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The Importance of documenting autonomous tests

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Abstract. This paper presents how autonomous tests can be documented and why this is important. A test area in Norway, more specifically the Trondheimsfjorden Test Area for Autonomous Ships, is used as a pilot to conduct tests with autonomous vessels and for demonstrating the procedure of documenting results. There are typically three stages in such a documentation process; 1) To register and inform about a planned test on the fjord, 2) To inform about ongoing tests and to document test results by collecting data from the vessel and from the sensor infrastructure, 3) To show historical tests and be able to do analytics or conduct learning from previous tests. The Trondheimsfjorden Test Area has been instrumented with communication and navigation infrastructure, a control centre for control and monitor of the install infrastructure and for remote operation of a ship, and a data centre for planning autonomous tests, storing data, and for sharing of test results. By documenting test results in a standardized format, this can be used to verify new technology and solutions, share knowledge and experiences, and for documentation procedures and guidelines used for the purpose. A demonstration held in The Trondheimsfjorden Test Area showed the importance of streamlining the process of conducting autonomous test and documenting them in a standardized format. This work is based on the results from the research project NAVISP-EL3-005 "Trondheimsfjorden Test Area for Autonomous Ships". The Navigation Innovation and Support Programme (NAVISP) is the programme of the European Space Agency to support the competitiveness of the European industry in the wide field of positioning, navigation and timing while supporting member states in enhancing national objectives and capabilities in the sector.

1. Introduction

Even with a slower grow in transport demand than expected before the Covid-19 pandemic, the total transport activity is still expected to more than double from 2015 to 2050 [1]. Maritime transport is today the main sector regarding tonnage transport. Autonomous shipping is one promising element in future transport, as it is counted to be safer and more sustainable than road-based transport. Sailing unmanned, the autonomous vessels will be lighter by reducing hotel loads for humans and can reduce the speed compared with conventional shipping without increasing crew and management cost. This can lower the energy consumption of the vessel and increase the cargo to weight ratio. Additionally, autonomous shipping is expected to have lower operating costs than traditional shipping, e.g., by reducing the number of crew onboard and

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creating more space for goods to carry. Operators at a control centre can also manage several vessels in parallel, which will be an added value regards cost. The autonomous shipping sector is still at an early stage, but many ongoing projects are developing innovation and technology. The technology needs to be tested and verified before it can be applied on board vessels. A test area can be used for such a purpose, where typically navigation and communication technology can be tested in a small scale to achieve a higher technology readiness level.

Another challenge regarding the implementation of autonomous vessels is to develop the regulations in parallel with the technological innovation. The International Maritime Organization's (IMO) has conducted a Regulatory Scoping Exercise for use of Maritime Autonomous Surface Ships (MASS) identifying gaps in the current regulations [2], For instance, the regulations are developed with the assumption of having a master onboard the vessel. A master is responsible for the vessel, its operations, and the crew and cargo at the vessel. The introduction of autonomy will require new regulations since the master might not be onboard the vessel (unmanned).

The general situation of today's testing regime is that plans and results from autonomous tests are not shared, they are in best cases described in a power-point presentation after the tests have been finalised where the results only are available internally. A reason for this is that the test infrastructure is usually experimental, types of tests between the sites may differ significantly, and the users are developing new technology that is part of the innovation process before a product is ready for commercialization. Moreover, it is hard to compare results from different tests. Another drawback is that procedures for documenting results are not well established.

In this paper we seek to identify the importance of documenting autonomous tests. Documented test results can be used to test and verify the quality of service of technology and solutions for maritime operations, and to give input to the development of the regulations in parallel with the technological development. As different actors are testing new technology and solutions for autonomous vessels, the test results should be standardized and categorized making it easy to compare results. The knowledge and experience regarding autonomous innovation should be shared, since this will accelerate the technological and regulatory development, moving one step closer to a higher level of autonomy.

