A MODEL OF THE VESSEL TRAFFIC PROCESS

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ABSTRACT

This paper deals with a model of the total vessel traffic control process. This includes human operator (HO) functioning as the human factor plays a dominant role in the complex vessel traffic process. Also the vessel traffic services (VTS) is modeled in it's possible role of monitor, conflict detector and advisor of the total vessel traffic system.
This implies a number of ships, with a given planned route, in a given confined area. The navigation of each ship is based on a planned route, which is updated via information of the visual scene, instruments and the VTS. Both normal operation and collision avoidance is modeled. The latter implies the detection of a possible conflict by the navigator(s) and/or the VTS.

The model is implemented in a (in C-written) computer program. Typical traffic situations are simulated showing the capability of the model to address realistic vessel traffic scenario's. The time simulation results can be summarized in statistical measures of relative ship positions.

The model of the vessel traffic process is capable to answering questions related to: safety and efficiency, the effect of HO functioning, necessary information to perform the tasks, communication between ships and VTS, the optimization of procedures, automation of the total vessel traffic process, etc.

VESSEL TRAFFIC MODEL STRUCTURE

General

The vessel traffic process implies a number of ships, with a given destination in a given confined area, including the supervising role of the vessel traffic services (VTS). This is summarized in the block diagram of Fig. 1. For details the reader is referred to references 1 and 2.

The ultimate criteria of the traffic process are safety and efficiency.
Derived measures for these are collision risks (probabilities) and traffic flows. These are related to the following components, which are included in the model: ship dynamics, on board instruments (radar, compass, log) and environmental aids to navigation (buoys, leading lights, conspicuous points, etc.), environmental disturbances (wind, current), number of ships and their planned route (tracking), interaction between ships (collision avoidance) and navigator and VTS functioning. This involves visual perception, information processing, decision making and control.

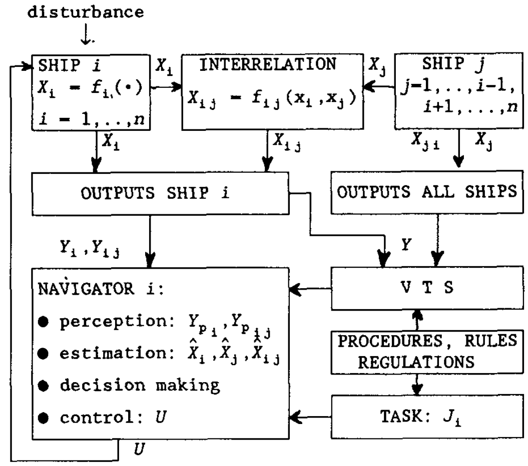

Fig. 1. Block diagram of the vessel traffic model.

The result is a stochastic (both random system disturbances and human randomness is included), nonlinear, estimation and control problem. In the following, the system components are discussed in more detail.

Ship control

Normal operation amounts to steering the ship along the planned route (LQG control). The ship dynamics involved are a simplified version (assuming no drift) of the complete nonlinear equations of motion, yet describing the main response characteristics.

The model of ship i is given by

$$X(k) = f(X(k-1), U(k-1), W(k-1), k) \tag{1}$$

with

state $X(k) = \text{col}\ (U, R, \Psi, X, Y)$ at time k
control $U = \text{col}\ (\Delta U_c, \delta)$
disturbance $W = \text{col}\ (W_1, W_2)$

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and

$$f = \left| \begin{array}{l} (1+a\Delta_k)U + b\Delta_k \Delta U_c \\ (1-\Delta_k/T)R + k\Delta_k/T.\delta \\ \Delta_k R + \Psi \\ \Delta_k U\cos\Psi + X + \Delta_k W_1 + \Delta X_s \\ \Delta_k U\sin\Psi + Y + \Delta_k W_2 + \Delta Y_s \end{array} \right| \qquad (2)$$

where U is the longitudinal speed relative to the water, R is the rate of turn, Ψ is the heading, X and Y are the earth-fixed coördinates, ΔU_c is the commanded speed change, δ is the rudder angle, $W_{1,2}$ represent the random system disturbances and ΔX_s and ΔY_s represent the effect of the current.

