple mission or test scenarios. Typically such autonomous vehicles must have good maneuverability and be able to keep an optimal path, normally in shallow waters and confined spaces, under the influence of external disturbances such as currents, wind and waves. Therefore we introduce a guidance and control system capable of controlling the path followed by marine surface vehicles.

In this chapter, we design a model of the "Esso Osaka" tanker to demonstrate the performance of the guidance and control systems. The whole system can be implemented and evaluated through tests in lakes or other confined bodies of water.

Basically, autonomous vehicles must have three subsystems on board the platform: guidance, navigation and control. Here we offer a line-of-sight (LOS) algorithm to solve the above problem. Trajectory points can be generated using many criteria, usually based on the specific vehicle and relevant

Table 2. Four sub problems of the Mayer problem.

Year	Author	Method	Main idea
2000	Chung, Qi [84]	Successive learning track-keeping control (SLTC) algorithm	1. Correctly maintain track-keep the requirement target track of set points or minor path. 2. After the initial off-track disturbance, the first 3 to 5 tracks of the learning process are taken to move the vehicle in a zigzag track.
2003	Fossen [90]	Trajectory tracking control based on LOS	1. Geometric assignment based on the LOS projection algorithm for minimization of the cross-track error to the path. 2. The desired speed along the path can be specified independently.
2003	Velagic, Vukic, Omerdic [191]	Adaptive Sugeno fuzzy type autopilot	Used in an ordinary feedback loop. The adjustable scaling factor mechanism in an additional feedback loop.
2004	Breivik, Fossen [11, 12]	Guidance-based approach	1. A way to specifically control the velocity vector of the vehicles in such a way that they converge to follow the desired geometrical paths in a natural and elegant manner.
2007	Moreire, Fossen, Soares [156]	Way-point guidance algorithm based on LOS	1. Calculation of a dynamic LOS vector norm to improve the convergence of the vehicle to the desired trajectory. 2. Independent of the initial design value for the LOS distance (radius).
2009	Lee, Surendran, Kim [112]	PID control algorithm and fuzzy logic	Numerical simulations are carried out to discuss heading control.

information such as environmental and geographical data (wind, waves, currents, shallow water, islands, etc.), obstacles and collision avoidance (introducing safety margins) and feasibility meaning that every point must be satisfied [87].

There are several methods for determining the optimal path of ship maneuvers summarized in Table 2, Fossen, Breivik and Fossen offer a general method for finding the optimal path, but Moreira, Fossen and Soares use a special approach that is based on a way-point guidance LOS algorithm [94] A new approach can improve the convergence of the LOS algorithm to minimize the crosstrack error by the calculation of a dynamic LOS vector norm. For example, the shortest distance between the vehicle and a straight line [160].

A mathematical model of the ‘‘Esso Osaka’’ tanker is used to simulate the results an demonstrate the performance of the system. This approach is simple to apply to other vehicles or extend to higher dimensional control and guidance problems.

3. Inland Ship Maneuvers

First we discuss ocean-going ship-steering autopilots designed to implement course-keeping maneuvers in the open sea and course-changing maneuvers along the coast. Typically, the most important performance criterion for the course-keeping maneuver is minimum course deviation with smallest control exertion. However, it is desirable to track the new set course as quickly as possible with minimum overshoot [86]. Many controllers arc designed to achieve optimal control performance during course-keeping and course-changing maneuvers [106]. Of greatest concern for control of ocean-going vessels is the heading angle.

For inland ships, the autopilot does not so much aim to control the heading angle of the ship as the turning rate. In practice, the captain should track the ship route and consider this when calculating the required turning rate. This is reference input for the inland ship autopilot serves [85]. Hence, the yaw-rate-control is a useful tool for the inland ship captains.

Recent progress in computer science progress has made the use of Global Positioning System (GPS) technology for track-keeping autopilots become more practical. Theoretically, once the track of the ship is defined the ship can sail automatically without interference from the captain [95]. However, we still believe that an experienced captain is more reliable than an autopilot for inland sailings and then human beings are better at dealing with unexpected incidents. Hence, the captain’s input is indispensable to help determine the turning-rate-control of the autopilot. This is the preferred operation mode.

