Internship Report

An assessment of the potential applications of AUV/gliders in offshore windfarm site surveys.

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in partnership with the Marine Autonomous Robotic Systems group at the National Oceanography Centre.

Global Position of MARS Activities and Demands of Renewable Energy Sector of Private Industry

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Executive Summary

The renewable energy sector has been growing with the 1990s, marked by increased licence applications for wind farm development offshore UK. UK AUV and glider development has also been growing, especially within the commercial sector. The MARS facility at NOC represents a scientific initiative to both develop and deploy AUV and glider technology. This report provides a summary of MARS capacity and a summary of UK and global scientific and commercial AUV and glider development and deployment. The project provided an opportunity to develop knowledge exchange between the NERC MARS facility and the marine renewable energy sector. Further to this the project provided an opportunity to ascertain AUV and glider use currently within site surveying for the sector, in particular wind farm development.

Key findings include:

- MARS identified as a key organisation within the UK, Europe and internationally in both the scientific and commercial sectors concerning the development and deployment of AUVs and gliders.
- The key end-user data include geophysical data including swath bathymetry, sidescan sonar and shallow seismic reflection surveys have been highlighted as the key end-user data sets, in addition to sea be photography and current velocity data. Data collected by AUVs is deemed most useful, when compared to gliders.
- Main drivers for adoption of AUV technology are cost-benefit of collation of survey data during multi-disciplinary operations and the added quality of data collected by AUVs flying 20-40m above seafloor.
- Risks have identified and these restrict the deployment of AUVs. Risks during open water surveying include: inadequate up-to-date bathymetric charts to combat collision avoidance, strong currents, collision with shipping or fishing apparatus on surfacing and data quality. Risks during repeat monitoring of a developed site include: increased turbidity affecting navigation and data quality, and collision with infrastructure.

The results of the project demonstrate that at present ship-board surveying is preferred to that of AUVs. This is based primarily on cost-benefit of the data potentially collected and the risk of loss of vehicle. Since wind turbine farm development in offshore regions is limited to the shelf regions, at present there is therefore limited use for AUVs within the renewable energy industry.

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Introduction

The commercial renewables sector has been growing since the 1990s, and has increased almost four-fold since 2001[1]. The Energy Act 2004 showed testament to the future importance the Government perceives in the sector.[2] Indeed, from 2007 to 2011 the contribution of renewable sources to UK energy increased from 1.8% to 3.8%, with the Government committing to having 15% of UK energy consumption sourced from renewables by 2020.[3] To aid reaching these targets £12.7bn has been invested into renewables between April 2011 and July 2012.[3]

Of the different contributors to renewable energies, UK wind energy has grown the most, with an increase in electricity generation from wind (overall) by 34% between July 2011 and June 2012. Installed capacity for wind generated both onshore and offshore increased by 34% between July 2011 and June 2012. Offshore wind energy alone has shown marked increases since 2007.[1] In particular, between July 2011 and end of June 2012 offshore wind generation increased by 9544MW to 2.5GW. Furthermore, once all offshore wind farms currently in development (those approved as of end-June 2012) are operational the capacity will be above 10.5GW.

As part of the Energy Act 2004 large swaths of offshore marine areas, including those outside of UK territorial waters, were designated as The Renewable Energy Zone.[2] As a result, the offshore renewable energy sector will be planning, commissioning and installing vast quantities of infrastructure in UK waters. However, only 26% of the UK EEZ has been mapped using multibeam sonar. This means that for investors to evaluate likely sites, expenditure on site surveys for reconnaissance is inevitable. Furthermore, as with all seafloor infrastructure installation adequate high resolution geological, geotechnical, oceanographic and biological site surveys are required. With the increase in expenses surrounding ship-board surveying there is a growing interest to utilise unmanned surface and underwater vehicles (USVs and UUVs respectively).

AUVs (autonomous underwater vehicles) and gliders have been regularly used for scientific operations for the last two decades. AUVs and ROVs (remotely operated vehicles) have also been used extensively by the oil and gas industry for both site surveying and infrastructure monitoring. With the potential cost and data quality benefits of using USVs in comparison to ship board surveys, there is a growing market need for AUV and potentially glider deployment for operations regarding site surveying for the renewable energy sector.

[1] Digest of UK Energy Statistics (DUKEs), 2011, Department of Energy and Climate Change
[2] Energy Act 2004
[3] UK Renewable Energy Roadmap Update 2012, 2012, Department of Energy and Climate Change

Aims

The aims of this report are detailed below:

1. Develop a better understanding of customer and end-user (Renewable Energy Sector) awareness of MARS activities, instrumentation and planned developments.
2. Identify where the MARS group is situated within a global context of provision of AUVs and gliders for scientific and commercial operations.
3. Identify the main parameters being measured by AUV/gliders, and identify which parameters are most useful for commercial operators (specifically the Renewable Energy Sector). Determine how useful the data acquired is for meeting the survey needs.
4. Identify what the main drivers for adoption of AUV/glider technology.
5. Identify issues and barriers for inclusion of AUV/glider surveying in routine expeditions and what the logistical and cost implications of running mixed survey technology.
6. Identify what additional training (if required) and/or logistical support would be needed to support inclusion of AUV/glider surveying into established surveying methodologies.
7. Identify the additional risk involved with conducting surveys in the regions targeted by the renewable energy sector.
8. Determine to what extent validation of glider data is required to enable comparisons with other field data. Determine whether repeat surveying is required.

Current Capacity of the Marine Autonomous and Robotic Systems (MARS) at the National Oceanography Centre

The NERC-owned AUV/glider fleet is based at the MARS group at NOC Southampton, and also at the North Atlantic Glider Base (NAGB) at the Scottish Association for Marine Science (SAMS) in Oban and the Physical Oceanographic and Biogeochemical Observations of the Southern Ocean (PHOBOS) at the British Antarctic Survey in Cambridge.

NOC Southampton have designed and developed the Autosub family of vehicles, of which Autosub3 (1600m depth rated) and Autosub (6000m depth rated) vehicles are in operation and the Autosub Long Range (depth rated 6000m) is in testing. NOC have also procured several commercial-off-the-shelf (COTS) undersea gliders including four Teledyne Webb Slocum gliders (depth rated 1000m) at NOC Southampton and three Teledyne Webb Slocum gliders at NOC Liverpool (depth rated 200m). The NERC fleet also comprises four iRobot Seagliders at NOC Southampton.

SAMS have a REMUS 600 AUV and two iRobot iRobot Seagliders. PHOBOS have two G2 Slocum gliders from Teledyne Webb and an iRobot Seaglider.

Specifications for NOC AUVs

Autosub3

Autosub3 is especially effective in remote regions with minimal access, such as beneath sea ice or floating ice-tongues of glaciers. With upwards and downwards facing sonar it is able to map both sea ice above and the seafloor below the AUV track. It can be deployed to survey up to 400km on a single set of batteries and can conduct operations to 1600m water depths.

