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A new method for underwater archaeological surveying using sensors and unmanned platforms

Øyvind Ødegård*, Asgeir J. Sørensen*, Roy E. Hansen, Martin Ludvigsen***

* Centre for Autonomous Marine Operations and System (NTNU AMOS),
Department of Marine Technology,
Norwegian University of Science and Technology (NTNU),
Otto Nielsens Veg 10, NO-7491 Trondheim, Norway.
(e-mail: oyvind.odegard@ntnu.no, asgeir.sorensen@ntnu.no, martin.ludvigsen@ntnu.no)

** Norwegian Defence Research Establishment (FFI), NO-2027 Kjeller, Norway (e-mail: roy-edgar.hansen@ffi.no)

Abstract: As most of the world's oceans are inaccessible to diving archaeologists, we must rely on advanced underwater technology and marine robotics to explore, map and investigate ship wrecks in these areas. New sensors and unmanned sensor platforms represent huge potentials for archaeological applications, but require a scrutinous look at how established archaeological methods and approaches must be adapted or rejected to optimize the results. Surveys done on a disintegrated wreck site with acoustic sensors like side scan sonar and synthetic aperture sonar, and optical sensors like stereo cameras, video and underwater hyperspectral imager, are compiled to serve as a case study to demonstrate the method. Challenges regarding guidance, navigation and control are discussed.

Keywords: Wreck, sensors, marine archaeology, underwater robotics, control, navigation

1. INTRODUCTION

Diving archaeologists are normally constrained to operate no deeper than 30-50 meters due to physiological limits and safety regulations. Since the average depth of the world's water bodies is approximately 3700 meters, this constraint considerably limits the reach of marine archaeology as a discipline based on diving only. One way to overcome this limit is to apply unmanned underwater vehicles such as remotely operated vehicles (ROVs) or autonomous underwater vehicles (AUVs). The tools used by marine archaeologists for the last couple of decades have been towed side scan sonar for detection and ROV with camera for inspection, although other sensors are also becoming more common (Plets, 2013). The integration of these technologies into marine archaeological methods has been very successful, and fundamental for providing knowledge of cultural heritage located beyond human diving capabilities. However, the methods have their limits – challenging bathymetry, currents, ultra-deep waters, and the need for a surface vessel to navigate freely limits the ability to reach some areas, and also the quality of the acquired data may suffer due to lack of appropriate sensors and control performance of the underwater vehicles. With the advent of more sophisticated underwater robotics in recent years, especially with regards to control and autonomy, the outlook for better investigations of areas and objects of interest on the seafloor is improving for all marine sciences – not least marine archaeology. Advances within sensor technology, control systems and computer science combined heralds great possibilities for extending the discipline's reach both physically and epistemologically. By adopting the concept of *Integrated Operations* different platforms and sensors can be used to complement each other, and data can be processed and used for planning and re-planning during a survey (Ødegård et al., 2012). Nilssen et al. (2015) proposes an Integrated Environmental Mapping and Monitoring (IEMM) model for dynamically selecting different sensors and platforms in iterations and feedback loops where sensor data is continuously compared to mission goal to guide operational decision making.

This paper will describe sensors and platforms relevant for seabed mapping tasks typical for marine archaeological surveys. We will show how data from one task can be used to plan and execute the next in a method for detecting, investigating and recording underwater cultural heritage (UCH) using underwater robotics. The sequential steps in the method will be exemplified with a case study from *the Reference wreck*, a site in Trondheimsfjorden, Norway (10°24'23E,63°27'12N), that has been investigated with a range of different platforms and sensors.

The main scientific contribution of the paper is the outline of a method for applying sensors and sensor carrying platforms for different tasks in typical marine archaeological surveys. The method is based on experiences from field work involving integrated operations and the IEMM model.

Section 2 describes the different sensors and platforms for marine archaeological surveying, and introduce three main mission objectives, detect, investigate and record, within the concept of the IEMM model. In Section 3 we present a case study with results from the Reference wreck obtained during several surveys using a range of sensors ad sensor platforms. In Section 4 we discuss the method, and finally, the conclusions are given section 5.

2. METHOD

A typical marine archaeological survey of previously unmapped areas could have the following mission objectives:

- Detect any possible wreck sites in the area;
- Inspect sites to determine if they really are wrecks;
- Record any established wreck sites.

With advances in technology and engineering the number of sensors and platforms available for seabed mapping is growing. They can be deployed in various combinations and configurations, and good planning and effective management

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of operations is becoming increasingly important to ensure good results. The IEMM model (fig.1.), proposes a method for selecting appropriate sensors and platforms to perform in different spatial domains iterated in a sensor data feedback loop until a set of pre stated mission objectives are satisfied (Nilssen et al., 2015).

