SEATONOMY

Design, development and validation of marine autonomous systems and operations

E.I. Grøtli, T. A. Reinen, K. Grythe, A.A. Transeth, M. Vagia, M. Bjerkeng
SINTEF ICT
Trondheim, Norway

P. Rundtop, E. Svendsen
SINTEF Fisheries and Aquaculture
Trondheim, Norway

Ø.J. Rødseth
MARINTEK
Trondheim, Norway

G. Eidnes
SINTEF Material and Chemistry
Trondheim, Norway

***Abstract*— The SEATONOMY methodology provides a structured approach for design, development and validation of mobile autonomous maritime operations and systems. The goal is to achieve this by providing system developers of autonomous systems with suitable guidelines, principles, best practices and tools. The methodology encompasses three viewpoints: operational, system and verification & validation. Industrial use cases are used as both input to the methodology, as well as pilot-cases for an iterative testing and development of the methodology.**

Keywords—marine; autonomous operations; industrial autonomous systems;

I. INTRODUCTION

SEATONOMY encompasses strategic research collaboration between SINTEF ICT, SINTEF Materials and Chemistry, SINTEF Fisheries and Aquaculture, and MARINTEK (also part of the SINTEF Group). SINTEF is a research organization in Norway and all the aforementioned entities in SINTEF are developing or utilizing autonomous mobility technologies in cooperation with industry customers. During this work, we have found that there is a need for coherent, structured and scientifically rooted methods and tools for designing autonomous technologies for industrial use.

By combining our efforts and know-how with current state-of-the-art research within disciplines such as ergonomics, autonomy and mobile robotics we are creating a common methodology – the SEATONOMY methodology – for design of marine autonomous mobile systems that is useful for engineering of industrially viable solutions. A methodology is a systematic set of tools, methods, principles, rules, and analyses for regulating a given discipline. In other words, the SEATONOMY methodology offers a way to understand which methods, techniques, etc. can be applied to designing autonomy for marine systems.

In this paper we provide an overview of the current SEATONOMY methodology and its structured approach to design, development and validation of autonomous marine operations and systems. We describe input-cases used as background for the methodology, as well as pilot-cases which will be used to test and further refine the methodology. SEATONOMY is subject to ongoing work. However, current results regarding overall methodology and approach reported in this paper are sufficiently mature to be employed in a design and development phase.

II. INDUSTRIAL AUTONOMOUS SYSTEMS

The word autonomy has several definitions throughout the literature, and is often referred to as the ability of an engineering system to make decisions about its own actions while performing a task, without the direct involvement of an exogenous system or operator. We emphasize that this does not limit autonomy to be an all-or-nothing property of a system, but rather characterizes the system at its highest level of autonomy. In fact, the level of autonomy of a system is not fixed, but can change throughout the course of an operation, and will be in many cases be important for the system to have commercial value.

SINTEF defines an industrial autonomous system as an autonomous unit, or a collection of such, that can operate safely and efficiently in a real world environment while doing operations of direct commercial value and which can be manufactured, maintained, deployed, operated and retrieved at an acceptable cost relative to the value it provides. This distinguishes industrial autonomous systems from many academic, space and military projects in that industrial autonomy is directly linked to commercial value creation. There are several important applications of industrial autonomy within ocean space, typically associated with remoteness, dangerous or challenging areas or long duration missions.

III. BACKGROUND

Today, autonomy is only to a limited degree used in industrial marine systems. There is substantial research within academia and the military, but current research and systems are often theoretical, based on very expensive technology or too fragmented for the development of systematic knowledge of efficient and safe design and operation. The industry has adopted a wait-and-see attitude and rather chosen traditional, but less efficient and future-oriented solutions.

Low levels of autonomy are starting to become more and more common in cars (anti-collision, lane-control), airplanes (autopilot, automatic landing systems, drones) and in particular in underwater vehicles for military- or surveillance applications.

