

Towards autonomy in ROV operations

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Abstract: This paper presents an on-going research project focusing on the development of technology to enable autonomy in ROV operations. The project is a collaborative project between Norwegian offshore industry and academia. Currently, there is a large focus in research on the development of navigation, guidance and control for autonomous underwater vehicles (AUV). This is important as there will be a future demand for subsea inspection, maintenance and repair (IMR) operations with non-cabled systems. A future scenario is to have AUVs stationed on the seafloor in subsea garages. However, state of the art for IMR operations on the Norwegian Continental Shelf is to apply vessel supported ROVs in IMR operations. Efficiency in such operations will imply large cost and time savings. Increased autonomy enables the ROV operator to shift from manual to automatic control utilizing autonomous functions for a number of specific tasks. The research project presented in this paper is novel and the goal is to improve the capabilities of the ROV leaving the operator mainly to supervise operation. The paper discusses different aspects of the technology requirements. This may be useful for researchers working in the area of AUV research, relating this research to industrial needs. The presented project will develop novel integrated sensor platforms with robust perception methods and collision-free motion planning algorithms for subsea inspection and light intervention operations. Moreover, the project will also focus on subsea factory design enabling autonomous operations. The results will be tested, verified and demonstrated in full-scale test beds, as well as at an offshore location.

Keywords: Autonomy, subsea, ROV operations, safety

1. INTRODUCTION

Subsea processing is the factories of the future for the oil and gas industry and is being developed for deep water and arctic areas. The Norwegian oil and gas company Statoil has the goal to install the first subsea factory in 2020 and is currently starting the installation of the first subsea compressor; the Åsgard compressor (Statoil, 2007). Subsea factories of the future constitute complex installations, including pump stations, compressors, storage tanks, etc. Next generation tools and sensor platforms may be situated on the sea floor in garages next to the factory in an on demand state, for example, as autonomous underwater vehicle (AUV) inhabitants. Vessel independent hot-stab operations, automatic connector inspection, autonomous docking, and component replacement are foreseen future operations executed by AUVs. Maintaining high regularity with such complex subsea systems requires reliable installed equipment, but also efficient ways for inspection, condition monitoring, and early detection of equipment fault.

There exists more than 500 subsea wells on the Norwegian Continental Shelf and with aging equipment it is expected that the need for inspection, maintenance and repair (IMR) operations will increase significantly in the coming years. Moreover, there is a risk for damage of subsea equipment due to collision with unknown objects, entanglement in fish net, in addition to component failure.

Currently, all inspection, maintenance and repair operations require support from offshore vessels, ROV systems, tools and experienced ROV operators. The day rate for a support vessel is in the range of 100 000 - 300 000 dollars per day, depending on the vessel size. Vessels available in the spot market operate on-demand and this may increase the prize and time of operation. Other vessels operate on more long-term contracts and are available on shorter notice. There is, however, always a need for flexible weather windows to be able to perform operations.

In general, current industrial ROV operations are directly and manually controlled, with neither automatic control functions nor autonomy. Efficiency in operations is highly dependent on the experience of the ROV operator. Autonomy in ROV operations is a stepping-stone towards increasing the efficiency and thereby reducing the costs. This is in the timeline awaiting the development of autonomous underwater vehicles (AUV) with intervention capabilities (Marani, et.al., 2009; Gustavson et al, 2011). Semi-autonomous control of ROV operations is the solution to reduce the workload on operators, reduce human errors in operations, and increase efficiency. Insofar this topic has too a limited extent been covered in literature or industry. The objective of this paper is to present and discuss the technology components needed for autonomy in ROV operations, as well as the Norwegian research project addressing this topic.

The main contribution of this paper is the discussion on the gap between research and state of the art in industry, and the research and industrial challenges that need to be solved to enable autonomy in ROV operations.

Section 2 gives a short overview of relevant state-of-the-art and challenges which form the research activities in the project. Research topics are presented in Section 3. Section 4 discusses risk management and safety aspects, and Section 5 holds the conclusions.

