Control concepts for navigation of autonomous ships in ports

Conference Paper · October 2016

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Abstract
In this paper we present a solution for autonomous navigation of ships in a port environment. Said environment is characterized by continuous communication between vessels and traffic control stations, which poses various challenges for autonomous navigation. We tackle these challenges in four control levels that permit the navigation of an autonomous vessel in today's port environment, based on whether the ship is underway and the need for VHF-communication. The paper concludes with the development and evaluation of operational concepts to make autonomous navigation within the control levels possible. However, (partly) human control is still assumed to be necessary in critical situations.

Keywords: unmanned ship, human involvement, dense traffic, human-machine interaction

1 Introduction

Contemporary developments in autonomous transportation like Tesla Motors' autopilot, Google's trials with selfdriving cars but also developments in the field of drones, will spill over into the shipping sector sooner rather than later. Although research for autonomous shipping is younger than its land- and air-based counterparts, recent studies show the potential of increasing autonomy in one of the oldest and most conservative industrial sectors. Both the European research project MUNIN, *Burmeister et al. (2014)*, the zero-emission, unmanned, short sea concept of DNV GL, *Tvete and Brandsæter (2015)*, and a cooperation between among others Rolls-Royce and DNV GL in the AAWA project, *Rolls-Royce (2016)*, are conducting research into the topic of autonomous shipping. The focus here lies on longer distance autonomous and unmanned sailing outside ports, presenting impressive figures on cost savings due to the absence of crew on board, *Burmeister et al. (2014)*. On the other hand there is a noticeable drive towards increasing autonomy in the optimization of inter-terminal transport of containers by using autonomously guided vehicles (AGVs) within the port of Rotterdam to reduce costs and waiting times, *Negenborn (2014)*, *Brands (2015)*. Here the focus was on autonomous transport over land, with in one case also on waterborne AGVs, *Zheng et al. (2015)*. This last research however assumes a fully autonomous environment. Neither one of those researches looks into the application of an autonomous container shuttle within the current port environment, characterized by otherwise only manned ships. The reason for this exclusion are the challenges posed by the combination of autonomous and conventional vessels in close spaces as ports, *Porathe et al. (2013)*.

This paper addresses the navigation aspect within the port environment. Navigation in ports is marked by a vast amount of traffic situations. At this point in time, VHF-communication is paramount in port movements and inter-vessel communication. Computerized VHF-communication within this context being currently unrealistic, a different way is needed to communicate vessel intentions between manned and unmanned ships.

Within this paper we provide an overview of different solutions for autonomous vessel navigation in an environment of manned vessels. We have evaluated these solutions using a framework of possible future developments. This paper adopts the inter-terminal transport of containers in the port of

Rotterdam as a framework for the solutions on navigation of autonomous vessels. It is our aim however that the reader can use this paper as a general outline and starting tool for research into autonomous navigation in ports.

The paper first elaborates on the research method used to structure and analyze the process of navigation in ports, followed by the different solutions that have been identified. Subsequently, possible future developments are introduced that provide the framework to evaluate the different solutions. Finally, this paper offers a more in-depth discussion and conclusion on the solutions and the framework that was used to evaluate them.

2 Approach

To get an overview of solutions for autonomous navigation inside the port environment, the navigation process is split into control levels so it's different aspects can be structured and analyzed. The applicability of the solutions is then analyzed and evaluated based on the area of operation and prospective operators of the autonomous vessel. The technical feasibility is assessed by determining the demands of different solution concepts for innovations in sensing and artificial intelligence.

2.1 Classifying autonomous navigation into controllevels

Similar to the use of control levels in management and for the purpose of this research, four control levels for navigation are identified: strategic, tactical, critical and super critical. Clear and strict boundaries between control levels are applied. This way all possible situations are inside the scope of the control levels and thus can be handled. The inputs and outputs of each control level are used to identify and evaluate multiple particular solutions. In the following four subparagraphs, each of the control levels is briefly linked to the issue of autonomous navigation.

