WHITE PAPER

Vessel Automation: The autonomous navigation challenge

Author Dimitrios Kotiadis

Introduction to autonomous navigation

The push for autonomous systems within the maritime industry is aimed at addressing several main factors, namely:

- Efficiency primarily related to fuel consumption & optimum routing
- Safety primarily related to human error
- Reduction of crew primarily to overcome lack of skilled personnel or cost reduction

The introduction of technologies to address these factors have targeted mainly the engine room in the form of alternative fuels, optimized engines & engine room automation.

The next stage of further addressing these factors involves bridge automation and specifically autonomous navigation where a technological solution takes over part or all the human task either onboard or offboard. The main focus area is seen to be in the inland navigation areas where dense traffic exists as well as multiple applications such as ferries, tugs, inland barges, cargo vessels etc. This whitepaper addresses how Damen is approaching the quest for autonomous sailing through its research. The first research question usually is; is it even allowed!

Legal aspects of autonomous shipping

In current legislation the onboard captain is held responsible for many things. Autonomous and remote control are not explicitly prohibited, but it is often simply impossible to meet current regulations when the captain is on shore or when an autonomous system is in control. Looking forward:

- International (IMO), national (e.g., ministry of I&W) and regional (e.g., CCNR) maritime authorities have recognized regulatory restrictions and are working on addressing these. Temporary exemptions are already possible and more permanent legislative changes can be expected over the course of the next years. Limiting risks will be key also in the new legal framework, so uncrewed transport of passengers or dangerous goods will likely not be accommodated in the near future.
- Autonomous shipping technologies have in fact always been allowed in niche applications because there simply are no rules that restrict these. Examples include very small vessels (USVs or drones).

The current legislation and related legal working groups propose a set of levels to best classify the capabilities of such advancements in the form of degrees of automation described below:

- Degree one: Ship with automated processes and decision support. Seafarers are on board to operate and control shipboard systems and functions. Some operations may be automated and at times be unsupervised but with seafarers on board ready to take control.
- Degree two: Remotely controlled ship with seafarers on board. The ship is controlled and operated from another location. Seafarers are available on board to take control and to operate the shipboard systems and functions.
- Degree three: Remotely controlled ship without seafarers on board: The ship is controlled and operated from another location. There are no seafarers on board.
- Degree four: Fully autonomous ship: The operating system of the ship is able to make decisions and determine actions by itself.

The proposed degrees introduce two new control possibilities in addition to the onboard bridge, namely, the remote control center (on shore) and the onboard autonomous navigation system as seen in Figure 1.

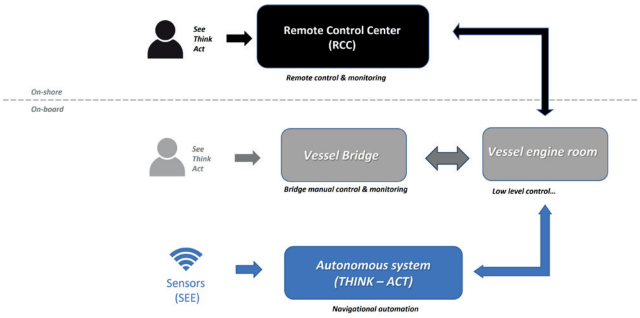


Figure 1. Depiction of the resulting three control elements, namely RCC, Bridge (crewed) & autonomous system. (Source: Damen RD&I)

Many companies today offer capabilities such as RCC – Seafar, some application specific autonomous functions such as Zeabuz. These examples can give insight into the current offering of various levels of automation and their basic setup yet also raise questions on their actual capabilities for the various maritime applications.

To better understand the complexity of the autonomous navigation challenge, in any system or offering we must dive into the basics of the proposed control elements, the RCC and the Autonomous navigation system and their functionality.

Remote control

Remote control essentially creates a crewed bridge off-board and subsequently requires the wireless transfer of the current bridge system data and controls as well as the normally observed environment around the vessel as if the RCC bridge was onboard. This would normally be achieved by providing video streams from around the vessel in addition to the bridge system data.

The main challenge in achieving this is in the provision of a secure and stable communication link between the vessel and the RCC with minimal delay as well as the provision of high bandwidth to share the necessary vessel information. As with many communication links maintaining the link can be challenging and as such onboard support would be required to address this by a crewed bridge or a supporting autonomous system.