Industries within aviation, ground vehicles and astronautics are far ahead of marine systems with respect to methodology; see [1], [2] and [5]. The SEATONOMY methodology employ results from these areas, but targets essentially different applications, most importantly systems with a more heterogeneous module structure and looser integration, which prevents direct adaption of this knowledge to our systems.

One example is an EU-project called MUNIN where SINTEF with partners are investigating the feasibility of unmanned ships [6]. The project is briefly described in Section VII.A. There, industrial autonomy has to be achieved in a framework of already existing and interconnected computer systems, e.g. a bridge system, engine automation, integrated communication systems and so on. The autonomous system has to be designed by using and interfacing to already existing off-the-shelf software and hardware components and one cannot easily apply an integrated and uniform development and design strategy on this problem.

In addition autonomy in the marine section is hampered as the applications are characterized by a combination of the following constraints:

1. Always on – no "safe state".
2. High reliability – the system must behave according to the operations intentions.
3. Unreliable communication – handle limited communication or drop-outs in communication with operator.
4. Unstructured environments – must be able to avoid collisions in complex environments.
5. Own energy-supply – be in control of own energy production and consumption.
6. Cost focus – solutions must be efficient and have low risk in development and use.
7. Time focus – well known methods that work now are better than unknown that might not work.

MUNIN is a relevant example: The project has shown that an unmanned dry bulk carrier is economically and technically feasible, but it has to be designed very differently from today's ships, e.g. it needs a dedicated shore control center, it needs redundant energy production and propulsion systems, it has to be built without any accommodation section and all onboard systems must be optimized for predictive and periodic maintenance only. These and other requirements are derived from various combinations of the seven constraints above through a risk based design strategy [7].

IV. Challenges and General Framework

An overall challenge in design of autonomous systems is to create a cost effective trade-off between the different operational and design choices and the seven constraints that has been identified in Section III. In SEATONOMY this challenge has been mapped onto three main high level challenges that a design methodology for industrial autonomous systems has to address:

1. Determine the correct set of degrees of autonomy for a given application.
2. Ensure that all relevant critical situations have been identified and can be handled.
3. Ensure a predictable behavior within predefined boundaries for all relevant operational scenarios.

This requires a flexible and risk based approach to operability and process analysis.

Tools for analyzing safety and reliability, and tools for validating systems without the need for full-scale tests are important. This includes tools to analyze effects of limited quality of service in communication and localization systems.

Industrial autonomous systems will in many cases need a human supervising operator. It is necessary that the operator has the proper level of understanding of limitations and capabilities of the system, including trust in its performance. There are two obstacles for this trust:

1. Execution barrier: Is there accordance between the acts of the system and operators intentions?
2. Evaluation barrier: Can the state of the system be monitored, and is it different from the intended state?

A suitable hardware realization of an autonomous system will depend on application and cannot easily be standardized. On the other hand, it is possible to develop common higher levels of an ICT architecture for marine autonomous systems. The architecture is illustrated in Figure 1.

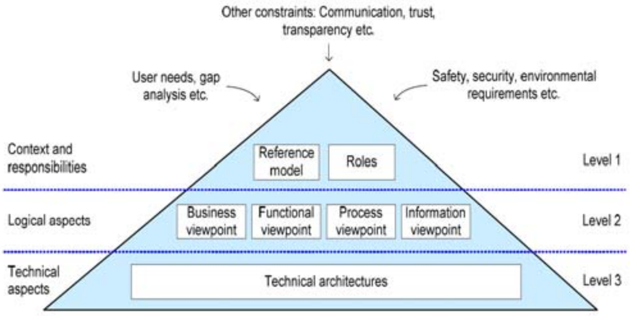

Figure 1: ICT architecture

The ICT architecture includes semantic (Level 1: context and responsibilities) and logical components in addition to the more conventional software framework and other technical components. This is necessary to capture all aspects of system internal and external communication as well as the higher level functional considerations that, e.g. divide responsibilities between the autonomous system and a remote human-operated control center.

