Balancing efficiency and safety in maritime traffic management when approaching a port

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Abstract. This paper discusses maritime traffic management in the boarding process of pilots when approaching a port. For efficiency reason ships are brought as close together and as close to shore as possible. For safety reason ships should remain well separated from each other and at a safe distance from shore. By realising a clear traffic structure the shore-based pilot maintains situation awareness and manages workload while realising safety and efficiency.

1. INTRODUCTION

Efficiency and safety are the two key factors in maritime transport. For economic reasons, principles like chain planning and just-in-time delivery become more important. To realise this, system availability, reliability and safety is paramount. In this study it is analysed how efficiency and safety are realised in the approach of a port.

Each phase of the voyage poses different requirements to the ship's navigation. At open sea the ship navigates autonomous, optimising its state locally. Near the shore radar guidance is provided to realise fluent traffic. Finally a local pilot navigates the ship into port and moors it at its berth. This change in ship navigation over the voyage is governed by the changing dominating constraints.

In piloted waters the dominating constraints are the navigable area, with the risk of stranding, and the traffic, with the risk of collision. A pilot is a local navigation expert with extensive training and experience in ship handling in constrained situations, unlike the average crew. Pilots also have the ability to make optimal use of local service providers.

Modern technology allows the pilot to provide navigation assistance from ashore in the form of shore-based pilotage, in which a pilot-operator provides heading and speed advise for safe navigation. However, the sensors available are limited in their information, not providing the entire state of the ship. Additionally, when giving shore-based pilotage the workload of the operator will increase with the number of ships.

Shore-based pilotage is discussed by various authors, e.g. National Research Council (1994), Hadley (1999) and Bruno & Lützhöft (2009). These publications largely focus on the limitation of remote pilotage in relation to human control limitations. This paper will focus on a specific part of remote pilotage and look at the process from a control system perspective.

Shore-based pilotage operates within a larger structure of Vessel Traffic Services, that support traffic safety in and around all major ports. While the primary task of a pilot is to provide safety and expedience, the safety perspective of the VTS is not that clear (Praetorius et al., 2010). Within this article the interaction between shore-based pilotage and VTS is not discussed, and differences in safety perception are not addressed.

Ship arrive at a port from different directions at open sea, while in port ships must manoeuvre well separated in a narrow fairway lane. The topic of the study is how the ships, coming from different directions, are merged in a single stream and a pilot is brought on board. Safety needs to be assured under all conditions: Shipping is a continuous process, 24/7. The operating conditions vary considerably, regularly beyond design specifications, requiring the system to adapt and reorganise to maintain safety. It is for this reason that an analysis was done from a resilience perspective, focussing on monitoring and adaptation.

2. PILOT BOARDING PROCESS

The analysis is based on three older studies. The first study was an observation of the boarding process from the ship's perspective. For this over 20 boardings were observed on various ships (Van Westrenen, 1994). The second study was about the pilots work. For this ten pilots were observed during more than 40 voyages (Van Westrenen, 1999). Finally six shore-based pilots were observed during their work and actions, objectives and strategies were discussed. In addition, documents were studied and observations were discussed with trainers and supervisors. Information were collected in notes, illustrated with a few photos and video, for later analysis.

For safe navigation a pilot will board before the ship enters port. At deep sea the ships are free to manoeuvre while in port the navigable area is very constrained. The pilot will assist the ship in this constrained situation. Figure 1 represents the basic structure of the situation. Ships arrive from three directions (traffic lanes) and need to merge at the small arrow in the centre. This is where the pilot boards. The pilot comes from the port towards the boarding area in a fast pilot tender. The ships slows down at the boarding location, the tender comes alongside, and the pilot changes ship. The three sets of lines spreading out from the port represent the navigable area for different draughts, where deep-draught ships need to stay in the narrow channel, and small ships need to stay between the most northern and southern line.

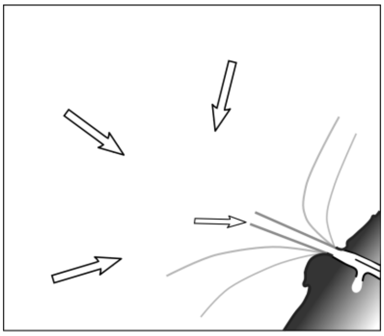

Figure 1: Representation of the boarding area with three traffic streams and the fairway leading into port.

To allow a safe and efficient merging of the ships and co-ordinating with the tender, a shore-based pilot monitors all traffic with sensors (e.g. radar) and instructs the ships to safely merge, slow down the ships, and meet the tender. In addition to the ships that need a pilot there will be other ships in the area that are informed about the navigation and traffic situation. The basic structure of this process is shown in figure 2.

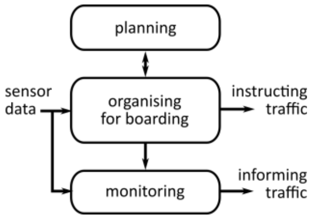

Figure 2: Primary functions in the shore-based pilot process.

