

AUTOTRACKER: Autonomous Inspection – Capabilities and Lessons Learned in Offshore Operations

Jonathan Evans, Pedro Patron, Benjamin Privat, Nicholas Johnson [*], and Chris Capus [**]

[*] SeeByte Ltd, Orchard Brae House, Queensferry Road, Edinburgh, SCOTLAND, UK

[**] Ocean Systems Laboratory, Heriot-Watt University, Edinburgh, SCOTLAND, UK

Abstract—This paper presents AUTOTRACKER, an autonomous pipeline inspection system that operates as a dynamic mission payload for an Autonomous Underwater Vehicle (AUV). The paper describes the mode of operation, together with the validation & trial operations AUTOTRACKER has undertaken over the years, and how this valuable experience has been fed back into the future development of the system.

I. INTRODUCTION

Probably the most mature of AUV applications is the use of vehicles for seabed area survey. The main aim of using AUVs is to improve the quality of the survey data (for instance, by decoupling the motion of the sensor platform vehicle from the surface), and to reduce the reliance on costly surface ship support. However, for fixed asset inspection such as export pipeline inspection where the distances involve many tens (or even hundreds) of kilometers, accumulated navigation errors and the accuracy of baseline route information mean that AUVs cannot autonomously swim a pre-programmed waypoint mission.

AUTOTRACKER is a vehicle agnostic pipeline inspection payload, which can perform onboard dynamic mission replanning to maintain the AUV and its inspection sensors in an optimum attitude for extended durations.

AUTOTRACKER's innovative system architecture provides:

- Fully **autonomous** pipeline tracking.
- Vehicle platform **independence**.
- High-resolution, low altitude (2-6 m), high-speed (2-5 knots).
- Active tracking of pipeline using various sensors, including: **Sidescan**; **Multi-beam**; assisted by **Legacy route data**
- Full onboard mission **re-planning**.

The ultimate operational aims of using such as system as part of the offshore inspection strategy are improved field reliability and reduced cost of production. In general, the use of autonomous technology is an enabler to different ways of working. For example:

Parallel operations on a ROV (Remotely Operated Vehicle) support vessel:

- *Integration into vessel ROV-based inspection regime*
- *AUV runs ahead of survey vessel (e.g. 1 day)*
- *1st pass of data processed overnight*
- *ROV and crew follow-on doing spot-checks on anomaly reports the next day*

Alternatively, AUVs can often use smaller, non-dedicated Vessels of Opportunity:

- *Very useful following events such as post-hurricane cleanup*
- *Also, more routine inspection from smaller, flexible vessels – reducing costs and encouraging more routine planned approach to inspection.*

The AUTOTRACKER inspection system has been developed and thoroughly de-risked before entering commercial operations offshore by a series of trials on a variety of vehicles. This paper outlines the operation of the system and provides an insight into the development and de-risked process.

II. AUTOTRACKER: SYSTEM DESCRIPTION

A. Inspection Payload

The AUTOTRACKER system is comprised to two groups of software components. The group that executes on the host-vehicle platform is referred to as the AUTOTRACKER inspection payload.

The onboard payload components are responsible for the live detection and tracking of pipeline in the data obtained from the various onboard sensors, together with the dynamic (not pre-programmed) mission control of the AUV to maintain the optimum vehicle attitude to the actual pipeline position; regardless of errors in the legacy pipeline route file or the accumulated position error on the AUV's navigational systems.

Most AUTOTRACKER configurations for pipeline inspection use sidescan sonar as the primary tracking sensor as this provides the widest area coverage and is present on most AUVs. On vehicles which support additional sensors such (downward-looking) profiling sonars these can be used for tracking at pipeline-vehicle offsets of near zero which cannot be done with sidescan alone because of the transducer and

sonar beam pattern creates a narrow blind-spot beneath the vehicle.