While the ICT architecture has to be generic to be able to handle operations in very different contexts and with different types of vehicles or systems, it plays an important role in providing a standard reference for maritime autonomous systems so that tools and results can be reused as much as possible. Level 3 (technical aspects) will be very thin in the generic ICT architecture as it is where most of the system specific differences can be found [8], [9].

V. THE SEATONOMY METHODOLOGY

The SEATONOMY methodology provides a structured approach for design, development and validation of mobile autonomous maritime operations and systems. A focus in SEATONOMY is on the demands and limitations technologies impose for design and development of autonomous systems. For communication technology this can be represented as the Quality of Service (QoS) of a combined communication systems in use for an autonomous system. For other key-technologies such as perception, localization, fault detection and handling, anti-collision and human-machine interface (HMI) similar metrics can be developed.

SEATONOMY views the challenge of designing autonomous systems from three *viewpoints*, and the workflow is incremental and iterative – see Figure 2.

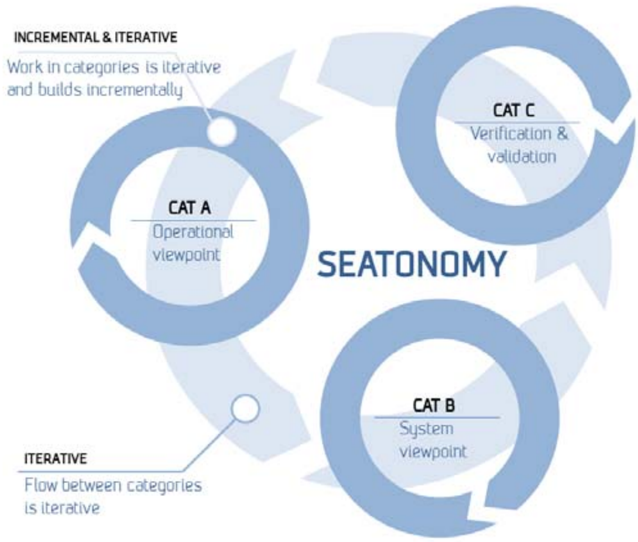

Figure 2: SEATONOMY work flow

A - The operational viewpoint concerns the overall design and specification of the operation. This means analyzing the operation(s) the system is intended to execute disregarding physical implementation. The reasoning behind this viewpoint is both to facilitate a common understanding between system designers and end-users, as well as making sure that the system design will be grounded by the actual operation it is intended to solve.

B - The system viewpoint concerns the realization and composition autonomous functionality in the physical system. This viewpoint is concerned with the needs and requirements concerning how to create a working autonomous system. Hardware and software requirements are taken into account in order to accomplish the system's design and implementation. Within this viewpoint, details of the system itself will be analyzed.

C - The verification and validation viewpoint is concerned with how to make sure both system and operation behaves according to requirements (verification) and according to reason (validation).

The three categories or viewpoints must all be covered in order to make a design in accordance with the SEATONOMY methodology. As suggested by Figure 2, each category should be worked on in an iterative manner when the SEATONOMY methodology is applied for realization of autonomous systems. Furthermore, the whole process should be iterative, meaning that the result of one category may lead to the redesign of the next category. Answering all questions and covering all angles is usually not feasible during the first iteration, since detailed information of either the operation or system is not available. The initial work on each category must therefore be based on limited information regarding e.g. available equipment, current best practice, physical and legal limitations, etc.

The SEATONOMY methodology is further more divided into two layers where layer 1 covers a more generic analysis and design issues while layer 2 is concerned with a more rigorous technical design which is optional and more specialized for different types of autonomous systems. In short, layer 1 provides an overview while layer 2 gives much more details concerning the methodology. The rest of this paper will mainly refer to layer 1 of the methodology.