Autonomous navigation system: Automation elements

To understand and potentially replace a human operator three distinct functionalities must be introduced, namely:

- **SEE**: Humans observe the environment and in the case of the mariner, will observe the operational area from the bridge providing an unobstructed view and can quickly identify an object type, its relative distance and motion. Mariners are aided in this via onboard bridge equipment such legislated navigational equipment such as radar, AIS or lighting and signage.
- **THINK**: Human operators are further trained to assess the intended behaviour and relative risk that observed objects may pose and all in the context of its own behaviour. Through observed bridge dials (i.e. ECDIS) or by experience & “feeling”.
- **ACT**: Primary choices of decision making are guided by rules (i.e. COLREG’s) and others by experience (i.e. docking) which are unified in the human ability to act appropriately in situations arising or under normal sailing conditions.

The human ability to learn, pass on and perform these main functions has led the maritime industry through centuries of growth and evolution to make maritime the large industry of today with myriads of applications around the globe.

The replacement of a human operator in any capacity requires fulfilling these functionalities through introduction of technologies that can meet the functional requirements within the operational envelope of the application.

The SEE-THINK-ACT approach therefore becomes the basis for the introduction of autonomous navigation and additionally aligns with the introduction of autonomous systems in other industries.

Damen is structuring its RD&I activities along the lines of this approach and in this paper gives a short introduction on our view and developments to each element:

SEE: (Environmental) Perception

The current perception sensors on most vessels can be listed as Radar (X,S-Band) and communicated information is received by Automated identification system (AIS). Both systems are only mandated for larger vessels and in the case of radar the positioning norm creates a large gap surrounding the equipped vessel as seen in Figure 2.

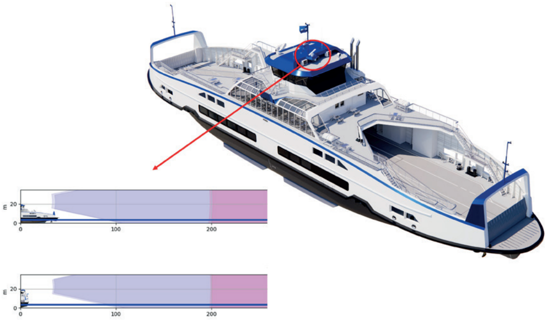


Figure 2. General depiction of a typical vessel with installed radar on mast (highlighted) and FoV (bottom left) (Source: Damen RD&I)

The resulting field of view (FoV) of the standard maritime radar creates a large gap surrounding the vessel in most cases up to 100m and subsequently presents challenges for proximity observation for applications such as docking. Furthermore, the world in which vessels navigate is essentially 3-D while these sensors provide 2-D information creating gaps in the translation of the navigational environment (i.e. bridge height etc.). The sensors remain navigational aids to the crew who compensate for the limited information and visibility prescribed by SOLAS requirements for bridge visibility. In most autonomous navigation applications, for the far range which is covered by the vessels radar & AIS, the information can be considered sufficient since the primary goal is detection of an obstacle. To provide a comprehensive FoV that would allow a full range of autonomous navigation applications the vessel must be surrounded by a dense 3-D FoV comprised of technologies that will detect & classify all objects within the vicinity of the vessel. The requirements are depicted in Figure 3.

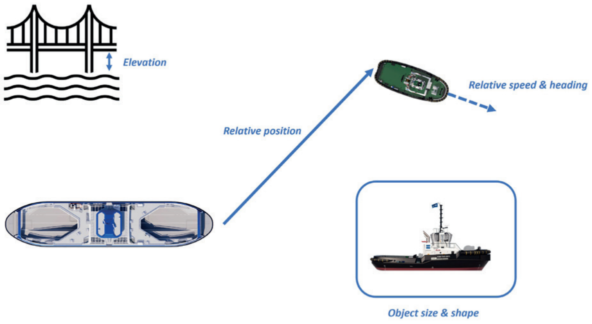


Figure 3. Depiction of FoV detection requirements (source: Damen RD&I)

To achieve this goal many technologies can be looked at from other industries, namely automotive, in which sensors are used similarly for enabling applications, namely 4D-Radar, Lidar, Cameras etc.

These sensors are relatively small, low cost and similar to automotive, can be used in groupings to surround the vessel fulfilling the detection requirements of the individual applications.

The research primary goal has been to identify the best Sensor combination for the task and fulfilling the requirements within the maritime environment operating conditions.