Technical Specification for Autosub3

Physical Characteristics	6.8m and 2,400kg (dry)
Depth Range	1,600m
Endurance Range	400km or 80hours at 5km/hr
Energy Supply	Primary batteries, which take 12hours to charge
Navigation	150kHz DVL bottom track range 400m. Has accuracy of 0.1% of distance travelled.
Collision Avoidance	Forward-looking single beam for ice berg, and a ground-line avoidance when under ice.
Communications	• Acoustic modem with 2km range. WiFi radio link when on surface enabling access to vehicle data.
Control	• Constant depth, altitude and distance below a surface overhead. Depth profiling and a a defined track using a

	holding station.
Launch and Recovery	• Dedicated LARS needing hydraulic power (210bar). Optimised for deployment under ice, thus has a heated container system for polar expeditions.
Sensors	• Multibeam – EM2000, 400m swath at 3m resolution. Capable of mapping 1.75km^2/hr and can have a system configured to be upward-looking. • Sidescan – none • Sub-bottom Profiler – 2013 • ADCP – down 150kHz and up 300kHz • Magnetometer – none • CTD – Seabird 911 with pumped twin CTD sensors, dissolved oxygen transmissometer, light scattering sensor and flourometer. • Camera – none • Additional Sensors – Power: 48V and up to 200W. Communications: RS23.2 ethernet.

Autosub6000

Autosub6000 can operate in water depths of 6000m and pressures 600 times atmospheric pressure. The operating depth is reached by redesign of the battery and buoyancy system, rather than the pressurisation system.

Technical Specification for Autosub6000

Physical Characteristics	5.5m and 1,800kg
Depth Range	6,000m
Endurance Range	150km or 30hours at 5km/hr
Energy Supply	Secondary rechargeable batteries, which take 7hours to charge.
Navigation	300kHz DVL bottom track range 200m. Has accuracy of 0.1% of distance travelled. Although acoustic tracking to within 15m when at >5,000m waterdepth.
Collision Avoidance	Scanning Tritech Seaking sonar for near seabed, which is optimised for rough terrain.
Communications	Acoustic modem with 7km range. WiFi radio link when on surface enabling access to vehicle data.
Control	Constant depth, altitude and distance below a surface overhead. Depth profiling and a a defined track using a holding station. Box survey with configurable line spacing, altitude, orientation and extents.
Launch and Recovery	Dedicated LARS needing hydraulic power.
Sensors	• Multibeam – EM2000, 400m swath at 3m resolution. Capable of mapping 1.75km^2/hr. • Sidescan – Edgetech 2200.410/12.0kHz sonar. 0.3m resolution at 0.8km^2/hr (410kHz) or 1.5m resolution at 3.0km^2/hour (120kHz)

- Sub-bottom Profiler – 2013
- ADCP – down 150kHz and up 300kHz
- Magnetometer – none
- CTD – Seabird 911 with pumped twin CTD sensors, dissolved oxygen transmissometer, light scattering sensor and flourometer.
- Camera – none
- Additional Sensors – Power: 48V and up to 200W. Communications: RS23.2 ethernet.

Autosub LR

Autosub Long Range is in the testing phase. The primary aim is to extend the endurance of the vehicle with a capacity to operate at 6000m for up to six months. It can be set the task of analysing the seafloor on ocean basin scales without the need for vessel support. During these extended periods the vehicle can surface and transmit the data via an Iridium satellite.

Technical Specification for Autosub LR

Physical Characteristics	
Depth Range	
Endurance Range	~6,000km or 6months
Energy Supply	40kg of primary lithium chloride cells, providing 68M joule of energy. Each pack costs £7000.
Control System	Magnetically coupled DC
Navigation	GPS on surface. Dead reckoning using TCM5 flux gate compass, RDI Teledyne 300kHz ADCP. Seabird strain gauge pressure sensor for depth sensing. ADCP beams used for constant altitude control. Relocation backup with an ARGOS beacon, in addition to Iridium system.
Collision Avoidance	ADCP beams also used for collision avoidance.
Communications	Two-way Iridium satellite communications for data download, mission and configuration upload.
Control	Constant depth, altitude and distance below a surface overhead. Depth profiling and a a defined track using a holding station. Box survey with configurable line spacing, altitude, orientation and extents.
Launch and Recovery	
Sensors	Seabird SBE 52 CTD RDI Teledyne 300kHz ADCP

Specifications for NOC Gliders

Teledyne Webb Slocum Electric Gliders

Contact: David Smead (das@noc.ac.uk) for Ammonite, Bellamite and Coprolite gliders from NOC Ocean Modelling and Forecasting Group or Stuart Cunningham (scu@noc.ac.uk) for Dolomite glider from NOC Marine Physics and Ocean Climate Group or Phil Knight (pjk@noc.ac.uk) for gliders (Units 117, 175 and 194) at NOC Liverpool.

Powered by alkaline batteries, the electric glider can be deployed for a period of 15 to 30 days at a 600-1500km range. Has capacity to carry customised sensors. The Slocum 1-km gliders can operate in water depths of 1000m, while a coastal model (Slocum200) operate only in water depths up to 200m.

The glider is very suitable for long-range and endurance, where low-to-moderate speed is desired. A 'sawtooth' measurement profile is produced for optimal vertical and horizontal measurements in the water column. The glider is programmed for regular surfacing to provide excellent GPS positioning and allow two-way communication; no other navigation aids are required. This particular glider system is also very portable.

Technical Specification (from Teledyne)

Weight	52kg
Hull Diameter	21.3cm
Depth Range	1.5m
Speed	4-200m (coastal model) or 1000m (1-km model)
Endurance	0.4m/sec (horizontal average)
Range	1,500km
Navigation	GPS, magnetic compass, altimeter, subsurface dead reckoning
Sensor Package (Teledyne Provision)	Conductivity, temperature and depth
Communications	RF modem, Iridium satellite, ARGOS and Telesonar modem

The Ammonite, Bellamite and Coprolite gliders (NOC Ocean Modelling and Forecasting Group) are first generation (G1) Slocum 1-km gliders with a 1000m depth range. They carry a non-pumped SeaBird CTD package and has a proven endurance of 86 days using primary lithium batteries. However, these are in need of upgrade.

The Dolomite glider (NOC Marine Physics and Ocean Climate Group) is a G1.5 version 1-km model equipped with SeaBird CTD and has a proven endurance of 86 days. Currently in use for the RAPID-MOC programme.