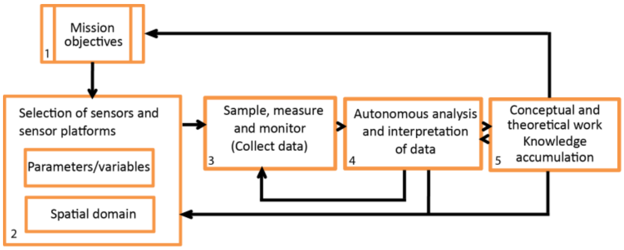

Fig. 1. Section of the IEMM model, modified to show sequences of operations in a marine archaeological survey.

Typically a general mapping of a survey area will initially use long range acoustic sensors providing bathymetry and imagery sufficient for a general characterization of the area. If the purpose of the survey is to detect and map any previously unknown objects or areas of interest within the survey area, the choice of the initial sensor must correspond to the resolution and data type expected to be necessary to detect such objects or areas. Depending on the mission objectives it may be necessary to deploy multiple sensors and platforms to acquire data that satisfies the mission objectives (Ludvigsen et al., 2014). Since range and resolution often are inversely proportional, the choice of platform can be very important as it can increase the data resolution by bringing the sensor closer to the object of interest. Table 1 (appendix 1) gives an overview of commercially available sensors relevant for marine archaeological surveys showing range, resolution and data type also with regards to different platforms. Fig. 2 illustrates the relationship between the sensor coverage and the ability to detect and record wrecks in different states of disintegration (size of shipwrecks and sedimentation are also important factors for the x-axis).

2.1 Payload sensors

The payload sensors are typical optical, acoustical and other mission specific sensors installed on a sensor carrying platform in order to gather data of any area and object of interests.

2.1.1 Optical sensors

Green Light Detection and Ranging (LiDAR) for bathymetric mapping is similar to airborne LiDAR for land mapping with one main difference: it uses a green laser for maximum range in the water column (green is the colour that is least attenuated in water), in combination with an infrared beam. The infrared beam measures the water surface, while the green beam measures the seabed (Song et al., 2015). Platforms could be fixed or rotary winged, and the speed above ground will affect the data resolution. Bathymetric LiDAR requires clear water, and the maximum mapping depth decreases with water turbidity.

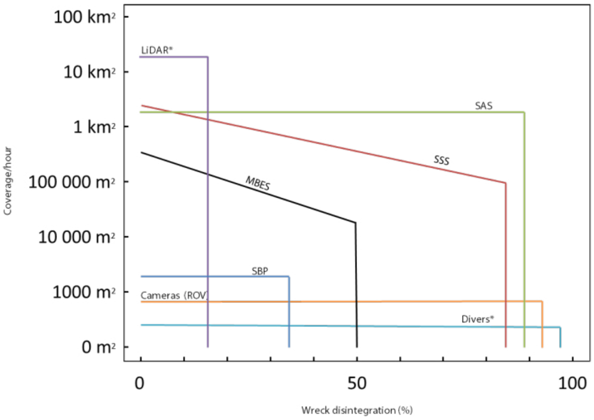

Fig. 2. Coverage and ability to detect wrecks. * LiDAR and Divers are constrained to max depth of approximately 30m.

Photo/Video cameras come in all sizes and can be put on any platform, but require external light sources as depth increases. Due to light scattering and attenuation in water, some distance between camera and lamp will yield better image quality. Maximum range will depend on water visibility, but is typically below 10 meters. High definition video cameras are standard for ROVs used both for visual guidance by the pilot, and also for gathering data. Still cameras can be put in a stereo rig set to capture images synchronized (Nornes et al., 2015), or a single camera could be configured to capture images in intervals to ensure overlap between frames in sequence. Overlapping images can be processed using special software to create photomosaics and photogrammetric models.

Underwater Hyperspectral Imaging (UHI) is a novel technology with a considerable potential for archaeological applications. The basic principles are the same as for hyperspectral imaging used in satellite based remote sensing, but with some differences regarding environmental considerations (Johnsen, 2013). Hyperspectral imagery can be defined as images that contain the visible spectrum of reflected light with a spectral resolution of 1-5 nm per image pixel. Materials or compositions of materials will absorb, scatter and reflect light of different portions of the visible spectrum, giving them their own optical fingerprints that are unique, and can be used for classification and identification (Johnsen, 2013).