The strategic control level only spans decision making before the autonomous vessel leaves the berth. This level relates to all preliminary planning of the autonomous vessels. This requires information about destination and estimated time of arrival (ETA) from the operator, as well as information about the fixed environment such as port structures and buoys and possibly information about previous voyages and expected traffic density within the area. Actual location and behavior of other vessels is not taken into account to determine a preliminary route and sailing profile for the autonomous vessel. Real-time behavior of vessels is constrained to subsequent control levels.

The tactical control level starts as soon as the autonomous vessel leaves the berth and becomes part of active traffic. In this control level the main goal is to follow the route that has been determined in the strategic level. The autonomous vessel now has to deal with live information about other vessels which operate in the area. The tactical control level contains solutions which can deal with predictable behavior of the other vessels, so that no VHF-communication or special intervention of any kind is required.

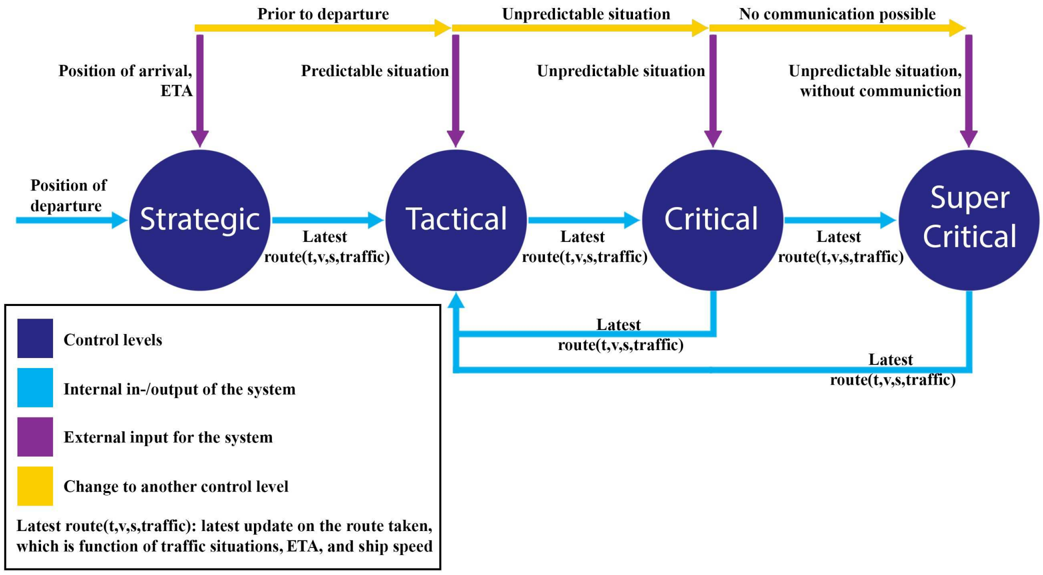

Fig.1: Control levels and interconnections

The critical control level narrows the tactical decision making down to dealing with unpredictable behavior of other vessels. Communication between autonomous and manned vessels is, however, possible. Solutions within this control level are mainly concerned with changing autonomous vessel speed and heading so that the situation can be solved.

As an extension of the critical level, we define the super critical level. Within this control level the autonomous vessel now not only has to deal with unpredictable situations, but also with alien objects within its perimeter with whom, to solve the situation, communicating is deemed impossible. This includes but is not limited to a person or object in the water, a vessel with a black-out or without communication equipment and oil spills. For these situations special solutions are required.

2.2 Evaluating solutions based on operational scenarios

The solutions for autonomous navigation are subsequently evaluated by means of two domains of future development. A first evaluation was made by assessing the applicability of the solutions based on the area of operation; i.e. the traffic density and range of the autonomous vessel. Next, we looked at prospective operators and investors. Based on personal communication and research we were able to profile their priorities and the influence these had on the applicability of the solutions. Finally we were able to also link the solutions to necessary technological breakthroughs in the field of sensing and development of artificial intelligence.