The onboard software components capture live sensor data without disturbing the host AUV's normal data logging mechanisms. This is then processed in real-time to identify the highlight/shadow signature of a pipeline of a specified diameter. This system is also employed to detect the trench itself in the case of buried pipelines. This additional data can be used to minimize spurious detections, as well as acting as an alternative tracking target in cases when the pipe itself is not visible. Figure 1 shows a section of a sidescan waterfall showing the automatic detection of a trench (marked with red lines) within which lies a partially exposed pipeline; a second exposed (non-trenched) pipeline is also present (and marked with blue dots).

It is evitable that false positive detections will be produced by the live sidescan and (if available) profiling detectors. Some of these will be spurious in nature, while others could be caused by the presence of another pipeline within the tracking sensors' swath. Regardless of the source of the additional detections, it is necessary for the system to ensure that they are ignored, and that it keeps following the correct pipe.

In order to deal with the first of these, a GMPHD Filter [1] based tracker is used to track individual detections over time. As each of the detections is considered to be an independent point in three-dimensional space, association between detections made by difference sensors is easy. The output of the tracking system is zero or more "tracks", one for each consistent series of detections. Each of these represents the path of a candidate pipe (or a pipe's enclosing trench, should this be required).

The next software component in the processing pipeline is the "fusion" system, so named as it fuses the incoming data with the previously collected and trusted legacy data. In the instance that no candidate pipes are detected, this fact is passed on to the control system together with the position on the legacy pipe where the detection "should" be. Otherwise, the fusion system considers each of the candidate pipes, and then selects the estimate with a history that is most closely aligned to the known path of the pipe which is to be tracked. The details of this detection are then passed on to the control system. In the event that none of the candidate pipes are considered to be a good match for the target, the behavior of the system is essentially the same as the case in which there are no candidate detections.

The primary responsibility of the control system is to maintain the vehicle's position and heading, such that it remains at the specified offset from the tracked pipe. It does this by taking into account the position of the detection, the required offset from the pipe, the direction of the pipe (taken from the legacy data), and from these calculating the ideal heading for the vehicle to take. This heading is then achieved by holding a "carrot" waypoint at a pre-defined distance in front of the vehicle. Also calculated are waypoints at two and three times the distance of the "carrot" from the vehicle, which also take into account changes in the direction of the pipe. These are not used for navigational purposes, but are passed to the topside systems (see section II.B) to act as predictions of the vehicle's future path to the operator.

The control system's secondary responsibility is dealing with a loss in the detection of the pipeline. In the instance that a section of the pipeline is known to be buried, this can be marked in the legacy route file and the control system will take this into account. In this case, the control system will simply follow the legacy data at the predefined offset up to the end of the burial, at which time normal operation resumes.

If the pipeline is lost during a section that is not known to be buried, AUTOTRACKER can operate in two modes preselected by the operator before mission execution. Firstly, the system can behave as with a known burial, and simply follow the legacy data until a new detection occurs. Alternatively, the system can perform a search, or series of searches, in order to relocate the pipeline. Searches are calculated by the control system to perform a "lawnmower" pattern over the area considered most likely to contain the pipe, using an angle of incidence at which detection is most likely. Additionally, the search calculation takes the dynamics of the vehicle into account; ensuring navigation requests never violate the vehicle's minimum turn radius.

In instances in which the system is forced to fall back on the legacy route data, it should be noted that this is not implemented as a sudden transition. Instead, a gradual decay is used to switch from the previous trajectory to that suggested by the legacy data. This increases the likelihood that the pipe will be redetected after short hidden sections, and prevents the vehicle from making sudden turns which might adversely affect its navigational control.

