Fuzzy Modelling of the Behaviours and Decision-Making of Ship Navigators
-- An Application to Ship Auto-Navigation Fuzzy Expert System (SAFES) --

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ABSTRACT As one of the most complicated human operation, the behaviours and decision-making of ship navigators are dealt with fuzzy theory. Almost all part of the navigators' judgements are found to be represented by fuzzy reasoning fairly well. The fuzzy modelled navigator is implemented into Ship Auto-navigation Fuzzy Expert System (SAFES) and it works in various situations of multi-ship encounters and of other complex waterways.

Keywords: fuzzy modelling; fuzzy reasoning; fuzzy theory; expert system; knowledge-based system; ships; navigation; collision avoidance; path planning; autopilots

INTRODUCTION

Among many traffic vehicles, a ship is different in her unique navigational operation. As she has been privileged from Archimedes' principle, she has comparatively large mass and therefore time constant. It requires long-term exercise and experience for a navigator to manoeuvre her. She has no braking facility except reversing thrust. Furthermore, there is, in general, no traffic signals, no separation lanes, nor even any traffic lanes at all. Lastly, she cannot stop for many days. Therefore, automation of ship operation is natural requirement and advanced quite well. Ship autopilots have already been used since 1920s. However, there remains some functions which are not automated yet; watching, berthing and unberthing.

A ship navigator, such as a captain, an officer or a pilot, should order rudder angle or propeller revolution to keep her on scheduled path, watch surroundings such as coastal lines or other encountering ships and decide to avoid them, if necessary. Even if an autopilot and a radar are available, they cannot decide or judge when she should change her course, whether she should avoid any approaching ship(s) or not etc.

These decisions are not deterministic nor probalistic. For the modelling of a ship navigator, fuzzy theory is suitable. Besides, a fuzzy autopilot is developed, which has ability of course-changing and path-keeping as well as an ordinal function of course-keeping. Lastly, combining with an expert system, Ship Auto-navigation Fuzzy Expert System (SAFES) is developed. The system is applied to some different applications in which ship navigators' judgements are essential. In this paper, some functions of ship navigators are reviewed and discussed how the functions are modelled and why fuzzy theory is used.

FEATURES OF SHIP OPERATION

There are many operational jobs which a navigator should do, but here path-keeping manoeuvre and collision avoidance manoeuvre are to be explained to understand the following sections.

Path-keeping of vehicles with large time constant is very difficult. Here path-keeping is defined as to sail on the fixed path just as in Fig. 1a. Figure 1b shows a typical rudder command of path-keeping manoeuvre. The basic pattern of the order is bang-bang control. First, a navigator should decide how degree of rudder angle to be took for course-changing. Next, he should decide when the command will be ordered. If he fails the timing, he should adjust the rudder angle, or the ship will sail offset from the correct path as shown in Fig. 1a. However, as the time constant is large, it is difficult to detect whether the timing is suitable or not. A kind of prediction with navigator's experience is necessary. Lastly, he should decide, after taking the first rudder command, when and how degree the counter rudder command is. The matter is worse in narrow straits or in harbours. Usually a pilot will aboard there to take command. Though he has deep knowledge about the seaway, tide and other necessary information around there, he is unfamiliar with the ship. Each ship has different manoeuvrability characteristics.

Collision avoidance is another special but very common feature in ship navigation. The International Regulations for Preventing Collisions at Sea specifies three encounter situations as shown in Fig. 2. The burdened ship should avoid the other ship, if the fear of collision occurs, while the privileged ship should keep her speed and course for the convenience of the burdened ship. The burdened