3 Concept solutions for handling navigation planning and inter-vessel communication in ports

For each of the four control levels various concepts have been identified. These concepts transform the inputs of each control level to outputs that will be used for the next control level. It is possible to create concepts that focus solely on one control level. In practice however, there are preferable combinations of concepts in different control levels due to similar organizational or technical requirements. This is of importance for the selection of an all encompassing navigation system which has solutions on all control levels.

3.1 Solutions within the strategic control level

The inputs of the strategic control level are the current position of the autonomous vessel, the destination of the vessel and the corresponding scheduled time of arrival. The solution concepts for this level provide the preliminary route from the current position to the set destination as well as a corresponding sailing profile for the autonomous vessel.

3.1.1 Liner service scheduling and route planning

The liner service concept is based on a shuttle service between two or more container terminals, with a fixed route. This route is dependent on participating terminal operators. The port authority has the best overview of vessel traffic flows and collects lots of data of ships and their positions. This knowledge of vessel traffic could be used to avoid busy waypoints in the initial route planning, based on statistical traffic density. Therefore involving the port authority in the implementation of an autonomous vessel in a port would be favorable to minimize the impact of the fixed route on non-automated traffic. The departure and arrival times are also predefined and can be optimized based on information about transport supply and demand of the participating terminals. This is an economical trade-off, for which a fair amount of information sharing between terminals is required.

3.1.2 Cargo based scheduling and route planning

The cargo based concept that has been evaluated uses a dynamic route planning to minimize the impact on other traffic inside the port. More specifically this translates to a route near the right side of the waterway and usage of waypoints as in aviation. The knowledge of the port authority could again be used to avoid busy waypoints in the initial route planning. Individual arrival and delivery times of containers at terminals form the constraints for the scheduling of the autonomous container shuttle. This means that in this concept the destination and ETA are based on previously gathered information. This can be solved by the extension and more widespread use of the current Portbase system. This is a logistical planning tool for cargo vessels used by several Dutch ports.

3.2 Solutions within the tactical control level

For the tactical control level, the inputs are the preliminary route and the corresponding sailing profile chosen within the strategic control level with an according ETA. The outputs from the tactical solution concepts are continuous iterations of the original route, sailing profile and ETA as the autonomous vessel deals with predictable behavior of other traffic participants.

3.2.1 Following manned ships in platoons

The concept of ship platooning implies the autonomous vessel following manned cargo ships that sail (partly) the same route on a fixed distance to get to the desired destination. All communication about traffic situations is handled by the manned vessel, so that the autonomous vessel merely has to mimic the leading vessel's behavior. This reduces the amount of situations that fall inside the critical control level. It is important to stress that the leading - manned - vessel will not assume the responsibility for the unmanned vessels in the platoon. The leading ship merely provides a 'safe-to-sail' route for the unmanned vessels. Ship platooning requires manned vessels that pass through the area of operation of the autonomous vessel to determine and communicate a preferred route based on waypoints. These routes are then centrally monitored by the ship owner within a shore control center (SCC). Involving the port authority for traffic monitoring is preferable. Three main elements are needed from an organizational point of view. First, an online platform is needed where captains of manned ships and terminal operators enter ship and route information. This online platform is monitored within the SCC. Ship routes can subsequently be set by using waypoints and more strictly determined lanes from which captains can only deviate in case of emergency or special maneuvers (e.g. mooring). This concept works best when it is applied in larger areas of operation with relatively high traffic. To ensure maximal efficiency on longer routes, the third organizational element needed is thorough coordination between current VHF-sectors in the port. In this way, both manned and unmanned vessel predictability is highest.

