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Towards integrated autonomous underwater operations for ocean mapping and monitoring

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ABSTRACT

The NTNU Centre for Autonomous Marine Operations and Systems (NTNU AMOS) is as a ten-year research program, 2013-2022, addressing research challenges related to autonomous marine operations and systems applied in e.g. maritime transportation, oil and gas exploration and exploitation, fisheries and aquaculture, oceans science, offshore renewable energy and marine mining. Fundamental knowledge is created through multidisciplinary theoretical, numerical and experimental research within the knowledge fields of hydrodynamics, structural mechanics, guidance, navigation, control and optimization. This paper gives an overview of the research at NTNU AMOS related to mapping and monitoring of the seabed and the oceans. Associated definition and requirements related to autonomy are also addressed. Results and experience from selected field trials carried out in the Norwegian coastal and Arctic waters will be presented. Integrating different sensors and sensors platforms such as Autonomous Underwater Vehicles (AUV), Remotely Operated Vehicles (ROVs), and ship-based systems will be shown.

1. Introduction

The vision of NTNU AMOS is to establish a world-leading research centre on autonomous marine operations and systems where fundamental knowledge is created through multidisciplinary theoretical, numerical and experimental research within the knowledge fields of marine technology, guidance, navigation and control. NTNU AMOS addresses the main application areas for ocean space science and technology (Fig. 1) including offshore oil and gas, maritime, fisheries, aquaculture, offshore renewable energy, marine science and marine mining. Cutting-edge interdisciplinary research involving technology, science and application knowledge will provide the needed bridge towards autonomous underwater operations in order to make high levels of autonomy a reality. This paper is an updated version of the work “Towards Integrated Autonomous Underwater Operations” by Sørensen and Ludvigsen (2015) presented at NGCUV in Girona, Spain.

Developments in technology platforms, sensors and control methods including autonomy have in many cases been driven by the needs in marine sciences as described in Bellingham (2014), Seto (2013), Williams et al. (2015) including contributions from several authors, Berge, Båtnes, Johnsen, Blackwell, and Moline (2012), Bingham et al. (2010), Clark et al. (2013), Ludvigsen, Sortland, Johnsen, and Singh (2007), Moline et al. (2005), Moline, Woodruff, & Evans (2007), Pizarro and Singh (2003), Singh et al. (2001), Singh, Whitcomb, Yoerger, and Pizarro (2000), Williams et al. (2012), and the references therein. The research group of Sousa (2010) at the Underwater Systems and Technologies Laboratory (LSTS), University of Porto, Portugal has done pioneering work in the development of software platforms for networked vehicle systems operating underwater, at the sea surface and in the air. In particular, they have been successful to support integrated operations using the open software package Neptus/DUNE tool set.

Another successful concept for autonomy of underwater vehicles is described in Hagen et al. (2009), making autonomous underwater vehicles (AUVs) truly autonomous. Here, more than 15 years of experience on the Hugin AUV concept is described. Sotzing and Lane (2010) and Insaurralde and Lane (2012) at Heriot–Watt University, Scotland have during several years been working with a hybrid control architecture with different control layers addressing autonomy. In addition to the mentioned references there is a vast and increasingly research activity on autonomous underwater vehicles in many other strong research groups around the world, e.g. Japan, US, Canada, Brazil, India and Europe.

In this paper, we will address various aspects of the on-going research activities at NTNU AMOS on underwater operations for

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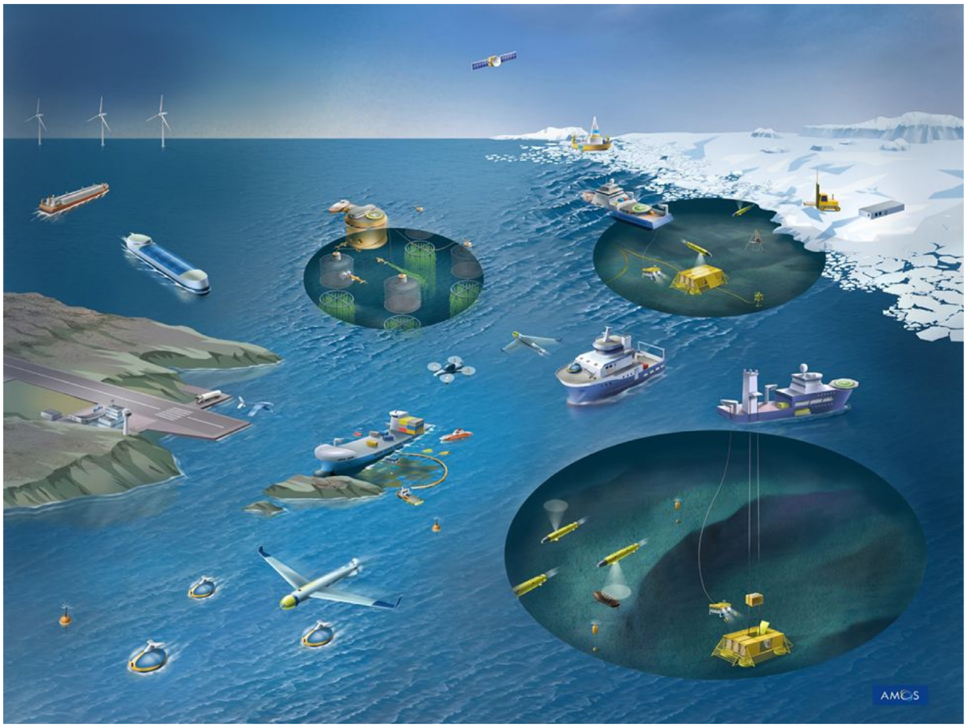

Fig. 1. Ocean space science and technology, illustration by AMOS/NTNU and Stenberg.

mapping and monitoring purposes. The main contributions of the paper are; evaluation of different technology platforms subject to spatial and temporal coverage and resolutions and a presentation of a control architecture considering a bottom-up approach towards autonomy. Selected results from field campaigns will also be shown.

The paper is organized as follows: In Section 2 integrated technology platforms and sensors will be presented. Autonomy aspects are discussed in Section 3. Examples from field campaigns are shown in Section 4. Future trends are discussed in Section 5, and finally the conclusions are given in Section 6.

2. Integrated platforms and sensors

2.1. Spatial and temporal coverage and resolution

Nilssen et al. (2015) proposed a concept for integrated environmental mapping and monitoring (IEMM) based on a holistic environmental monitoring approach adjusted to purpose and object/area of interest. The proposed IEMM concept describes the different steps in such a system from mission of survey to selection of parameters, sensors, sensor platforms, data collection, data storage, analysis and data-interpretation for reliable decision-making. In addition to measurements of essential parameters, the quality of the data interpretation is dependent on the spatial and temporal resolution and coverage of the data. Hence, the dynamics in both space and time have to be considered in the mission planning process. The temporal and spatial resolution and coverage capabilities for the relevant technology platforms are shown in Fig. 2 indicated by orders of magnitude. The spatial and temporal coverage and resolution needs will depend on the mission purpose (e.g. processes, organisms of different sizes) and the different decision-makers such as scientists, authorities, and industry may have individual needs and requirements. As suggested by Nilssen et al. (2015) the platforms' capabilities and limitations, mission purpose and object/area of interest are of importance as well as the ability to participate in integrated operations including