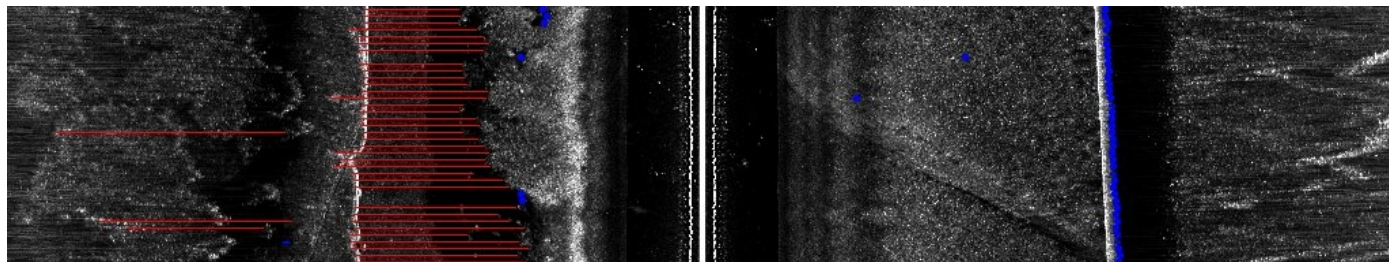


Figure 1, sidescan waterfall showing (on left) detection of partially buried trench (RED) with pipeline; (on right) a 2nd pipeline is present and detected (BLUE)

Inter-module communication is performed by the OceanSHELL communications library [2], which implements a connectionless UDP broadcast-based embedded communication system. This same method is used for communicating with the topside systems whenever an Ethernet based connection is available. During a mission, AUTOTRACKER is able to send custom CCL [3] messages via the vehicle's own modem hardware in order to appraise the operator of the system's current status. Again during a mission, all of the system's internal OceanSHELL traffic is recorded in order to enable full mission replay, which is described in section II.B.

AUTOTRACKER is designed to be vehicle agnostic and so employs the OceanALI (Abstraction Layer Interface) system (jointly developed by Heriot-Watt University and SeeByte) in order to decouple the components that are AUTOTRACKER specific, and those which facilitate the control of the host vehicle. Using such design and integration methods, all that is required to port and integrate the AUTOTRACKER system onto a new vehicle platform is the implementation of a single software module, which handles the direct control of the vehicle. At present AUTOTRACKER has been integrated with three distinct vehicle platforms: Subsea 7's GEOSUB, Hydroid's REMUS and Hafmynd's GAVIA.

The overall operational effect in the water of all these embedded software components is that the AUTOTRACKER system can control the host AUV to autonomously locate, track and perform an extended optimum inspection.

B. SeeTrack: Operator Topside

AUTOTRACKER topside software is a user friendly interface based upon SeeByte's SeeTrack platform. Its role is to facilitate the AUV mission planning, in-mission monitoring and rapid post-mission analysis (see Figure 2).

In order to perform an AUTOTRACKER pipeline inspection mission it is necessary to have two elements, a mission file and a legacy pipeline route file. The mission file is a list of nominal waypoints located close to the pipeline route. The route file supplies an estimate of the estimated position of the pipeline for the section to be inspected. These files are prepared by the operator using the SeeTrack tools, and are used by the onboard payload for its dynamic mission control.

SeeTrack facilitates the programming of the mission plan by displaying the chart of the survey area. Furthermore if a legacy route file is provided to SeeTrack, an appropriate AUTOTRACKER mission file is automatically generated saving time and effort (and potential operator error) by avoiding the user to enter a mission manually.

Once the files are uploaded to the AUV the payload is ready. The AUV mission is then started in the normal way for that platform. However, when the appropriate point in mission is

reached for the inspection to start, the AUTOTRACKER payload takes control of the AUV, directs it towards the pipeline, and once acquisition and identification is complete, the payload conducts the inspection. If the AUV has a suitable acoustic modem, then during the mission the vehicle's dynamic path is drawn in real time on the SeeTrack display. The user is always aware of the vehicle behavior underwater. Pipe position, vehicle position and status of the tracking (pipe detected, section buried...) are also reported back from the vehicle. Once the pipeline section is complete, the payload hands back control, and the AUV is recovered in the normal manner for that vehicle type.

When the mission is finished, data logs such as vehicle navigation files and sonar sidescan images are downloaded and processed through SeeTrack. The files imported and displayed for post-mission analysis. The operator can then use the geo-referenced sensor logs such as sidescan mosaics of the pipe, and record any identified anomalies. These are then automatically compiled into a report for later investigation.