A. Operational viewpoint

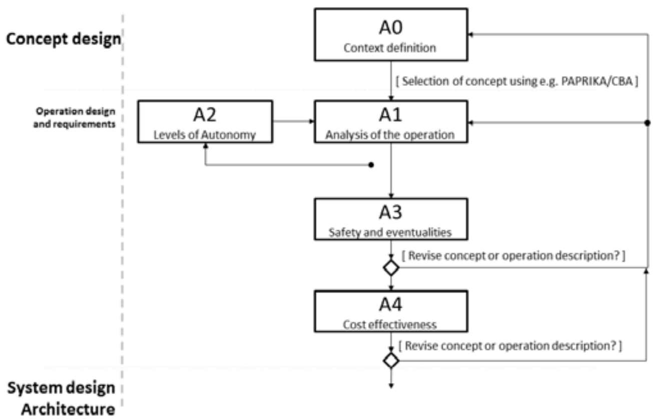

Figure 3: Workflow of operational analysis

The operational viewpoint shall capture and adjust the way the autonomous system performs its task without dealing with detailed technical issues. From these activities, a thorough understanding of the operation, i.e. the problem that is sought to be solved, should be available.

Figure 3 contains a flow chart illustrating the typical work flow of category A. The key elements are:

A0 – Context definition: Overall description of the operation concepts and alternatives to possible solutions.

A1 – Analysis of the operation: Break-down of operations, e.g., according to the SEATONOMY Autonomous Job Analysis (AJA) [17]. Uncover operational modes, design challenges, needs/limitations on autonomous behavior. Facilitates common understanding among stakeholders.

A2 – Levels of autonomy: Identify wanted/required degree of human-machine collaboration. Handle trade-offs between stakeholders with varying interests. Account for varying level of autonomy throughout a timeline of an operation.

A3 – Safety and eventualities: Ensure operations can be performed at a defined and acceptable level of safety. Document and plan for mitigation of events outside normal operations. Identify safe states.

A4 – Cost effectiveness: Measure the positive and negative consequences of choices related to an operation and assess the intrinsic value of project alternatives.

B. System viewpoint

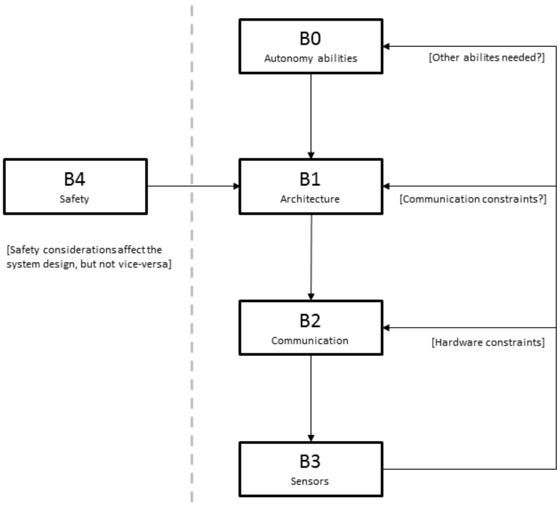

Figure 4: Workflow of system analysis

The system viewpoint concerns issues related to the system itself, mainly software, but also hardware such as sensors. The goal of category B is to create a solution for the problem formulation that was specified through category A.

Figure 4 depicts a flow chart illustrating the typical work flow of category B. The key elements are:

B0 – Context Definition: Bridge between Viewpoint A and B. Formalization of which are the needed abilities of the system in order to execute the operation analyzed in Viewpoint A.

B1 – Architecture: Concerns the software architecture, i.e. how to code autonomy into the system.

B2 – Communication: Communication design is dependent on aspects such as the necessary levels of autonomy, type of sensors and corresponding band-with requirements, physical medium for communication (e.g., water), and regulatory constraints.

B3 – Sensors: The choice of sensors is related to B0 and affects B1.

B4 – Safety: Guidelines for developing safe and reliable systems.

