A need for cognitive models in maritime traffic simulation

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Abstract. This paper presents a design for a cognitive navigator model based on Rasmussen's model of skill- rule- and knowledge-based behaviour. The basic assumption is that navigators do not attempt to minimise the deviation from a track-line but attempt to realise efficiency and safety by balancing prediction and mental workload. The resulting model is rather simple in its structure but can display complex behaviour in a traffic environment.

1. INTRODUCTION

Most complex control systems are underspecified and require human control to realise efficiency and safety. In general humans are very successful in this. When looking at transportation, all cars, ships and aircraft are under full human control, show an efficiency that is considered well within the objectives and have safety records that are considered good. The risk of death for air, ferry and car transport is $16 \cdot 10^{-8}$/hr, $8 \cdot 10^{-8}$/hr and $25 \cdot 10^{-8}$/hr respectively (European Transport Safety Council, 2003). The risk of a deadly collision by car is $1.5 \cdot 10^{-9}$ per encounter (Hale & Heijer, 2006). In order to increase system availability, efficiency and safety, we need to get a better understanding of human control.

Maritime traffic is a complex system, built on independent transport agents. To know the potential, the system needs to modelled, depending on an accurate model of the agent, the ship. A ship is a control system consisting of the machine and the navigator controlling the ship. The ship's manoeuvring characteristics are highly dependent on ship with navigator (Stassen et al., 1990). Simple behavioural models do not suffice when analysing such a traffic system.

When designing a system the organisational structure and control principles have a significant effect on the potential. In traffic the dominant resource is space. While navigational area is mostly abundant, in a few locations navigational space is constrained most, notably near ports. When resources are limited the allocation becomes crucial. System design determines the potential of capacity and safety, while actual participant characteristics determine the actual and capable.

At the open ocean, when space is abundant, only the state of other ships needs to be observed for safe and efficient ship control. When navigation space becomes constrained, ship interaction is more complex and ship control depends on planning, exchange, and plan adaptation in addition to observation and ship control. When navigation space becomes insufficient negotiation is needed to allocate space. A control model providing each of these three control mechanisms is proposed. The basic structure is based on the SRK-model by Rasmussen (1983). It attempts to provide human navigation characteristics, not optimal control characteristics. Perceptual limitations, user-centred and sub-optimal decision making are contained in the model.

Maritime operations are a complex system in this respect. Ships show complex dynamics that are difficult to control. Manoeuvring a large ship is generally executed by a specialised team, each performing a specific task, using specialised tools (Hutchins 1990). The team is organised in a layered structure with the navigator operating the tactical level. The navigator realises the voyage plan by deciding on heading and speed, based on knowledge about the manoeuvring characteristics of the ship, the sailing environments with other traffic, and reacting on disturbances acting on the ship.

Heading is realised by the helmsman and speed is set by a mate. Although heading control in itself is complicated, it is fully understood. Various models of a helmsman have been made, based on optimal control (Veldhuijzen 1979), fuzzy control (Papenhuijzen 1988) and neural network (Zhang et al. 1996). Most ships have an auto-pilot to maintain heading at open sea. Interestingly, in restricted waters the helm is controlled by a human. The reasons for this is that a helmsman can reliably switch between various types of control, can be instructed remotely by voice, reports back, there is no need to switch to manual control in case of system failure, and he can inform the navigator about ship-handling quality. The speed of a ship is not set directly, instead engine-speed is selected manually.

While heading control is well understood, the actual navigation task is analysed very sparsely. Hutchins (1990) made an extensive ethnographic description of the navigation task on board a navy ship on how they gather information and resolve conflicts. Papenhijzen (1994) made a control model of a navigator based on fuzzy logic. A cognitive model of bringing a ship on the planned route was presented by Itoh et al. (2001). Van Westrenen & Praetorius (2012) presented a functional model of the bridge-team. A variation of that model, a model of the ship with the bridge-team used in this paper is shown in figure 1. All models focus on the primary task of navigation: Finding the own position and deciding on how to bring the ship to her destination. However, navigating the ship and reacting to disturbances by sea, current and wind is only part of the task. In confined waterways the task of dealing with traffic is equally important, increasing the navigator's task complexity significantly.