It is also possible to replay the mission using the SeeTrack mission replay tool. It gives a clear idea of the result of the mission. The sidescan hits of where a pipe is likely to be are displayed, the "carrot" waypoint is also shown with the intermediate waypoints showing the next estimated positions to be reached by the AUV.

III. DE-RISKING TRIALS & PROCESS (ORKNEY)

The origins of the AUTOTRACKER system date back to the European Union Competitive and Sustainable Growth Programme of the same name that took place between year 2001 and 2005. The initial development work was reported in [4].

Since then, the AUTOTRACKER system has been de-risked in many trials under the three development phases that took place during the years 2005, 2006 and 2007.

These trials took place in a variety of locations in Scotland and Iceland. Among these places, well-known locations such as Scapa Flow in the Orkney Islands in Scotland, and Reykjavik harbor in Iceland were included. They provided a set of real benchmark pipelines with different curvatures, diameters and length, burial zones, rock dumps and trenched characteristics. The outcome was a robust, reliable and therefore safe to operate product.

During these trials, sponsors required different vehicle capabilities capable of going from the near-shore shallow water to the deep regions of the North Sea. Thanks to the generality of the system, AUTOTRACKER was easily integrated in three different platforms, the GEOSUB AUV from Subsea 7, the REMUS 100 AUV from Hydroid Inc. and the GAVIA AUV from Hafmynd.

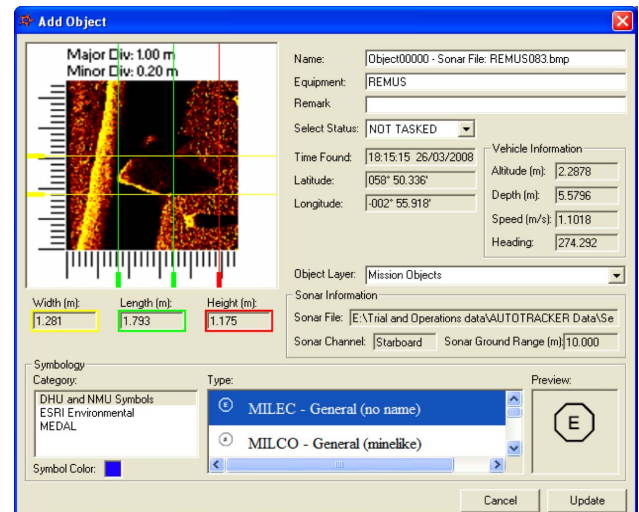
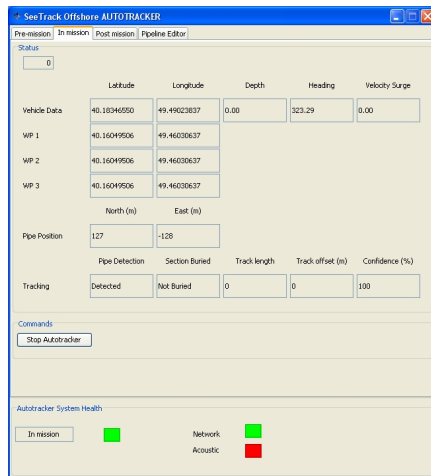
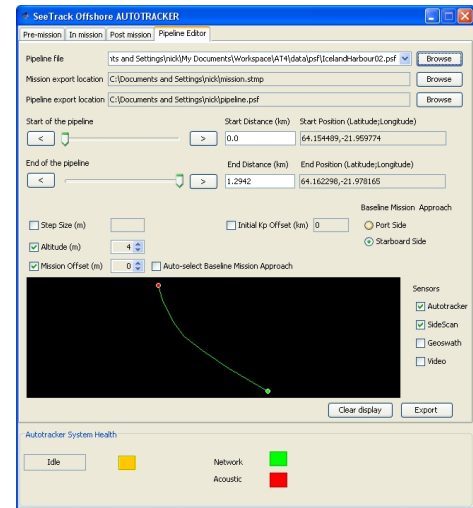
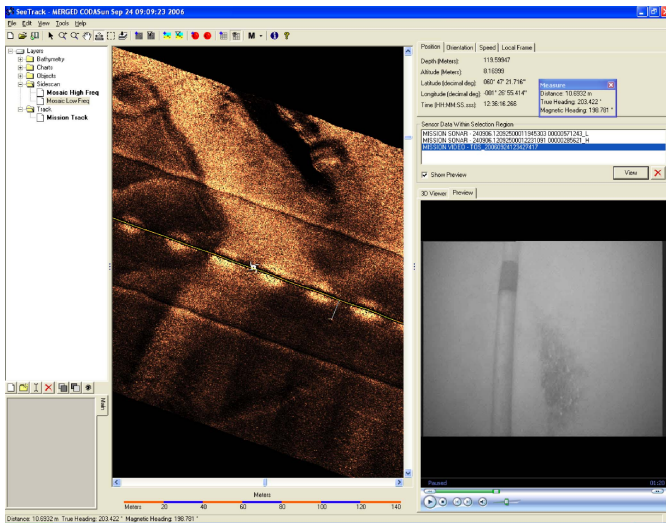