Within this concept the autonomous vessel can make decisions about the best combination of ships to follow, based on the constraint of the initially determined ETA and the available vessel routes. The combination that comes closest to this original ETA will be chosen and communicated with. Captains of manned ships have the last word in approving the platoon with the autonomous ship. This concept requires exact positions and speeds of possible platoon combinations. This could be realized by increasing the Automatic Identification System (AIS) accuracy and refresh rate as well as further improvement of the possibilities regarding route projection of AIS. To determine the safe following distance, the autonomous vessel needs information about ship characteristics and cargo hazards. This could be provided by the Harbour Master Management Information System (HaMIS). Thorough data integrity and security is needed for the transfer of this data. To mimic movements of the leading vessel, Laser Imaging, Detection and Ranging (LIDAR) sensors could be used to constantly maintain the autonomous vessel within a fixed distance interval in a line behind the leading vessel. Whenever the autonomous vessel is not in a platoon (i.e. between the release and rendezvous points), other tactical solution concepts are required to navigate the vessel to the next platoon. Another possibility would be to control the autonomous vessel remotely from the SCC in these instances. Finally we foresee the need for the development of a module on board the manned ships which would transfer and display all ship and platoon information for the participating captains.

3.2.2 Anticipating traffic situations

The second concept is based on the capability of the autonomous vessel to anticipate traffic situations. This means adapting the sailing profile and route to avoid critical situations (i.e. the need for communication with manned vessels). For anticipation traffic situations two major parties should be involved. The port authority that already has the general overview of traffic inside the port, and a SCC that also requires the same overview to be able to monitor or control the autonomous vessel remotely. Within this concept solution different gradations of autonomy can be chosen with consequences for technical requirements and the organization of the SCC. This is visualized in table [Tab. 1]. The information about manned vessel positions and behavior can be communicated to the autonomous vessel by either SCC or port authority. In case of local, fully autonomous anticipation, a combination of AIS, LIDAR and stereo cameras is recommended for complete situational awareness. Traffic cameras on shore near harbour entrances would provide better vision for blind spots behind buildings. Prediction of planned traffic participants could (for the port of Rotterdam) be provided by an extension of HaMIS. The range of the route optimization distance could be set to 2 km ahead of the autonomous vessel, based on practical observations. The optimal route is chosen with the original ETA as constraint. Furthermore a safety perimeter, based on ship and cargo characteristics, around autonomous and manned vessels is advised to ensure safe passing of ships. The critical control level will be triggered once the safety perimeter is breached.

Table I: Gradations of autonomy and shore control center role within the concept of anticipating traffic situations

Degree of autonomy	Role of shore control center
Remote control	Determines path solution, controls autonomous vessel
Remote decision, local control	Determines path solution, communicates solution
Local decision and control, remote approval	Checks autonomous path solution
Fully autonomous	Monitors autonomous vessel behavior only

3.2.3 Portwide route optimization for all vessels

The concept of portwide route optimization assumes that routes of all cargo vessels in port are centrally planned based on actual time of departure from berth, destination and ETA. This concept drastically reduces the need for direct communication between vessels in the area of operation. The central planning system would need to process a substantial amount of information from ships and terminals to determine the optimal routes for all vessels in port. A possibility would be to use the current HaMIS system as a starting point for further development, albeit with an extension for inland vessels. The autonomous vessel would follow the route and sailing profile set by the central planning system to its destination. The captains of the manned ships would also need to follow the set path and speed instructions for their vessels. The way the routes are displayed for the captains would be based upon the current Electronic Chart Display and Information System (ECDIS), accompanied by the sailing profile. Current port regulations as e.g. preference for portside-portside crossings and right of way for 'vessels constrained by draft' are accounted for in the central planning. Nonetheless, captains are still required to apply 'good seamanship', i.e. use their own judgement, in case of an emergency. This concept is, however, not easy to realize. The requirement of an extension of HaMIS and the implementation of an update of the ECDIS systems on board of inland and seagoing ships will take several years. It is therefore unlikely this concept will be realized within the next few years.