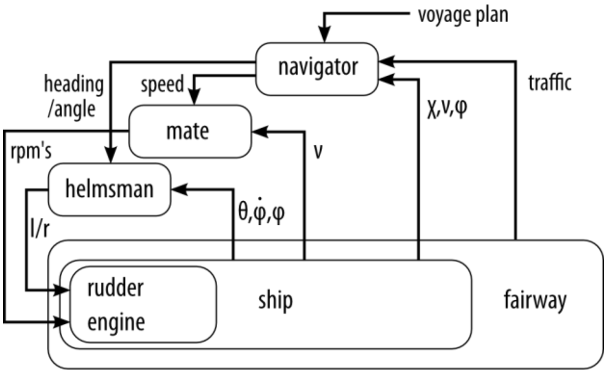

Figure 1. Bridge team controlling the ship. The helmsman controls a tiller, the mate the engine setting. The navigator gives speed and heading orders that are realised by the helmsman and mate. Information that allows for state estimation is represented by Greek letters: rudder-angle (θ), heading (φ), speed (v), position (χ).

To gain a deeper understanding of the variability seen in human behaviour when coping with system complexity, a cognitive model of the navigator is needed. Such a model would allow for studying ship system behaviour by simulation and obtaining knowledge about how navigator performance is realised. A navigator will need to include a mental model of the system under control, the ship with the crew, manoeuvring in the fairway. The need for a mental model in order to control a system effectively is long recognised and described in more detail by Stassen et al. (1990). A navigator model will therefore include a mental model of the ship in addition to observation and control strategies.

2. OBSERVATION AND CONTROL

System observation, or estimating the system-state, needs to be done from a ship's perspective. The ship's perspective is largely a bridge-view since radar is hardly used in port situations. Apart from a map with navigation plan, the information used by the navigator is shown in figure 2. Some state variables can be observed very accurately, like bearings of objects, especially when the objects are straight ahead or abeam. Others are much more difficult, like distance and speed. And some cannot be observed at all. The dynamics of the state variable are very important in the observation. This was recognised by Gibson when modelling car driver behaviour (Gibson 1938) and pilot skill level behaviour (Gibson 1950) based on optic-flow. Although speeds are much slower with ships, this difference in speed is largely compensated by distances, allowing for a similar approach.

Figure 2. View from the bridge as seen by the navigator in the Port of Rotterdam: bulk ship, 225m long, 32m wide (photo Marijn van Hoorn, with permission).

In optimal control, navigation is often modelled as a tracking task, whereby a cross-track error is minimised. However, in real navigation there is no need to minimise a track-error. In addition, optimal to a control engineer may mean something different from a navigator. An operator will generally balance effort and performance (Hollnagel, 2009). Effort can be expressed in terms of observations and control actions. The most crucial performance criteria are grounding/collision risk and fuel efficiency: Safe movements within navigable waters while realising efficiency is important. A model would need to show control behaviour based on observation and state prediction while realising sufficient safety and efficiency. As a result, there is no track line but a path, and cross-track error is replaced by realising an acceptable time-to-boundary, expressing effort on observations and control decisions. The control criterion is to maintain an acceptable position and speed in the fairway while minimising (mental) workload, which depends on the actual situation. The resulting tracking task is not modelled as an optimal control model but a control model that attempts to stay within the path while keeping time-to-boundary sufficiently long, as shown in figure 3. This matches maritime pilot behaviour (van Westrenen, 1999) and observations by VTS operators (personal communication); Vessel Traffic Services (VTS) provides navigation assistance using shore-based radar.

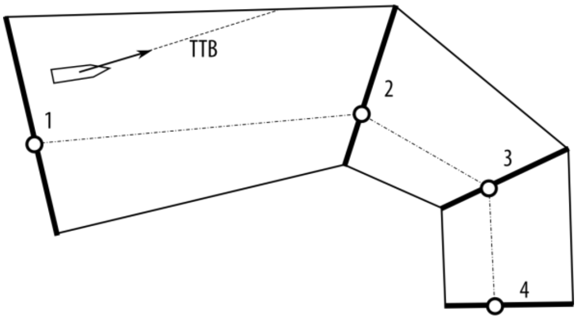

Figure 3. Route based on waypoints and fairway-width, with a ship and its time-to-boundary (TTB). The navigator will set a course with max TTB and maintain a minimum TTB.