2.1.2 Acoustical sensors

Multi Beam Echo Sounder (MBES) also emits acoustic pulses in a fan shape using multiple transducers. By measuring the time and direction of the echoes one can produce point clouds with XYZ values for each point. This requires exact measurements of the position and pose of the sensor platform, traditionally a surface vessel. State-of-the-art MBES covers up to 3 times the sensor altitude at highest resolution. In addition to point clouds, most MBES can also produce backscatter imagery similar to SSS. Due to the grazing angle this imagery will show intensity of echoes, but to a lesser degree produce shadows. For an extensive discussion of MBES technology used in marine archaeology, the reader is referred to Bates et al. (2011).

Side Scan Sonar (SSS) backscatter imagery shows intensity and shadows on the seabed enabling visual interpretation of features that could possibly be wreck sites/UCH. The processing of standard SSS imagery is basically a function of time and speed of sound. The instrument repeatedly emits a pulse and records the time and strength of the echo (Blondel, 2009). The imagery produced assumes that the sea bed is a flat surface, and that the navigation of the platform is conducted in straight lines with constant altitude. Common frequencies for SSS used in marine archaeology are in the range 100 kHz to 1000 kHz, where the higher frequency signals are attenuated faster than lower frequencies. This means that there is a range/resolution trade off. As shown by Quinn et al. (2005) the resolution of SSS imagery is not solely dependent on frequency, but also other factors and in particular transducer size and pulse bandwidth. Their results maintains that maximum effective range for high resolution mapping of archaeological sites is 40 meters for detection (i.e. 80 m swath), and 10-15 meters for site specific investigations. SSS sensors can also be interferometric. By using two or more vertically displaced receivers it is possible to calculate depression angle of the incoming signal and derive bathymetry directly from the SSS data. The most common instrument carrier for SSS is a tow fish dragged by a cable behind a surface vessel. Position of the towfish can be measured by using an Ultra Short Base Line (USBL) positioning system. More commonly, it is calculated as a function of the heading of the vessel, the cable length and the depth of the towfish.

Synthetic Aperture Sonar (SAS) imagery is produced by processing acoustic backscatter using positioning data from the navigation of the vehicle. In recent years SAS has become a commercially available product for seabed surveying and mapping (Hansen, 2013). By emulating a synthetic array independent of its physical length, each pixel in a SAS image is calculated based on the combination of echoes from multiple pings. This enables SAS data to retain a very high resolution (2 cm x 2 cm) independent of range and frequency. The quality of the imagery depends on very accurate navigation, and currently AUVs are the most appropriate platforms. Most SAS systems today are interferometric. Compared to the 80 meter effective swath width of the SSS, an SAS can map at 500 meters swath width at a much higher resolution (Ødegård et al., 2013). For a more detailed account of the technology, the reader is referred to Hansen (2011).

2.2 Detection

Within a survey area with little or no a priori knowledge, the first mission objective will be to detect possible objects or areas of interest. Coverage effectiveness and required resolution must be balanced, often a negotiation between stakeholders in development projects where time and costs are important issues. If there exists a priori knowledge of the potential for UCH in the survey area (i.e. certain categories can be excluded), sensors and sensor platforms that are appropriate for the survey area can be selected.

For shallow waters airborne sensors like green light LIDAR (Light Detection and Ranging) can produce relatively high resolution bathymetric data (Doneus et al. 2013), but for depths beyond a few tens of meters required light will be attenuated and submerged acoustic sensors are a better choice. LiDAR data have been used to successfully identify large wrecks in shallow waters with very good visibility (Tian-Yuan Shih et al., 2014).

Acoustic sensors like MBES, SSS and SAS are based on similar technological principles, but produce very different data. As shown by Bates et al. (2011) SSS is better suited for detecting objects, while MBES can produce very high resolution bathymetry of a wreck site. To produce good data for detecting disintegrated wooden shipwrecks with low vertical profiles the sensor should maintain a low grazing angle to increase the shadow effect. In addition to the properties of the instrument itself, MBES data quality also depends on the platform guidance navigation and control, yielding best results if navigated directly above the area of interest at low speed (Lurton, 2010). The most common platform for MBES is a surface vessel, and since spatial resolution of the data depends on range, increasing water depth usually means poorer data resolution and quality. By co-registering SSS and MBES data one can get complementary images of the seabed giving better possibilities for visual interpretation and detection of possible wreck sites.

Transferring SSS and MBES to a joint underwater platform like an AUV makes it possible to improve data quality for both sensors by adapting navigation to the sensor properties. The AUV can keep a constant altitude above the seabed to keep optimal aspect angle sideways for SSS acquisition. The AUV can also navigate directly above an area of interest to map with MBES, and adjust its altitude to optimize swath width/resolution aspect to create bathymetry appropriate for the mission objective.