There are three Slocum 200m gliders at NOC Liverpool. Unit 117 is a G1 model with a 200m depth range. It is equipped with a non-pumped SeaBird CTD, an Aanderaa oxygen optode, a Wetlabs triplet sensor for CDOM, Chl-a and turbidity. Unit 175 is a G1 model, again with a 200m depth range, equipped with a non-pumped SeaBird CTD and a Rockland Scientific MicroRider turbulence probe (microconductivity, shear and temperature at up to 512kHz). Unit 194 is a G2 model with a pumped SeaBird CTD, an Aanderaa oxygen optode, and a Wetlabs triplet sensor for CDOM, Chl-a and turbidity.

iRobot Seaglider Gliders

As a modular AUV, Seaglider accommodates a variety of sensors that expand the robots measurement capacity and the overall range of the mission. The iRobot Seaglider also has a number of operational modes that further increase the research capacity, which range in water depth from 50-1,000m. There are four iRobot Seagliders in operation with MARS at NOC, Altair was lost offshore El Hierro in February 2012. Altair was in primary use by RAPID-MOC programme. Bellatrix is in use by the Ocean Biogeochemistry and Ecosystems Group at NOC. Canopus and Denebola are to be used in the Sensors-on-Gliders programme. Eltanin also joined the fleet in June 2012.

Technical Specification (from iRobot)

Body Size	1.8-2.0m and 30cm diameter
Wing Span	1m
Antenna Mast	0.43-1.00m
Weight	52kg (dry)
Operating Depth	50-1,000m
Maximum Range	4,600km (650 dives to 1km depth)
Battery Endurance	Lithium sulfuryl chloride primary batteries, with 24V and 10V packs, providing 17MJ for 10months
Typical Speed	25cm/s
Glide Angle	16-45^o
Standard Componets	Wings, rudder, isopycnal pressure hull, lithium batteries, paine pressure sensor, GPS, Iridium modem, 3-axis compass, acoustic transponder, altimeter.
Sensor Components	CTD (SeaBird), Wetlabs backscatter/flurometer (BBFL2 VM650/CHL-A/CDOM), Aanderaa 4330 dissolve oxygen sensor.

Planned Vehicle and Sensor Development at Marine Autonomous and Robotic Systems (MARS) at the National Oceanography Centre

Currently the key payloads for data collection regarding site surveying for the renewable energy sector include swath bathymetry, sidescan sonar and sub-bottom profiler. These payloads are off-the-shelf and development is restricted to power consumption.

Additional sensor development includes:

- Carbonate system sensor
- Holographic camera
- Nutrient sensor
- Iron sensor
- Nucleic acid analysis system

In addition to sensor and data acquisition/processing, development is focused at MARS within risk assessment and management, and in future towards policy and litigation.

Comparison of MARS Current and Future Capacity with Institutes and Commercial Operators on UK, European and Global Scales

A comparison between the vehicle capacity currently at MARS and that of the UK and Global research and commercial sectors is important. It will enable a realisation of trends in development and production of both AUVs and gliders, affirm the position of MARS within those trends, and better guide future development to compete on scientific and commercial scales.

MARS AUVs

Within the UK Research Institute Marine Equipment Pool

MARS currently has three AUVs at NOC, which include Autosub3, Autosub6000 and Autosub LR. All of these models are designed primarily for offshore deployment. Although Autosub3 is limited to 1,600m water depths, both Autosub6000 and Autosub LR are capable of operations in water depths up to 6,000m. Both Autosub3 and Autosub6000 have a broad sensor suite; both have multibeam sonar, CTD sensors, ADCP, collision avoidance sonar and in 2013 both will have a sub-bottom profiler. Presently, Autosub6000 has sidescan sonar capability, while this additional sensor system will not be added to Autosub3 until 2013. Autosub LR has a limited sensor suite, only including CTD and ACDP constrained by payload battery consumption. Autosub LR is alternatively designed for endurance and can be deployed on six month (6,000km) operations, compared to the 80 hour (400km) or 30 hour (150km) deployments of Autosub3 and Autosub6000 respectively.

Within the institutes affiliated with MARS, namely SAMS and BAS, there is one other AUV. SAMS are in possession of a REMUS 600, which can operate in water depths up to 600m for periods of 70 hours. Although it can be configured for operations in water depths of up to 1,500m and 3,000m it is confined to relatively shallow water operations. The vehicle model, like the NOC AUVs is better designed for offshore work in reduced ocean currents. The vehicle is equipped with ADCP, CTD, fluorometer and sidescan sonar, but lacks a bathymetric or geophysical survey suite. Although the AUVs at NOC have broader functionality in regards to payloads, namely multibeam bathymetry, there could be occurrences where the SAMS REMUS 600 would be appropriate to use, with regards to reducing budget spends and the need for larger support vessels. Certainly future development plans feature a bathymetric payload for the REMUS 600, which would further support its use on missions where vessels of opportunity are smaller or where water depths are shallow (below 600m).

Heriot-Watt University (HW) has a REMUS and have developed a number of small in-house AUVs. The REMUS at HW is equipped with dual frequency sidescan sonar, CTD and ACDP, however only has 22 hour endurance and is restricted to 100m water depths. The Nessie models at HW only operate to depths of 100m and, apart from navigation sensors, are only equipped with cameras. Of note Cambridge University are developing small AUVs, but have only had limited success thus far.

Therefore within the UK research network, the AUVs at NOC within MARS pose the most sophisticated vehicles available in regards to payload, communications, navigation and obstacle avoidance. However, they are limited to offshore operations. Areas with heavy traffic and in areas with strong ocean currents may be problematic.

Within the Global Research Community

Woods Hole Oceanography Institute has the National Deep Submergence Facility, which have a range of both AUVs and gliders. The AUVs include the 4,500m depth-rated Sentry, a series of REMUS AUVs including REMUS 100, 600, 3000 and 6000, and finally two 6,000m depth-rated SeaBed-class AUVs. Sentry has a 36hour endurance but is fitted with multibeam sonar, magnetometers, sidescan sonar, sub-bottom profiler, CTD, turbidity meter, cameras, Eh sensor, mass spectrometer and fluorometer. Sentry is commonly deployed for oceanographic studies but with a broad sensor suite it can also be used for mapping hydrothermal plumes and operating in extreme terrains. The two SeaBed-class AUVs Jaguar and Puma are fitted with CTD, pressure sensors, ADCP, Eh sensors and optical backscatter. Jaguar is also fitted with downward-facing cameras and imaging sonar. These SeaBed AUVs are deployed for water-column surveys and seabed mapping operations, while Puma is also used for mapping hydrothermal plumes.

The REMUS fleet at WHOI have a broad range of functionality. The shallow-water REMUS AUVs are equipped with bathymetric, temperature, depth, optical backscatter, sidescan sonar and fluorescence payloads. The deep-diving REMUS AUVs at WHOI are still fitted with sidescan sonar, mapping sonar, CTD and pressure sensors, ADCPs, digital cameras and collision avoidance sonar.

Monterey Bay Aquarium Research Institute (MBARI) have a Dorado-class AUV and a long-range AUV called Tethys R-One. Information is scarce for Tethys apart from its 740hour or 1,000km endurance. The Dorado-class AUV at MBARI is 600m depth-rated and has a limited 17hour or 55-85km endurance. However, the Dorado-class AUV is fitted with CTD, fluorometer, multibeam sonar, sidescan sonar, sub-bottom profiler, pressure sensors, DVL and INS for navigation, and a forward looking sonar for collision avoidance.