2. SHORT REVIEW

Research on guidance, dynamic positioning and coordinated control of marine vessels and ROV/manipulators has been on-going for more than 20 years (Fossen, 2011; Roberts et.al, 2006; Schjølberg et.al, 1994). Recent progress is related to coordinated control and stability analysis, as well as guidance and control of marine crafts, underwater robots, and hydrodynamic parameter identification (Antonelli, 2010). Practical aspects of ROV systems are presented in Christ (2014). Research and progress within the area of vehicle-manipulator systems is summarized in From et.al (2014). Moreover, dynamic positioning (DP) is developed and demonstrated for ROVs (Sørensen, 2012). Research work has also been performed related to station-keeping (Dukan et.al, 2012), recently by using observer theory (Candeloro et.al, 2012). Other relevant theoretical work and results from tele-robotics (Niemeyer, 2008) are highly relevant in the development of autonomy in ROV operations.

2.1 Control algorithms and models

Industrial implementation of model-based control algorithms in ROV control is limited. Complexity is linked to the identification of hydrodynamic parameters of the mathematical models describing the vehicle-manipulator system. This has been a constraint in the development of more advanced control structures and implementation in commercial systems. Moreover, this could be a hindrance for future development of autonomy in ROV operations. The fundamental for development of model-based control algorithms is the standard vehicle-manipulator equations of motion, as written in the form

$$M(q)\dot{\vartheta} + C(q, \vartheta)\dot{\vartheta} + D(q, \vartheta)\dot{\vartheta} + g(q, \varphi) = \tau \quad (1)$$

where

$$\vartheta = [v^T, \dot{q}^T]^T \quad (2)$$

and M is the mass matrix, C is the coriolis matrix, D damping and g gravity. v is the ROV velocity and orientation vector, q is the joint angles of the ROV mounted manipulator. φ is the position and orientation vector for the ROV and manipulator and τ is the control input. There is currently no standardized software or methods for determining the elements of the

abovementioned matrices. A challenge is, for instance, the complex form and shape of working class ROVs (Fig. 1).

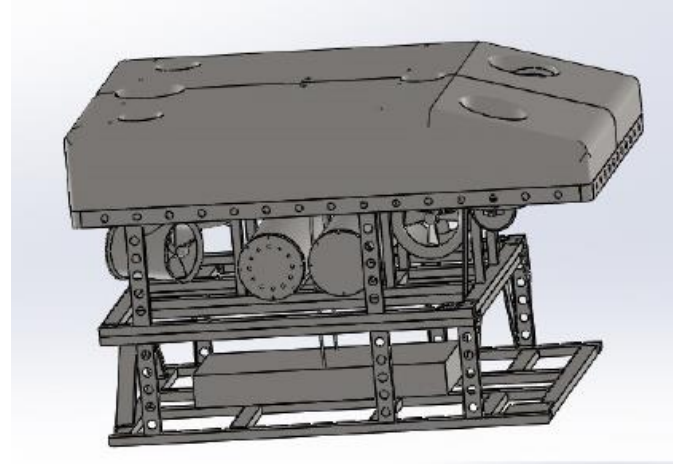


Fig. 1. Complex shape of an ROV

Empirical formulas for deriving parameters of the matrix M , C , D are typical strip theory and empirical 3D data. For ROVs with simple symmetric planes and known CAD model, CFD computations can be performed to identify the diagonal terms in these matrices (Avila et.al, 2013). Potential flow theory is another approach, as well as experimental methods. Use of any of these methods requires specific knowledge in hydrodynamics and testing facilities to verify results by experiments. Moreover, any of the methods will introduce a degree of uncertainty in the matrix parameters.

Development of algorithms for station-keeping was an important breakthrough for ROV systems and this is now applied on many working class ROVs. Station-keeping is the first stepping stone towards autonomy in ROV operations as it enables decoupled control of the ROV and manipulator. Thus, the arm can be controlled independently of the ROV. Development of model-based control of manipulator arms is less complex. Identification of model parameters for a hydraulic manipulator is simpler due to the more regular shape of links (cylindrical or rectangular). However, Fig. 2 shows that some hydraulic underwater manipulator arms also have a complex shape. Currently most arms on working class ROVs are hydraulic, but the tendency is towards electric systems and this would be a paradigm shift also in the design of manipulator arms.