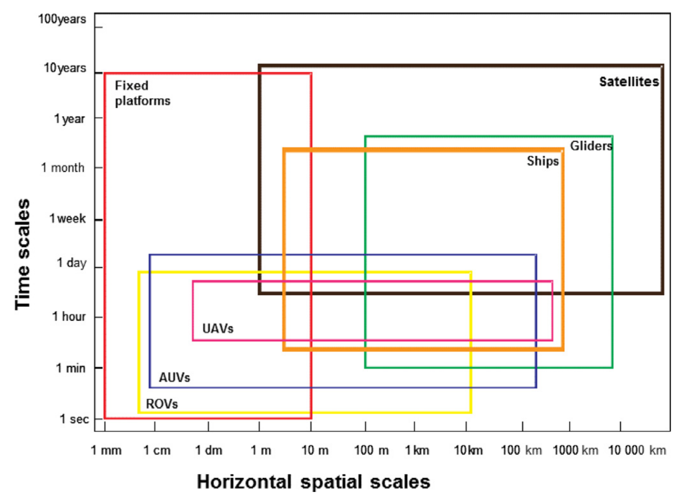

Fig. 2. Spatial and temporal resolution and coverage of different platforms, Nilssen et al. (2015).

also complementary platforms. In this context, underwater platforms may be landers or moorings, remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), and gliders. In order to be successful, improvements of the individual platforms as well as integration to different platforms in a network are of importance. As indicated in Fig. 1 this integrated approach does also include unmanned surface vessels (USVs), ships, unmanned aerial vehicles (UAVs), airplanes and remote sensing by satellites. Lately, research on unmanned aerial vehicles (UAV) and autonomy has increased the interest to apply low-cost UAV as sensors platforms and communication hubs between sensor platforms in the surface or the air and e.g. a mother vessel supporting AUV operations with some distance to the launching vessel.

For shipwrecks, the time constant of magnetic signatures and decompositions is in the order of years dependent on water depth,

Table 1
Time constant of processes measured by instruments.

Process	Optic. img.	Sonar	Mag.	ADCP	Optic.refl.	CTD
Archaeology	10 – 100 years	10 – 100 years				
Geology	10 – 1 M years	10 – 1 M years	10 – 1 M years			
Industry operations	Sec – years	Sec – years	Years			
Biology	Sec – years			Sec. – Years	Hours – Years	
Oceanography				Hours - Years	Hours – years	Hours

temperature and location. The decomposition of a ship wreck can take from a few years and up to thousands of years. However, for geology changes, the time constant is in the order of thousands up to millions of years such that the dynamics of the process is not observable. For industry operations, one might be interested in pipeline or other structures that can change in years. Biological and oceanographic processes often have much lower time constants and change several decades faster. Such processes can e.g. be the distribution of plankton or the mixing between two different water masses.

For oceanographic processes like tide, currents and seasonable variations are observable using acoustic doppler current profiler (ADCP), the time constant can be in the orders of hours up to years.

The process accuracy defines both the sensors precision required and the navigation accuracy necessary. Table 1 reflects typical dynamics of the processes we are attempting to document using our payload sensors, see also Fig. 2. The numbers for the process time constants proposed in the table are generalizations made to emphasise the influence of the process dynamics in the planning of the operations. Processes with time constants more than ten years can be considered constant in this context. When the time constant is between 10 years and 1 week, it can be documented using repeated surveys for a time series. When the time constant is lower than one week, it can be attempted resolved within a single operation. Lower time constants require higher temporal resolution, possibly requiring multiple vehicles, or maybe landers.

2.2. Underwater platforms

In this section we will briefly discuss various underwater platforms used in mapping and monitoring.

Lander: Landers are stationary platforms deployed by ship and crane to the seabed equipped with sensors and instruments. They can be self-sufficient with energy and data storage, or they can be connected to power and communication cables from shore. The temporal resolution can be high, given that sufficient energy supply and data storage capacity is present. However, the spatial resolution will be limited to the coverage and range of the mounted sensors. Most sensors are point samplers, while others, such as active acoustics can cover a wider area. The range of active acoustics is dependent of the frequencies used, varying from meters to several kilometres (Godø et al., 2014).

ROV: ROVs are connected to the surface using umbilical. The umbilical gives unlimited electrical power and high bandwidth communication. They are mobile sensor platforms operating in the water column or on the seabed and are normally deployed from ships. There are three main categories: 1) Eyeball ROV, 2) Observation ROV and 3) Work class ROV. Eyeball vehicles are small, they work best in shallow and protected waters and can be manually handled. They will normally carry only a camera and have very limited capacity for equipment. Observation class ROVs are larger, can handle smaller payload instruments and tools. Manipulator arms can be mounted on them and they are robust to operations in the open ocean. Work class ROVs will normally be hydraulically powered, can handle many types of tooling and have a mass of several tons. These large vehicles will in most cases require dedicated launch and recovery systems and will be integrated into the vessel. ROV motion control systems Caccia, Bruzzone, & Veruggio (2003), Silvestre, Cunha, Paulino, & Pascoal (2009), Fernandes, Sørensen, Pettersen, & Donha (2015), Dukan & Sørensen (2014), Sørensen, Dukan, Ludvigsen, Fernandes, & Candeloro (2012) provide manoeuvring capabilities like station keeping/hovering (dynamic positioning) and target and bottom tracking. High-resolution data from the survey area can be provided including detailed seabed and sampling data with down to mm spatial resolution.

AUV: AUVs have their missions programmed ahead of the operations. The mission programmed contains the actions necessary to fulfil the objective of the user. I.e. for seabed mapping the mission file will contain information of which waypoints the vehicle should visit, the speed and altitude to use, and when to switch instruments on and off. These vehicles are untethered and do not rely of operators to be present. They may be divided into small AUVs and large AUVs. Small AUVs may be handled manually and operated from small boats and from shoreline. Large AUVs may weigh up to several tons and require a research vessel with a dedicated launch and recovery systems. So far, there is limited access to AUVs with station keeping/hovering capabilities. This is at present also the situation for AUVs with manipulator capabilities doing light intervention and sampling. AUVs can provide seabed and water column mapping with high spatial resolution data over large areas. The survey area coverage per time is significantly higher compared to the ROV capacity as the latter has limited spatial range due to the exposed current loads/drag forces on the umbilical.

Glider: Glider is a variant of AUV, but propelled using a system of variable buoyancy for propulsion. Like AUVs, they are programmed prior to their missions and execute their missions without direct control from operators. Gliders' operational ranges and spatial coverages are high compared to AUVs and ROVs because they spend less energy for propulsion. The speed is rather low, following ocean current systems at a minimum of energy. The operation may go on for weeks, and for measuring water column parameters, the glider is an effective tool. However, the accuracy in navigation and manoeuvring is limited.

The potential benefits of collaborating vehicles where demonstrated by Norgren, Ludvigsen, Ingebretsen, and Hovstein (2015) combining AUV and USV in a limited network. The objective of the mission was to map an area searching for the wreck of an airplane from World War II. The USV was programmed to stay near the AUV while carrying an acoustic modem and relay the information to the operations centre. The concept demonstrated can enable operations with extended standoff and reduce the AUV dependence of expensive surface vessels.

2.3. Sensors

Sensors for underwater vehicles can be categorized into two main groups: payload sensors and navigation sensors.