The functional structure showing the primary functions enabling merging and boarding is shown in figure 3. It has the same three-level basic structure, but now the supporting functions are laid out. These functions are based on the activities displayed by the pilots and discussions about their work. Each function has an input (left), output (right), controls (top), and resources (bottom). The planning process is realised by a specialised planner. The shore-based pilot manages the boarding process and the information provision for other traffic. Important functions for this are monitoring, queuing, deconflicting, instructing/informing, and process management. Various aspects of the functions are discussed in detail later.

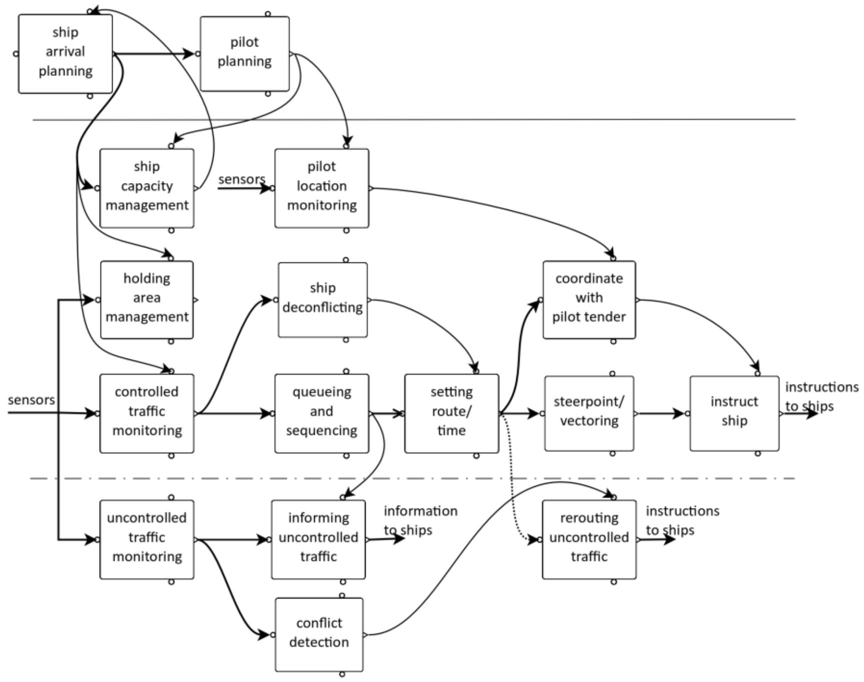

Figure 3: Diagram with the basic functions of the boarding process (simplified). The top functions are provided by planners. The lower functions are for traffic not in the boarding process.

Ships arrive in the area from sea where they manoeuvre completely autonomous. When approaching the boarding area they will accept instructions from ashore to realise co-operative and co-ordination manoeuvring. If the co-ordination fails, the ships are expected to stay clear from each other in the navigable area but the merging and boarding process will stop. The relevant ship functions are presented in figure 4. This model is derived from the model by Van Westrenen & Praetorius (2012).

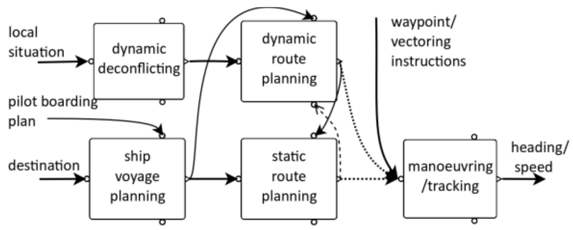

Figure 4: Diagram with the basic functions of the ships.

2.1 Operating Principles

For efficiency, ships must come as close together as possible. Decreasing their separation also decreases their freedom to manoeuvre, requiring more strict control to realise the same level of safety. Stricter control is realised by changing the type of control, providing control at a lower level.

Ships can be controlled remotely in two ways: by giving it waypoints to be navigated, or by giving it heading instruction to be steered. Some characteristics are in table 1. It shows that control accuracy can be achieved at the expense of workload.

Table 1: Characteristics of two types of ship control.

	control level	movements	operator workload
waypoint/speed	high	approximate	low
heading/speed	low	precise	high

While adapting the level of control to maintain safety and at the same time increase efficiency, the operator has three basic strategies to mitigate the effects of temporarily increased traffic density. Given that ships arrive at random times with a Weibull-like distribution, they will arrive in “lumps”. By adjusting their arrival speed, spreading them longitudinally, peak-densities are minimised, thereby increasing capacity, but requiring planning and adjusting. The second strategy applied is using the width of the navigable area to spread traffic laterally. This allows the ships more manoeuvring space, allowing for higher levels of control by the operator, but increasing traffic complexity. Thirdly, buffer areas are created to make the ships wait until traffic density decreases, allowing for safe separation but requiring more complex planning.

Pilots arrive in the area from the other side then the arriving ships. They require travel time and time to get on board. Since pilots need to be on the bridge before the first critical event, and smaller ships have a larger navigable area and sail slower, smaller ships can be served closer to the port, increasing efficiency by depending on shorter travel times. However, this can only be done when the ships are spread lateral, separating ships controlled from ashore and by the pilot on the bridge, and spreading increases traffic complexity which might have a negative effect on situation awareness.