3.3 Solutions within the critical control level

For the critical control level, the inputs are the current location, path and vessel speed. The ETA is not an input for the critical control level. The critical control level is triggered by unexpected situations in the surroundings of the autonomous vessel. These need to be identified first, then evaluated and solved. The first part of this paragraph is on the identification. After consulting with parties involved, human intervention was seen as necessary for problem-solving at the critical level and is discussed subsequently. The outputs of the critical control level are an altered path and speed (as a solution of the situation) and the autonomous vessel's navigation model returns to the tactical control level.

3.3.1 Identification of unexpected situations

A whitelist is a first way to identify unexpected situations. This whitelist contains previously known information about the immediate surroundings of the autonomous vessel. By using different types of sensors, the actual perception of this environment can be compared to the whitelist. If the information does not match, an unexpected situation is identified and the critical control level is triggered. Constant human supervision is the second way to identify such situations. This would translate into continuous camera-based surveillance as in automated industrial processes. Human judgement of possibly critical situations would in this case trigger the critical control level. The third method of identification uses a safety perimeter around the autonomous vessel. The size of this safety perimeter depends on characteristics and status (underway, mooring and anchored at berth) of the autonomous vessel. The critical control level would in this case be triggered by a violation of said safety perimeter by another vessel.

3.3.2 Handling the critical control level

Three ways have been identified to solve critical traffic situations by human intervention from the SCC. A first way is to introduce a remote control handover to an operator. Based on a virtual reality bridge and simulation like transmission of acoustic and motion senses this operator would be able to solve the situation. In this case, getting the human-machine interaction right is extremely important. A quick selection of waypoints by the SCC is a second way to solve the situation, be it on a much smaller scale than previously discussed within the tactical control level. After identification of a critical traffic situation, a shore-based operator could use a selection of waypoints to set a new path for the autonomous vessel. Alternate route proposal is the third way by which the critical control level can be handled. In this case, whenever the tactical route planning of the autonomous vessel has failed and the critical control level is triggered, a human operator asks the autonomous vessel for a series of new paths to solve the situation. The operator then selects the optimal path based on his judgement. In any such case, the human operator uses the VHF-infrastructure to communicate about his actions to other traffic participants in the sector.

3.4 Solutions within the super critical control level

The super critical control level is triggered when the critical solution model is unable to solve the situation. The inputs are the same as for the critical control level. However communication with the super critical element is impossible, and the control level therefore requires more specialized concepts that do not rely exclusively on externally provided information.

3.4.1 Identification of super critical situations

Super critical situations require sophisticated sensors and control systems on board of the autonomous vessel to identify alien elements in the immediate surroundings. To classify situations like encountering a person or debris in the water or an oil spill as (non-)hazardous, a whitelist could be used again. This idea has been introduced in paragraph 3.3.1. A blacklist can be used as an alternative. In that case a list of hazardous items and corresponding reactions is used to assess and, in the next stage, solve the situation. A last possibility is again continuous human supervision. This would require extensive concentration and high work load for the operator at any time and is therefore not recommended.

3.4.2 Handling the super critical control level

This control level can be handled in three ways. Either the systems on board the autonomous vessel are fully autonomous. In this case, an autonomous reaction of the vessel is triggered when a super critical situation is encountered. This requires significant advances in artificial intelligence research. The second way is again remote control. This possibility does not differ significantly from the concepts proposed in paragraph 3.3.2 and will not be further elaborated in this research. A third conceivable concept would be to have an automatic reaction to super critical situations, i.e. a warning to the SCC or other vessels, after which remote control takes over to actually solve the situation.

4 Future developments

By outlining certain future developments, it was possible to link the identified concepts to certain developments and provide a discussion on their applicability. Both the area of operation as well as possible investors are used to assess the qualities of the concepts. The concepts each require certain technical breakthroughs to assure their full functionality. This is treated in the third paragraph of this section.