The number of sensors is vessel specific as each vessel size and shape will vary and form the majority of the hardware (HW) added to create the autonomous system. The remaining HW is essentially processing units for the sensor data and the THINK – ACT elements.

The Use of specific types of sensors also defines the HW requirements and relative networking requirements such as cameras (RGB & IR) require artificial intelligence (AI) processing for detection of objects within their resulting images unlike Radar & Lidar that provide detections.

AI processing requires vast amounts of data for training, validation & testing to achieve a reliable detection.

Understanding these complexities is essential in setting out the requirements for the systems and generally require a hands-on approach. Some early research results are demonstrated in the Damen AI models in Figure 4.

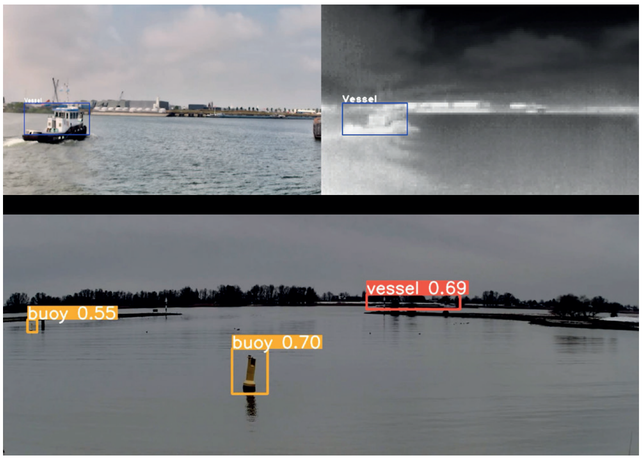
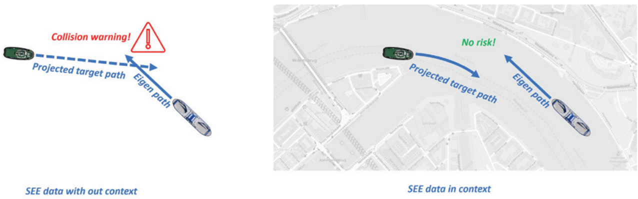


Figure 4. Examples from Damen AI (DANN-I) applied to RGB image (top-left & bottom) and LWIR image (top right). (Source: Damen RD&I)

The resulting detections are mainly classification of objects (type – vessel / buoy) while radar & lidar can provide position, size & velocity (radar only). Hence only through fusion of information from different sensors can a setup be effective.

THINK: Situational Awareness

Situational awareness can be defined also as putting the perception (SEE) data into context and is dependent on the quality of the data. A typical example scenario depicting this can be seen in Figure 5.



SEE data with out context

SEE data in context

Figure 5. Example scenario of SEE data used out of context (left) to calculate collision risk and in context of map data (right) similarly projecting path and calculating collision risk (Source: Damen RD&I)

Beyond the SEE data, the main two inputs for this functionality is, map and localization data that are available on most vessels with GPS / Compass and ENC's used by the ECDIS visualizer.

In order to assess the relevance of the SEE data a vessel should be given a mission (Global path planning). The mission sets a general course from point A to point B from which an automation system projects its motion capabilities and within the confines of regulations (i.e. speed limits, COLREG's) follows the mission. During this process all objects (SEE data) are similarly projected with an estimate of their intended mission and interactions/overlaps are assessed for risk.

One of the key issues is the uncertainty of the capabilities of the detected object (i.e. its motion envelope & intended destination) which heavily depends on the quality of the SEE data. A typical scenario is depicted in Figure 6.

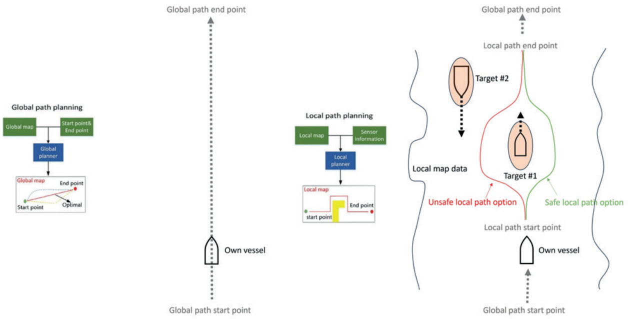


Figure 6. Example depiction of Global Path planning (left), Local path planning (right) scenario and functional planners. (Source: Damen RD&I)