It is assumed that the navigator may observe variables provided by instruments (radar, compass, log, etc.). And by the visual scene (buoys, leading lights, conspicuous points, distance a and direction φ of an other ship, etc.) with a given inaccuracy.
Based on these perceived data the navigator estimates his own ship related state ($\hat{X}_i$) in order to track his planned route.

It is assumed that each navigator knows the nominal state of his own ship i. Thus the estimation of his nonlinear ship can be described in terms of a Kalman filter of the linearized ship model.

The estimation of the other ships can not be treated in a similar way, as it is assumed that the navigator of ship i does not know the nominal behavior of the other ships. In other words, it is not possible to specify a reference state and follow the standard linearization scheme. The assumption is that navigator i perceives quantities Y_{ij} that are related to both his own ship and ship j. In this paper a minimum variance estimation procedure is followed (extended Kalman filter) to solve this general nonlinear filter problem.
The third category of estimates concerns the variables X_{ij} that describe the interaction between ships (see collision avoidance). In this paper, the approach is taken to derive stochastic differential equations for X_{ij} and to obtain a minimum variance estimate of X_{ij} in terms of an extended Kalman filter. This is the same approach as taken for the estimation of other ships as, again, no state reference can be specified a priori.

These estimates ($\hat{X}_j, \hat{X}_{ij}$) are used to decide about the possibility of a collision, hazard or grounding. Such a situation is simply indicated with collision avoidance and will be discussed in the next section.

Collision avoidance

Collision avoidance is modeled by defining a dangerous encounter if the (estimated values of the) following three variables are smaller than their corresponding criterion value: the distance a_{ij} between two ships, the closest point of approach c_{ij} (defined as the distance between the relative velocity vector and ship i) and the time T_{ij} to reach the closest point of approach.
The relationships X_{ij} between these variables and the state of the ships involved are clarified in Fig. 2 and given by

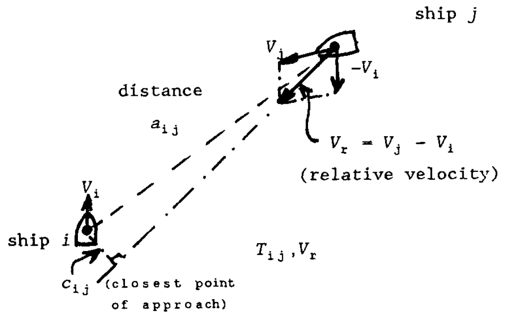

Fig. 2. *Geometry of an encounter.*

$$X_{ij} = f_{ij}(X_i, X_j)$$

with

$$X_{ij} = \mathrm{col}(a_{ij}, c_{ij}, T_{ij})$$

and

$$f_{ij} = \begin{bmatrix} \left[(X_j - X_i)^2 + (Y_j - Y_i)^2\right]^{1/2} \\ \dfrac{(U_j\cos\Psi_j - U_i\cos\Psi_i)(Y_j - Y_i) - (U_j\sin\Psi_j - U_i\sin\Psi_i)(X_j - X_i)}{(U_j^2 + U_i^2 - 2U_jU_i\cos(\Psi_j - \Psi_i))^{1/2}} \\ \dfrac{(U_j\cos\Psi_j - U_i\cos\Psi_i)(X_j - X_i) + (U_j\sin\Psi_j - U_i\sin\Psi_i)(Y_j - Y_i)}{U_j^2 + U_i^2 - 2U_jU_i\cos(\Psi_j - \Psi_i)} \end{bmatrix}$$

So we have an encounter, if all elements of (the estimate of) X_{ij} are smaller than the corresponding elements of the criterion $X_{c_{ij}}$.
Three types of encounters are distinguished each requiring a specific, pre-programmed, avoidance action: meetings, overtakings and crossings. The precise classification is depending on the relative positions and orientations of both ships. It is assumed that a collision avoidance situation can be described as an encounter of two ships at the time. The situation that more than two ships are involved is considered as a sequence of encounters between two ships.