Data from SSS, MBES and SAS are all processed and geo-referred using positioning data from the sensor platforms to stitch together imagery from each separate survey line into coherent mosaics for visual or Geographic Information Systems (GIS) analysis. There are several software products available for this purpose, most of them can show bathymetry and backscatter imagery together. Archaeologists analyzing the data will typically look for salient features in both backscatter and bathymetry that corresponds with plausible wreck site formation processes.

2.3 Inspection

Next mission objective in a survey will be to inspect the possible wreck sites at close range with video camera. This is typically done by revisiting the sites with an ROV equipped with positioning system and scanning sonar. For an AUV unaided by external positioning systems like Long Base Line (LBL), Short Base Line (SBL) or USBL that are referenced to the surface Global Navigation Satellite System (GNSS), positions are not very accurate, and gets poorer with time due to navigational drift (Jalving et al., 2004). Revisiting an AUV detected target with an ROV could therefore require a bit of searching. Depending on turbidity and light conditions, using scanning sonar to find features matching the targets detected in the SSS/SAS data sets could be very helpful or even necessary. Having located the site, the archaeologist will look for objects or features that can be identified as belonging to a wreck. By getting an overview of objects and possible structures he or she will heuristically form an understanding of the site based on types and spatial distribution. Diagnostic objects like anchors, cannons, bottles or ceramics can help establish age, type and size of the wreck. An event logger coupled to the ROVs control system can be used to tag the ROV's position on the site together with time stamp corresponding to video recording, and short textual descriptions of observations. For this task it is important to have close communication between the archaeologist and the ROV pilot, as it is very easy to loose orientation on a wreck site, especially in turbid waters. Based on the observations from this inspection, especially logged positions of objects and features, together with the previous data sets from the long range acoustic sensors, the archaeologist will establish the boundaries of the wreck site, in effect delimiting an area of interest expedient for the next mission objective.

2.4 Recording

Recording underwater cultural heritage is traditionally done by diving archaeologists using different methods (drawing, measuring of dimensions and photography) to record what he or she can perceive of the wreck site. For an overview see Bowens (2009). Photogrammetry has become a very powerful tool for archaeologists the later years (McCarthy and Benjamin, 2014). With better quality digital cameras and even more powerful computers this method produces results with accuracy and resolution surpassing most traditional methods at less cost and time. Diver based photogrammetry surveys have rapidly gained popularity in marine archaeology, and the method can also be carried out by ROVs(Nornes et al., 2015) and even AUVs (Henderson et al., 2013).

Detailed planning is essential for successful photogrammetry of wreck sites. The ability to navigate with precision can ensure complete sensor coverage of an area or object of interest. At least 60% overlap between images is required for photogrammetric processing, and keeping exact survey lines and constant altitude are of paramount importance to avoid data gaps. For ROV-based photogrammetry a high grade vehicle control system and accurate positioning will hugely benefit the results. Depending on the apparent optical properties of the water at the site, an adequate range is found – usually 1.5-2 meters. Knowing the field of view and altitude above the seabed we can find maximum line spacing to ensure necessary across track image overlap. Similarly we know the frame capture frequency of the camera and can calculate maximum along track speed. For ROVs with advanced control systems featuring dynamic positioning (DP) capabilities (Sørensen et al., 2012), photogrammetric data capture for defined areas can be automated in "mowing the lawn" survey grids. It is important that any protruding objects within the area of interest that could obstruct the planned path of the ROV must be identified in the bathymetry data acquired earlier (MBES or interferometric SSS/SAS), and avoided in the path planning. Photogrammetric recording of such upstanding objects must currently be based on manual navigation by human pilot aided by altitude control to ensure both adequate sensor coverage and safe navigation (Nornes et al., 2015).

Positioning data from the control system synchronized with timestamps on the image data can be used by some software to sort and group data for processing, increasing efficiency and improving accuracy. Processed photogrammetry data produce high resolution orthophotos co registered with very high resolution micro bathymetry, enabling 2D and 3D analysis in a number of visualizing and modelling software suites.

3. CASE STUDY - THE REFERENCE WRECK

Since 2012 the Applied Underwater Robotics Laboratory (AUR-Lab) at the Norwegian University of Science and Technology (NTNU) have tested new sensors and platforms on a previously investigated 17th century wreck site in the Trondheim harbor, Norway (Søreide, 2000). The wreck is at 61 meters depth, and is structurally disintegrated with part of the keelson and a small piece of a stem or stern post protruding from a mound on the seabed as the most salient features. The state of the wreck is typical for wooden ship wrecks along the Norwegian coast after hundreds of years on a sandy seabed, and it has aptly been named "The Reference Wreck".