Figure 2: Various screenshots showing the SeeTrack AUTOTRACKER topside components:
(a) High-resolution geo-referenced sidescan mosaic and video; (b) Pipeline route data editor;
(c) In-mission monitoring via acoustic data; (d) post-mission reporting tools (example of debris lying next to the pipeline)

They also required different sensing capabilities that went from low altitude sidescan imagery for span detection; to “fly” above the pipeline for video inspection. The system implemented pipeline detection algorithms for different sensors enabling active tracking of the pipeline at different offsets.

The process of de-risking on a new AUV platform typically requires dry simulation and integration tests to ensure the AUTOTRACKER-to-AUV interfaces are operating correctly. This is then followed by a series of “low logistic trials”, ideally in a weather sheltered environment with a real-pipeline. The AUTOTRACKER development team has used Scapa Flow, Orkney Islands (Scotland) many times for this purpose. The site offers 12km of the 36-inch Piper/Claymore oil export line

running between the islands and sheltered from most wind directions. This is important because it allows small working boats to be used, and typically only few days are lost to foul weather. This can have a significant impact on the financial cost (and perhaps viability) for integrating onto a new AUV platform.

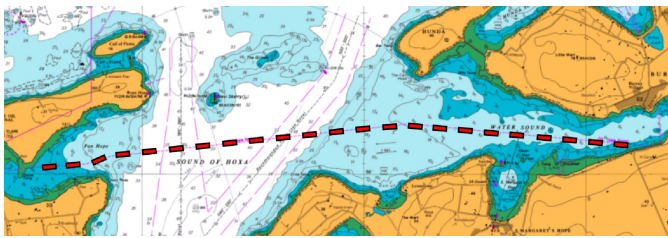
The methodology of using such a de-risking trials site to fully validate the AUTOTRACKER system and its interface’s to various host-AUVs has been proved over several years and on multiple vehicle platforms. It provides the confidence to a client that a new system is ready for a (potentially) expensive offshore operation.



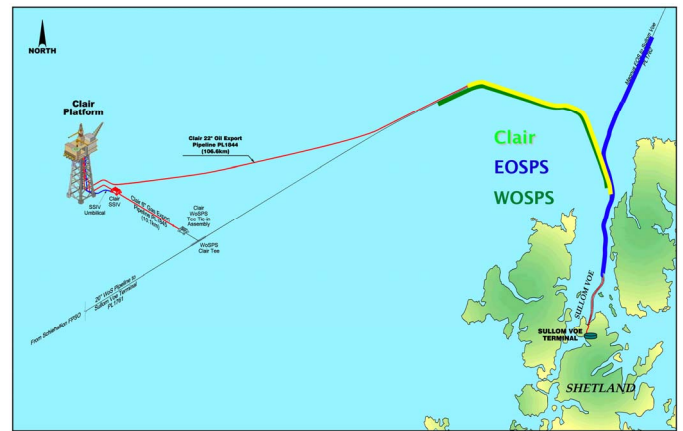
(a)