There will be large differences between navigators in how they take position in the fairway; positioning preference is a navigator characteristic. Some navigators prefer to minimise the need for accurate predictions at the cost of large safety boundaries and a high rate of control actions. Other prefer to minimise control activity by predicting the ship's path accurately and using the full space available for safe navigation. Most navigators will balance prediction accuracy and control actions, and use some of the available space. In fuzzy control like manner this can be modelled elegantly by setting the shape of the relationship function.

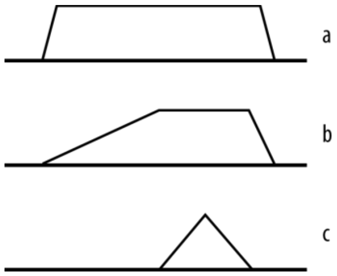

Figure 4. Preferred position in the fairway, showing three different types: a) minimise control, b) normal, c) minimise prediction. Two are skewed to the right because of traffic regulations.

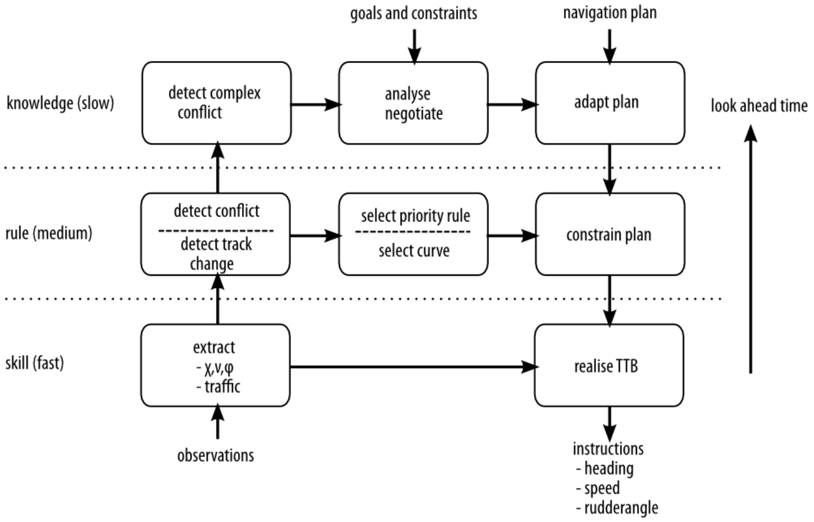

Figure 5. Skill-Rule-Knowledge navigator model, based on Rasmussen's model (1983). Higher levels of control are more complex and require significantly more time and depend on more look-ahead time. All layers function in parallel.

The model proposed is based on the skill-rule-knowledge model by Rasmussen (1983, 1986). The skill-rule-knowledge (SRK) model is chosen because it is widely used and easy to comprehend and use in a navigation context. It consists of three levels of control. The lowest level is skill-based behaviour, realising control based on implicit knowledge, using opportunities offered by the environment without reasoning about it. It is a fast system, requiring little effort, and does not depend on additional resources. The next level is the rule-based behaviour. Rules describe how to respond in a certain situation, very much like logic programs and traffic- or priority rules. Rules are less fast, use procedural knowledge, require more effort in selecting and applying the rule, and do require resources for rule- and response selection. The highest level is knowledge based behaviour, a system that can reason about the situation using generalised knowledge, declarative, to analyse the situation, and procedural, like manoeuvring principles. It is slow, and its function is resource intense. All three levels function in parallel, allowing the results, control actions, to appear in sequence; “changing it's mind”. On the differences in speed between different types of mental processing, see e.g. Kahneman (2011).

3. DIFFERENT MODES OF CONTROL

The model does not include voyage planning. It is assumed that the navigator is given a voyage plan, as is the normal situation with sea-going vessels. In realising that plan the navigator shows three modes of control: tracking, turning, and conflict detection & resolution. The three modes are hierarchically organised, conflict detection & resolution being dominant, then curves, than tracking. Switching between modes takes time.