The evasive maneuver is characterized by a given lateral displacement and a given (specified or reasonable) heading change. This standard maneuver is uniquely realized by a bang-bang control sequence with a given maximum rudder angle. The switching times are determined by the (linearized) ship dynamics. For details the reader is referred to Ref. 2. It is assumed that the evasive maneuver is followed by a symmetric maneuver to resume the originally planned route.

Vessel Traffic Services

Various ways to model the VTS are considered. The simplest way to model a VTS is to assume that the *navigator receives given (extra) observations from* the VTS. A more advanced role of the VTS can be modeled assuming that the VTS will have information to estimate the total vessel traffic process, detect any conflict and advise or command the navigators (based on the same model concept as used for the navigators).

MODEL CAPABILITY, EXTENSIONS AND APPLICATIONS

The vessel traffic control model is nonlinear, because of the nonlinear estimation process. Therefore, no closed form expressions can be derived for statistical measures. Thus, the model must be used for time (Monte Carlo) simulations.
For example, for typical (crucial, or interesting) configurations (many of) such simulation runs must be made. The resulting trajectories can be considered and combined to obtain measures for collision probabilities and traffic flows. In addition, measures will be available for the effect of visual informational variables on system performance and measures of HO behavior related to visual scanning, situation uncertainty and workload.

At the moment three model aspects are investigated into more depth.
So far a collision avoidance situation has been described as an encounter of two ships at the time. In very congested areas encounters can involve three or more ships. This problem is investigated to establish the realistic collision avoidance maneuver, based on rules and a rationale for optimal maneuvering behavior.
In addition, various collision avoidance maneuvering strategies are considered. Various optimality criteria are investigated (minimum time, terminal control). These conditions are compared with more simple solutions (a.o., steady-state LQG).

Finally, it will be investigated whether collision avoidance as a open-loop maneuver yields realistic model results. Both the rules and the large time scale suggest pre-programmed (open-loop) control behavior. This is supported by interviewing nautical experts. However, in reality navigators observe the traffic scene and take changing circumstances into account by control compensation.
Partly, this behavior is accounted for by modeling collision avoidance as a stochastic control problem. In that case, the nominal maneuver is open-loop, combined with a compensatory closed-loop control to account for random effects.
In addition, possibilities will be investigated to model collision avoidance more as a closed-loop process (adapting plans, etc.).

The model can be applied to a variety of vessel traffic problems. It provides the structure to analyze the effect on safety and traffic handling of (among others) the following variables: ship dynamics, on board navigation instruments, visibility and environmental conditions, aids to navigation, HO functioning, number of ships and their planned route, traffic area, procedures and rules, information available to the VTS, role of the VTS, automation issues of the total vessel traffic process, etc.

CONCLUDING REMARKS

A mathematical model is presented of the complex, large scale vessel traffic process, including human operator functions. This implies a number of ships in a given confined area. The navigation of each ship is based on a planned route, which is updated via information of the visual scene, instruments and vessel traffic services.
Apart from this normal operation the interaction between ships is modeled. This collision avoidance process involves the assessment of collision risk and the execution of a collision avoidance maneuver.
The VTS is considered in it's possible role of monitor, conflict detector and advisor of the total vessel traffic system.

Furthermore, in the paper the capabilities of the model are discussed. Three modeling issues are being investigated into more depth: encounters involving more than two ships, alternative collision avoidance maneuvering strategies, and open-loop versus closed-loop collision avoidance maneuvers.
Finally, model applications are briefly indicated.

REFERENCES

1. Wewerinke, P.H. et al., Model of large scale man-machine systems with an application to vessel traffic control. IEEE SMC, Conference, Cambridge, USA, 1989.
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