Wave filtering is a central issue when designing the autopilot for ocean-going vessels. It is important that the autopilot only compensate for the low-frequency wave force rather than the high-frequency oscillatory force [96]. The central issue for inland vessels is avoidance of collisions. Interference mainly comes from wind gusts and encounters with other ships.

Therefore, inland ships should have optimal maneuvering to avoid collisions. Always pushing the actuator to unknowingly exceed its saturation (SAT) and slew rate limitation (SRI) boundary will lead to considerable deterioration of the

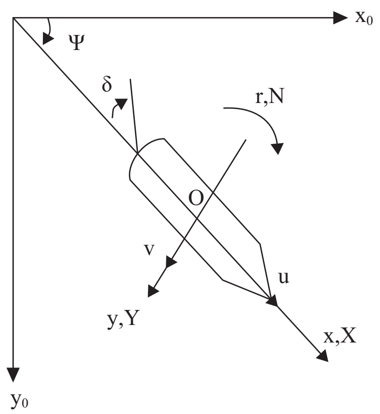

Fig. 2. Definition of motion in the horizontal plane [189].

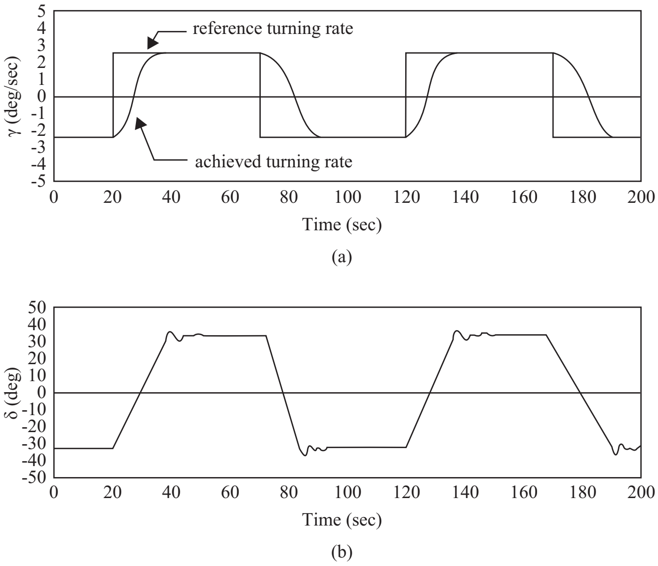

Fig. 3. (a) Controlled turning rate (b) Rudder angle [189].

maneuverability of the ship [6]. An automatic gain reduction technique has been offered to avoid actuator SRL which may lead to the controller wind-up problem [190]. Another technique is the reference conditioning technique to avoid actuator SAT that may also lead to undesirable controller wind-up problems [162].

When designing ships for inland waters both the actuator SAT and SRL should be considered. There is a technique for realizing an inversion in terms of non inverted dynamics in a local feedback loop, the inversion by feedback technique [92]. If this can be accomplished the SAT and SRL boundaries will be avoided.

Based on Newton's law in space-fixed coordinates x_0-y_0 are used to define the equations of motion describing the steering dynamics of a ship arc (Fig. 2).

In the section we discuss the internal model control (IMC) approach to designing a turning rate control autopilot. The most important thing to remember is that IMC is a model-based design approach, so it satisfies the required system response time [155]. After numerical testing we discover that this approach offers captains a very convenient way to tune the autopilot to meet different maneuvering requirements.

The above complex formula of motion in the horizontal plane is simplified, after which the IMC is used to solve the problem and the results tested. Fig. 3(a) shows that a smooth transition is reached and the reference turning rate is also achieved within in 20 s when the initial speed of response parameter β is set to 0.1 and the controller uses a constant reference turning rate of 2.5 o/s. Fig. 3(b) gives the regular pattern for the rudder angle. Specifically, the SRL and SAT have been reached. After a short period of oscillation, the rudder is maintained at a constant value slightly lower than the SAT limit.