2.3.1. Payload sensors

Payload sensors are measurement units that are carried by a platform for collecting data either by remote sensing or by direct measurements. The objective of the platform is to position the sensor or instrument at a specific location. If the process subject to the investigation is dynamic, there may also be temporal constraints that the platform needs to fulfil. In the future, a development where underwater vehicles becomes more autonomous may require that these instruments are no longer passive payloads, but that their measurements are forwarded to the mission planning layer and the guidance and optimization in the operations control for mission optimization. Also for surveys of static processes, increased autonomy will have to consider findings and react on them. For dynamical processes, the development of the process must be considered along with their driving parameters – often realized through a world model containing estimates of states describing the environment and the processes in the mission.

Camera Video: Optical imaging of the seabed provides high-resolution qualitative information about shape, colour and texture of the seabed. To identify objects on the seafloor, optical imaging is still the most reliable method due to the high resolution of the colour and texture information. However, to obtain quantitative data from imaging is challenging. Seawater visibility also limits the range for the optical cameras constraining the area coverage. The processes measured by optical imaging can be e.g. geological conditions, archaeological conditions, and biological behaviour.

Underwater hyperspectral imaging (UHI): Applying hyperspectral imagers, the colour information can be quantified at all wavelengths of the visible light as presented in Johnsen et al. (2013). By measuring the full light spectrum, the light absorption of the seabed and the seawater can be quantified and characterized. Using knowledge of the spectral distribution of the light applied, many substances can be characterized by their reflection spectrum. The hyperspectral imager can hence be used to prove presence of substances like chlorophyll, pigments or e.g. seabed minerals. The UHI technology opens up for fast processing of data for automatic identification of any objects of interest (OOI).

Conductivity temperature depth (CTD) sensors measure conductivity, temperature and pressure. Salinity, speed of sound and seawater density are calculated from these fundamental parameters. Salinity and density are key parameters for oceanography, while speed of sound is essential for all sonar applications such as seabed mapping and acoustic navigation.

Magnetometers can be used for localizing man-made objects like shipwrecks in archaeology. They are also used to measure the magnetic characteristics of seabed rocks, see Bloomer, Kowalczyk, Williams, Wass, and Enmoto (2014).

ADCP are used to measure velocity of the currents. The instrument will measure backscatter intensity and Doppler shift of an acoustic reflection signal. Based on this measurement, the instrument provides a profile of three-dimensional current vectors. The current profile is a dynamic process influenced by tides, lunar cycles, climatic variations, weather and many other factors.

Active sonars are used to measure reflected acoustic signals documenting the objects on the seabed or in the water column. These systems are effective documenting and mapping geological features, archaeological objects and other man-made structures. Multibeam echo-sounders (MBE) transmit an acoustic impulse (ping) by a transmitter. Acoustic beams with known directions can measure hundreds of ranges for each ping establishing xyz points on the seabed surface resulting in a 2.5D or 3D model of the seabed. Side scan sonars (SSS) measure the surface reflectance of the seabed. Sending out thousands of pings while moving in lines and measuring the intensity of the reflected pings and the time of flight for the signals, a map of the seabed's acoustical reflectivity can be produced. Initially only time and intensity is measured, and flat seabed assumption is necessary to provide an image. But several SSS can also measure phase information of the signal reflected from the seabed to produce both range and bearing. These SSS's are called interferometric and can provide also bathymetry information of the seabed. Sub bottom profilers (SBP) produce information about the sub-seabed structures. The system transmits low frequency, high power acoustical pulses that are able to penetrate the seabed. Measuring the intensity of the reflected signal, the sub seafloor conditions are recorded.

During the last decade, synthetic aperture sonars (SAS) have been implemented on AUVs. These systems use several pings simultaneously for each seabed point establishing a virtual transducer array providing better range and increased seabed resolution compared to conventional SSS. The HiSAS system marketed by Kongsberg Maritime has also implemented interferometric processing omitting the flat seabed assumption, see Sæbo, Callow, E., Langli, and Hammerstad (2007).

Optical backscatter and attenuation measurements can be used to characterise the seawater with instruments like fluorometers, turbidity sensors and scattering sensors. Monitoring the biological and chemical conditions in the sea, oxygen concentration and saturation can be measured by an in-site optode. These data can be used to distinguish between water bodies, but also to investigate the bio-chemical development in the water.

2.3.2. Navigation sensors

Acoustic baseline sensors: For several decades, acoustic baseline sensors like long base line (LBL) and ultra-short base line (USBL) have been the preferred positioning sensors for underwater operations. These systems measure the time of flight for the signals, and by applying the speed of sound, the range is calculated. USBL also measures the phase of the incoming signal to determine direction. The result is a position derived from range and phase angle. Their advantage is that the errors are observable and bounded and the disadvantages are the required installations on the seabed (LBL) or on the vessel (USBL). For ROV operations, this might be acceptable. However, for AUVs, one of the prime arguments has been lower dependence on pre-installed infrastructure and vessels.

The Doppler velocity log (DVL) measures Doppler shift in the incoming signal reflected off the seabed (bottom track mode) or particles in the water (water track mode) column using the same principles as ADCP. Having several transducers pointing in different directions – velocity of all three axis is observable.

Pressure sensors: Depth is related to pressure through knowledge of gravity and the density of seawater. Both are easily observable with high precision. Given accurate pressure readings, knowledge of tides, profile of the seawater density and latitude to estimate gravity are necessary to provide accurate depth estimates.

The heading sensor will provide a measurement of the heading of the vehicle. There are three main concepts of measuring the orientation of the vehicle around the vertical axis; the rotation of the earth, the magnetic field of the earth, or the relative position of two or more points. The former is the most common and accurate for underwater applications.

Inertial sensors form the basis for most dead-reckoning systems. Integrating the acceleration and rate of changes of the orientation angles in the time domain an observer provide state estimates for position, orientation angles, velocities and accelerations. The error component in the inertial system will cause the position estimates to drift at increasing rates. To limit this drift, inertial navigation systems use auxiliary sensors such as DVL, pressure sensors, acoustics or even GPS to augment the measurements.

3. Autonomy aspects

3.1. NTNU AMOS research objectives

The research areas addressed in NTNU AMOS are complex and multi-disciplinary. The methodology will have a solid foundation on theoretical, numerical and model- and full-scale experimental studies. The core aim is to achieve autonomous operations and systems. The latter is often referred to as intelligent systems due to their ability to manage unexpected events in unstructured and unknown environments. More than mimicking a human operator, this means integrating mathematical models with real-time data from sensors and instruments and allowing algorithms with optimized responses to be designed and embedded in computer systems. Enabling technologies and sciences that are essential to realize autonomy include radio and hydroacoustic communication, embedded computer systems, communication networks, sensors and instruments, human-machine interaction, cognitive science, power electronics and electric drives.

3.2. Types of operation

There are different definitions of autonomy levels; defining the steps from manual or remote control, teleoperation, semi-autonomous to highly autonomous vehicles. The levels of autonomy are characterized subject to the level of human-robot interaction (HRI), mission complexity and environmental complexity.

1. **Automatic operation (remote control)** means that even though the system operates automatically, the human operator directs and controls all high-level mission-planning functions, often preprogrammed (**human-in-the-loop/human operated**).
2. **Management by consent (teleoperation)** means that the system automatically makes recommendations for mission actions related to specific functions, and the system prompts the human operator at important points in time for information or decisions. At this level, the system may have limited communication bandwidth including time delay, due to i.e. distance. The system can perform many functions independently of human control when delegated to do so (**human-delegated**).
3. **Semi-autonomous or management by exception** means that the system automatically executes mission-related functions when response times are too short for human intervention. The human may override or change parameters and cancel or redirect actions within defined time lines. The operatorś attention is only brought to exceptions for certain decisions (**human-supervisory control**).
4. **Highly autonomous**, which means that the system automatically executes mission-related functions in an unstructured environment with ability to plan and re-plan the mission. The human may be informed about the progress. The system is independent and ”intelligent” (**human-out-of-the loop**).