The National Institute for Undersea Science and Technology (NIUST) is a research group comprising NOAA, the University of Mississippi and University of Southern Mississippi. NIUST have two SeaBed-class AUVs (Eagle Ray and MolaMola) which are depth-rated to 2,200m and 6,000m respectively, with 30hour endurances. They are principally deployed on mapping operations and are fitted with multibeam sonar, CTD and sub-bottom profilers.

The Memorial University of Newfoundland (MUN) has an Explorer-class AUV (C-SCOUT) from International Submarine Engineering (ISE Canada). The MUN vehicle has a 6hour endurance with a depth-rating of 3,000km. C-SCOUT is currently only fitted with a CTD, dissolved oxygen sensor and a fluorometer. Canada Natural Resources (CNR) also have two Explorer-class vehicles purchased in 2010. The NURC facility at the University of North Carolina Wilmington (UNCW) also has an Explorer-class

PeRL at the University of Michigan have two Ocean-Server Inver2 AUVs that have been modified with additional navigation payloads but is principally only fitted with a camera suite.

MIT Sea Grant's AUV Laboratory has an Odyssey IV-class AUV, a Caribou AUV developed with Bluefin Robotics amd two LAMSS Bluefin 21 AUVs. Odyssey IV is depth-rated to 6,000m and is equipped with multibeam, cameras and a NEREUS mass spectrometer. Caribou is equipped with sidescan sonar and can operate in 3,000m water depths with a 20hour endurance. The Caribou has been specifically designed for operations in beach and coastal environments, as well as operations involving freshwater mapping in rivers. The Bluefin 21 AUVs in operation are depth-rated to 4,500m and are equipped with CTDF, pressure sensors, Chlorophyll a sensors, and dissolved organic matter sensors.

The Waitt Institute of Discovery have two REMUS 6000 AUVs both depth-rated to 6,000m and have endurances of 22hours. Both of these are fitted DVL and ADCP, as well as sidescan sonar, multi-beam sonar and sub-bottom profiler. Florida Atlantic University has the Morpheus AUV, which is only depth-rated to 200m. Georgia Tech have developed a low-cost AUV named Yellowfin which is fitted with sonar.

MARUM at the University of Bremen also have an Explorer-class AUV named MARUM-SEAL. It is depth-rated to 5,000m and has an endurance of >19hours. It is currently fitted with CTD, fluorometer and turbidity sensors, sub-bottom profiler, sidescan sonar, obstacle avoidance sonar, and INS and DVL for navigation. It is primarily deployed for seabed mapping and basic water column surveys. The University of Berlin has the DNS Pegel AUV, however a specification is not available. IFM-GEOMAR has the Abyss AUV which is depth-rated to 6,000m and has an endurance of 24hours. The Abyss is fitted with multibeam sonar, still camera, sidescan sonar and sub-bottom profiler.

IFREMER have an explorer-class AUV as well as the Aster AUV. The Aster AUV is designed for work within coastal settings, although it has a depth-rating to 3,000m. It is fitted with an ADCP, fisheries echo-sounder, spectrometer and multibeam sonar.

The Institute for Systems and Robotics (ISR) in Lisbon have developed the Infante AUV for environmental monitoring in shallow coastal environments. It is depth-rated to 300-600m and has an endurance of 19hours.

Lastly are the AUVs from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). The Urashima AUV is a large ocean-going AUV with a primary function of collecting oceanographic data including salinity, temperature and dissolved oxygen. As well as obstacle avoidance, the AUV is also fitted with side scan sonar, multibeam echo sounder and a camera.

The MARS AUV fleet is excellently placed within the Global Research sector. The Autosub models have superior depth-coverage and endurance compared to many other AUVs from international institutes. However, from a competitive prospective the multibeam bathymetric sonar payloads are standard, as is CTD, dissolved oxygen sensors, fluorometers and turbidity sensors. Fewer vehicles are fitted with sidescan sonar and sub-bottom profilers. However, with advances in power delivery new vehicles have sidescan sonar and sub-bottom profilers fitted as standard payloads. The 2013 upgrades to both Autosub3 and Autosub6000 should see the vehicle fitted with sidescan sonar and sub-bottom profilers. These additions will make the vehicles very competitive is the data collection services they provide, in addition to their reliability. However, institutes such as WHOI have fitted AUVs with spectrometers, optical backscatter and Eh sensors. This may be something to consider at NOC for future development.

Within the UK and Global Commercial Sectors

Kongsberg are a major producer and commercial user of AUVs. Kongsberg have two ranges of AUVs, namely HUGIN and REMUS. HUGIN include the 1000, 3000 and 4500 models, which are depth-rated to these in meters with endurances of 24-62 hours. These are fitted with CTD, ADCP, turbidity sensor, multibeam sonar, sidescan sonar and sub-bottom profiler as the main payloads. These larger AUVs are used in seabed surveying as well as Naval operations. Kongsberg, through subsidiary Hydroid, also produce the REMUS AUVs. These include REMUS 100, 100-S, 600, 600-S and 6000, which are depth-rated to those depths and have endurances between 10 and 50hours. REMUS AUVs are equipped with ADCP, sidescan sonar, CTD and bathymetric sonar. Optional sensor packages include dissolved oxygen, pH, multibeam sonar and cameras.

International Submarine Engineering (ISE) are responsible for the Explorer-class AUV and its derivatives such as Arctic Explorer and Theseus. These can operate in depths of 300m, 1,000m, 3,000m and 5,000m and are equipped with variable payloads that commonly include multibeam sonar and sidescan sonar. Natural

Resources Canada has acquired two Explorer-class AUVs named Yamoria and Qaujisati.

Bluefin are a wholly-owned subsidiary of Battelle Memorial Institute, and was developed by former robotics researchers at MIT. Bluefin produce a series of vehicles designed for research, surveying and military countermeasures, these include Bluefin9 (200m), Bluefin12-S (200m), Bluefin12D (200m), and Bluefin21 (1,500m). These are commonly equipped with sidescan sonar or cameras, as well as CTDs and turbidity sensors. Bluefin21 has a sub-bottom profiler and multibeam echo-sounder within its payload.

OceanServer of Fall River Massachusetts produce the Inver2 AUV. Inver2 is only depth-rated to 100m and typically has endurances up to 14hours. The Inver2 is fitted with side scan sonar, multibeam sonar and a CTD probe. In collaboration with OceanServer, YSI Integrated Systems and Services have produced the EcoMapper AUV, which is again depth-rated to 100m and has endurances of up to 12hours, but is equipped with CTD, salinity, blue-green algae sensor, chlorophyll a sensor, dissolved oxygen sensor, ORP, pH and turbidity sensors, side scan sonar, 6-beam and/or 10-beam DVL for navigation, bathymetric sonar and current profiling ADCP.