To demonstrate how tests can be conducted and documented, the Trondheimsfjorden Test Area for Autonomous Ships (TTA) located in Norway has been used as a pilot. This test area is instrumented with sensor infrastructure, control centres, and a platform for documenting and reviewing previous tests and historical data. In this way, TTA will play a key role in the contribution of autonomous shipping development and can be considered an important tool and laboratory for the maritime industry when developing technological innovation.

2. Background

2.1. Autonomous Tests

In this paper, the term "autonomous tests" include tests of both vessel-related systems and infrastructure related to autonomy. For instance, this can involve testing different levels of autonomy for a vessel. The IMO has defined four degrees of autonomy [2]:

(i) Degree One: Ship with automated processes and decision support.
(ii) Degree Two: Remotely controlled ship with seafarers on board.
(iii) Degree Three: Remotely controlled ship without seafarers on board.
(iv) Degree Four: Fully autonomous ship.

Another example of an autonomous test can be testing communication infrastructure. The duration of the tests can range from a few minutes to several weeks or years.

2.2. Test Areas for Autonomous Ships

International Network of Autonomous Ships (INAS) has defined a test area as "a facility for doing in situ tests of MASS and MASS systems which may or may not be open for any user" [3]. A test area's main purpose is to facilitate for tests, to offer a reliable site equipped with technological infrastructure and a data storge platform for documentation, and to assure that a test can be done together with conventional operations and are following legal regulations. A test area can include both land- and space-based sensor technology that can be used for navigation, communication, and monitoring. For instance, radars installed onshore can provide vessels and traffic surveillance with improved situational awareness. Additionally, a test area may be an information centre providing historical data from e.g., traffic, weather, sensors in the area, and test results.

In order to test and verify new technological capabilities and applications, several test areas for autonomous ships have been developed [3]. They exist in several countries, e.g., Norway, the United Kingdom, Finland, Belgium, and the USA to mention some. The responsible organizations of these test areas seek cooperation for the development of autonomous vessel, and are all members of INAS, a network for sharing information on autonomous ships. INAS actively gives inputs to authorities for the development on standards and regulations for MASS.

One of these test areas is the TTA that was established in 2016 as the world's first test area for autonomous ships [4]. The test area has been approved by Norwegian maritime authorities for test purposes. It is an area covering more than 17 000 km2 and covers open sea to inner fjord. The test area is located in the center of Norway, see Figure 1.

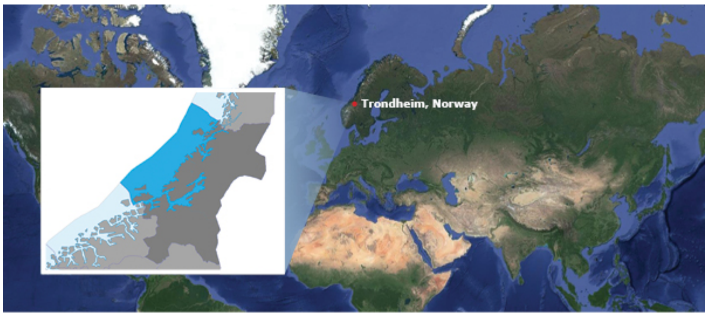

Figure 1: Trondheimsfjorden Test Area for Autonomous Ships in Trondheim, Norway marked as red.

2.3. Guidelines for MASS Tests

There exist several guidelines for tests of MASS. The IMO's Maritime Safety Committee (MSC) has approved interim guidelines for MASS trials (MSC.1/Circ. 1604)[5]. The guidelines are made to assist authorities and relevant stakeholder to ensure that MASS trials are conducted safely, securely, and protects the environment. Taking into consideration and complementing IMO's Interim Guidelines for MASS trials, the EU Operational Guidelines for Trials of Maritime Autonomous Surface Ships (MASS) [6] has been developed. This is a guidance for authorities and applicants that want to perform MASS tests. The guidelines provide an example for developing relevant documentation when applying for MASS tests, including test plan and reporting descriptions.

There exist specific guidelines on reporting of results of e-navigation testbed [7, 8]. The guidelines states that the test results should be harmonized such that the results can be shared and easily compared so that the maritime community can learn from the tests. A template for reporting the results of testbeds is included in the guidelines. In the UK, an industry code of practice has been developed for vessel up to 24 meters that includes practical guidance, standards, and best practice [9]. In Belgium/Flanders it exists a code of practice for automated vessel technologies on the inland waterways in Flanders [10].