Another option is the one of Han et al (2014) who propose a more model independent approach, namely a framework for actively using restoring moments requiring only masses, buoyancy forces and centers' of gravity, and reducing the need to identify all parameters in the equations of motion.

2.2 Autonomy levels

In the development of autonomy in ROV operations it is important to have a clear picture of autonomy levels and steps needed to move from one step to another. Christ et al. (2014) divide ROV control levels into five levels. Current ROV operations are mainly in level a, b and c. The ROV LATIS project (Omerdic et. al, 2012) is one of the first

project to demonstrate levels d and e. Future autonomous ROV operations will cover levels d and e:

- a) The term direct control is related to control of manned submersible vehicles.
- b) Remote control is control of vehicle motion through line of sight.
- c) Teleoperation is current operational solutions based on direct joint stick control of each manipulator joint from a control room running the operations through camera views. Currently, operations are totally dependent on the training and experience of the operator.
- d) Logic driven vehicle control is semi-autonomous control where some operations are performed through automatically generated wave points.
- e) Logic driven with goal orientation is when high-level task instructions are uploaded and the operations are performed autonomously.

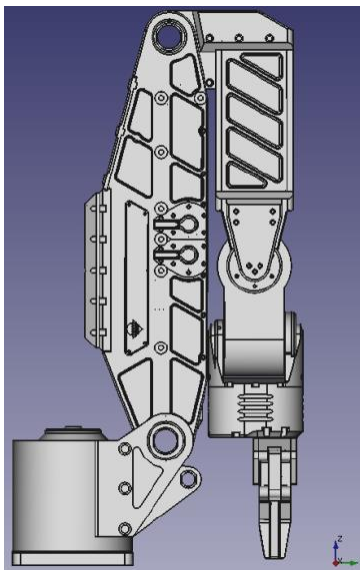


Fig. 2. Complex form of ROV manipulator arm

2.3 Operator support

Development of real-time virtual environment models, including collision detection, will be an important part of future development for more efficient remote and autonomous operations. In logic driven vehicle control (autonomy level d), position and velocity commands are sent to the remote unit, while in goal orientation mode (level e), such commands are locally calculated. In future systems, the change of modes of operation and transition periods must be handled by varying the control gain at the operator site and remote site during complex operations. System stability analysis by linearizing the various blocks in a control architecture for autonomy will be an important part of future research.

System architecture developed for logic driven solutions may exploit solutions developed for other applications. One example is Robot Operating System (ROS, 2015) which supports real-time control, as well as functionalities, such as environmental description and collision-free path planning.

Such architecture will support logging of data on-line both for documentation purposes, as well as post analysis of operations.

To achieve semi-autonomous control and autonomy in ROV operations, system architecture must support operator-guided control and autonomous functionalities for cooperation on solving tasks, ranging from high-level task planning or autonomous control to direct forward control with tactile feedback.

There is a large gap between research and current operations where all ROV intervention operations are manually performed. In addition, subsea templates have in general not been designed for autonomous intervention. Moreover, the use of virtual environment models and sensors for ROV/AUV collision avoidance are scarce. Hence, there are shortcomings related to realizations of autonomous subsea intervention operations required for ROV or using AUV inhabitants.

3. RESEARCH TOPICS

On-going research work at the Norwegian University of Science and Technology (NTNU) includes development of essential software and hardware components enabling autonomy in a selection of ROV operations for increased efficiency and cost reduction. The operations in focus are yearly inspection of subsea templates, valve intervention and change of template components. Main challenges to be solved are: localisation, path planning, design of templates, and risk management during autonomous operations, as illustrated in Fig.3.

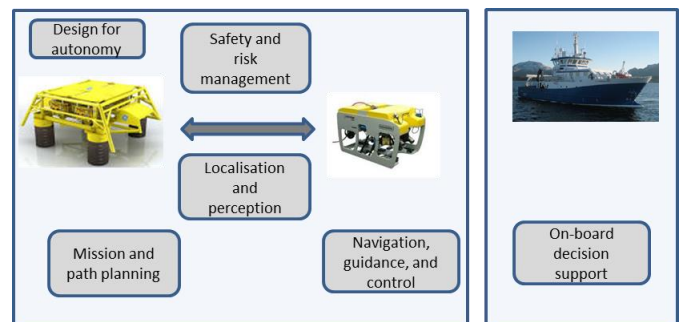


Fig. 3. Modules under development.