C&C Technologies have a fleet of AUVs, predominantly HUGIN AUVs, including C-Surveyor II to V. Fugro Marine also have a fleet of HUGIN AUVs, including Echo Surveyor I to IV. Both these companies primarily survey regions of seafloor for geohazard mapping. These geohazard surveys contribute to site planning for seafloor infrastructure including wind turbine pilings and drilling sites. The AUVs of both C&C and Fugro are commonly depth-rated between 3,000-4,500m and endurances of 25-70hours. The payloads are commonly multibeam bathymetric sonar, sidescan sonar, camera systems and sub-bottom profiler, the emphasis being collection of geophysical data.

Phoenix International provide marine services using a Bluefin-21 AUV equipped with side scan sonar, multibeam sonar and sound velocity sensor (SVS). In collaboration with Bluefin, the Columbia Group of Washington have produced the Proetus AUV. Proteus has an endurance of 50hours, but has only a shallow water depth-rating and is primarily used for sensor development.

Falmouth have developed a solar-powered AUV (SAUV) that operates at the surface or at depths of 500m. Two vehicles have been issued to AUV Associates (named SAUV II) and the University of South Florida (named TAVROS SAUV).

Lockhead Martin Mission Systems and Sensors are based out of Houston, Texas. They have developed a series of AUVs called Marlin. The Mk1 has an operational water depth of 100m, while the Mk2 and Mk3 models have a 4,000m depth-rating, however both only have endurances of up to 6hours. Both Mk1 and Mk2 (Mk3) models are equipped with turbidity sensors, CTD, side scan sonar, multibeam sonar, sub-bottom profiler, optical cameras, ADCP current profilers.

ESC SA are a French-based robotics company that produce the Alistar AUVs. These AUVs are either single or twin hulled, with operating water depths of 300-600m and 24hours endurances. They are commonly fitted with Side scan sonar, synthetic aperture sonar, interferometric sonar, obstacle avoidance sonar, multibeam echo sonar, CTD probe and video camera.

Teledyne Gavia produce the Gavia model of AUVs that are designed from offshore surveying, scientific research and defence. They are equipped to operate in water depths of 500-1,000m but have limited endurances of up to 6hours. The Gavia AUVs can be fitted with CTD, ADCP, dissolved oxygen, and swath bathymetry, in addition to side scan sonar, sub-bottom profiler, sound velocity meter and obstacle avoidance sonar. NCS of Aberdeen operate a Teledyne Gavia AUV depth rated to 1,000m.

DSME E&R are a subsidiary of Daewoo Shipbuilding and Marine Engineering Group. They have experience in underwater vehicles and instruments, such as AUV, side scan sonar, sonar boat and underwater multi-directional cameras. They produce the OKPO AUVs that have 300m, 600m and 6,000m operating water depths and typically 10hour endurances. Mitsui Engineering and Shipbuilding (MES) are based in Tokyo. They are developing and producing a wide variety of AUVs primarily for commercial use. The R-One and R2D4 models are the commercially available vehicles with 400m and 4,000m operating water depths respectively. The R2D4 is equipped with side scan sonar, video cameras, interferometry sonar, pH sensor, turbidimeter and oxygen densitometer.

Within the international commercial sector the AUV capacity at MARS is still competitive. With the planned additions of side scan sonar and sub-bottom profilers to the Autosub3 and Autosub6000 models will become competitive commercially given their extended range and endurance. The obstacle avoidance system on each is also an important feature compared to other commercial models. The operating depths of Autosub6000 and Autosub Long Range also far exceed those commonly found for commercial vehicles, although commercial surveying is principally limited to water depths <4,000m, and most commonly <1,000m. Although ADCP are fitted to Autosub a turbidity sensor may be important for assessing currents. A magnetometer for locating infrastructure (and mines commercially) would also be useful. Other environmental sensors would of course be useful, however may be surplus to requires for seafloor mapping, which is the activity (other than mine countermeasures) most commonly undertaken commercially.

MARS Gliders

Within the UK Research Institute Marine Equipment Pool

NOC MARS at Southampton have a broad range of gliders, including three G1 1-km electric Slocum gliders and a G1.5 1-km Slocum glider. NOC Liverpool have two G1 200m electric Slocum gliders and a G2 200m electric Slocum gliders. These are principally fitted with CTD, optode and turbidity sensors. Although these differ in the water depths they are able to gather data in (200m against 1,000m), they have endurances of 1,500km. NOC Southampton also have four iRobot Seagliders. These have operating depths of 50-1,000km capable of endurances of 10months or 4,500km. The iRobot Seagliders are fitted with CTD, fluorometer, optode and turbidity sensor.

Within the MARS umbrella, PHOBOS at BAS have two G2 1-km Slocum gliders and a single iRobot Seaglider. These are deployed to the Antarctic. Furthermore, NAGB at SAMS have two iRobot Seagliders. These are fitted with CTD, optodes and fluorometer. UEA have three iRobot Seagliders. The MARS glider fleet represents the broadest range of gliders within the UK research institute marine equipment pool. Developments in regard to mounting new sensors on the gliders and fitting fisheries echo-sounders will set the fleet apart from others.

Within the Global Research Community

There is a fleet of gliders at Ecole Nationale Superieure de Techniques Avancees Unit de Mecanique (ENSTA). This fleet includes one Slocum 200, five Slocum 1000 and one Spray glider from Bluefin. There is an additional fleet of gliders at the Observatoire Oceanoiogique de Villefranc and Laboratoire d'Oceanographie de Villefranc (OOV-LOV), which includes four Slocum 1000 gliders. The Laboratoire d'Oceanographie et de Climatologie Experimentations et Approches Numeriques (LOCEAN) has a further fleet of gliders including one Slocum 200 and a series of Slocum 1000 gliders operated by ENSTA. French institute Division Technique de l'INSU (DT INSU) have a fleet of one Slocum 200 and two Seagliders. GEOMAR operate a fleet of 11 Slocum gliders while HZG Institute of Costal Research operate two Slocum gliders.

The PLOCAN Canary Island Oceanic Platform have a selection of Slocum, Seaglider and Spray gliders. Sistema de Observacion y Prediccion Costero de las Islas Baleares (SOCIB) have four gliders. Instituto Mediterraneo de Estudios Avanzados (IMEDEA) have built on an original fleet of four to create a fleet of seven. The Council for Scientific and Industrial Research (CSIR) is one of the leading research institutes in Africa. At part of its development CSIR purchased two Seagliders.