4.1 Area of operation

Within the area of operation domain there are two main parameters that influence the concept solutions of control levels. In the first place the operational range for the autonomous shuttle service determines the size of the area of operations. The operational range influences the design (i.e. capacity) of the vessel. Furthermore, the operational range determines the organizational complexity for monitoring/controlling the autonomous vessel. Secondly the traffic density, i.e. the amount of vessels in the area of operation, is of importance.

4.1.1 Operational range

The operational range has two major extremes: locally, within a single port basin, and covering the entire harbor. This influences the maximum distance the autonomous vessel has to travel. Increasing the operational range of the autonomous shuttle service influences organizational requirements the most. Examples are the increased risk of disruptions in planning schedules and difficulties regarding intersectoral communications and autonomous vessel coordination. Furthermore, increasing the range means a longer tactical route, with possibly more elaborate information processing requirements followed by an increased likelihood of critical and super critical control level triggers.

On the strategic control level, a longer distance makes a *liner service* preferable. The *cargo based* concept solution would be much more organizationally complex due to the increased number of variables in container transport time optimization. On the tactical level, a longer distance results in more possibilities for *ship platooning*. For critical situations the use of *safety perimeters* or a *whitelist* are preferred because continuous human supervision would not be feasible on the long distance.

4.1.2 Traffic density

An increased number of vessels and thus a decrease in the amount of space for maneuver directly results in more situations that pertain to the critical control level. The volume of container transport by ship is expected to grow within the port of Rotterdam, *Rotterdam Port Authority (2011)*, which stresses the importance of this parameter mainly for critical solutions.

On the strategic control level, a higher traffic density has consequences for route planning abilities in for instance the *cargo based* solutions. The strategic control level does not use real-time vessel locations, but does benefit from statistical traffic data. By using statistical data on traffic density more efficient routes can be planned, which avoid high traffic areas as much as possible. On the tactical level higher traffic density favors the *portwide route optimization* most, since in this concept all routes are planned. Therefore critical are situations avoided and communication through VHF becomes unnecessary. On the critical and super critical level, sensor systems and object classification systems would seem more suitable for a *white*- or *blacklist*, as more information could be processed faster compared to human supervision.

4.2 Investors

The second subject of future development refers to parties that could be interested in investing in the concept of an autonomous container shuttle. Five major possible investors have been identified: terminal operators, the port authority, the inland shipping community, shippers and external high-tech companies. The vision on the priorities and attitudes are based on interviews conducted with different parties prior to this paper.

4.2.1 Terminal operators

The first possibility is that one or more terminal operators invest in the concept. The important aspect in this case is that there should be no interference with the schedules of their clients; i.e. the seagoing ships. The priorities of terminal operators are flexibility and realizing a profit by saving time (and preferably also money) compared to alternatives like inland shipping.

On the strategic level, *cargo based* scheduling provides the most efficient and flexible solution for the terminal operators. On the tactical control level, the concept of *anticipating traffic situations* is preferred. The flexibility of *ship platooning* is deemed too low because of the dependency on other vessels to follow and the *portwide route optimization* is too expensive for terminals. Having continuous *human supervision* is quite expensive, since a specially trained person will have to be employed. On the critical and super critical control level, *autonomous identification* of these situations is therefore expected.

4.2.2 Port authority

The port authority already gathers and processes large amounts of information on vessel and planning information with systems like HaMIS and Portbase for the port of Rotterdam, which stresses their organizational value. The port authority is concerned with improving the port image by investing in innovation whilst still maintaining high standards of sustainability and safety. This safety constraint might lead to a less progressive stance than terminal operators. The port authority will not become an operator of the autonomous vessel, but its involvement is favorable, because of the existing IT-infrastructure and data provided by HaMIS and Portbase.