3.1 Localisation

Localisation for subsea intervention is a challenging task. Localization is the task of obtaining an accurate estimation of a mobile robots position relative to its environment. The main steps in such systems today are predict, observe and update. Perception is the understanding of one's position and attitude relative to the surrounding (Correa et al., 2010). In current ROV operations the operator in terms of visual inspection performs localization by use of 2D camera images. Subsea templates are marked with letters and numbers to aid the operator in the localisation and perception process. Thus, a

large effort is needed to develop automated localization solutions.

A well-known approach is SLAM based solutions (Ferreira et.al, 2012). However, these solutions are less appropriate for localization for intervention.

Available sensors, such as cameras, sonars, and acoustic transponders, can be combined to design a sensor system that provides sufficient input for high-precision localization and a degree of accuracy enabling robust and safe intervention. Ongoing project work includes the development of fusion methods for combining stereo camera information with acoustic sensor data from a novel high bandwidth acoustic link. The methods will seek to use the existing markers on the structures and knowledge of 3D CAD models of the structures. The sensors will be mounted in the Marine Cybernetics Lab (MC-lab, Fig. 4) at NTNU enabling testing and verification of algorithms in lab before performing offshore experiments.



Fig. 4. Marine cybernetics (MC) -lab at NTNU.

3.2 Guidance and path planning

Mission planning is crucial for safe operation of ROVs and is related to operating procedures (Utne et. al, 2014). Since current ROV operations are dependent on vessel support, an important part of the planning is to consider the environmental conditions, i.e., the sea state, the current weather and the weather forecast at the launch and recovery location, and effects of currents in the area. The sea floor and nearby installations, such as pipelines and subsea templates, have to be considered in the operational planning. The water temperature and water density may affect the buoyancy and sensors and could therefore potentially affect the robustness of the autonomy algorithms.

Wave points are applied in current operations, both for inspection and intervention tasks. For instance in inspection tasks wave points are generated during the planning of the operation to assure that the whole structure has been accessed. The operator runs the ROV through all the wave points using visual information. A first step towards

autonomy is automating this type of operation. This could reduce the strain on the operator during operations and make operations less dependent on the operator qualifications. To enable this, robust localization algorithms are required.

Solutions for dynamic path planning are needed and this requires algorithms for robust navigation around structures. A number of solutions have been suggested, e.g., Kinsley et al (2006), and the project will build on this work to enable, for instance, autonomous yearly inspection of structures. Optimal methods for ensuring total coverage are essential.

3.3 Future design of equipment

A key challenge is to optimize the design of future subsea equipment to enable autonomous IMR operations. This includes optimization of tools, tool exchange systems, and design of valves and sensors for intervention. In addition, manufacturing functions, such as fabrication, assembly, test and installation will have an impact on the design. The basis for this part of the project is to study existing production procedures, through factory visits and logistic analysis of the existing production processes. Research and development of logistic and equipment design will be followed by simulations and experiments to verify results. Multidisciplinary teamwork is essential since combined knowledge in path planning, localization methods and operations is needed to enable optimization of the equipment design.

4. RISK MANAGEMENT IN AUTONOMOUS ROV OPERATIONS

Complexity in operations, software systems, sub-systems and components is increasing and current decision support systems are insufficient. One operation – one view supporting integrated views, early warnings, and predictive analyses are features necessary for reducing risk in autonomous ROV operations.

Currently, API 17h (API, 2013) and NORSOK U-102 (Standards Norway, 2012) cover important aspects related to ROV operations. The generic IEC 61508 standard (IEC, 2010) is also relevant, because it offers a safety lifecycle that covers all project phases from concept, through design, implementation, operation, and maintenance, to decommissioning of a safety-related system. An overview of relevant standards for ROV operation can be found in Hegde et al (2015a).