The tracking task is to go towards the next waypoint within the path set, using heading control. Control is exercised at the skill-based level and is implemented as a fuzzy-control model. The control signal is a heading command. Realising the heading is delegated to the helmsman. The helmsman is modelled separately as a fuzzy control system setting the rudder-angle. The ship itself is modelled as a set of differential equations. Within the tracking task the desired speed is taken from the voyage plan. Because the plan is fixed during the voyage the range of disturbances the ship can handle is limited; the overall plan is not modified to adapt for changes in the environment. The navigator will however respond to disturbances acting on the ship. When TTB drops below a minimum set while change in heading does not increase TTB, speed is set accordingly.

A second mode is turning. In a turn a preselected curvature needs to be realised. Turns are marked by waypoints. The navigator estimates the rate of turn and the moment of initiation based on actual heading and speed, and the goal is to arrive at the centreline of the next leg using the largest curve that fits the environment. This process includes manoeuvring characteristics of the ship based on rules-of-thumb (lookup-tables). Thrust-control is applied to realise the desired rate-of-turn (direct engine control is assumed). When turning the task of the helmsman changes from realising a selected heading to realising a rate-of-turn. Marginal situations are not considered.

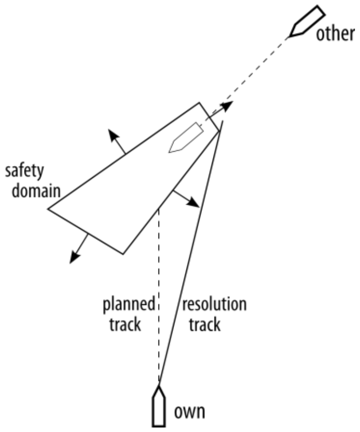

Figure 6. The basic conflict detection and resolution mechanism. The own route is known, the other's route is estimated from a standard route or linear extrapolation. The arrows determine the direction of resolution direction. If the change in course results in leaving the route-path, speed is reduced. Imperfections in path prediction are be corrected over time.

A third mode is conflict detection & resolution. From the current state the intended track with curves is analysed for conflicts. The time-horizon over which conflicts are detected is selectable and is a navigator characteristic. For all other ships the assumption is made that they continue following their current heading and speed, or keep following the fairway. When another ship crosses the own ship's safety domain it is considered a conflict and all three levels of control activate to resolve the conflict. At the skill-based level a heading-change will be chosen to enlarge the time-to-boundary. If an intended change in heading and/or path does not enlarge the time-to-boundary significantly speed is reduced. At the rule-based level a priority rule will be selected. And at the knowledge based level the model will attempt to resolve the conflict if the skill- and rule-based levels fail. For this it will be assumed that the other ship has the same characteristics as the own ship and applies the same strategy (skill-rule). If this does not work, plans are exchanged between ships and checked for a continuing conflict. If the conflict is not resolved the biggest ship takes priority, as a fail-safe last priority rule. Conflicts beyond the time-horizon are not detected.

4. SIMULATION ENVIRONMENT

A system was built to provide a simulation environment for human-in-the-loop navigation instrument evaluation. Up to 20+ ships can be simulated together in the same area (the number of ships is limited by computer capacity). The primary objective of the system was not to study emerging traffic behaviour under various conditions but show realistic behaviour for system evaluation.

By setting navigator parameters traffic behaviour can be influenced. The model allows for setting three groups of parameters.

1. Look-ahead time. The navigator does not include all traffic in his decision making process, but only traffic that is on the planned route over a selected period. In addition, the width of the path observed is a fixed multiple of the navigation path-width. Used values for the look-ahead time are 5 and 15 minutes.

2. Control level. The model has three layers of control. Each of these layers has its own reaction time that can range from a fraction of a minute to several minutes. Reaction times are considered cumulative between layers. Used values are 0.33 minutes, 1 minutes, and 3 minutes for the skill, rule and knowledge level, where the cumulative effect is included in these times. Navigators could show skill level alone, or all three levels of control.

3. Lateral position preference. Different navigators show wide differences in their preference of the lateral position on a safe navigation path. This can be the result of personal preferences, standing orders, or bridge-team organisation. The three patterns shown above are implemented.