Within the strategic control level, the *cargo based* scheduling could use the mentioned infrastructure and is therefore the preferred solution. On the tactical level *portwide route optimization* is favored because it offers a route optimizing solution for the entire port and therefore improves planning not only for the autonomous vessel, but also for other vessels. However, due to the far-stretching implications of this concept it will not be easily implemented. For reasons of safety, human supervision and remote control are expected to be favored on the critical and super critical control level.

4.2.3 Inland shipping community

The Dutch community of inland shipping has already expressed some interest in autonomous shipping in talks with this sector, *(priv. comm.)*. Its main characteristics are the limited budget available for research and development purposes and a rather conservative overall stance. This means they remain a strong advocate of the current system of VHF-communications. The autonomous vessel should,

understandably, interfere as little as possible with manned (inland) vessels.
On tactical level this means that strong resistance against the concept of *portwide route optimization* is to be expected, since the job of captain would lose a lot of its prestige. *Ship platooning* is likely to be the best accepted solution within this community. On the critical and super critical level a combination of a *whitelist* or *blacklist* and a *safety perimeter* is to be expected, coupled to an *automated object detection* system.

4.2.4 Shippers

Shippers choose the modalities used for container transshipment and the technology of the chosen modality is secondary to the costs of the transport. Their priorities lie with safety, reliability and sticking to the set schedule for the container transport. They might see the concept of an autonomous container shuttle as a way of lowering the cost of container transport within the port.
On a tactical level *anticipating traffic situations* is favored, based on the ability to find the fastest route to the destination without deviating too much from the original planning. *Ship platooning* could be an alternative, but only in combination with a long operational range due to possible lack of effectiveness (i.e. lack of sufficient ships to follow) otherwise.

4.2.5 External high-tech companies

External companies involved in high-tech system development could see the autonomous container shuttle as a source of income. If profitable, the concept could be used to showcase the state-of-the-art in technological achievements of the company. The concept could also be implemented in various ports. External companies hold little to no relation to the port organization. As a result and because of stringent organizational requirements throughout the concept solutions it is unlikely that any such party would be the sole investor.
The drive for innovation within these companies combined with their technical expertise leads to critical and super critical concepts which are outside the current scope of this research due to their expected complexity. Highly automated detection and response systems are to be expected from this party.

4.3 Required technological evolutions

After discussing the possible control concepts by looking at the area of operation and possible investors in the previous two paragraphs, it is now possible to link them also to necessary technological breakthroughs or innovations. We look at the field of sensing and artificial intelligence and then discuss the concepts that are the most demanding.

4.3.1 Sensing

Within the field of sensing, one can distinguish the detection of situations or obstacles around the vessel and the ability of humans to remotely monitor these surroundings and interpret the information as if they were on board themselves. As the facilities for remote control, not the suggested control concepts, largely determine the quality of remote sensing, we focus solely on improvements in the field of camera optics, LIDAR range and imaging improvement as well as object identification and classification. On the tactical level, the concept solution that benefits most from this development is the *anticipation of traffic situations*. This is due to the requirements for this concept regarding LIDAR range and accuracy. *Ship platooning* would also benefit from this development, however the requirements are less stringent because of the shorter range needed. On the critical level object classification and improved situational awareness make the *whitelist* concept more likely. This whitelist could be more detailed and therefore critical situations could be identified earlier, with fewer false alarms.

4.3.2 Artificial intelligence

The form of artificial intelligence that we suspect to be of major importance for the application of autonomous ships is machine learning. This denotes the ability of the system to learn from previous experiences and use this gained experience for solving or avoiding future situations. As the machine

learning ability of the vessel increases, this directly influences the autonomy and the involvement of humans in the control. On the tactical level, evolution in this field would be most beneficial to the concept of *anticipating traffic situations*, since this is the most autonomous within the provided concept solutions. On the critical control level, increased autonomy in combination with a continuously decreasing blacklist can in the long run replace the currently expected need for remote control in critical and super critical situations.
If improvements in artificial intelligence are linked to speech recognition technology, this combination would strongly influence the ability of the autonomous vessel to participate in port traffic through the current standards of VHF-communication. The autonomous vessel would be able to interpret and broadcast information through the existing VHF-infrastructure. This evolution would be the most useful for *anticipating traffic situations* as intentions can now be easily communicated to other non-autonomous vessels.