To illustrate the method for underwater archaeological surveying using sensors and unmanned sensor platforms proposed in this paper we will now go through the steps of the model using example data from a series of surveys done on the Reference wreck. By putting the different surveys and corresponding data sets into the framework of this model we will highlight the relations between tasks and sequences, and accentuate data dependencies in task planning.

DETECT: First mission objective is to map a large area (Trondheim harbor) and detect possible ship wrecks. Surveys with three different acoustic long range sensors have been done on the wreck site. The research vessel RV Gunnerus is equipped with a hull mounted Kongsberg Maritime EM 3002D multibeam echosounder for shallow water high resolution seabed mapping. The instrument can produce both bathymetry and backscatter imagery. RV Gunnerus is equipped with Kongsberg Simrad Dynamic Positioning system (SDP-11) combined with Kongsberg Seatex Differential Positioning Sensor (DPS-232), Kongsberg High Precision Acoustic Positioning system (HiPAP 500), and a Kongsberg Seatex Motion Reference Unit (MRU-5) integrated in a Kongsberg Seapath 300 system. The ship can keep low speed and steady heading providing optimal conditions for MBES data acquisition. In 2014 four low speed passes were made over the reference wreck, but the site was not detectable in the MBES data. With the seabed at a depth of 60 meters a hull mounted MBES is not able to acquire data with sufficiently high resolution to detect a disintegrated wooden wreck such as the reference wreck, but could possibly provide bathymetric information relevant for site formation analysis, e.g. scouring, ripples or larger anthropogenic disturbances.

In June 2014 the wreck site was surveyed with a Marine Sonic 900 kHz side scan sonar on a Kongsberg Hydroid REMUS 100 AUV (fig.3). The REMUS passed the wreck site with a fixed 5 m altitude above seabed and at 3.5 knots speed. The sensor range was set to 30 meters, and across track distance to the center of the wreck was approximately 15 meters. The SSS imagery renders the wreck's salient features in high resolution, and a pronounced shadow makes it easy to identify both stem post and keelson. An experienced marine archaeologist would tag the site as a probable wreck site based on this data.

During a research cruise in December 2012 (Ødegård et al., 2013), the Kongsberg Hugin HUS AUV equipped with a 1030 HiSAS Synthetic Aperture Sonar system performed eight passes of the Reference wreck to capture data at different ranges and angles of approach (fig. 3). Altitude was constant at 20 meters above bottom, and due to variations in the seabed bathymetry, data was acquired at different grazing angles. The HiSAS 1030 is interferometric, meaning that it produces data that contains bathymetric information as well as imagery. Based on the same data, imagery and bathymetry are exactly co-registered and can be fused for enhanced visual interpretation where a scaled color layer shows depth directly in the backscatter image. The distinct line in the middle of an elliptic mound is a typical signature for a disintegrated wooden ship wreck. Compared to the SSS imagery the HiSAS outperforms with regard to resolution and range, and with the added bathymetric information makes it easier to identify wreck sites, and also indicate the boundaries of the areas of interest. As for the SSS imagery, the stem post casts a distinct shadow here as well – and in addition the bathymetric data can be modelled to give a 3D representation of the site of high value for planning close range inspections of the site. In addition to the Reference wreck data, some other possible wreck sites were detected, and their positions were compiled in a target list for ROV inspections.

INSPECT: Next mission objective is to inspect possible shipwrecks and determine if they really are wrecks. ROV-Inspection of the Reference wreck site and a few other possible wreck sites nearby was planned based on the SAS imagery. The RV Gunnerus navigated to the proximity of the positions from the AUV survey, and ROV MINERVA was deployed to relocate and inspect the possible wreck sites. The ROV Minerva is a Sperre SUB-fighter 7500 ROV with Dynamic Positioning (DP) capabilities (Sørensen et al., 2012). The RV Gunnerus' HiPAP ensured accurate geographic positioning of the ROV during operations. Scanning sonar and HD-camera were used to guide the ROV to the different SAS targets. Every target was inspected by an archaeologist sitting next to the ROV pilot. The archaeologist could assess the sites and determine if they were wreck sites, and if so – were they of interest (archaeologically). While navigation was done manually by the pilot, the ability to perform DP based maneuvers like e.g. station keeping was a clear advantage for this kind of tasks. Maneuvering around on the wreck site with HD video camera is of course a method very similar to actual presence on the site. Pilot and archaeologist can move intuitively around on the site based on observations, and little pre-mission planning is required. Two parallel lasers with known distance were directed into the field of view and enabled exact measurements (fig.4). The archaeologist operates an event logger to tag position and time to any interesting observations, and to mark the boundaries of the site, thus demarcating an area of interest for possible subsequent inspections. If the investigation revealed that the target was not of interest, the mission objective would be to move to the next target.