The setting was the Port of Rotterdam: Europort and Maasvlakte area, and 12NM out to sea. Docking was not considered. No tugs or other supports are included. There was no centralised planning, no other information than what can be observed from the bridge and from the plan exchange (on request). The estimation of all navigation parameters is considered perfect. Exchanged plan is perfect. Three sea-going ship models were available. Two types of scenarios were used: Ships with plans generated at random, while maintaining a total of ships in the selected area, or constructed scenario's providing complex conflicts or geometric patterns.

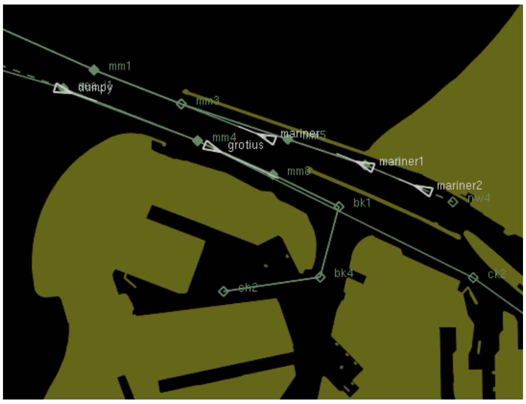

Figure 7. A console view of a simple traffic situation.

5. INITIAL RESULTS

While no performance criteria were developed yet because behaviour turned out to be rich, initial tests allowed to observe some interesting phenomena resulting from the different navigator parameters settings.

1. The navigators could be set with two time-horizons: 5 minutes and 15 minutes. The short period could be used at sea but was was dangerous in port, resulting in near-misses and even collisions. The longer period showed to be effective at sea and in port.

2. Navigators could be set to use skill-based control alone, “opportunists”, or the full SRK control system, “planners”. At sea, with large navigation space, the opportunists were highly effective, solving complex patterns elegantly. In port, with constrained fairways, opportunists caused accidents while planners operated effectively.

3. Finally, the lateral preference setting. This turned out to be rather complicated. The “minimise prediction” navigator-type setting was safe but did not allow for a high traffic density, causing traffic-jam like situations, which are a serious risk. The “minimise control” navigator-type setting allowed for high density but sometimes caused highly complex traffic situations the system could not solve.

An important observation was that in port, only observing the own path for planning is insufficient for safe navigation: Conflict detection is too late for a resolution when crossing traffic interferes. However, in a port situation ships cannot “look around a corner”. This is where Vessel Traffic Service comes in, not implemented in this system.

6. DISCUSSION

To optimise efficiency, availability and safety, one needs to understand navigator behaviour. In analysing ship manoeuvring it is crucial to know the underlying behavioural rules. One cannot predict “ship behaviour” without having a proper cognitive model of the navigator. Validation will be required to know whether the model proposed is sufficient to explain the behaviour of interest. However, given the complexity of navigator behaviour it is unlikely to achieve a good descriptive model by observing the system alone.

Initial results show that small changes in navigator performance or navigator character can have a dramatic effect in traffic capacity. In order to represent the rich behaviour displayed by ships it is essential to have a representative model of the various control systems on that ship: the bridge-team with the navigator. A representative ship model includes a cognitive model, a model that observes, interprets, and controls the ship, communicates with other ships about their plans, and negotiates with other ships to distribute the insufficient resources. These functions form the base for the efficiency and safety seen in maritime traffic.

The mathematical ship model used is a rather simple one and does not include shallow-water effect and ship-ship interaction. In controlling speed, heading and rate-or-turn these effect are very important. It is however unclear if they have any effect from a traffic point of view. The navigator model can include these interactions. It is however unclear if the ship needs to display hydrodynamic interaction-effects.

In solving conflicts, one is resolved after another in this system. This may be a simplification of reality. However, it appears to be effective and may very well be what most humans do. One of the tasks of VTS is to prevent the development of complex conflicts, conflicts that involve more than two ships at a time. Negotiating with more than two ships is much more complex since the number of negotiations will grow with an order of $\binom{n}{2}$. It would be interesting to learn how real navigators deal with this type of complexity.

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