2.4. Related work
We have seen that there exist several guidelines describing how MASS tests should be conducted and documented (see Section 2.3). However, to the authors knowledge, there is a lack of platforms or applications that enables documenting autonomous test results in a standardized format and sharing the results available in the market. The Designing the Future of Full Autonomous Ship Project (DFFAS Project) aims to conduct crewless maritime autonomous surface ship demonstration trials in domestic coastal areas [11]. 30 Japanese companies are taking part in the project. The project aims to move towards the standardization of technology and establish systems and infrastructure.

3. Important Tasks When Conducting Tests
When conducting a test with autonomous vessels, the test can be divided in three phases, i.e., before the test, during the test, and after the test. Figure 2 illustrates different tasks that should be done depending on the test phases.

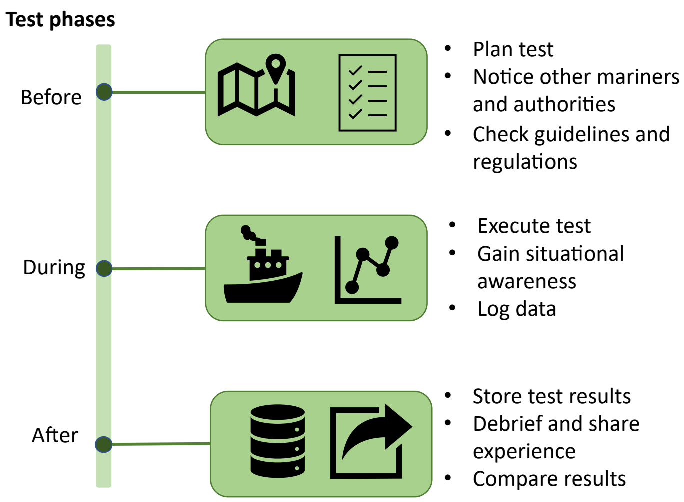

Figure 2: Different tasks to consider for different test phases.

Before a test is executed, it is necessary to plan the test. This could include checking the weather forecast and weather statistics, see available sensor infrastructure and resources in the area, and check traffic statistics and status. For instance, getting an overview of the communication system available in the test area may be essential to decide if the test area is suitable for the planned test purpose. Additionally, other mariners and authorities should be noticed that an autonomous test is going to be performed. Moreover, one should verify that the test plans are in accordance with relevant guidelines and legislations and apply for relevant permissions to conduct the test. A description of what may be included in a test plan is described in [6].

During the execution of a test, it is important to gain situational awareness. This can include accessing live camera feed from the test area, viewing local wind measurements at port, and checking infrastructure status, e.g., the position accuracy or possible communication failures in the area. Additionally, data from the test should be logged.

After a test has been conducted, the test results should be stored such that the results and experience gained can be shared with others, or for documenting purposes. The test results should include the location, time period, test type, equipment and technology used, level of autonomy, traffic picture, weather conditions, the logged data, and lessons learned, as illustrated in Figure 3.

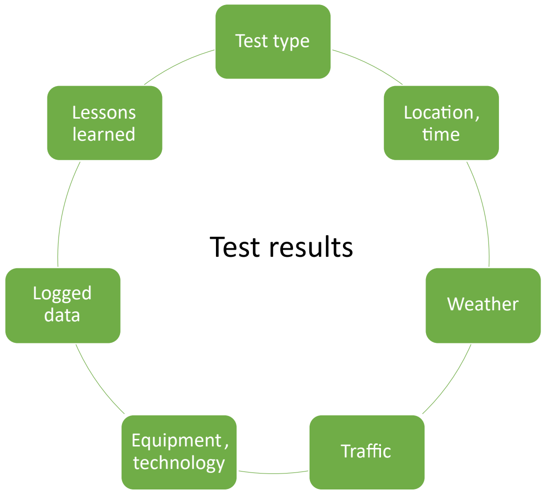

Figure 3: Information that should be included when documenting results from autonomous tests.