C. Verification and validation viewpoint

The SEATONOMY methodology can readily be used within existing systems development processes such as the traditional V-model or agile processes. It should be noted that SEATONOMY is not an alternative to such processes. Note also that the iterative and incremental approach for using the three viewpoints of the methodology means that purely sequential processes (such as the waterfall model) are not the best suit for SEATONOMY. Purely sequential development processes are discouraged in SEATONOMY.

The V-model is a model of how a development process can be implemented, and is used here as an example since the model is well-known and easy to understand. The SEATONOMY methodology does not make recommendations to what kind of development process should be followed, except for recommending an iterative and incremental process, so use of the V-model should just be considered an example application.

The V-model process is bent downwards (in level of detail) as problem definition and design are detailed, and upwards again as the system solving the initial problem is composed and tested, forming the typical V. The name of the model stems from the two phases comprising the model; the verification phase (left arm of the V), and the validation phase (right arm of the V).

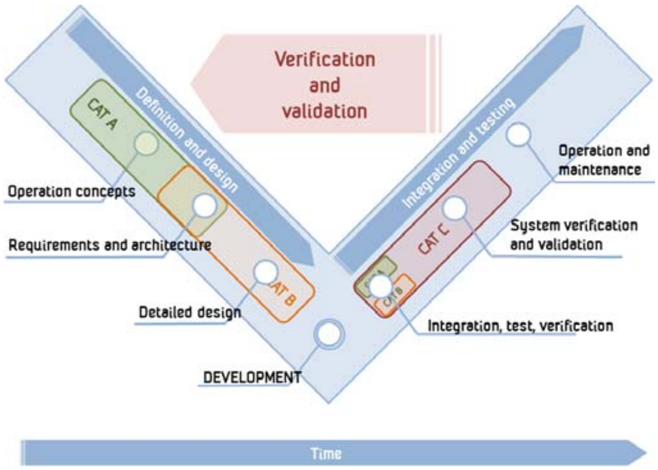

Figure 5: Relation between SEATONOMY methodology and V-model development process

An example of how the SEATONOMY methodology can be used as part of the V-model development process is given in Figure 5. The different categories of SEATONOMY involved in the different phases of the development process are color coded in the illustration. Notice the importance SEATONOMY methodology lays on the illustrated feedback component of the model.

VI. Limitations of the Methodology

The SEATONOMY methodology is a structured way for design, development and validation of *autonomous functionality*. This implies that functionality not directly tied to autonomy is outside the scope of the core methodology. Choices such as e.g. hull design, mechanical and electrical construction, waterproofing, placement of life-vests, etc. are clearly outside the scope of the methodology, but can at the same time set limitations or requirements for the autonomous functionalities of the operation or system. Thus, output from the SEATONOMY methodology can work as input to overall system design and vice versa.

One simple example from the aforementioned MUNIN project is that the methodology will provide targets for system availability and maintainability, e.g. four weeks operation without human intervention at a certain confidence level. This in turn may preclude the use of heavy fuel oil due to complex on-board processing requirements and may also require the ship to have dual propulsion systems. This in turn increases operational and capital costs compared to traditional ships which have to be offset by other measures, e.g. lower operational speed or significantly less off-hire. The methodology will support the logical reasoning, but will not support the selection of technical solutions in this particular case.

The Sensors-Intelligence-Communication (SIC) architecture defines the system boundaries of the SEATONOMY methodology, and is illustrated in Figure 6.