During the past decades, larger focus has been placed on defining the role of the human operator and determining which functionality should be automated. Parasuraman et al. (2000) proposes four classes of functions for which automation can be applied, with resemblance to the four-stage model of human information processing. Working with development of autonomous ROVs affects and challenges the role and working conditions of the human operator. An operator may be highly capable of reducing risks in ROV operations by taking the proper actions. An operator, on the other hand, also introduces the risk of human error. Important

psychological constructs to highlight when working with automated systems are trust, complacency, situation awareness, vigilance, and mental workload (Karlsen, 2014).

As ROV operations become more autonomous, the number of manual actions required by the operator is reduced, and the operator's role becomes supervisory. This means that the operator needs increased monitoring abilities of the operational performance of the ROV, and improved information about the operational state of ROV, to be able to determine if and when intervention is necessary. Improved decision-support can be achieved by development and implementation of an online software platform to be used during complex and autonomous subsea operations. A decision-support system is under development at NTNU, to supply the operator with a real-time risk picture, as well as a sense of tele-presence.

Autonomous ROV systems will require systematic analyses and implementation of barriers, such as integrated collision avoidance systems. This has been developed for AUVs (Tan et al, 2007). An online decision – support system needs to interact with a collision avoidance system, because it may be decisive for the activation of the collision avoidance system.

Work related to risk management in the present research project builds upon the hazard identification (HAZID) performed for autonomous subsea operations (Utne et.al 2014). The starting point for risk modeling is fault trees developed, e.g., with basis in the HAZID, but fault tree analysis has limitations (see, e.g, Rausand, 2011). Hence, more advanced modeling is required, for example, use of state modeling and fuzzy logic (Hegde et al., 2015b). Human and organizational factors in AUV operations has been addressed in Thieme et al. (2015).

Data models in the online decision –support system need to be built upon empirical models representing condition data and online operational data. Data will be continuously fed to the risk models to generate an online risk picture of the operation. Java applications will visualize the risk to the operator.

Typically, an AUV has a pre-programmed course of action, meaning that the vehicle has a limited degree of autonomy. Some tasks are completely autonomous, while others were interfered by the operator. The overall automation level could be described as semi-autonomous. No real-time data is available to the operator during AUV missions, due to lack of broadband acoustic link between the AUV and the surface vessel. The position of the AUV is based on its relative position to the surface. This will also be the case in autonomous ROV operations and needs to be improved before an advanced online decision-support system can be implemented. Strain factors, such as loss of communication, will not be a challenge in autonomous ROV operations.

5. CONCLUSIONS

The state of the art for IMR operations on the Norwegian Continental Shelf is the use of vessel supported ROVs. Large

cost and time saving are expected if these operations can be performed more efficiently by introducing autonomy in ROV operations. There is a need for focused research to enable development of such solutions.

Currently, there is a large effort in academia on research on autonomous systems, such as AUVs, including development of enhanced solutions with improved functionality to allow for subsea intervention. Autonomy in ROV operations, however, is a stepping-stone towards these future intervention solutions. This paper presents an on-going research project focusing on the development of technology to enable autonomy in ROV operations.

The research project is a collaborative project between industry and academia in Norway to improve the capabilities of the ROV leaving the pilot to supervise the operation. This would enable the ROV operator to shift from manual to automatic control utilizing autonomous functions for some specific tasks.

The paper discusses different aspects of the technology requirements and this may be useful for researchers working in the area of AUV research. The presented project will develop novel integrated sensor platforms with robust perception methods and collision-free motion planning algorithms for subsea inspection and light intervention operations. Moreover, the project will also focus on developing a safety philosophy for design and operation of autonomous ROVs, and subsea factory design for autonomy.

ACKNOWLEDGEMENT

This work is funded by the Research Council of Norway, STATOIL and FMC Technologies through the project Next Generation Subsea Inspection, Maintenance and Repair Operations, 234108/E30. The work is associated with AMOS, 223254. Special thanks to project colleagues Aksel A. Transeth (SINTEF), Brede Thorkildsen and Tor B. Gjersvik (FMC), Arild Ramstad and Knut Sveberg (Statoil).

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