2.2 Predictability and Control

There is a large variability in the system. Ship sizes, meteorological conditions, hydrodynamical conditions, traffic density, ship condition and crew quality are just a few examples of this variability. For efficient and safe control, the shore-based pilot depends on the prediction of ship movements. This prediction depends on his knowledge of the ships' characteristics, state and the environmental conditions the ship is in. Current state-information of ships and environment is provided by the sensors and information systems. Knowledge is obtained through training and experience, on board and as a shore-based pilot.

The less predictable the ships' movements are, the larger the minimum separation needed. Because there is such a large variability in the traffic, the shore-based pilot has a large freedom in how he realises efficiency and safety. The merging and boarding process is not fully constrained in procedures, rules and strict criteria. Only a few guiding principles are applied that focus on maintaining separation and flow. For this the shore-based pilot applies the basic strategies, discussed above. In doing their work they focus on maintaining good situation awareness by realising a clear traffic structure and maintaining a sufficiently low workload by realising a minimal conflict rate and choosing the appropriate control level.

3. RESILIENCE CHARACTERISTICS

The domain focuses on separation, buffering capacity and flexibility as the main characteristics of safety. This is very comparable to the resilience system-characteristics defined by Woods (2006): buffering capacity, flexibility versus stiffness, margin, and tolerance.

System resilience is realised by a layered design of control that allows to adapt over a large range of variability. At the lowest layer are the (potentially autonomous) ships. In the middle layer is the shore-based pilot, realising choreography between the ships, utilising the ship's autonomy. At the top layer is planning, spreading the load over time to avoid peak loads. These three levels co-operate to achieve the overall system goal. The system resilience is analysed using system diagrams, focussing on information streams, and on the strategies applied.

Functional resilience is realised by maintaining three charateristics: separation, buffers, and flexibility. Maintaining separation is the primary task while realising traffic fluency. Minimum following-, crossing- and lateral-distance are maintained appropriate for the ship and the meteo-hydrodynamical situation. The resilience is realised by monitoring and applying the strategies and associated traffic-organisation plans.

Traffic complexity can be high in maritime traffic due to the large variation in ships, crews, and sailing conditions. Standard routes and organising principles for the traffic allow for maintaining situation awareness. Workload depends largely on the required accuracy of ship control. When ships come close together more accurate control is required, depending on another type of control, which in turn will increase workload. Workload management requires traffic planning to assure separation minima while realising productivity.

Ship separation is not fixed but depends on ship characteristics, conditions and uncertainty; when uncertainty decreases, separation can be lowered. When separation can no longer be maintained, buffers at predefined waiting locations are brought into use to temporarily lower the traffic load or decouple the chain of ships. Rules of thump are used to decide on the need of buffers. The holding areas are designed together with the standard routes. While separation and buffering allow coping with all standard variations unexpected event may disturb the process. Basic procedures guide the reorganisation required to maintain safety and preferably realise traffic fluency.

Apart from this control structure, there is an organisational structure. All functions needed by the system are not only available via the primary operator but can be provided by others (not presented here), within the team or by other teams ashore or at sea. This functional redundancy is utilised by the organisation to reorganise the system when minimum performance requirements are threatened.

Ships separate themselves which potentially makes the system very tolerant towards a failure of the organising process: When the entire shore-based pilotage system fails, ships will continue to maintain separation. It may even function when the shore-based pilot directs ships against each other and ships themselves avoid collision.

The system design shows various monitoring and management functions. Monitoring is considered a vital function for resilience but depends on the availability well-chosen set of system parameters (Wreathall, 2010). In addition the system needs the ability to anticipate. The system analysed contains these two properties embedded in the three-layer design, although it is unknown how well it functions.

4. CONCLUSION

The shore-based pilot optimises traffic flow while coordinating pilot boarding. For this they focus on maintaining situation awareness and workload development. To maintain the flow pilots use a limited number of basic principles and a basic pattern on which they vary. Their primary control strategy is focussed on accepting no more control from the ship than necessary for the required accuracy. By minimising workload they maximise for opportunity to maintain situation awareness.

There are two trade-offs that are considered important with respect to pilotage. The first one is the trade-off between safety and efficiency. For maximum efficiency the ships are brought as close to the coast as possible, and are grouped as close as possible to minimise the travel-time for the pilots. However, coming close to the coast unaided increases the risk of grounding, and bringing the ships close together increases the risk of collision. By dynamically adjusting the boarding strategy a minimum separation is guaranteed while maximising efficiency. The second trade-off is between required navigation accuracy and workload. The pilot ashore attempts to optimise his control. When safety margins are large, low accuracy is required, demanding low workload. When the navigational area becomes narrower and ships come closer, accuracy demands increase, increasing workload demands. Controllers compensate by changing their control strategy, while workload constraints set an upper limit for traffic capacity.

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