(b)



(c)



(d)

**Figure 3: AUTOTRACKER payload being deployed during
(a) REMUS 100 AUV at trials in Scapa Flow, Orkney; (b) GEOSUB AUV in Atlantic Frontier waters around Shetland;
(c) AUTOTRACKER trials sites, Orkney - Map of Piper/Claymore pipeline crossing Scapa Flow;
(d) Map of East and West of Shetland pipeline systems**

IV. OFFSHORE TRIALS – SHETLAND (UK)

The first commercial trial of the AUTOTRACKER payload took place during September 2006 to demonstrate the commercial viability of the product. The three Northern pipelines offshore from the Shetland Islands (Clair, WOSPS and EOSPS) were inspected achieving a record 22.2 km of continuous autonomous tracking and a total of 107 km of pipeline inspected.

A new capability for simultaneous tracking of multiple (3x) pipelines was also demonstrated during this campaign. This feature was able to maintain survey speeds of around 4 knots using the AUV even inside the complex and crowded area of Sullom Voe, where multiple pipelines arrive to the terminal. This posed a great improvement from the traditional average 0.8 knots of the ROV-based approach.

V. OPERATIONS – BAKU, AZERBAIJAN

Previous operations with the AUTOTRACKER system had been performed in water deep enough (>8m) to allow the vehicle to operate without surface effects, and at ideal offsets for sidescan detection/inspection (in the region of 15m) without the risk of approaching the surface. Operating close to the surface not only makes navigation more difficult, but also introduces kinematic instability and therefore adversely affects the quality of the data produced.

Ideal conditions are not always available, however. One of the strengths of AUVs is they are able to operate in conditions which larger survey ships are cannot. As chance would have it, one of these conditions is very shallow water, such as may be found around the Sangachal pipeline terminal just outside of Baku, Azerbaijan. In May 2009 NCS-Survey Ltd was commissioned to perform a pipeline survey of this area, in

collaboration with SeeByte Ltd's AUTOTRACKER system, and Hafmynd's GAVIA AUV.

Very shallow water presents some new challenges, and as a consequence of this, the vehicle must also operate at smaller offsets to the pipeline in order to keep it in the ideal portion of the sidescan swath. As a result, the margin for error in the vehicle's control is significantly reduced, as the chance of the pipe being lost in the sidescan's blind spot is much higher. Furthermore, the reduced range leads to a narrowing of this ideal window itself.

VI. LESSONS LEARNT

One of the many attractions of underwater robotics is that the environment can be harsh, complex and unknown. These factors, together with the well known problem of through-water communication's limited bandwidth, make the development, testing and verification of autonomous underwater systems challenging.

Two distinct lessons were learned regarding this during the development of the AUTOTRACKER system: while some testing can be done on dry land using logged data, a transparent simulation system is indispensable and in water testing and debugging is an absolute necessity. This approach can be seen mapped over development process of AUTOTRACKER – over the years it has adopted a distinct strategy of simulation, followed by realistic but (relatively) low cost trials in sheltered coastal conditions. Only then was the system considered ready to commit to expensive offshore commercial operations.

The use of previously logged or synthetic data allows the testing of the low level detection system, and even allows sanity checking for the higher level systems which process their output. It does not, however, enable closed loop testing of an entire system such as AUTOTRACKER.

Exploiting OceanSHELL's connectionless data transport allows the transparent substitution of the real hardware for a simulation system. All OceanSHELL modules are concerned with is the data they receive, not the identity of its source. Hydrodynamic models with integrated control components were made available by Hydroid and Hafmynd for their respective AUVs, allowing the control of a simulated vehicle. This just left the requirement for an input to the detection system. Two alternatives were developed for this purpose. The first was a simple drop in replacement for the detection system itself, which used the legacy data and the vehicle's position to calculate and output "detections" to be used by the other systems. This provides a low footprint option, which can easily be run embedded on a vehicle itself, should testing be required in areas which do not contain a candidate pipeline. The second option leverages a full 3D simulation environment called ARF [5] and thus requires a significantly larger footprint.