Woods Hole Oceanographic Institute has a Spray glider and a fleet of 20 Slocum gliders. University of Fairbanks Autonomous Remote Techology Lab use Teledyne Webb Slocum gliders. Rutgers University Costal Ocean Observation Lab (COOL) have a fleet of four Slocum 1000 gliders. The Robotic Embedded Systems Laboratory (RESL) operate two Slocum 1000 gliders. However, University of Fairbanks also use the Exocetus platform for the ANT LLC littoral glider. The littoral gliders is designed for used in coastal environments with increased stability. University of Connecticut uses two Slocum gliders adapted for use in coastal settings. University of Hawaii School of Ocean and Earth Science and Technology (SOEST) operate a Seaglider. The NURC facility at the University of North Carolina Wilmington (UNCW) operate a Pelagia glider.

MARS at NOC operate Slocum and Seaglider gliders. The predominance of global institutes operate Teledyne Slocum gliders have operational water depths of 1000m. equipped with CTD. The iRobot Seagliders are commonly fitted with CTD, backscatter sensors, fluorometers and dissolved oxygen sensors. The Spray glider from Bluefin is equipped with CTD, dissolved oxygen sensor, fluorometer and turbidity sensor. Currently the NOC fleet of gliders are predominantly off-the-shelf commercial products. However, sensor and vehicle development will potentially set the NOC fleet apart from other research gliders.

Within the UK and Global Commercial Sectors

The Slocum gliders are developed and produced by Teledyne Webb. iRobot produced the Seaglider vehicle at the Seaglider Fabrication Centre (SFC) at the University of Washington. Production of the vehicle has ceased with work now focused on providing services to the current customers. Spray gliders are currently being produced by Bluefin robotics. Exocetus produce the Coastal Glider which is able operate in shallow water coastal environments. This platform can be fitted with dissolved oxygen sensors, hydrophones and Caesium-137 radiation sensor. Mote Marine Laboratory have produced the Waldo glider fitted with CTD sensors as well as red tide sensors and a fluorometer. The SeaExplorer from ACSA Alcen is equipped with CTD, dissolved oxygen sensor, backscatter, fluorometer, RDI current profiler, ACSA acoustic profiler, and altimeter.

The NOC fleet represents off-the-shelf commercial vehicles. However, current research and development at NOC will potentially broaden the types of data measured by these instruments, and broaden the payload capacity beyond the commercial specification.

Current Application and Development of AUVs and Gliders within the Renewable Energy Sector

The following results and discussion arise from a telephone conference call with members of Gardline Marine[4] and a later formal meeting with Kongsberg Hydroid[5].

Data Collected and Potential UUV Application

Future and current sites for wind farms need to be monitored for potential geohazards prior to foundering of infrastructure and to monitor infrastructure for their impact on the seafloor and development of future geohazards. For geological pre-installation site surveys geological (predominantly Quaternary) and hydrographic data are required. Therefore the information sought primarily regards accurate sea floor bathymetry (swath bathymetry), seafloor composition (sidescan sonar) and gross seafloor structure (shallow high-frequency seismic reflection). These geophysical data can be calibrated by seafloor sampling, which cannot be completed with purely AUV or glider surveys, or in part by seafloor photography. Both these geophysical data and photography can be collected using AUVs and ship-board instrumentation.

Hydrographic data, such as current velocity, is required for modelling of infrastructure impact on the seafloor and for design of installation strategy. This information is commonly gathered by ship-board instruments or through the use of buoys. However, gliders with ADCP could potentially be deployed over large swaths of seafloor to understand current intensity. However, often currents at certain depths especially near the sea bed are most valuable data, which promotes use of an AUV capable of surveying at a constant designated depth.

Once infrastructure has been installed, continued monitoring is essential. Monitoring of existing bathymetry within a developed site and monitoring of localised current velocity are amongst the most important data required, especially concerning the development of scouring around pilings. The presence of infrastructure presents an added risk to vehicle deployment, which will be dealt with later, however in regards to data acquisition only, both AUV and glider surveys would be capable of collecting this data. Although in specific regards to scouring, ROVs are currently used by the hydrocarbon industry to monitor this around sea floor pilings.

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[4] Gardline members part of the telephone conference call on Tuesday 2nd April 2013 included Liam McAleese and Gavin Campbell.
[5] Graham Lester of Hydroid Southampton represented Kongsberg.

Rationale for Adopting AUVs and Gliders

Cost-benefit is the primary control on the adoption or not of AUVs and gliders for marine mapping in open water where infrastructure is not present. The value of data gathered by AUVs, which is primarily geophysical data, permits their use ahead of gliders. Due to the cost of AUVs and the often short duration of operation (6-24 hours) the deployment/recovery vessel remains in the vicinity of the survey. Therefore AUV surveys are expensive operations, although there can be cost-benefit when planned coring, other seafloor sampling or other data collection can be completed synchronously by the deployment/recovery vessel while the AUV completes a geophysical site survey. Indeed seafloor sampling has become essential for testing the geotechnical properties of the soils in which infrastructure would be founded. Therefore there is potential to exploit multidisciplinary cruises using AUVs to save time on surveys.

However, ultimately the geophysical data still has to be of monetary value, enough to warrant mobilisation and deployment of a deployment/recovery vessel. This 'monetary value' is primarily controlled by data quality afforded to by use of an AUV. In deep water (above 700-800m water depths) the AUV can be programmed to gather data 20-40m above the sea floor, therefore collecting higher resolution and higher quality data compared to ship-board or towed instruments. In water depths below 700m the cost benefit of collecting AUV data verses ship-board data is reduced. AUVs are also capable of gathering geophysical data unaffected by noise introduced during poor weather; however deployment and recovery is often not safe in poor weather and operations in shallow water during these periods incur higher risk of loss of vehicle. Therefore on cost-benefit AUV application to initial site mapping is primarily restricted to water depths of more than 700-800m. This will change as the cost of construction and purchase of AUV declines, however at present AUV cost and the risk of loss is too high.

Issues of Deployment of AUVs and Gliders for Mapping and Monitoring of Wind Turbine Installations

There are additional issues to consider with the use of AUVs and gliders within both open-water mapping and later monitoring of developed sites. These sites are often in less than 50m water depths and therefore shelfal current activity is often higher (above 2-3m/s). Current activity firstly interferes with navigation, which can affect data quality and potentially even result in loss of vehicle in extreme circumstances. The effect on navigation, especially in complex terrain, is the primary risk to loss of vehicle through collision. Although geophysical data would remain unaffected, photographic suites are ineffective in areas of high turbulence due to poor visibility created by suspended sediment.

With the presence of infrastructure, deployment of automated vehicles has increased risk due to the risk of collision. This is further increased due to increased current activity and turbulence in regions of infrastructure, which affects navigation. Indeed, even ship-board surveys in development sites is not ideal. Due to the cost of AUVs and the current low value of data used to monitor sites, deployment of AUVs to complete repeat surveys in developed sites is not recommended. When the cost of AUVs and their deployment decreases the use of AUVs in repeat surveying of already developed sites may increase. Certainly an ambitious aim would be to have an AUV seconded to a particular wind farm with a docking station from which it can be deployed autonomously without need for surface vessels; however at present the cost of AUV technology and then singular secondment to one site is too great for this to be realised at present.