When inspecting results from previous tests, the location and time of the test are useful for navigating to relevant tests. The test type can be divided in different categories, e.g., communication or navigation tests. The test type is highly important when inspecting results since it gives a clear indication of what has been done during the test and helps navigate to the relevant test results. Moreover, information on the equipment and technology used during the test specifies in more details what has been done. Let's say a communication test has been conducted. To learn from this test, it is essential to know what type of communication technology was used, e.g., a Maritime Broadband Radio. As mentioned in Section 2.1, a vessel can be operated under different levels of autonomy, where each level will have different requirements to systems and technologies used. The weather and traffic conditions experienced during a test give an indication of the complexity of the test performed. For example, testing an autonomous vessel in a traffic dense area impose a risk and navigational challenge for the vessel. Other information documented that may be relevant for other stakeholders includes the contact information, permits used in test, and the logged test data.

The above-mentioned information included in the test results enables categorizing of test results such that one can easily compare the results with other autonomous test, regardless of where the tests were performed. Furthermore, perhaps the most important information when reviewing previous test results would be the key findings and lessons learned from the tests. This information allows other actors to learn from the previous tests and can contribute to accelerate the development of autonomous vessels. Taking the autonomous vessel Mayflower[1] developed by the non-profit research organization ProMare and IBM as an example. This is a fully autonomous vessel using different on board sensors to obtain situational awareness and

[1] https://mas400.com/

makes operational decisions by itself. The plan is to sail across the Atlantic to gather ocean data. During this project, they have run in to some challenges and issues. Some lessons learned from the Mayflower project includes [12, 13]:

(i) Design to follow COLREGs, but other ships may not.
(ii) Data quality matters.
(iii) Think creatively about how to obtain data.
(iv) There's an advantage in a component-based system.
(v) Sometimes hard coded-rules are necessary.

Looking in to the first lesson learned (i), it is about the how autonomous vessels handle the maritime regulations in their navigation system. At sea there are specific regulations for preventing collisions called COLREGs. The developers of Mayflower have designed the navigation system such that it will follow these rules. However, according to Brett Phaneuf, the director of the Mayflower Autonomous Ship project, many ships do not follow these regulations [13]. This issue has also been highlighted previously, e.g. in [14]. This makes it difficult to design a decision making system for an autonomous vessel. This experience is important for other actors developing an autonomous vessels, knowing that the decision making can not be solely based on the rules, but on how the vessels actually behave. A test area equipped with an application providing traffic information could be used to learn the typical ship behavior. For instance by inspecting historical AIS data one can learn patterns and behavior modes of the traffic. However, ship behavior may change depending on the region of interest. This means that one may need different behavior models for different regions.

4. Instrumenting Trondheimsfjorden Test Area

When conducting autonomous tests, it is important to have a well-established sensor infrastructure in the test area. Several measurements from different sensors and data sources give the users a complete picture of the test situation and make it easier to reproduce a test and compare with other tests. Having sensor data available is essential for documenting autonomous tests. To perform and document test of autonomy, the Trondheimsfjorden Test Area has been instrumented with several technologies and systems. The infrastructure includes systems for communication, navigation, control and monitoring, and information sharing.

Communication infrastructure can be used for communication between vessels or between a vessel and shore (e.g., a control centre or port). In TTA, several communication systems with different coverage areas and characteristics have been installed. The communication infrastructure includes a Mobil Broadband Radio (MBR) and a VHF Data Exchange System (VDES) Satellite terminal in addition to existing 4G and 5G networks.

When operating a vessel, the navigation requirements, e.g., position accuracy, depend on the operation that is being performed. For instance, if a vessel is doing a docking operation, the position accuracy requirements will be higher than when sailing in a coastal area with less traffic. For testing different operational scenarios, a well-established navigation infrastructure is essential. In TTA there has been installed a navigation infrastructure including coastal surveillance radars, Automatic Identification System (AIS) base station, Global Navigation Satellite System (GNSS) monitoring station, and Differential GNSS (DGNSS) reference stations.