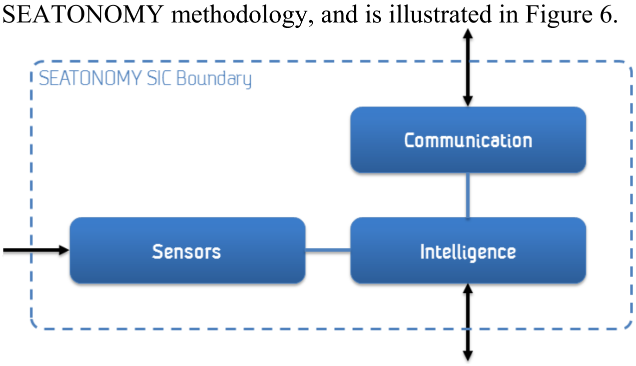

Figure 6: Boundaries of the SIC architecture

Sensors are the means of an electromechanical system to perceive its surrounding environment as well as its internal state. Without the sensors, it is impossible for them to react to any kind of exogenous environmental events, and thus any mechanism that needs to reason about and make its own decisions concerning the environment needs to take sensors into account. Perception is also one of the phases in common models of cognition or decision such as the OODA loop (observe-orient-decide-act) or SA (situation awareness).

Intelligence entails the sub-systems and algorithms that deal with comprehension, projection, decision-making, and action implementation in order to make the system behave as intended. In the SIC architecture, (low level) control and actuators are intentionally left out to indicate that both are outside the scope of autonomy albeit setting limitations on *how* decisions can be put into action in the environment.

Communication is the third component of the architecture, and it has a vital role concerning decisions that need to be made that concern how autonomous the system *can* be and how autonomous the system *must* be. It is the possibilities for, or limitations to, communication with the external operator or supervisor that in many cases guide the choice of autonomous capabilities.

VII. Pilot-cases and input-cases

To aid in the development of the methodology two input-cases have been be considered; one on unmanned merchant ships and the other on autonomous robots for inspection and maintenance of petroleum installations. The input-cases are used as background into the development of the SEATONOMY methodology. The methodology will be tested on two pilot-cases; one case on aquaculture net pen inspection and the other on waste water plume detection. The pilot-cases are utilized in order to iteratively test and further develop the SEATONOMY methodology.

A. Input-case 1: The unmanned ship

The EU-project MUNIN has been used as one of the input cases to SEATONOMY [6]. The main purpose of MUNIN is to perform a concept study of an unmanned dry bulk carrier of around 50 000 tons dead weight (Handymax). Thus, MUNIN has developed initial ideas for many of the methods covered by viewpoints A and B in SEATONOMY. Viewpoint A has been based on UML (Unified Modeling Language) techniques and in particular scenario and use case descriptions. In addition, elements from Formal Safety Assessment, the standard cost-benefit analysis recommended by the International Maritime Organization, has been used [7]. Most of viewpoint B has been handled less systematically in MUNIN. The methods has been ad hoc workshops and discussions based on descriptions developed in viewpoint A. One part of B which has had particular attention is communication. Many of the communication requirement specifications included in B2 have been established from use cases as well as a safety analysis based on the FSA methodology [15]. In addition, an analysis of the security of the communication systems has been an important component in MUNIN [15]. For Viewpoint C there are less extensive results as MUNIN was limited to a concept study.

B. Input-case 2: Autonomous robots for inspection and maintenance of petroleum installations

With funding from Statoil and the EU-project R5-COP, SINTEF has been working on concepts and demonstrators for remote inspection and maintenance of petroleum installations with robots for more than a decade in total. Concept operations such as autonomous inspection and teleoperation with mobile robots, as well as remotely operated valve operations with gantry-mounted robots have been developed and demonstrated [16]. During the work on these systems and operations, Viewpoint A has been based on use case description methods. We have used requirements found from the work with the use cases as a basis for realizing various autonomous systems and system functionalities. This work is relevant for Viewpoint B. As for Viewpoint C, we have gathered feedback on e.g. system functionality and user experience in a structured manner from relevant personnel during demonstrations of the systems developed at SINTEF.

C. Pilot-case 1: Aquaculture net pen inspection

In modern aquaculture using gravity net cages, holes in the net and other type of net failures constitute a challenge with respect to fish escapes. Based on the Norwegian reports of escape incidents for salmon farming, more than two thirds of the registered escape incidents are related to holes in the net [18]. One important measure established to reduce escapees is a mandatory net inspection after all operations involving manipulations of the net and weighting system. For this purpose Remotely Operated Vehicles (ROV) has proven to be a safe, robust and cost efficient alternative to divers.