RECORD I: Record the wreck site using photogrammetry. In August and November 2014 AUR-Lab conducted photogrammetry surveys of the Reference wreck site. A stereo camera rig consisting of two Allied Vision GC1380C cameras was deployed on ROV Minerva. HiSAS imagery and positions noted during the video inspection (event log) were used to determine the boundaries of the area of interest The photogrammetry survey of the wreck was executed using two different methods for navigation. Since successful processing by the photogrammetry software requires at least 60% overlap between image frames, a lawn mower pattern with adequate line spacing and fixed altitude for covering the entire wreck site was planned in the interface of the ROV's DP control system. Most of the wreck site is relatively flat and well suited for an automated navigation by the ROV's DP system. However, in the north-western end of the site a stem or stern-post protrudes almost a meter from the seabed, apparent in the bathymetric SAS data. The post posed a problem for automated navigation, and required a different image capture strategy. The task we wanted to accomplish was to ensure good data coverage of the post from every direction, and at the same time take good care to avoid that

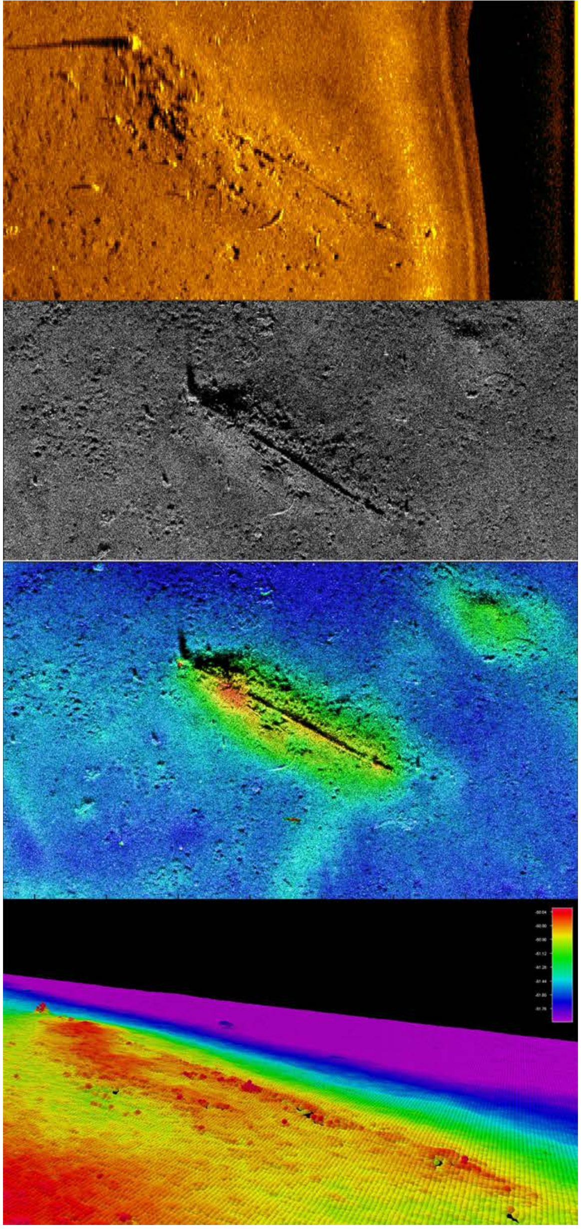

Fig. 3. From top: SSS image of the Reference wreck; HiSAS image of the reference wreck; HiSAS image fused with bathymetry; HiSAS bathymetry

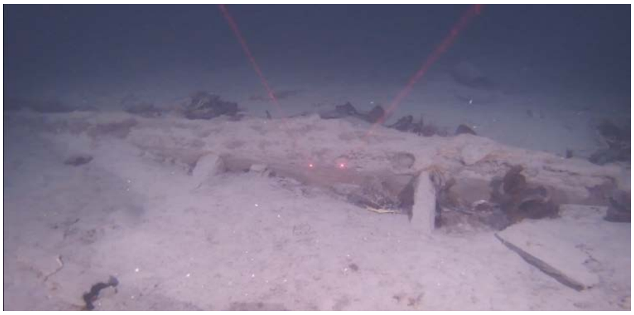

Fig. 4. HD video frame grab showing bilge section with keelson and two frames. Distance between laser dots is 10 cm.

the ROV came in contact with and potentially disturbed or damaged the wreck. The DP planning interface was not well suited for this kind of object centered navigation, and this part of the wreck site had to be navigated manually.