When performing tests with the sensor infrastructure, systems for monitoring and controlling the sensor data is needed. TTA has been instrumented with a Test Area Control Centre (TACC) with central monitors that can monitor and control the infrastructure. For instance, a DGNSS central monitor has been installed to test and validate the position accuracy. Moreover, to test different levels of autonomy, a remote control centre is needed. The TACC is installed with applications enabling remote control of vessels.

4.1. Data Centre
As described in Section 2.4, when conducting an autonomous test, it is important to plan the test, check guidelines and regulations, store test results, and share and compare knowledge and experiences from autonomous tests. In TTA, a Data Centre has been developed to support users of the test area with information and functionality to assist maritime operations and to collect test results. The Data Centre can be used when planning, conducting, and post-processing autonomous tests. A screenshot of the Data Centre is shown in Figure 4. At the top of the window is the Area map, which is a graphical representation of the data where sensors are installed and dynamic data is displayed. The time window is a time slider to be used when the data can be represented with a time series, such as weather status last week. At the bottom of the page is a list of the resource available in the area. The menu sections present Data Centre functionalities Some of the data is integration from external WMS services, such as AIS data from the Norwegian Coastal Administration.

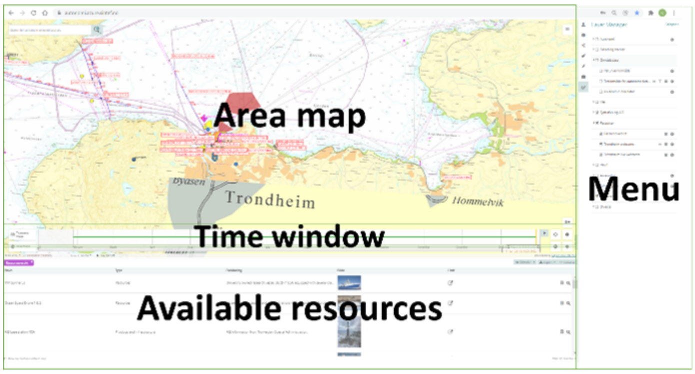

Figure 4: Screenshot of Data Centre.

The following functionalities are included in the Data Centre: Maps and satellite images, area data (ocean farms, protected areas, quays), reference routes, infrastructure coverage area (communication, navigation, observation), and guidelines and permissions overview. Moreover, the Data Centre includes weather (live and historic), traffic (live and historic), infrastructure status (e.g., communication availability), availability of resources (e.g., vessels, drones, service personnel, control room), test results (documenting and statistics), and statistics and analysis. From the available data it will be possible to achieve support in operational planning, for example if a MASS is heading for a quay at a terminal, the MASS operator can receive information (e.g., reference route, ongoing activities) as well as status from available sensors (e.g., local wind sensor at the quay) that can be used for the purpose. Some of the information and functionalities in the Data Centre are imported from other data sources.

5. Demonstration
The TTA has been used as a pilot to demonstrate how an autonomous test can be documented using the installed infrastructure and resources. The goal was to demonstrate remote control of a vessel and demonstrate automatic control where a vessel follows a pre-defined route. The purpose was to find out if this was possible and the performance of a vessel following a route automatically.

Before the test, the Data Centre was used to plan the operation of the test. This included checking the weather forecast to see if the weather was suitable for conducting the test, whom to inform, and status of the infrastructure. Moreover, recommended guidelines, procedures, and regulations were checked using the Data Centre. Based on this information, the route was defined and inserted into the controller for the vessel and at the TACC. Once the details of the test had been decided, the upcoming test was registered using a form in the Data Centre notifying other mariners and authorities that an autonomous test was going to be performed.

The Ocean Space Drone was used to perform the demonstration. The TACC was used to monitor and remotely control the vessel. The vessel and the TACC communicated using MBR. This communication link was used to send video stream and navigation data from the vessel to the TACC, and used to send GNSS corrections and control commands from the TACC to the vessel. The vessel received IALA beacon corrections (RTCM 2.3 format) from the DGNSS reference station installed and GNSS corrections (RTCM 3 format) using MBR from the TACC. Position data (NMEA messages) from the vessel was logged during the demonstration.