For more details, see e.g. NIST (2015) and National Research Council (2005).

3.3. Control architecture

Sotzing and Lane (2010) addressed the problem of coordinating multiple AUV operations. They proposed a framework for intelligent mission executive that uses multiagent technology to control and coordinate multiple AUVs in communication-deficient environments. Inspired by this work and the work of Hagen et al. (2009), we have proposed a “bottom-up” approach towards autonomy where the architecture is shown in Appendix A, Fig. 8.

Three control levels (partly renamed compared to the references above) are defined:

- Mission planner level: Here the mission objective is defined and the mission is planned. Subject to contingency handling, any input from payload sensor data analysis and any other input from the autonomy layer, the mission may be re-planned.
- Guidance and optimization level handles waypoints and references commands to the controller.
- Control execution level: At this level the plant control and actuator, control takes place, (Sørensen, 2005).

Improved autonomy with adaptive sampling with re-planning may occur if payload sensor data are processed aboard as close to real time as possible. If data collected is not in accordance with the data request, new adjusted data request can be made automatically and be a feedback for the controller to adjust the sampling area, sampling frequencies, range until the request is satisfied. Such a strategy will be pursued by the following to enable increased levels of autonomy:

- Mathematical modelling will be achieved through a systems perspective integrating models and knowledge from the different domains. Models at different fidelity will be used for design, simulation, real-time monitoring, decision and control. States and parameters will be estimated using real-time data in order to adaptively update models in order to detect normal and abnormal changes in the systems or their environment.
- Advanced sensor fusion for perception of the environment and any object of interest (OOI) will include integration of imaging sensors such as optics, and acoustics with inertial and navigation sensors for accurate detection and tracking of objects and environmental parameters.
- Model-based nonlinear optimization and hybrid control will be realized with coordinated control and robust networked communication in complex environments with simultaneous operations, robotics, and mobile sensor networks.
- Integrated guidance and path-planning with high-level mission planning will be achieved using numerical optimization where data, decisions, rules and models are represented as constraints, as well as discrete search algorithms and computational intelligence.

Intelligent control command and task execution with obstacle avoidance, fault-detection and diagnosis as a basis for reconfigurable control and re-planning of path and missions will be targeted. In the years to come we will approach the field of artificial intelligence and learning systems as driven forward in the field of software science. In order to improve capabilities to operate in an unstructured environment with little or no a priori knowledge we believe it will strengthen the interactions between top-down and bottom-up approaches towards autonomy.

To increase autonomy in underwater vehicles a hybrid of reactive and deliberative control could be applied. Palomeras et al. (2010) present a proposal for mission management and planning using a deliberate approach. These models can combine the different interest in a mission such as survey area availability, area coverage, survey efficiency, with mission feasibility and vehicle integrity. For the latter, certain reactive behaviours are implemented to handle situations that require more immediate actions like mechanical or electrical failures.

Candeloro, Mosciaro, Sørensen, Ippoliti, and Ludvigsen (2015) proposed a sensor driven path planner allowing an ROV to use the output from an optical camera and a processing algorithm to continuously re-plan the path proposing new waypoints to the control system based on the presence of Object Of Interest (OOI) in the data stream using certain assumptions of the area coverage of the OOI. Simulations based on the characteristics of the biological habitat of cold-water corals have shown that such online data driven path planners can increase the efficiency of a survey by making the vehicle map detected OOIs completely before progressing the search for new OOIs.

For archaeological applications an approach based on a three-step survey has been proposed by Ødegård, Nornes, Ludvigsen, Maarleveld, and Sørensen (2015). The approach is a modification of a system for AUV based mine counter measures implemented in Hugin, Sæbo et al. (2007). The first step is to detect possible archaeological features, in the next step the potential features are verified before they are recorded more detailed in the final step. The motivation for this proposal is that it is too time consuming and expensive to map the full seafloor at a resolution necessary to document historical artefacts – but allowing the vehicle itself to identify and revisit interesting locations with high resolution instrument like optical camera – the overall survey efficiency increases.

4. Field campaigns

To support the cross-disciplinary research in underwater operations and robotics, NTNU established the Applied Underwater Robotics Laboratory (AUR-Lab) in 2009. AUR-Lab is a multidisciplinary laboratory employing scientists of biology, archaeology, geology, and engineering science. Currently, AUR-Lab owns and operates three ROVs and one AUV REMUS 100. In addition, NTNU is a member of the AUV Hugin HUS consortium in cooperation with Norwegian Defence Research Establishment (FFI), Kongsberg Maritime, University of Bergen and the Institute of Marine Research. Most of the ROV operations take place from the NTNU research vessel Gunnerus equipped with dynamic positioning systems and advanced sensor systems. The last two years NTNU has also built up a laboratory for unmanned aerial vehicles with several fixed-wing airplanes and hexa-copters. All together, these three labs are heavily used by NTNU AMOS researchers bridging the gap between theory and practice. This section presents typical campaigns involving ROV and AUV operations. The level of autonomy in the operations concludes the section together with a discussion of the potential for increased autonomy in the described e.

4.1. ROV operations

In 2009 NTNU AUR-Lab started the development of a dynamic positioning (DP) system for ROVs, based on the existing body of knowledge for DP for ships existing in the group, for references see Dukan and Sørensen (2014), Dukan, Ludvigsen, and Sørensen (2011), Sørensen et al. (2012) and Fernandes et al. (2015). The main users of our ROV Minerva came forward with wishes for improved accuracy for vehicle manoeuvring. One example was capability for flying lawn-mower patterns with one meter line spacing. In manual control, this is in best case challenging and exhausting, but often impossible.

4.1.1. Method

During our work, the ROV Minerva has been a workhorse for engineering trials and for scientific missions collecting data for end-users. The vehicle is actuated in 4 Degrees Of Freedom (DOF). Based on hydrodynamic tests, the actuation forces for the vehicle were known. A Field Programmable Gate Array (FPGA) was set up to take control over the vehicle. All sensor I/O and thrust commands go through the FPGA, while the software components run on a computer and is implemented using LabView code. The system consists of a user interface, a guidance system establishing references, an I/O system checking and filtering all instruments, and observer estimating position, orientation and seabed altitude. Based on the output from the observer and the guidance system, the controller determines desired thrust force, direction and yaw moment. In the thrust allocation system, forces and moments are converted into rotational speed for each individual thruster. Details of this system are found in Sørensen et al. (2012).

4.1.2. Results

The system is now implemented for routine operations. The system can run lawn-mower patterns with decimetre precision, and do station keeping with similar precision. For sensors with narrow swath width like the Underwater Hyperspectral Imager (UHI) and optical cameras, precision is particularly important as full coverage of the area or object of interest is wanted. Seabed altitude and yaw angle variations and cross track errors must be minimized to enhance data quality. In our applications, the system has enabled several datasets with images for photo mosaics, photogrammetry and UHI with perfect over lap and side lap. Fig. 9 shows a photomosaic collected with ROV Minerva and the described control system. In spite of high currents even survey lines resulted in full coverage of the survey area.