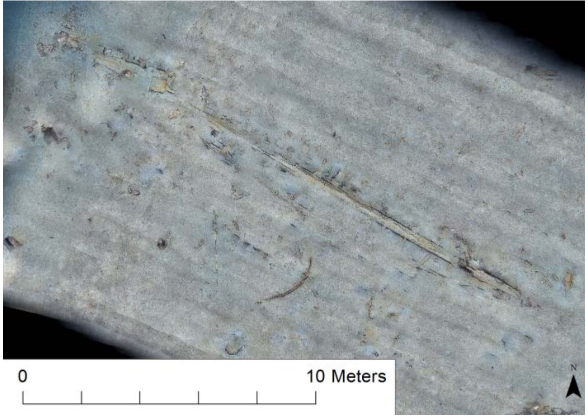

Fig. 5. Orthophoto based on photogrammetry

A total of 13.314 images were recorded during the survey. Agisoft software (http://www.agisoft.com) was used to process the images into 3D models and a high resolution 2D orthophoto (fig. 5) of the wreck site. These processed data sets were imported into other software (e.g. Global mapper, ArcGIS, QPS Fledermaus) for visualization and interpretation as textured 3D models, slope analysis, micro bathymetry and shaded reliefs (fig 6). Based on the orthophoto, bathymetry model and relevant derivatives, a traditional 2D archaeological site plan was drawn. Site plans are indispensable tools for interpretation and planning in archaeological investigations.

RECORD II: Record the wreck site using UHI. To map presence and distributions of materials on the wreck site we selected ROV with UHI push broom scanner facing directly downwards. UHI data quality depends on many factors, not least steady navigation and precise altitude positioning of the sensor above the seabed. Maintaining a constant speed and heading, while navigating along straight survey lines, are very important for good data acquisition. The UHI needed artificial light to illuminate the Reference wreck. It was therefore expedient that the survey lines for UHI acquisition, if possible, were planned in a manner that avoided slopes and large or abrupt bathymetric variations that would cause uneven light conditions in the data sets.

A site plan of the wreck site was made based on HD-video, orthophoto and micro bathymetry model of the site (fig. 6). This site plan was used to plan UHI transects corresponding with the most salient features of the wreck, and in parallel with the keelson. Knowing the field of view (swath width) of the UHI, a lawn mower pattern with adequate line spacing and altitude for covering the wreck site was planned in the interface of the ROV's control system and executed with pilot supervision. As the quality of spatial referencing of UHI data depends on constant speed, altitude and heading during data acquisition, attempts to record parts of the wreck site that requires manual control would not yield useful results.

Post mission the UHI data was processed and interpreted using specialized software for classification of hyper spectral data.

4. DISCUSSION

The aggregated results from the Reference wreck surveys are a variety of data sets at different resolutions and from different sensors. Together they provide a good basis for archaeological interpretation and analysis of the wreck site. However, the sequence of acquisition and choice of instrument carriers are not arbitrary. Data from one sensor can be used to plan and execute subsequent tasks, and the accumulated data sets will complement each other enabling better interpretation and understanding of the site. As the possible combinations of sensors and platforms increases, the opportunities for better applications and methods do also. A systemic approach to planning is needed to better exploit the opportunities for better data acquisition that this development offers. The classical trade off in choosing methods is the usual range vs resolution. Longer range sensors will typically be more area effective with regards to time than high resolution sensors that have shorter ranges. To benefit from a high resolution sensor an instrument platform with appropriate properties is required. For some sensors, like the SAS, UHI and photogrammetry the properties of the instrument platform and its navigation are integral parts of the data processing. We can safely say that sensors and platforms increasingly must be considered as integrated entities in planning and execution of operations. Having multiple sensors active simultaneously accentuates this point, as different conditions for each sensor may apply for how the platform should navigate and maneuver.

Traditionally marine archaeological investigations have been planned and executed based on a site plan as a coplanar representation of the wreck, basically is a bird's view map of the wreck site in 2D. Systematic recording of vertical surfaces or structures on wreck sites that transcend the 2D plan can be challenging (Rule, 1989). New digital technologies for 3D recording and representations are pushing the field forward (Bülow and Birk, 2011).