Using the logged position data from the vessel, the cross-track error of the vessel was computed. This is illustrated in Figure 5. Cross-track error is the perpendicular distance from actual position to intended track line of the pre-defined route. The pre-defined route is illustrated as the green solid line, while the actual track is the wide line with varying colors. The different colors indicate how large the cross-track error was at that location, where red symbolize a small error and blue a large error (see legend box in plot). During the demonstration, the vessel was run under different control modes between different waypoints (WPs), i.e. remote control from TACC from WP4 to WP5, manual control by on-board skipper from WP1 to WP2, and by autopilot for the rest of the route.

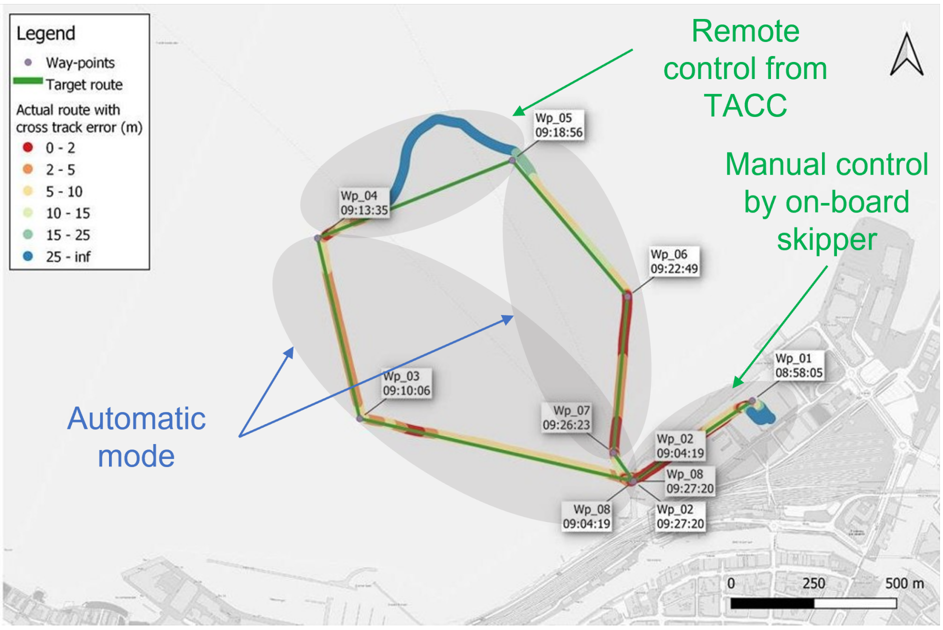

Figure 5: Cross-track error of vessel during the demonstration.

The vessel was successfully remotely controlled from the TACC. This can be seen between WP4 and WP5, where the vessel was steered away from the pre-defined route by intention, hence the large cross-track error on this leg. To see the performance of the autopilot, i.e. how well the vessel can follow the intended route in automatic mode, we inspect the cross-track error for WP2 to WP4 and WP5 to WP8. During automatic mode, the cross-track error is mainly below 10 m. Many factors will impact the cross-track error, for example navigation system accuracy, environmental conditions like wind and current, track complexity, and the vessel's maneuverability. One can see that the cross-track error differs between the different legs in automatic mode. During these different legs, the course of the vessel is different, meaning that the environmental conditions will affect the vessel differently for these legs. Another observation from the figure is that the cross-track error is slightly higher near the waypoints when the vessel is changing its course. This can be due to the fact that initial route does not consider the turning radius of the vessel. Two of the lessons learned from this demonstration is that (1) the vessel can navigate under different autonomy levels and (2) the established infrastructure simplifies in situ testing.

The test results were documented and stored in the Data Centre ensuring that results are shared. Parts of the test results are summarized in Table 1.

Table 1: Summary of test results from demonstration.