The local path planner will determine the safest option to reroute from the mission while risk exists. An important aspect of local path planning is the motion modelling of the vessel as well as the required detailed mapping. It is observed that

many systems currently offered on the market utilize mainly only global path planners and hence do not deviate from the intended mission, rather they will stop and hold position similar to dynamic positioning (DP). In addition to creating motion models of different vessel types is a very complex process and generally they do not exist full range (0 to max speed). Many parties therefore depend on generalized motion models and highly manoeuvrable vessel designs. Both aspects, the Local path planner and deriving full range (0 to max speed) motion models form ongoing studies within our research teams to address the THINK challenge also in line with the uncertainty of the SEE data.
The primary functionality within this element is algorithms, i.e. Software (SW).

ACT: Control
Finally, the local path generated must be translated to propulsion instructions that the vessel can actually respond to including any delays to the response. This system is usually termed a Path follower. The path follower tries to match as close as possible the intended route with the actual vessel capabilities with the current influences of wind, current and responses of the system.
The actual path of the vessel and the generated local path will not match exactly and hence the THINK systems is always checking the deviation is not creating an unsafe route.
In the event the vessel cannot follow the prescribed route, a fail-safety condition should be engaged such as Dynamic positioning (DP) or similar.
The Element is primarily algorithms (SW) and would interface to the propulsion system.

In conclusion the elements SEE – THINK – ACT form a pipeline heavily dependent on the flow of information & data from the new sensors and current systems as seen in Figure 1 and Figure 7.

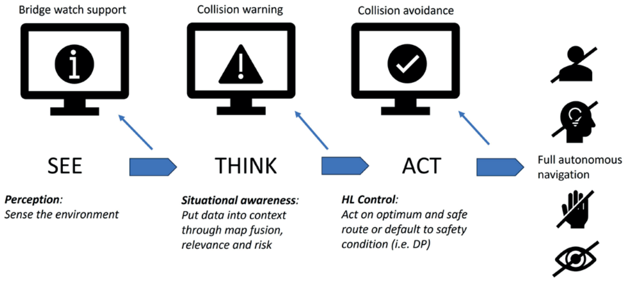


Figure 7. Depiction of autonomous navigation system and SEE-THINK-ACT elements (Source: Damen RD&I).

What can also be derived is that by enabling functionalities at different points of the pipeline you are essentially enabling functional applications capable of supporting crews and RCC.

The Main HW can be considered the distributed SEE elements (sensors & processing) while the THINK – ACT HW consists primarily of processing units.
The maturity of the systems must be similarly sought through and incremental approach where HW is in place and SW is slowly added to the pipeline based on achieving the maturity & trust of the previous functionality.
Damen Research has been exploring the HW ready concept on this basis with an incremental path to the application of SW and subsequently gaining maturity while slowly providing functionalities leading to higher levels of automation.

General Challenges and issues
Several challenges also remain with regards to the vessels that have yet to be addressed and closely relate to the introduction of these new technologies and systems onboard, namely:

Vessel control: in Figure 1 it can be seen that when multiple control elements (Bridge / RCC / Navigational Automation) have the ability to control a vessel this must be very carefully managed. It needs to be orchestrated who has control at any moment in time, how control is gained and where does control default in case of failure or dispute. Similarly, simplifying the interfaces between the propulsion system and the control parties is also a critical aspect of adding automation at any level. Within our research, an arbitrator concept has been developed to address these topics and provide a Damen global solution.

Networks & architectures: in enabling the possibility of these new systems it becomes evident that specialized critical networks are required for the sharing of large data volumes and providing for the security of safety critical systems. The research we conducted has already defined architectural needs in line with current onboard systems (bridge & engine room) preserving safety as well as incoming Cybersecurity requirements.

Integration & preservation of new technologies: Integration of the new sensors specifically on the many vessel types presents many issues in optimizing the positioning and survivability of the technology. New tooling has been explored for the vessel design phase as well tooling for the inherent calibration of the technologies to a single world point. These aspects of complex and distributed technologies have to be considered as they will impact the integration process as well as the capabilities of the system.