5. CONCLUSION

As the field of underwater robotics is developing at great speed, it is important that end users – in this case archaeologists, investigate the opportunities for exploiting this development to advances within their disciplines. This paper has shown that currently available underwater technology has capabilities for non-intrusive marine

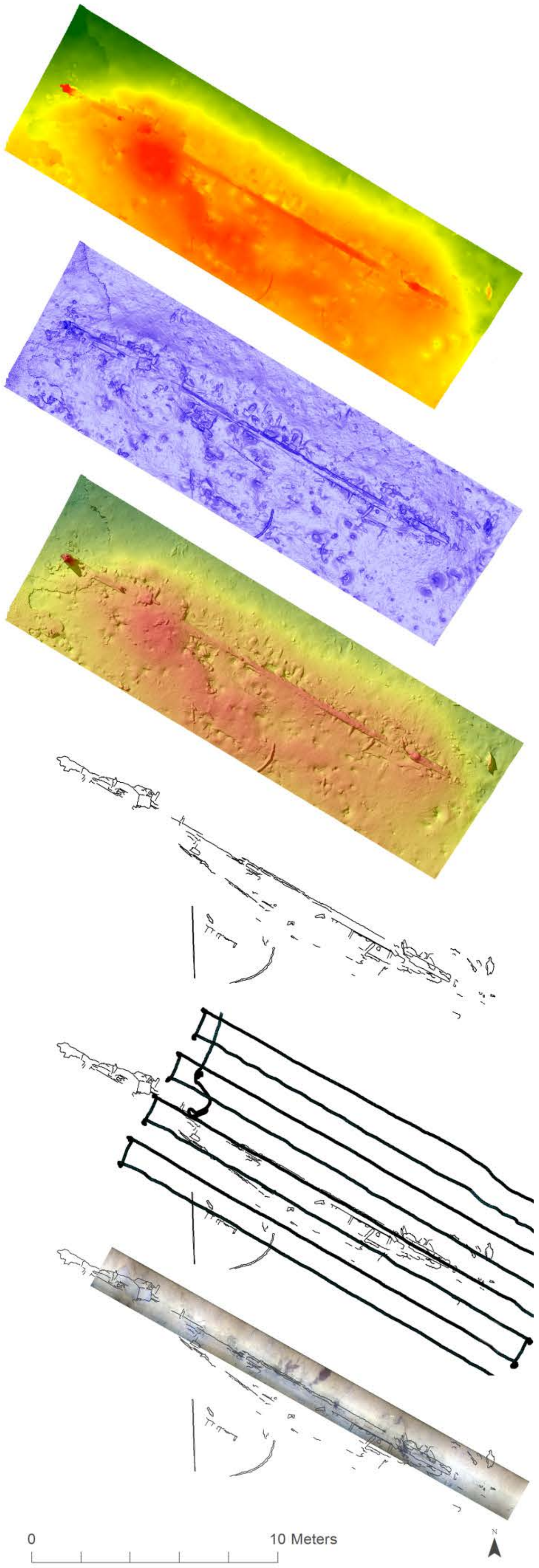

Fig. 6. Photogrammetry derivates, from the top: Bathymetry; Slope analysis; Hillshade with bathymetry; Site plan; Site plan with UHI survey track lines; Georeferenced UHI image

archaeological surveys. Further advances should be pursued in the current development of marine robot autonomy.

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APPENDIX

Table 1. Sensors for marine archaeological seabed mapping

Sensor		**SAS**[1]	**SSS**[2]	**Video**	**LIDAR**[3]	**MBES**[4]	**SBP**	**Photo**	**UHI**
Efficiency		2 km^2/h	0,58 km^2/h	7200 m^2/h	>15 km^2/h	0,5 km^2/h	7200 m^2/h	7200 m^2/h	7200 m^2/h
Technology		Acoustic	Acoustic	Optical	Optical	Acoustic	Acoustic	Optical	Optical
Bathy. Res.		8 cm	>10 cm	na	1 m	> 5 cm	na	0,5 cm	na
Imagery		x	x	x	na	x	na	x	x
Airborne	Range / resolution	na	na	na	< 50 m > 1 m	na	na	x	x
Surface		na	40 m > 4 cm	na	na	x	x	x	x
Towed		250 m 2 cm	40 m > 4 cm	x	na	na	x	x	x
AUV		250 m 2 cm	40 m > 4 cm	x	na	x	x	x	x
ROV		na	40 m > 4 cm	x	na	x	x	x	x

[1]Based on data from HiSAS 1030, [2]Based on data from Quinn et al. (2005) [3]Based on data from Doneus et al. (2013) [4]Based on 120 degree swath @ 2 kts, max depth 40 m