In this pilot, an ROV with autonomous functionality will be used to inspect the net cage in a sea-based fish farm. The ROV will be able to autonomously traverse the net on the inside of the cage without operator input. The following sensors-intelligence-communication will be used: A Doppler Velocity Log (DVL) for measuring net relative distance, net relative yaw angle as well as net relative surge, sway and heave velocities. An example is given in [3]. Yaw angle will be measured using a magnetic compass, and the yaw rate using a gyroscope. The horizontal position will be measured using an Ultra Short Base Line acoustic positioning system. An example is given in [4]. Absolute position will be measured using a GPS when surfacing. Depth is measured using a pressure sensor. In addition to sensors for guidance, navigation and control (GNC), the ROV will be equipped with an electro-optical HD camera for net inspection. Net damage will be assessed using machine vision algorithms.

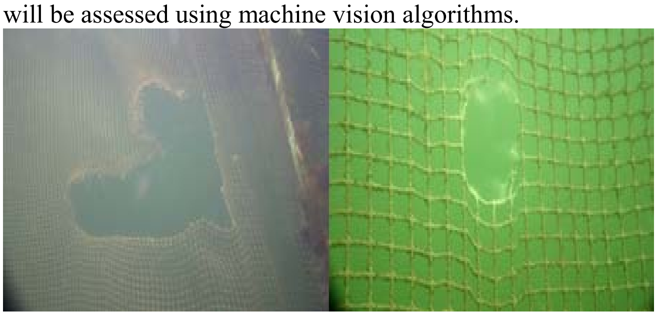

Figure 7: Examples of net damage

During net inspection, the AUV will traverse the net from a predefined distance and heading relative to the net. The main factors deciding the duration of a mission are the distance between the camera and net, the camera's field of view (FOV) and ROV velocity. These factors will be considered during mission planning. The system must also be able to document that the entire net area is inspected. In order to achieve this, several factors must be taken into account. For instance, the geometry of the containment net is not accurately known in advance since it is affected by time varying forces caused by currents. Furthermore, the path planning algorithms must cope with ropes and other structures inside the net. This challenge will be addressed by implementing adaptive mission planning and real-time evaluation of path following performance and collision avoidance. This is necessary in order to repeat inspection of a certain area or adjust the path being followed when necessary. This, in turn, increases the accuracy requirements and complexity of the GNC system. An observer for state estimation, wave filtering and dead reckoning will be implemented to obtain precise navigation data. The accuracy of the navigation system is paramount so divers can easily locate the damage for repair.

D. Pilot-case 2: Plume detection

In this pilot an AUV is planned to be used to map the spatial and temporal distribution of the discharge from a waste water plant.

The discharge stems from a treatment plant at Høvringen, Norway, approximately 3 km to the northwest of Trondheim harbor, which outlet is at 48-65 meters depth in the Trondheim fjord. There has been a major concern for waste water resurfacing, and many models have been proposed in order to predict the outcome of a possible discharge.

An AUV equipped with a conductivity sensor will be used to record the interface between sewage and sea, such that the measurements can be used for improvement of current discharge models. Both the shape and size of the horizontal and vertical cross section of the plume is of interest. In addition, salinity readings will be considered.

The pilot-case will be a test of the possibility of utilizing autonomous vehicles for subsea mapping of regular and acute discharges of various origins.

VIII. Conclusions

The SEATONOMY methodology provides a structured approach for design, development and validation of mobile autonomous maritime operations and systems. The methodology is still under development and we expect to continue to produce new versions over the years to come. However, the methodology is already mature enough to have provided valuable improvements in the two input cases, and parts of it can be utilized for other use cases also.

A common methodology for industrial autonomous systems simplifies the development process and makes it much easier to document the capabilities and limitations of the finished system. This is a target for the SEATONOMY methodology.