4.1.3. Discussion

This work belongs in the control layer in Fig. 8 and forms an important building block for developing autonomy further into ROVs. However, the system must be extended with higher developed mission planning layer and guidance and optimization layer. The relevant missions for vehicles like the Minerva can be optical inspections, intervention, and sampling. These tasks may also require a different control layer than for typical AUVs. In the operations mentioned a typical ROV operator currently uses the video imagery for visual feedback on position, site conditions and task progress. Replacements for video feedback to the human operator must hence be developed and implemented. In spite of the challenges for underwater imagery, computer vision holds a potential for such applications. Candeloro et al. (2015) demonstrated a further development to this system by integrating a Head Mounted Displays (HMD). By replacing the joystick with HMD, the operator could perceive a 3D view increasing the situation awareness and providing a more immersive experience. Enhanced immersive experiences can be expected to develop in parallel with autonomy for tethered vehicles. Controlling the vehicle manoeuvres with the HMD and his head, the operator has his arms free to control other equipment such as manipulators. The HMD provided control inputs both for open loop manoeuvres and for closed loop operations.

Increasing autonomy in the ROV operations holds a large industrial potential. Currently these operations are expensive as they require complex vessels. Making autonomous vehicles capable of performing tasks today executed by ROVs, the industry can reduce costs. However, also by automating typical operations like turning valves, hooking wires, following pipelines – the results will be less dependent of the skill of the present operator and possibly reducing required time.

4.2. Integrated operations

AUR-Lab has completed several integrated cruises, where AUV, ROV and vessel have been parts of an integrated operation. The complementary properties of these platforms have been exploited and by learning from experiences made underway, the operations have been refined incrementally. As opposed to the field experiments described in the previous section, the integrated operations have been scientific cruises with biological, archaeological and geological research content. The cruises have served as qualification of the technology and methodology developed in other projects and operations.

4.2.1. Method

For the first cruise, the RV Gunnerus was mobilized with a REMUS 100 AUV and ROV Minerva (Ødegård et al., 2012), see Fig. 3. The scientific question addressed was the occurrence of kelp forest in a coastal environment. A protected fjord bay was selected and mapped using the MBE aboard RV Gunnerus. Interesting areas were then mapped using the REMUS AUV and the SSS mounted on it. Finally, targets and particularly interesting areas were identified and inspected by ROV. In Fig. 9 ROV Minerva was operated on DP

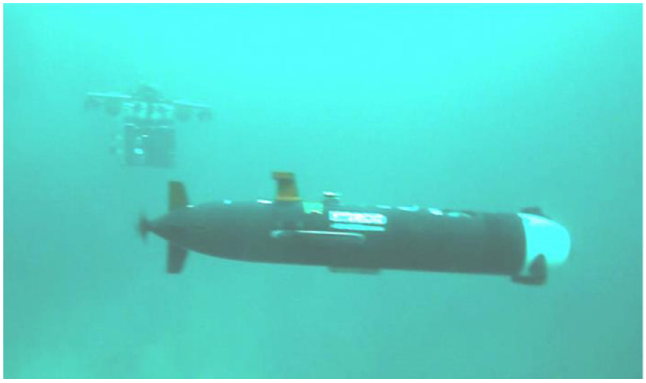

Fig. 3. AUV REMUS and ROV minerva together.

while the REMUS AUV did a survey operation. Since the AUV could operate independent of the mothership after launching, Gunnerus could either carry out MBE surveys or facilitate ROV operations to increase to overall operation efficiency during the AUV mission. To be able to benefit from parallel operations, it was essential that all data were processed as close to real time as possible. Throughout the cruise, operational sequences would depend on data acquired in the previous mission(s), as well as the prior knowledge of the area. Naturally, we experience that the operational complexity increased by introducing parallel operations.

During World War 2, crimes of war were committed Falstad concentration camp in Norway, (Ludvigsen, Johnsen, Sørensen, Lågstad, & Ødegård, 2014). At the end of the war these crimes were attempted hidden by placing the exhumed bodies of executed prisoners in a small vessel and sinking it in a nearby fjord. AUR-Lab mobilized AUV Hugin HUS (Fig. 4) aboard RV Gunnerus for an integrated operation. The cruise was organized as a collaboration with multiple scientific users, and we would visit the Tautra ridge mapping a cold-water coral habitat and the Trondheim harbour area for a marine archaeological survey. The Hugin AUV is considerable larger than the REMUS vehicle used in the previous operation, and it required an eight by three meter container on deck with a dedicated launch and recovery system and desk top areas for three operators. To ensure the highest possible position accuracy, the vessel tracked the AUV using the on-board HiPAP USBL system. This prevented us from performing parallel operations. However, the requirement for low processing time and coherent cruise planning applied also for this operation requiring immediate data processing.

The operation configuration including AUV Hugin HUS, ROV Minerva and RV Gunnerus proved efficient, and a new operation was conducted in 2013. The scientific target was cold-water corals and the geology of a dumping area. The AUV was used to map large areas with the HiSAS 1030 synthetic aperture sonar. Based on previous experience we expected the sonar to be very effective also for this purpose, and the HiSAS proved very suitable for mapping corals and the dumpsite. To document the findings, the ROV was equipped with a prototype UHI. We repeated the survey on the Tautra ridge (Fig. 5) to test change detection techniques developed for military applications also for biological research, (Hansen, Sæbø, Lorentzen, and Midtgaard, 2014).

4.2.2. Results

These cruises were performed on a modest level of autonomy. Both the vessels and the ROV were operated directly controlled, remotely controlled, with simple auto function like station keeping or path following. The AUV was programmed using mission scripts. Scientifically, the operations produced high quality data; the war prisoner remains have yet to be found, but the extent of the coral reef on Tautra (Fig. 5) is mapped for the first time, thousands of bombs and 25 wrecks were located in the dumping site and several wrecks were discovered in the Trondheim harbour. The ROV provided high quality data sets from the UHI, and stereo camera.

4.2.3. Discussion

What is the potential for autonomy in such underwater operations and what will it require to benefit from increased autonomy? For each individual platform, there are several areas for increasing the level of autonomy. For ROVs, improved autonomy can be achieved by automating defined tasks like manoeuvring, inspection, sampling and simple manipulations like valve turning. This will provide increased capabilities, repeatability and efficiency and be a step further towards the intervention AUV and persistent underwater vehicles. Increased autonomy in ROV operations will require online data processing and interpretation, but also contingency handling. More autonomy for ROVs can reduce the required surface support for these vehicles and hence reduce the overall cost of such underwater operations. This will require the systems to be more robust, but also a market adaption and the installation and standardisation of subsea infrastructure for the future vehicles for navigation and for docking to a tether for energy and communication.

Autonomy is naturally most developed for the AUV and increasing the level of intelligence in the vehicles will make the survey and mapping operations more efficient, either by optimising the available range or optimising the entire survey including prioritising the instruments. Mapping of processes non-constant temporal dynamics will benefit particularly of adaptive systems using aboard data interpretation creating adaptive path plans.

Combining the unmanned platforms can potentially represent a very powerful system for mapping and monitoring the marine environment. Having AUVs, USVs and UAVs working in collaboration can provide a persistence presence in the sea at lower cost than today as the human operators can be moved on land. For autonomy, a common mission management would need to coordinate the systems, while there are also many mechanical and practical solutions to be established.

In our operation, we have combined several platforms, but autonomous mission management is not implemented. Considering the whole operation as a system, there was mission feedback since all missions were based on the previous missions. However, the missions investigating coral reefs could potentially have experienced improved efficiency by implementing adaptive path-planning. If the vehicle could recognize a coral reef in real-time, an online path planner could ensure that each coral colony was completely covered with relevant sensors. Likewise, an online change detection algorithm could detect disturbances to the reef and pay special attention to these by imaging them using the optical camera.