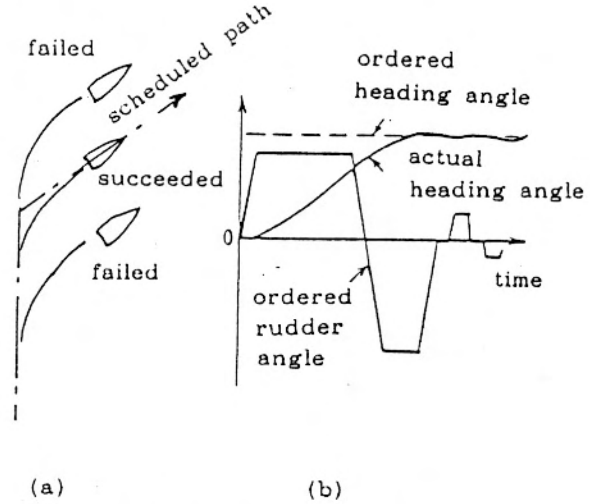

Fig. 1 Path-keeping manoeuvre

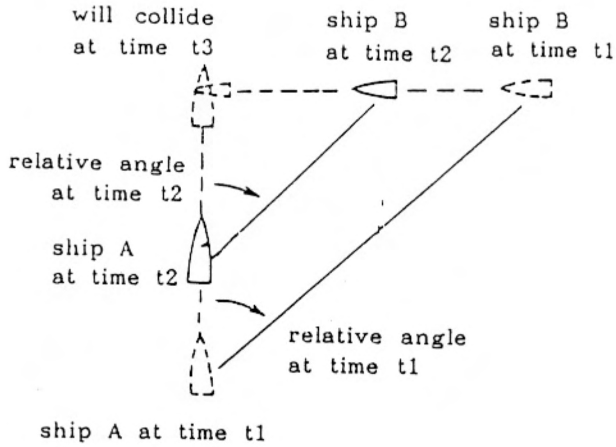

Fig. 3 The fear of collision

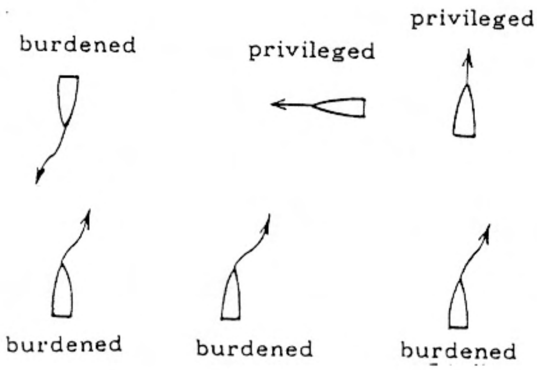

Fig. 2 Privileged and burdened ships

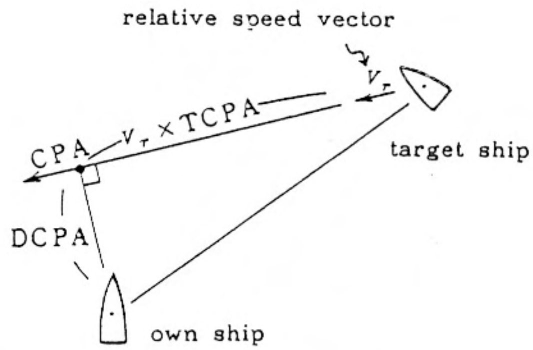

Fig. 4 Definition of DCPA and TCPA

ship should avoid *sufficiently* so as not to give the other ship any fear of collision and should return her original navigation path only after the fear *thoroughly* disappears. Generally speaking, the ship which watches the other ship in her right-hand is burdened and the ship which watches the other ship in her left-hand is privileged. This is very simply and clear rule. But there are some obstacles for computer processing. What is the fear of collision? How is the degree of *sufficiently* or *thoroughly*? Besides, there are no rules for multi-ship encounters. How should a navigator do if two ships are aproaching from both starboard and port sides? According to the regulation, he should avoid the right-hand side ship as well as keeping her course and speed for the left-hand side ship!

FUZZY MODELLING OF SHIP NAVIGATORS

To realize the above mentioned features of ship navigation as well as other functions, fuzzy theory is introduced. In this section they will be explained.

Fear of collision is judged easily on board. Navigators are taught that the fear of collision exists if the approaching ship's bearing course does change little (Fig. 3). This angle is proportional to the miss distance, i.e. the distance of closest point of approach (DCPA). It is clear that if DCPA is zero, both ships will collide in the future, but the burdened ship needs not avoid immediately. Suppose a ship just departs from Yokohama and another ship also departs from Seattle, whose DCPA is zero. The fear of collision (CR: collision risk) is not determined only by DCPA. The time until reaching to CPA (closest point of approach), which is called TCPA, is also related to the fear. Navigators do not say explicitly, but this value TCPA is another important factor to judge the fear of collision. If both ships approaching each other are assumed to keep their speed and course, the CPA is obtained by their relative movement as shown in Fig. 4.

Therefore, a fuzzy reasoning such that

"if DCPA is very short
and TCPA is also very short,
then CR is very big"