Although repeat surveys are conducted on developed sites to monitor physical impact on the seafloor. There is currently not a drive for monitoring of site impact on benthic or necktonic communities. AUVs could be deployed for seabed photography, both active and passive acoustic monitoring of the habitats and monitoring of bio-fouling. However, there is not currently government directive for biological monitoring of sites before installation or monitoring of developed sites, thus no drive for AUV application from this perspective. Furthermore, although bio-fouling is important to monitor, AUV cost and accuracy of navigation negate their deployment under this premise, with ROVs currently being used.

Other risks such as interaction with shipping vessels, interaction with fishing gear and vehicle reliability are less specific and covered in another broader section.

In regards to the data, geophysical data is predominantly collected. However, physical properties are not calibrated. This reduces the direct quantitative comparison of repeat surveys. A potential future development for AUV deployment can be to complete calibrations of sensors to provide fully quantifiable data.

Cost, Logistics and Risk associated with incorporating AUV and Glider Operations with current Commercial Surveying Operations

Whether or not the use of AUVs and gliders in ocean and seafloor surveying by the renewables sector is viable is regards to the applicability of data obtained. The cost, logistical requirements and the risk associated with incorporating AUV and glider operations into marine surveying ultimately control their application.

Cost and Logistical Implications of AUV and Glider Incorporation into Marine Surveying

Due to sensitivity of publishing costs incurred by companies for development and deployment of AUVs, neither Gardline nor Kongsberg were able to report. This was also an issue found when approaching Fugro.

Risk Associated with incorporation of AUVs and Gliders in Marine Surveying

There is a variety or risks associated with AUV and glider operations. These risks include: tidal currents, shipping traffic, fishing, turbidity and offshore infrastructure. This becomes pertinent to the renewables sector, since current and planned infrastructure is most commonly located on the shallow water shelf regions.

Tidal Currents

In regions of strong tidal currents the planned mission path and indeed the data quality (inadvertently affected by vehicle stability) may be affected. AUVs generally transit at speeds of 3-4 knots (1.5-2.0 m sec^{-1}), where currents peaking at speeds a third of this transit speed (0.5-0.8 m sec^{-1}) may cause problems with navigation and data quality[6]. However, both the NOC Autosub 6000 and the REBUS (REMUS 600) at SAMS have been deployed in costal settings in the UK[7,8]. Indeed, data collection

[6] Wynn, R.B., Bett, B.J., Evans, A.J, Griffiths, G., Huvenne, V.A.I., Jones, A.R., Palmer, M.R, Dove, D., Howe, J.A, Boyd, T.J. and MAREMAP partners (2012), *Investigating the feasibility of utilizing AUV and Glider technology for mapping and monitoring of the UK MPA network*. Final report for Defra project MB0118. National Oceanography Centre, Southampton. 244pp.
[7] Boyd, T. et al. (2010), AUV observations of mixing in the tidal outflow from a Scottish sea loch, *Proc. AUV.*, IEEE.
[8] Bett, B> Le Bas, T.P., and Coggan, R. (2012) Case Study 2: Shallow-water AUV mapping off SW UK, In: Wynn, R.B., Bett, B.J., Evans, A.J, Griffiths, G., Huvenne, V.A.I., Jones, A.R., Palmer, M.R, Dove, D., Howe, J.A, Boyd, T.J. and MAREMAP partners (eds) (2012), *Investigating the feasibility of utilizing AUV and Glider technology for mapping and monitoring of the UK MPA network*. Final report for Defra project MB0118. National Oceanography Centre, Southampton. 244pp.

from the Autosub 6000 remained high at Haug Fras, although minor navigational drift was monitored[6].

Figure 2.1 of Wynn *et al.* (2012) show the peak neap and spring tidal current speeds and can be used to highlight locations of potential risk. These locations are limited to shallow water shelfal areas especially around river estuaries and within the English Channel, Bristol Channel and North Channel. Infrastructure, both current and planned, for the renewables sector lie predominantly within the shelfal regions of the UK, and within water depths and tidal regimes that could potentially affect AUV navigation. Therefore excellent local hydrographic information is required before designed a geological sea bed survey either using/not using AUVs. Applications of gliders within these settings is not recommended, both of the count of the usefulness of the data they acquire, in regard to site surveying for renewables, and due to their susceptibility to navigation drift in high currents.

Shipping Traffic

Boat strikes are at highest risk while the vehicle is surfaced. AUVs and gliders surface at the end of their operation, but also when there is an unexpected fault or there is a mission interruption. Figure 2.4 of Wynn *et al*. (2012) demonstrates the density of shipping tracks (of large commercial vessels) in UK waters. Regions along the South Coast, English Channel and North Channel show the highest density of traffic. With much current and planned infrastructure located on the shelf and within potential shipping regions risk the risk of collision is important to consider.

Fishing

There is also risk of entanglement and/or damage to AUVs and gliders in areas with a high density of fishing activity, especially where static or mobile trawling and gill-netting are in operation. Using analyses of Witt and Godley (2007) it is possible to identify the regions of highest risk are: western English Channel, Celtic Sea, around Orkney and Shetland Islands, and at the shelf edge close to Goban Spur and Porcupine Bank[9]. Wynn *et al.* (2012) also identify pelagic trawling as a possible risk, indeed Coull *et al*. (1998) show that trawling is undertaken increasingly within the western Channel, Dover Strait, North Sea an Irish Sea.[10]

[9] Witt, M.J., and Godley, B.J. (2007), A step towards seascape scale conversation: using vessel monitoring systems (VMS) to map fishing activity, *PLoS One*, 10, E1111.
[10] Coull, K.A., Johnstone, R., and Rogers, S.I. (1998), Fisheries sensitivity maps in British waters, Published and distributed by UKOOA Ltd. Available at http://www.Cefas.Defra.gov.uk/media/29947/sensi_maps.pdf, accessed 5th September 2012.

Local knowledge of fishing regions is important to try and mitigate this risk. Coupled independent AUV surveying with ship-board work will at least enable rapid location and recovery of a vehicle at the end of an operation or having surfaced under fault.

Turbidity

The amount of suspended sediment in the water column and the currents suspending that sediment can have affects primarily on photography. High turbidity has been recorded in the Irish Sea, southern North Sea, and northern English Channel[4]. Turbidity should not directly affect geophysical surveying techniques.

Sea Bed Infrastructure and Marine Protected Areas

Although identified in the Wynn *et al*. (2012) report, the presence of sea bed infrastructure and location of marine protected areas should be identified by those planning the surveys. Surveys should be planned accordingly to avoid these regions.