To apply autonomy in a network of complementary platforms is challenging. It would require automated data processing and an event and feature classification across the platforms. This would include both data from payload and navigation instruments, but also vehicle status and diagnosis. The topic is addressed in the H2020 project SWARMS. The systems would also require different modes of communication between the platforms. A mission management system would need to continuously update the overall mission plan as well as the plans for each individual platform based on the information flowing over the communication network. Due to bandwidth limitations, each platform would need to identify and characterize features by automated processing before they could be passed on to the mission management. For the development to proceed to an autonomous network of complementary platforms, the first challenges to be addressed are automated

Fig. 4. AUV hugin HUS.

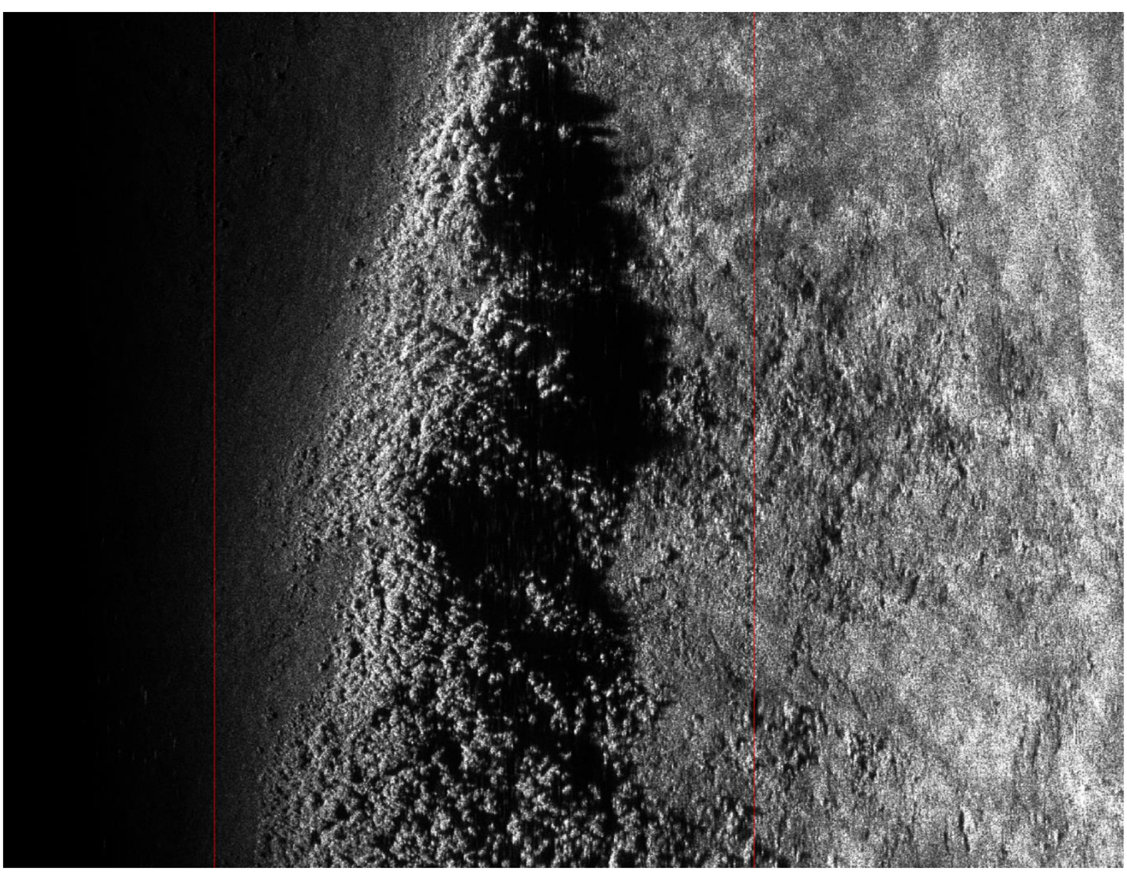

Fig. 5. SAS data showing cold-water corals on Tautra reef at ranges from 70 to 130 m. Ludvigsen et al. (2014).

Fig. 6. Recovery of the REMUS AUV after a successful mission measuring vertical zooplankton distribution.

data processing and a common ontology for all platforms. The next step could then be mission management.

4.3. Arctic operations

In January 2014 and 2015, AUR-Lab together with University of Tromsø, NTNU and University Centre in Svalbard (UNIS) mobilized for campaigns in Ny-Ålesund on Svalbard close to 79° north. These operations were part of a larger program investigating light in the Polar Night, (Berge et al., 2012). The motivation for the Polar night program is to achieve an understanding of the biodiversity and food web structure through the polar night including ecological processes, reproduction and growth. For our operations, the primary goals were to identify the vertical distribution of zooplankton and their diel vertical migration. Even in the polar night, there is variation of ambient light during every 24 h cycle – and the effect of this variation was one point of interest. Special attention was hence given to the solar noon.

The dynamics of the process impose both spatial and temporal requirements for our operations. We were interested in the zooplankton on a density level. On this level, the process noise could be regarded high, the resulting spatial requirements for the operation is hence less strict. As a side project during the campaign, AUV work was carried out to explore sensor capabilities and challenges related to communications and navigation related ice management activities, (Norgren & Skjetne, 2014). In ice management, AUVs are used for monitoring the ice conditions to obtain safe operations of vessels and platforms.

4.3.1. Method

During our operations, we launched a REMUS AUV, equipped with dual 1200 kHz ADCPs, CTD, O2 optode and an ECOpuck (Environmental Characterization Optics) triplet sensor configured to measure reflectance and fluorescence, see Fig. 6. The most promising sensor for detecting the zooplankton would be the ADCP and the backscatter information recorded. The AUV was sent on missions with one to four hours duration. The zooplankton was expected to be in the water column free from the seabed. Hence, the AUV had to operate in the water masses with no bottom contact. The absence of bottom contact would reduce the navigational accuracy due to lack of a stable velocity reference not obtaining bottom track for the DVL. Operating by LBL navigation and doing dead reckoning based on magnetic compass, the vehicle surveyed a partition of the fjord for zooplankton based on a sequential mission script of waypoints and objectives. Net samples and a vessel mounted Acoustic Zooplankton and Fish Profiler (AZFP) provided results supporting the AUV measurements.

4.3.2. Results

For the 2015 campaign, the water masses in our research area in the Kongsfjord were remarkably uniform. The variations in salinity, temperature and oxygen were very low and the oxygen levels and the chlorophyll levels were low and close to or below the noise floor for the measurements. In these uniform waters, we found a belt of zooplankton using the backscatter intensity from the ADCP. Horizontally the distribution was almost uniform, but vertically there was a clear stratification. However, the abundance was low and the signal was close to the noise level, but the findings were supported by results from the AZFP and net sampling.

4.3.3. Discussion

The type of operation carried out in the Polar Night cruise would also benefit from increased levels of autonomy. The sequential script based mission relied on the former experience of the involved scientists. A first step of increased autonomy could hence be to allow adaptive vertical path planning. Documenting the diurnal migration of zooplankton, the efficiency of the data acquisition could be increased. For the described operation, a multi vehicle operation would increase the scientific output by significantly increasing data sampling both temporally and spatially.