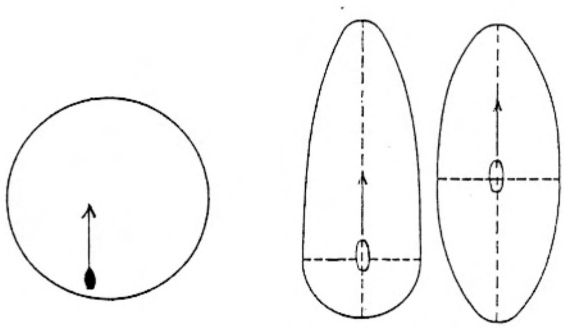

Fig. 5 Various definition of *the domain*

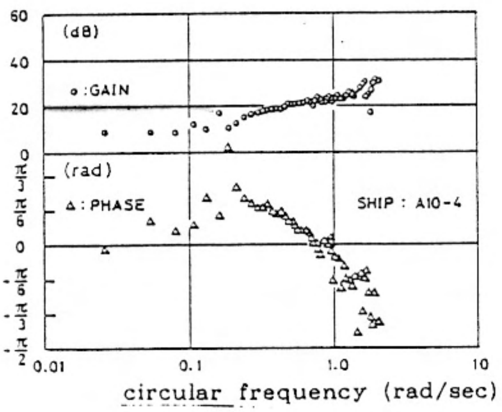

Fig. 6 An example of helmsman's transfer function

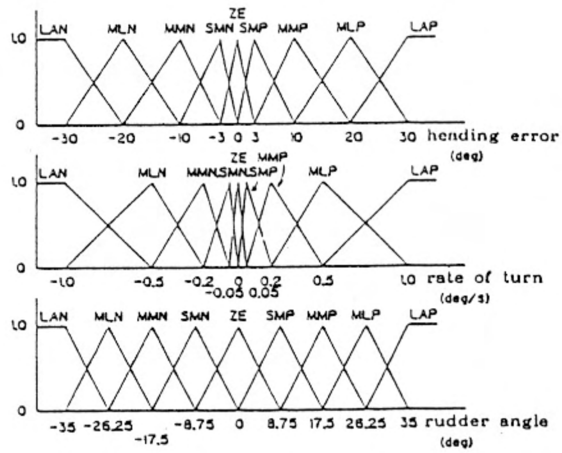

Fig. 7 Membership functions of fuzzy autopilot

Table 1 Control rules of fuzzy autopilot

rudder angle	heading error								
rate of turn	LAN	MLN	MMN	SMN	ZE	SMP	MMP	MLP	LAP
LAN				MLP	LAP	LAP			
MLN				MMP	MLP	LAP			
MMN	MMN	SMN	ZE	SMP	MMP	MLP	LAP	LAP	LAP
SMN	MLN	MMN	SMN	ZE	SMP	MMP	MLP	LAP	LAP
ZE	LAN	MLN	MMN	SMN	ZE	SMP	MMP	MLP	LAP
SMP	LAN	LAN	MLN	MMN	SMN	ZE	SMP	MMP	MLP
MMP	LAN	LAN	LAN	MLN	MMN	SMN	ZE	SMP	MMP
MLP				LAN	MLN	MMN			
LAP				LAN	LAN	MLN			

is used. For the membership functions and control rules, refer to Hasegawa(1987)[7].

It is, however, worthy to review other definitions of the fear of collision. The easiest way is to judge the fear arises if any approaching ship enters into a certain region around the own ship. This region is called as *the domain* or *danger zone* and defined variously as in Fig. 5[4,5,6]. But in this criterion, the fear is a crisp value and strictly speaking, the region should vary with the relative course and speed of the approaching ship. In the case of actual navigational aids such as Automated Radar Plotting Aids (ARPA), they have a function of tracking some amount of approaching ships and if DCPA *or* TCPA becomes less than a certain value defined by the user respectively, the alarm lump and buzzer will work. The fear in this case is also a crisp value. These definitions may be less effective for multi-ship encounters.

<u>Fuzzy autopilot</u> is designed to simulate human control. Human operator has a special ability to tune or adapt his control parameters to the environment. He will set a set of sensitive parameters in the steady state but he boldly changes them when an abrupt change of order is received. He always tries to adjust his gain parameter so as to set the system stable, while giving maximum phase lead. An example transfer function of a helmsman is shown in Fig.6 [13]. He has also a kind of filter whose phase lag is very small.

Fuzzy control is also suitable for these features. Fuzzy autopilot is first proposed by Amerongen and others(1977)[1]. The membership functions and control rules used by Hasegawa(1987)[7] are shown in Fig.7 and Table 1 respectively, where linguistic variables are corresponding each other. The irregular intervals in the membership functions of heading angle and rate of turn are the point.