Process for Calculating Reliability of AUV or Glider Deployment

Thus far in this report risk to the vessel and/or data has focused on external factors. However, vessel reliability is one of the most prominent risk factors to consider. Failure of systems may result in premature mission abortion, resulting in vehicle surfacing. This not only requires mobilisation to recover the vehicle earlier than expected, but also places the vehicle in increased exposure to collision from shipping and fishing activity. Where systems failures and mission abortion is not simply a sensor malfunction or minimal electrical damage, then often lengthy down-time is incurred for maintenance; resulting in either loss of field time or added expenditure for data collection. However, systems failures could ultimately end in the loss of the vehicle, especially when navigation or altimeter electrical failures are considered. Therefore unless in deep water >700-800m where there is cost benefit of data collection and quality against loss of vehicle, ship-board data collection is often preferred.

For terminology, from this point on, a fault is defined as a minor malfunction that results in mission abortion but safe vehicle recovery and damage <$1million, whereas a mishap is defined as loss of the vehicle or recovery of an reputably damaged vehicle.

In regards to fault analysis of two REMUS-100 vehicles, it was found that the mean fault recurrence time was 1.3hours.[11] Of these faults, 92% of the faults incurred were one of seven specific minor faults.[11] These seven faults include:

1. Vehicle bioluminescence data is old/corrupt.
2. Depth sensor is noisy – including self test failure with mission pause, sensor misread or single value missing.
3. Ground fault.
4. Delay in vehicle dive from surface.
5. Self test for altitude failed resulting in mission pause.
6. Vehicle at low altitude and executing emergency climb.
7. Bad conductivity reading for ocean salinity.

Although these statistics are not impressive 91.5% of the missions sampled were deemed to be successful. Furthermore, in regards to mission aborts, only 14.8% were fully automated aborts not sanctioned by the operators.[11]

It is inherent that with automated systems there will be issues with reliability. This is further compounded by differences in opinion from experts in regards to probability of loss of vehicle across a spectrum of environments, which were found to differ but up to two orders of magnitude. This range in derived probabilities has resulting in the production of survival modelling using mathematical aggregation from which more realistic mitigation strategies can be developed utilising both optimistic and pessimistic scenarios.[11]

Mathematical aggregation of expert judgements of risk has been taken further by application of a Bayesian behavioural approach.[12] Kaplan-Meier probability of survival for the Autosub/Explorer-class of vehicle showed that probability declined rapidly for the first 50km of transect, remaining constant for the bulk of the 250km transect before declining again in the last 10-50km of the mission. This demonstrates that the most likely faults occurred during the initial period after the vehicle become autonomous, and that if this period is completed unperturbed then at least 95% of the mission is likely to be completed.[11] A further result from application of Bayesian behavioural approaches to risk assessment, is that Kaplan-Meier probability of survival was markedly higher when fault mitigation strategies were in place.[11]

[11] Griffiths, G., M. Brito, I. Robbins, & M. Moline (????), Reliability of two REMUS-100 AUVs based on fault log analysis and elicited expert judgment, *Proc. Symp. on Unmanned Untethered Submersible Technology*, Durham, NH, AUSI.

[12] Brito, M., G. Griffiths, J. Ferguson, D. Hopkin, R. Mills, R. Pedersen, & E. MacNeil (2012), A Behaviour Probabilistic Risk Assessment Framework for Managing Autonomous Underwater Vehicle Deployments, *J. Amer. Metero. Soc.*, 1689-1703.

Therefore probabilistic approaches to risk assessment not only identify missions with unreasonable risk, but where there is moderate-to-low risk these procedures can allow pre-launch mitigation strategies to be established. Furthermore by application of Bayesian behavioural approaches, which enable experts to discuss and review judgements on risk, rather than simply mathematical aggregation of expert judgements provide a more unbiased view towards risk and especially towards loss of vehicle.

Conclusions and Recommendations

Firstly the original key questions will be addressed:

1. Develop a better understanding of customer and end-user (Renewable Energy Sector) awareness of MARS activities, instrumentation and planned developments.

   Contacts have been established and approached for open discussion at companies representing developers of AUVs (namely Kongsberg) and representing end-users of AUVs and their data within the renewable energy sector. Awareness of current MARS activities and future development has been achieved.

2. Identify where the MARS group is situated within a global context of provision of AUVs and gliders for scientific and commercial operations.

   A global survey of AUV development and deployment has been completed and the location of the MARS group within both academic and industrial sectors has been completed.

3. Identify the main parameters being measured by AUV/gliders, and identify which parameters are most useful for commercial operators (specifically the Renewable Energy Sector). Determine how useful the data acquired is for meeting the survey needs.

   Geophysical data including swath bathymetry, sidescan sonar and shallow seismic reflection surveys have been highlighted as the key end-user data sets, in addition to sea be photography and current velocity data. Data collected by AUVs is deemed most useful, when compared to gliders.

4. Identify what the main drivers for adoption of AUV/glider technology.

   The main drive for the adoption of AUVs with surveying for the renewable energy sector is cost-effective acquisition of high-quality data. A second drive is the autonomous collection of geophysical survey data whilst additional seabed sampling or data collection is completed.

5. Identify issues and barriers for inclusion of AUV/glider surveying in routine expeditions and what the logistical and cost implications of running mixed survey technology.

   In water depths exceeding 700m data collected by AUVs are used because of the cost-benefit of data acquired. At these water depths there is a benefit of the data quality acquired from an AUV surveying 20-40m above the seafloor. In shallow water depths, especially on the shelf, there is reduced cost-benefit of data collected by AUVs compared to that from ship-board surveys.

6. Identify what additional training (if required) and/or logistical support would be needed to support inclusion of AUV/glider surveying into established surveying methodologies.

   AUV programming training would be offered by developers of AUV should a vehicle be rented or purchased. However, application of AUVs with surveying sites for the renewable energy sector is not established.

7. Identify the additional risk involved with conducting surveys in the regions targeted by the renewable energy sector.

   Risks during open water surveying include: inadequate up-to-date bathymetric charts to combat collision avoidance, strong currents, collision with shipping or fishing apparatus on surfacing and data quality. Risks during repeat monitoring of a developed site include: increased turbidity affecting navigation and data quality, and collision with infrastructure.

8. Determine to what extent validation of glider data is required to enable comparisons with other field data. Determine whether repeat surveying is required.

   Currently geophysical data are not calibrated. Repeat geophysical surveying is important for developed sites to monitor impact on the seafloor of the installed infrastructure. Repeated photographic and acoustic surveying may be used to monitor sea bed and water column biota. However, impact of installations on the environment and biota has not been legislated and policy does not exist.

Given the results of the discussions with those actively involved in surveying sites for the renewable energy sector, it can be stated that at present ship-board surveying is preferred to that of AUVs. This is based primarily on cost-benefit of the data potentially collected and the risk of loss of vehicle. Since wind turbine farm development in offshore regions is limited to the shelf regions, at present there is therefore limited use for AUVs within the renewable energy industry.

When AUV manufacture is reduced and there are improvements to how AUVs maintain navigation and cope with strong currents, then AUV application can be readdressed.