References

[1] AUTOSAR. AUTomotive Open System Architecture. http://www.autosar.org/. Accessed 14 Aug 2015.

[2] SAVI. The System Architecture Virtual Integration Program. http://savi.avsi.aero/. AVSI. Accessed 14 Aug 2015.

[3] TELEDYNE. Workhorse navigator doppler velocity log. http://www.rdinstruments.com/. TELEDYNE RD Instruments. Accessed 14 Aug 2015.

[4] SONARDYNE. Scout USBL.http://www.sonardyne.com/. Accessed 14 Aug 2015.

[5] Intelligent Transport Systems (ITS); Communications Architecture, European Telecommunications Standards Institute, EN 302 665, 2010

[6] H.-C. Burmeister, W. Bruhn, Ø.J. Rødseth and T. Porathe (2014). Autonomous Unmanned Merchant Vessel and its Contribution towards the e-Navigation Implementation: The MUNIN Perspective. International Journal of e-Navigation and Maritime Economy, 1, 1-13.

[7] Ø. J. Rødseth, and H. C. Burmeister**.** Risk Assessment for an Unmanned Merchant Ship. *TransNav, International Journal on Marine Navigation and Safety of Sea Transportation* 2015 ;Volum 9.(3) s. 357-366

[8] Ø. J. Rødseth. A Maritime ITS Architecture for e-Navigation and e-Maritime: Supporting Environment Friendly Ship Transport. In proceedings of Intelligent Transportation Systems (ITSC), 2011 14th International IEEE Conference, Washington USA.

[9] Ø.J. Rødseth, Å. Tjora. A System Architecture for an Unmanned Ship. I: *Proceedings of the 13th International Conference on Computer and IT*

Applications in the Maritime Industries (COMPIT). Verlag Schriftenreihe Schiffbau 2014 ISBN 978-3-89220-672-9

[10] S. S. Wegener, S. M. Schoenung, J. Totah, D. Sullivan, J. Frank, F. Enomoto, C. Frost and C. Theodore, UAV autonomous operations for airborne science missions, 2005

[11] R. C. Arkin, Behaviour-based robotics, MIT Press, 1998

[12] Ø. J. Rødseth, B. Kvamstad, T. Porathe and H. C. Burmeister, Communication architecture for an unmanned merchant ship, In Proc. of the MTS/IEEE Oceans conference, 2013

[13] A. Jónsson, R. A. Morris and L. Pedersen, Autonomy in space: Current capabilites and future challenges, AI Magazine, Vol. 28, No. 4, 2007

[14] K. Grythe, T. A. Reinen, A. A. Transeth, Autonomy levels versus communication in an underwater environment, In Proc. of the MTS/IEEE Oceans conference, 2015

[15] Ø.J. Rødseth, K. Lee. Secure Communication for e-Navigation and Remote Control of Unmanned Ships. In Proc. of the 14th Conference on Computer and IT Applications in the Maritime Industries - COMPIT'15. Hamburg, Tyskland: Technische Universitat Hamburg-Harburg 2015 ISBN 978-3-89220-680-4

[16] A.A. Transeth, H. Schumann-Olsen, A. Røyrøy, and M. Galassi (2013). Robotics for the petroleum industry – challenges and opportunities, In Proc. SPE Middle East Intelligent Energy Conference, Dubai, 28-30 Oct.

[17] E.I. Grøtli, M. Vagia, S. Fjerdingen, M. Bjerkeng, A.A. Transeth, E. Svendsen, P. Rundtop (2015). Autonomous job analysis – a method for design of autonomous marine operations, In. Proc. MTS/IEEE OCEANS'15, Washington DC, 19-22 Oct.

[18] O. Jensen , T. Dempster, E. Thorstad, I. Uglem and A. Fredheim. (2010). Escapes of fishes from norwegian sea-cage aquaculture: causes, consequences and prevention. Aquaculture Enviroment Interactions, vol. 1, pp. 71-83.