<u>Path-keeping</u> is one of the most difficult functions as described in the previous section. There are already many proposals for treating this function in a computer system using PID control or optimum regulator, *e.g.* [2,11,14]. However, here also fuzzy control is applicable. Assuming the course changing point as a stopping ship or a buoy, we can judge the *nearness* by fuzzy reasoning just as the fear of collision. According to the

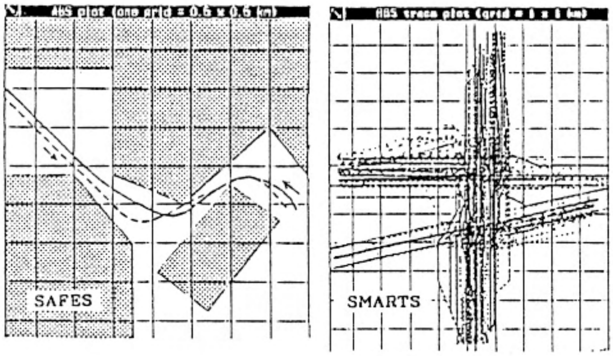

Fig. 8 Sample outputs of SAFES and SMARTS

nearness to the turning point, heading command is set between two course lines.

Navigation lane detection is also done assuming there is always a ship just on the crossing point of the heading line and the boundary of the lane.

SHIP AUTO-NAVIGATION FUZZY EXPERT SYSTEM[10]

The above mentioned model of ship navigators is installed as a basic function of the system called SAFES. For the strategy of multi-ship encounters and other navigational knowledge, expert system or production system is convenient as a programming structure. There are already some similar approaches[3, 12]. In open sea or restricted area, the modelled navigator watches and orders appropriate instructions for each ship to perform her scheduled navigation or to avoid any other ships or obstacles safely. For the detail description of the system, refer to Hasegawa and others[10].

There are many application fields using SAFES; evaluation of newly developed automated navigational aids, intelligent ship handling simulator for training or research, evaluation and design of waterways and harbours etc. Figure 8 is sample outputs of SAFES and marine traffic simulation called SMARTS[9], which fully utilizes the function of SAFES.

CONCLUDING REMARKS

The behaviours and decision-making of ship navigators are done using fuzzy theory. Fuzzy theory is suitable for complicated and hierarchical human behaviours. Furthermore, with combination of expert system, it is possible to apply to more realistic environmental conditions. Using these systems we can evaluate or design facilities which are largely affected by human behaviours. For other applications of fuzzy theory in marine systems are introduced in Hasegawa(1988)[8].

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REFERENCES

1. Amerongen,J.van, H.R.van Nauta Lemke and J.C.T.van der Veen, An autopilot for ships designed with fuzzy sets, 5th IFAC/IFIP Intern. Conference, Hague, 479-487, 1977.
2. Amerongen,J.van and E.F.Land, An adaptive autopilot for trackkeeping, International Symposium of Ship Operation Automation, Tokyo, 99-108, 1979.
3. Blackwell,G.K., R.S.Burns and C.T.Stockel, An expert approach to collision avoidance, Summer Computer Simulation Conference, Montreal, 43-48, 1987.
4. Davis, P.V., M.J.Dove and C.T.Stockel, A computer simulation of marine traffic using domains and arenas, J. of Navigation, 33, 215-222, 1980.
5. Fujii,Y., A consideration on the effective domain (in Japanese), J. of Japan Institute of Navigation, 44, 49-58, 1970.
6. Goodwin,E.M., A statistical study of ship domains, J. of Navigation, 28, 328-336, 1975.
7. Hasegawa,K., Automatic collision avoidance system for ships using fuzzy control, 8th Ship Control Systems Symposium, Hague, 2, 34-58, 1987.
8. Hasegawa,K., Ship auto navigation system, in Fuzzy Computer/Fuzzy Expert System, (in Japanese, ed. K.Hirota), Triceps, Tokyo, 135-159,1988.
9. Hasegawa,K., SMARTS - a new marine traffic simulation method for the development of waterways and marine traffic systems (in Japanese), J. of Japan Institute of Navigation, 81 (to be appeared), 1989.
10. Hasegawa,K., A.Kouzuki, T.Muramatsu, H. Komine and Y.Watabe, Ship auto-navigation fuzzy expert system (SAFES) (in Japanese), J. of the Society of Naval Architects of Japan, 166 (to be appeared), 1989.
11. Koyama,T. and K.Shimizu, Fundamentals of automatic harbour manoeuvring, 7th Ship Control Systems Symposium, Bath, 3, 123-145, 1984.
12. Koyama,T. and Y.Jin, An expert system approach to collision avoidance, 8th Ship Control Systems Symposium, Hague, 3, 234-263, 1987.
13. Koyama,T., K.Kose and K.Hasegawa, A study on the instability criterion of the manual steering of ships, Naval Architecture and Ocean Engineering, 16, 15-24, 1978.
14. Norrbin,N.H. and S.Göransson, A study of the safety of two-way traffic in a Panama canal bend, 5th Ship Control Systems Symposium, Annapolis, 3, K1-3, 1978.