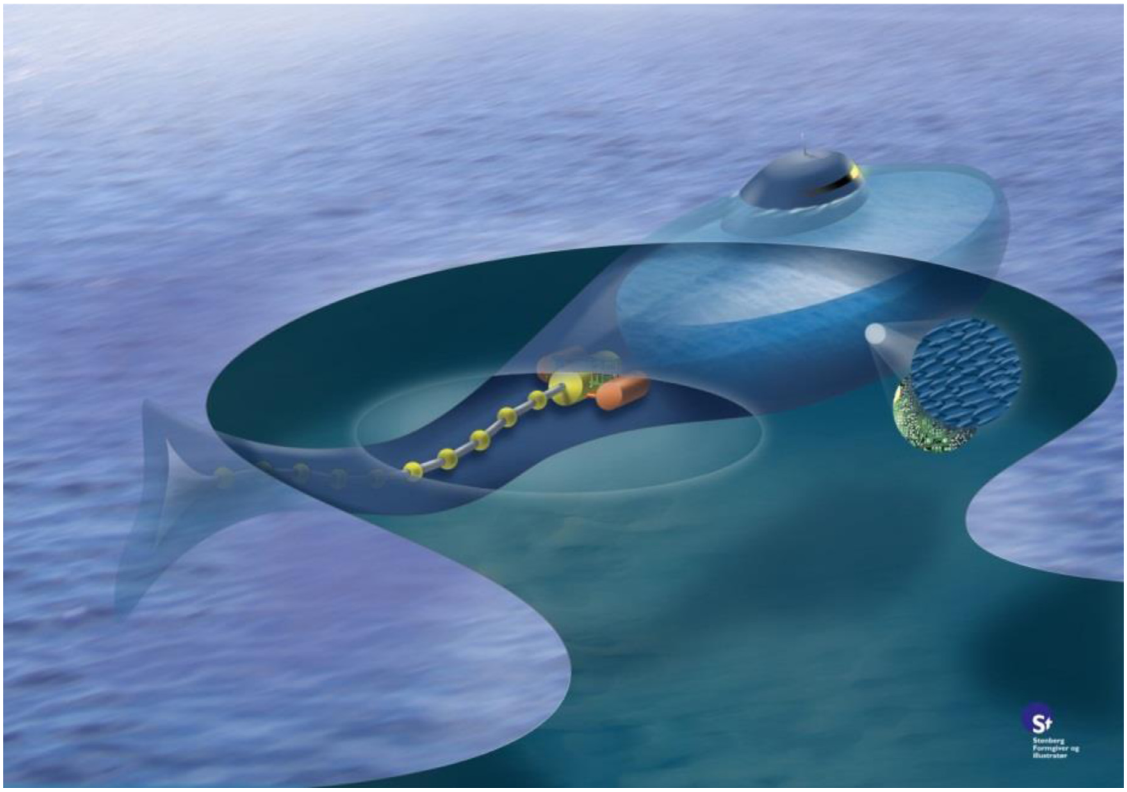

Fig. 7. Enabling technologies open up for radical new concepts, illustration by AMOS/NTNU and Stenberg.

5. Future trends and challenges

5.1. Enabling technologies

Enabling technologies will create new possibilities for disruptive game-changing technologies. We may here shortly list those areas that will be of importance for underwater vehicles:

- Information and communication technology
- Nano technology
- Bio technology
- Material technology

Integration of disciplines and technologies may enable development of multi-scale and distributed systems for sensing and actuation (Fig. 7). The ability to design new concepts in different spatial scales from micro to macro (M2M) enables us to better adapt to the “best-practice” behaviours from the nature. The field of bio-mimics is assumed to grow. Working with underwater vehicles, we have defined this as the field of cyber-bio-hydrodynamics. Currently at NTNU AMOS, this research is addressed by studying multi-flexible swimming robots inspired by whales, eels and snakes.

5.2. Trends and future concepts

5.2.1. Energy

Energy autonomy is essential to obtain increased autonomy for underwater vehicles. The energy storage capacity of the vehicle is strongly dependent of volume and weight allowed for the system. However, range depends of hotel loads from payloads and on-board electronic consumers together with the propulsion load of the vehicle. The propulsion load is dependent of the shape (and drag coefficient) and the dimensions of the vehicle. Energy storage capacity and consumption scale differently to physical dimensions and larger vehicles tend to have higher energy autonomy than smaller vehicles, (Brighenti, 1990).

The most common energy sources are batteries, fuel cells, buoyancy and solar power. For applications of shorter endurance requiring high navigation accuracy and manoeuvring precision, batteries and fuel cell are preferred. Buoyancy and solar power does not provide sufficient power output to obtain speed and facilitate energy thirsty navigation systems. However, for long-range missions, buoyancy and solar power dominate due to their total high-energy potential in spite of the low power. Higher energy densities in batteries are likely for the future. Increased attention to electric cars will increase the research and development effort in this field. Preliminary results indicate the fuel cell has the potential of doubling the energy density of current battery systems for AUVs (Mendez, Leo, & Herreros, 2014). Battery-driven AUVs are capable of going 400 km and this is likely to increase along with battery and fuel cell development.

5.2.2. Subsea docking

There has been experimental work on docking for many years (Brighenti, Zugno, Mattiuzzo, & Sperandio, 1998; Evans, Redmond, Plakas, Hamilton, & Lane, 2003; Singh et al., 2001), however, the technology is not yet implemented for commercial operation. When this technology matures, it will open up for applications such as range extensions, persistent vehicles, under ice operations, moon pool launches and intervention AUV’s.

5.2.3. Intervention AUV

Several attempts have been put forward for intervention vehicles: ALIVE (Evans et al., 2003), SWIMMER (Evans, Keller, Smith, Marty, & Rigaud, 2001), AIV (Mair, Jamieson, Tena, & Evans, 2010), Girona 500 I-AUV (Ribas, Ridao, Magi, Palomeras, & Carreras, 2011) and the SAUVIM (Kim & Yuh, 2004). They are however not fully implemented in the industry yet. AIV is the one being closest to