As useful as simulation can be, it cannot replace real world testing, only supplements it. No matter how accurate the simulation environment may be, it will never provide a perfect replication of difficulties which can be faced in the real environment. A simulation is deterministic (though not

necessarily observably so), the real world is not. Furthermore, testing in simulation does not provide an accurate picture of the logistics required by a real world operation, so these cannot be thoroughly prepared for. On a commercial operation, the team must be both functionally and observable professional. Knowledge is the key to this, and the appropriate knowledge can only be gained through real world experience of the deployment of a system.

VII. FUTURE APPLICATIONS – CABLE TRACKING

The excellent performance of cetaceans in target detection and recognition has been intensively studied with increasing interest in recent years in the development of bio-mimetic sonar systems [6, 7]. The Ocean Systems Laboratory (OSL) is developing a bio-inspired wideband acoustic sensing system for autonomous underwater vehicles (AUVs) for improved detection and recognition of subsea objects [8]. One application for the new system is the autonomous tracking of underwater cables. The bio-inspired approach offers potential for cable recognition as well as improved detection, making tracking more robust in cluttered environments. Nevertheless, effective tracking requires a robust framework and the flexibility of the AUTOTRACKER system, especially its ability to take inputs from novel sensors, makes it ideal for the continued development of the wideband tracking solution. Taken together these emerging technologies offer the potential to track unshielded communications cables with diameters below 20mm.

VIII. CONCLUSIONS

The development and trials program which has verified AUTOTRACKER fit of commercial offshore operations has taken many years from the initial technology development. The pace has by necessity been governed by the availability of the significant financial resources needed to test with real AUVs in real subsea environments over real pipelines. The use of a structured de-risking process that exploits the logistical advantages of certain trials sites has been invaluable. This has eventually led to the operational confidence to permit the system to enter commercial service.

ACKNOWLEDGMENT

The authors would like to sincerely thank all the members of AUTOTRACKER project over the years, too numerous to mention. Without their talent and enthusiasm the process would have been much harder and less enjoyable. This undoubtedly includes members of the original project consortium at UIB, NTUA and Subsea 7. Special mention should be made of the financial and technical support given by the BP, both in Sunbury and Aberdeen. Without such significant commitment the de-risking trials would have been impossible.

REFERENCES

- [1] Clark, D.; Ruiz, I.T.; Petillot, Y.; Bell, J.; "Particle PHD filter multiple target tracking in sonar images"; Aerospace and Electronic Systems,

- [2] Ocean Systems Laboratory, Heriot-Watt University; “*Ocean-shell: An embedded library for distributed applications and communications*”, Technical Report, August 2005
- [3] R. Stokey, L. Freitag, M. Grund, “*A Compact Control Language for AUV Acoustic Communication*”, Proc. OCEANS Europe 2005.
- [4] Evans J., et al; “*AUTOTRACKER: AUV embedded control architecture for autonomous pipeline and cable tracking*”; Proc. OCEANS 2003 MTS/IEEE; 22-26 Sept. 2003; Vol 5, pp 2651- 2658.
- [5] Davis B., Patron P, “*Augmented Reality and Data Fusion techniques for Enhanced Situational Awareness of the Underwater Domain*”, Proc. OCEANS Europe 2007, Aberdeen, Scotland, 8-21 Jun 2007, pp 1090-1095.
- [6] W. W. L. Au, “*The Sonar of Dolphins*”, Springer-Verlag, New York, 1993.
- [7] D. A. Helweg, P. W. Moore, S. W. Martin, and L. A. “*Dankiewicz. Using a binaural biomimetic array to identify bottom objects emulated by echolocating dolphins*”. Inst. Phys. Bioinspiration & Biomimetics, 1(2): pp. 41–51, June 2006.
- [8] C. Capus, Y. Pailhas, and K. Brown. “*Wideband sonar system for autonomous surveys using REMUS*”, In J. Acoust. Soc. Am., vol. 123(5) Pt. 2, p. 3466, May 2008