The IMC approach implements the SAT and SRL nonlinearities in a local feedback loop and allows the controller to exert its full power without pushing the actuator to exceed its SAT or SRL boundaries [188]. This is an important study because it describes inland ship maneuvering in a limited space with random encounters with other vessels.

III. APPLICATION SUMMARY

Our final goal is to find a approach which can arrive determine optimal maneuvering under any sea conditions. Unfortunately, this is a difficult task, because there are many factors that will affect the formulation. Motivated by the work of Bishop and Price [10] and Bailey *et al*. [7] a unified state-space model for optimal of ship maneuvering, state-keeping, and control in a seaway is derived. There are two main directions should be considered of the dynamic equations of motion for ship maneuvering:

- Maneuvering theory
- Seakeeping theory

An ideal unified theory for determining ship motion could be applied to different sea states, speeds and operations, assuming that the motion of the ship is in calm water, for example in a harbor or in sheltered waters.

In order to conveniently test performance and design of feedback control systems, the time-domain should be defined.

Feedback control system designs for ships have a long history, dating back to 1908. In recent yearsm the development of global satellite navigation systems and inertial measurements technology have made possible the design of nonlinear model-based ship control systems. This evolution is described in Table 3.

The unified model is derived using a state-space method. This is the standard representation used in feedback control systems. Hence the unified model can be used to simulate ship maneuvers given different sea states and at any speed. Note this model can also satisfy nonlinear maneuvering formulas by unifying the theories of seakeeping and maneuvering [89].

Table 3. Evolution of feedback control systems.

Year	Author	Contribution
1908	Anschutz	Invention of the North-seeking gyroscope
1911	Sperry [1]	Ballistic gyroscope
1922	Minorsky [154]	Analysis of the three-term PID-controller
1976	Balchen [8]	Wave filtering technique
1994, 2002	Fossen [86, 88]	Using Lyapunov methods for stability analysis to design nonlinear ship control systems

Table 4. Major ship maneuver pattern theories.

Central theory	Description	Usage
Sequential gradient-restoration algorithm (SGRA)	Solve special cases of the Mayer problem including the Bolza problem.	The algorithm can be used fo find the optimal seaway for a moving ship that needs to change course or sidestep with time.
''Esso Osaka'' model	Improve ship guidance and control to find an optimal seaway path.	Reduce overall distance for ships that want to dynamically call at many harbors.
Internal model control (IMC) approach	Design a model for inland ship maneuvering in a limited space with randomized encounters with other vessels.	In an environment where one can randomly encounter other ships, the captain will conveniently avoid such encounters given limited space.

The nonlinear unified state-space model is used to consider the three situations in Table 3. The method can improve performance to avoid collisions during ship maneuvering in natural environment, find the optimal seaway path that will reduce time wastage and satisfy the requirements for inland ship maneuvering in limited space.

Now the nonlinear unified state-space model is used to consider three situations as in the Table 4. It can offer improved collision avoidance performance during maneuvering in particular natural environments, optimize the path on the seaway to reduce time wastage and satisfy the requirements for inland ship maneuvering in a limited space.

IV. CONCLUSIONS

In this study the literature related to optimal turning and ship maneuvering has been reviewed. Simple classifications of different approaches depending upon different practical purposes and areas have been defined. However an overall model to control of ship maneuvering in a natural environment for any type of ship has not been designed, because there are so many factors that will affect the formulation. Hence our strategy is to use the nonlinear unified state-space model, joined with another approach according to the requirements of the situation. In this way, no matter what the conditions are, an optimal method to solve any problem can always be found, while still noting the restrictions of one of the whole approaches.

Future work will focus on particular problems related to this study. Perhaps some features in each approach can be combined with others. It is hard to determine which one is more significant and valuable than the other. Therefore, we hope to attract more scholars to join this work, and do a more comprehensive study. At the same time, the different types of ship should be considered gradually. Our final goal is to develop a suitable system to determine optimal ship maneuvering for any type of ship in our particular natural environment.

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