Learning by doing
Damen RD&I has invested in suitable enabling technologies to ensure the ability to fully explore the possibilities and capabilities of the new technologies (HW) within the maritime application area as well as the new algorithms and systems (SW). The enabling technologies are namely:

Simulations: Simulation provides a repetitive control environment suitable for rapid prototyping and testing algorithms specifically within the THINK – ACT elements. In addition it provides the capability to test edge cases that cannot be safely replicated in the real world and as such cannot subject the systems to the situation. The majority of current bridge simulators target human crew training and as such do not provide for interfacing the new sensors & systems limiting the ability to develop and test these. As such many custom solutions are utilized widely by parties involved in the development of this technology.

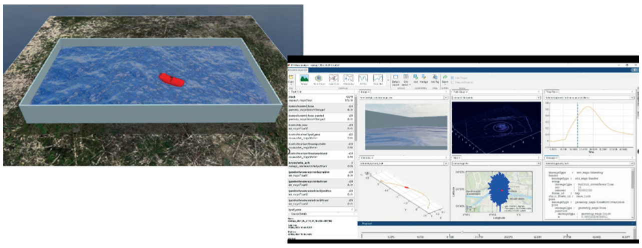


Figure 8. Examples of Damen simulation tools used in research (Source: Damen RD&I).

In partnership with academic and industrial partners, DRD&I is trying to convey the need & requirements for maritime simulators targeting the new technologies to ensure that similar to other industries these will be available also for the maritime industry. In the automotive industry, simulators also play a key role in building the safety case of systems.

Model vessel & RCC : DAVe (Damen Autonomous model Vessel), is an invaluable tool for low risk, rapid testing of systems in the entire SEE – THINK - ACT pipeline.

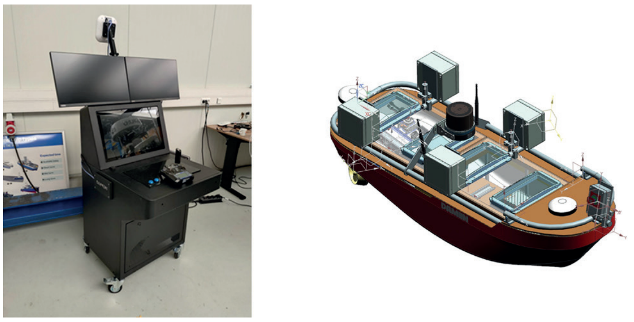


Figure 9. Depictions of DAVe (right) and Damen RCC (left) used for remotely operating & monitoring DAVe (Source: Damen RD&I).

The RCC allows for the remote control & monitoring of DAVe as well the study of RCC application especially in regard to the wireless connection and related issues. Coupled with a controlled (Research Pool) environment and the ability to deploy in the protected Damen harbour area we are able to build up complete pipelines with the maximum real-world effects.

Figure 10. DAVe in the Damen research pool (left) and in the Damen Harbor (right) (source: Damen RD&I)

Vessels: The research utilizes the available vessels of the Damen fleet when possible, to perform data acquisition and subsequent testing on the waterways. A sensor stand was developed to easily deploy the many sensors on vessels or shore areas to perform data acquisition. This is an invaluable source of real-world data and expected to extend to a dedicated research vessel in future.

Figure 11. Depictions of Research activities carried out on board a Damen vessel for purposes of Data acquisition. The sensor stand is visible on the bow of the vessel (left) and as seen from the side(right).

A key take away

In exploring these new technologies, it becomes evident that many of these while extensively used in other application areas such as automotive are not adjusted for maritime use. Although some technologies can easily be migrated and can pass on the benefits of their implementation in other sectors such as cameras, this is not the case for other new promising sensors such as 4D Radar. The research also focuses on addressing these aspects and ensuring when required the technologies are available and ready for use!

The focus is on perception as it forms the majority of hardware that needs to be designed into the vessel to maximize the performance and survivability of the technology.

The many vessel types, shapes and sizes present challenges in the integration of new technologies.

As a ship designer setting requirements on what is needed and as an integrator, we strive for creating standards and look for derisking implementation by creating test environments and understanding the hardware behaviour within the maritime environment.

Software becomes more of an element for the implementation of new functionalities and the hardware can be considered relatively available to be integrated. Damen sees this and moves forward by striving for a hardware ready vessel and an incremental software approach.

Full autonomy in shipping may still be further on the horizon, but technology is developing fast, building on other sectors like automotive and similarly looking at advisory and crew supporting functions based on the added hardware to aid perception that will one day lead to the autonomous vessel in an incremental and safe way! «