Test results	
Location	63.4N, 10.4Ø (Waypoint 1)
Time	06.12.2021, 08:30-10:00
Test type	Automatic navigation and remote control
Technology,equipment	Vessel, Test Area Control Centre, MBR, DGNSS navigation system
Weather	Calm
Traffic	Low
Test report	Project report NAVISP EL3-D5.2.pdf
Logged data	Position data from the vessel
Lessons learned	Can navigate under different autonomy levels. The established infrastructure simplifies in situ testing.

6. Discussion

In this paper, the benefits of documenting test results have been described and we have demonstrated how a test area can be used to conduct and document autonomous tests. So, how do we move on from a pilot and ensure that test results are documented and shared?

In theory, an autonomous test can be conducted at any location with permission from the authorities. However, by conducting an autonomous test in a test area, the test user will have access to a well-established infrastructure and resource in the area, as opposed to having to install and develop these on their own. Utilizing a test area simplifies the process of planning, executing and documenting a test. Users of a test area will save money and time using an established test area. "Being able to get out and test the sensors and systems in real life is the ultimate (test). You can get far with simulations at the laboratory, but out here there are weather and wind, and can verify if the systems behave as expected." - Geir Håøy, CEO in Kongsberg Gruppen, about the TTA[2]. A challenge of a test area is to make sure that the resources available in the test area are in fact known and easily accessible for parties that would benefit from using the test area.

Today, test plans and results from autonomous tests are not shared. To do so, there is need for a common platform for documenting and sharing results and experiences, like the Data Centre developed in this project. A challenge would be to ensure that test users utilize such platforms for documentation and sharing. A solution could be to encourage users of a test area to document the test results in a standardized format, e.g., by using a data centre developed for test areas. Another obstacle for sharing test results, is that the results may be confidential.

[2] https://www.mn24.no/nyheter/i/Jx4Wv8/viste-frem-trondheimsteknologi-til-toppsjefen?

Due to high competition in the maritime industry, many companies fear the consequences of sharing detailed test results. However, test results from the academia and research are typically shared openly. The whole maritime industry will be interested in viewing and learning from the experiences obtained in the test results that are shared, also between different regions and test areas.

The Data Centre developed in this project receives data from the vessel after a test has been performed. Getting data in real-time from the vessel is difficult due to security restrictions and limitations on the communication bandwidth when transmitting data. On the other hand, it can be argued whether there is a need for having real-time data in the Data Centre.

A test area will have different stakeholders with different needs. This contributes to the requirements for a data centre and the documentation process. In TTA, we have different stakeholders, including maritime authorities, infrastructure owners, service providers, classification, clusters, and research and education stakeholders. These stakeholders have been important for defining the requirements and functionality of the Data Centre. The involvement of existing and new stakeholders will be important for further development and use of the test area.

7. Conclusion

Autonomous shipping is important to meet the increasing transport demands of the future in a sustainable manner. To develop autonomous shipping, it is important to test and document autonomous tests. By documenting the test results in a standardized format, it is easy to categorize and compare the test results. Sharing test results is important so that others can learn for the experience gained. Moreover, documentation from autonomous test can help verify technological maturity regarding regulations and requirements. These are important steps for the development of autonomous vessels. Test areas for autonomous ships simplify the process of conducting tests and documenting test results since they have an established test infrastructure and may include a data centre for storing and sharing test results. Thus, utilizing well-established test areas are important to accelerate the development of sustainable transport means.

Acknowledgments

This work is based on the results from the research project NAVISP-EL3-005 “Trondheimsfjorden Test Area for Autonomous Ships” [15], which is founded by the European Space Agency under the Navigation Innovation and Support Program (NAVISP), and the research project IMAT [16], which founded by the Research Council of Norway. NAVISP is a program to support the competitiveness of the European industry in the wide field of positioning, navigation, and timing while supporting member states in enhancing national objectives and capabilities in the sector. These projects are based on a cooperation between Kongsberg Seatex AS, SINTEF Ocean AS, the Norwegian University of Science and Technology, Kongsberg Norcontrol AS, and Massterly. The Data Centre developed in this project is based on Adaptive, an application from Asplan Viak.

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