5 Conclusions and discussion

The various challenges that present themselves when an autonomous vessel navigates between conventional vessels in a port environment have been classified into four control levels: strategic, tactical, critical and super critical. This has proven to be a useful way to identify solutions that are able address these difficulties. Mainly the critical control level remains a challenge to solve autonomously, and human control is currently seen as the only way to solve these situations. Critical and super critical situations could however be detected by autonomous systems, which then transfer the control to a shore-based operator. To simplify the interaction between autonomous and conventional vessels, vessel behavior needs to be made more predictable. This predictability can be increased by sharing routes and schedules between autonomous and conventional vessels. The main requirement for an integration of manned and unmanned vessel routes is the gathering of information from multiple sources. Such can be concluded from the presented concepts on the strategic and tactical level. As the port authority already gathers a lot of this required information, we advise to include said party in the further development of this application of autonomous navigation. Collecting accurate vessel and route information will remain a challenge in the future *(priv. comm.)*.

VHF-communications are expected to remain of great importance. For the autonomous vessel this means that a part of the VHF-communication is to be taken over by a shore control center. On condition of further development of current systems like AIS and ECDIS, the remainder of the communication, i.e. communication regarding vessel intentions, can be sent digitally between vessels or from the autonomous vessel to the shore control center. This will strengthen concepts within the tactical control level.

We have assumed no change in responsibility for the platooning solution. It would be an interesting first application however to have a manned ship sailing a fixed route within the port, followed by a platoon consisting of various autonomous shuttles. The shuttles could then serve different terminals, joining and leaving the platoon when required. In this case it would be more convenient to make the leading vessel responsible for the autonomous vessels in the platoon. A special training for the captain of said vessel will probably be necessary.

One of the most important uncertainties that significantly influences the effectiveness of the proposed solutions, is the cooperation and the sharing of information between the various involved parties. Our experience is that there are objections mainly from terminal operators against sharing detailed information about for instance individual containers. The reason for this is their fear to endanger their market position by sharing information about their clients. In the view of the authors, cooperation remains however the ultimate means to realize the goal of an effective autonomous container shuttle within the port of Rotterdam. Leverage through policy control measures at the state level could be a conceivable move forward.

The role of the government can either be directive, subsidizing or facilitating. In the directive case, the government would actively pursue further research into autonomous waterborne transport in ports, by imposing e.g. innovation quota. That way strong incentives would be created for companies to participate in research and pilot projects. The subsidizing role implies that the government limits itself to creating financial stimulants, in order to passively stimulate innovative projects not specifically related to the implementation of autonomous waterborne transport in ports. A facilitating government would mean that the government creates a legal framework which simplifies implementation of autonomous waterborne transport in ports by solving the inherent legal and ethical issues.

No matter the assumed role, the government has to play an important part in regulating operational safety and acceptance by the general public. Regulation backlog on technological advances should at all times be minimized. For the application of autonomous transport within the port area, a small scale closed pilot and open test should be performed with permission from the regulatory bodies to gather information. In view of a possible control system failure, a thorough failure mode effect analysis should be performed for propulsion, navigation and communication systems on board the autonomous vessel. Subsequently emergency procedures should be determined. For classification societies it would be an option to introduce the autonomous vessel as an entirely new class. As with all autonomous systems, there is a large uncertainty about accountability and legal liability for the actions of the autonomous vessel. In case of remote control the liability is easier to determine than in case of fully autonomous concepts. Finally, we recommend consulting and working with a representation of the general public for a successful implementation and to enlarge public support for autonomous waterborne transport.

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