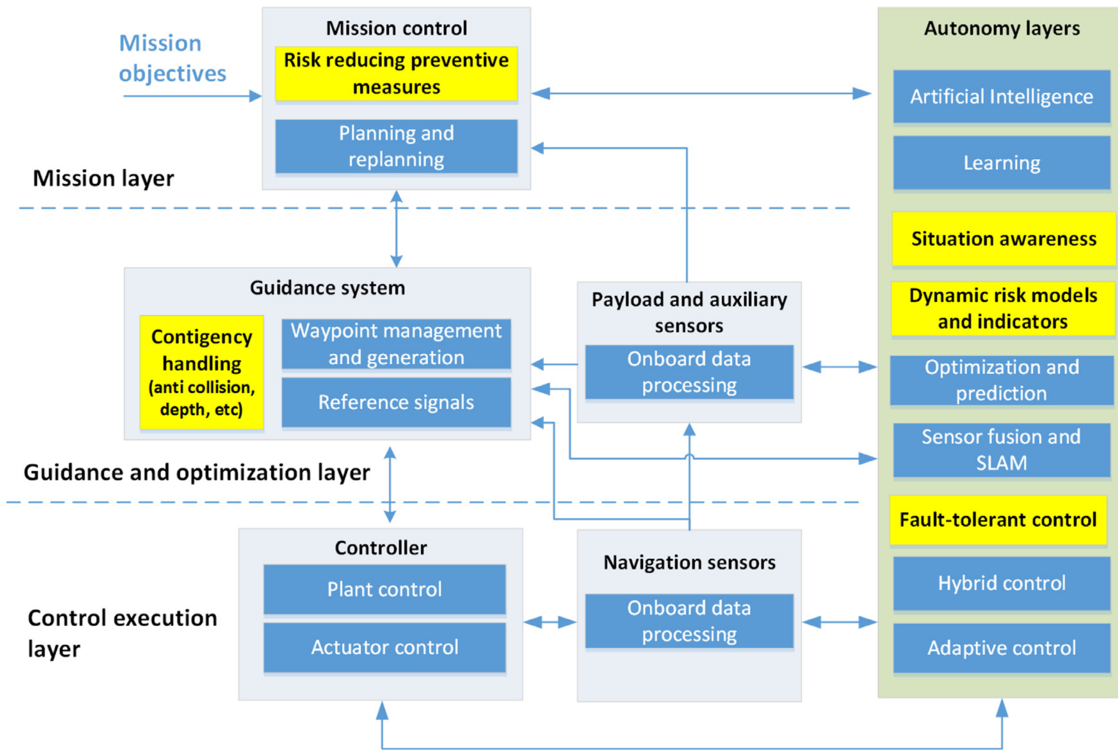

Fig. 8. Control architecture for unmanned underwater vehicles.

commercial application being developed and operated by the oil and gas service company Subsea7. There are several thresholds to overcome: communication, close range navigation and automation of intervention tasks to name a few. Each of these fields have matured and are showing many promising results.

5.2.4. Navigation

The limitations of acoustic baseline communication and dead-reckoning navigation must be challenged to achieve higher level autonomy. However, the dead reckoning methods are further decreasing the inherent drifting using more advanced observes and being aided with more precise sensors such as SAS and Displaced Phase Centre Antenna (DPCA) techniques, (Bellettini and Pinto, 2002). There is still a gap between the acoustical baseline methods with limited areal coverage and bounded error models and the dead-reckoning with unlimited areal coverage and unbounded error models. To close this gap, techniques like sensor fusion (Mišković, Vukić, Bibuli, Bruzzone, & Caccia, 2011; Vasilijević, Borovic, & Vukic, 2012), and terrain navigation and SLAM can be applied, see Ånonsen and Hagen (2011); Galceran et al. (2014), and Ribas, Ridao, Tardós, and Neira (2008). For close range navigation, high precision is required for docking and manoeuvring inside structures. Computer vision techniques have progressed and offers a promising solution making automated intervention more likely (Aulinas et al., 2011).

5.2.5. Hybrid AUV-ROV

In some hybrid AUV-ROV projects, the motivation appears to be a middle step towards advanced autonomous operations like manipulation. While some vehicles would work perfectly in AUV mode, but to allow telepresence, a hybrid configuration is chosen. AUVs are not inherently expected to offer telepresence and extended communication bandwidths. The reduced presence of communication is an important motivation for the development of autonomy. However, it is difficult to see that the need to be present, either physically or by remote connections will disappear completely.

5.2.6. Multiple vehicles

Multiple vehicle network can by driven by these elements:

- Force multiplication
- Complementary vehicle properties
- Dynamics (temporal changes) of the process of interest
- Increased spatial coverage

Deploying multiple vehicles from one surface unit may not multiple the operational efforts, and may hence increase the overall operational efficiency. The efficiency will be further increased by allowing the vehicles to communicate and run adaptive missions.

Networks consisting of vehicles with complementary configurations will require communication of adaptive missions between two vehicles to fully utilize the potential of the network. One could imagine a network consisting of a vehicle for coarser searches and large ranges identifying interest points, while a vehicle specialized for details investigations follow, and picks up interest point to cover.

Some oceanic processes changes so fast that one single vehicle cannot cover it all, before the conditions have changed. A network of multiple vehicle will hence be necessary to provide sufficient spatial and temporal coverage. Oceanic or seismic field investigations are examples of operations benefitting from multiple vehicle configurations. The latter example there will also require strict manoeuvring formation for the vehicles to detect the reflected acoustic signal optimally. For more details on formation control, see Soares, Aguiar, Pascoal, and Martinoli (2013) and Xargay et al. (2012).

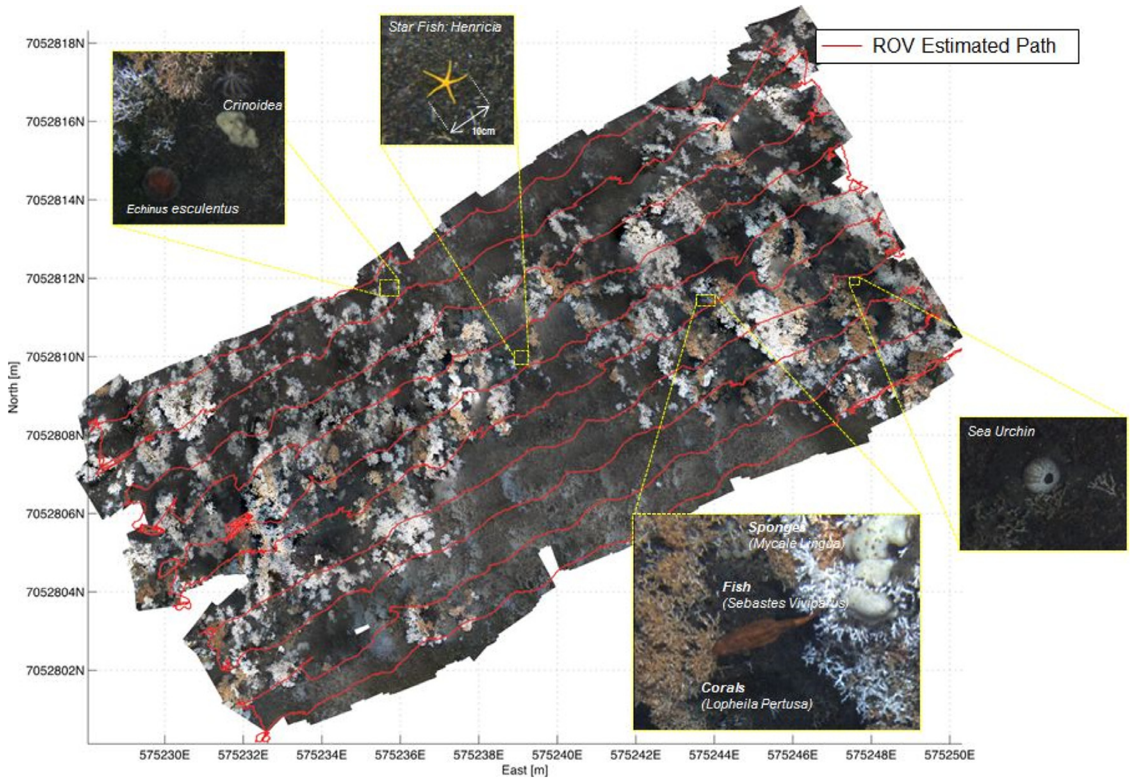

Fig. 9. Photomosaic from Tautra coral reef captured using ROV minerva with path following capability.

6. Conclusions

This paper gave an overview of the research at NTNU AMOS related to underwater operations. Different technology platforms subject to spatial and temporal coverage and resolutions and presentation of a control architecture considering a bottom-up approach towards autonomy were discussed. Selected results from field campaigns were shown. Enabling technologies will facilitate new radical concepts. Cutting-edge interdisciplinary research involving technology and marine science fields such as marine biology and archaeology will provide the needed bridge to make high levels of autonomy a reality towards autonomous underwater operations.

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