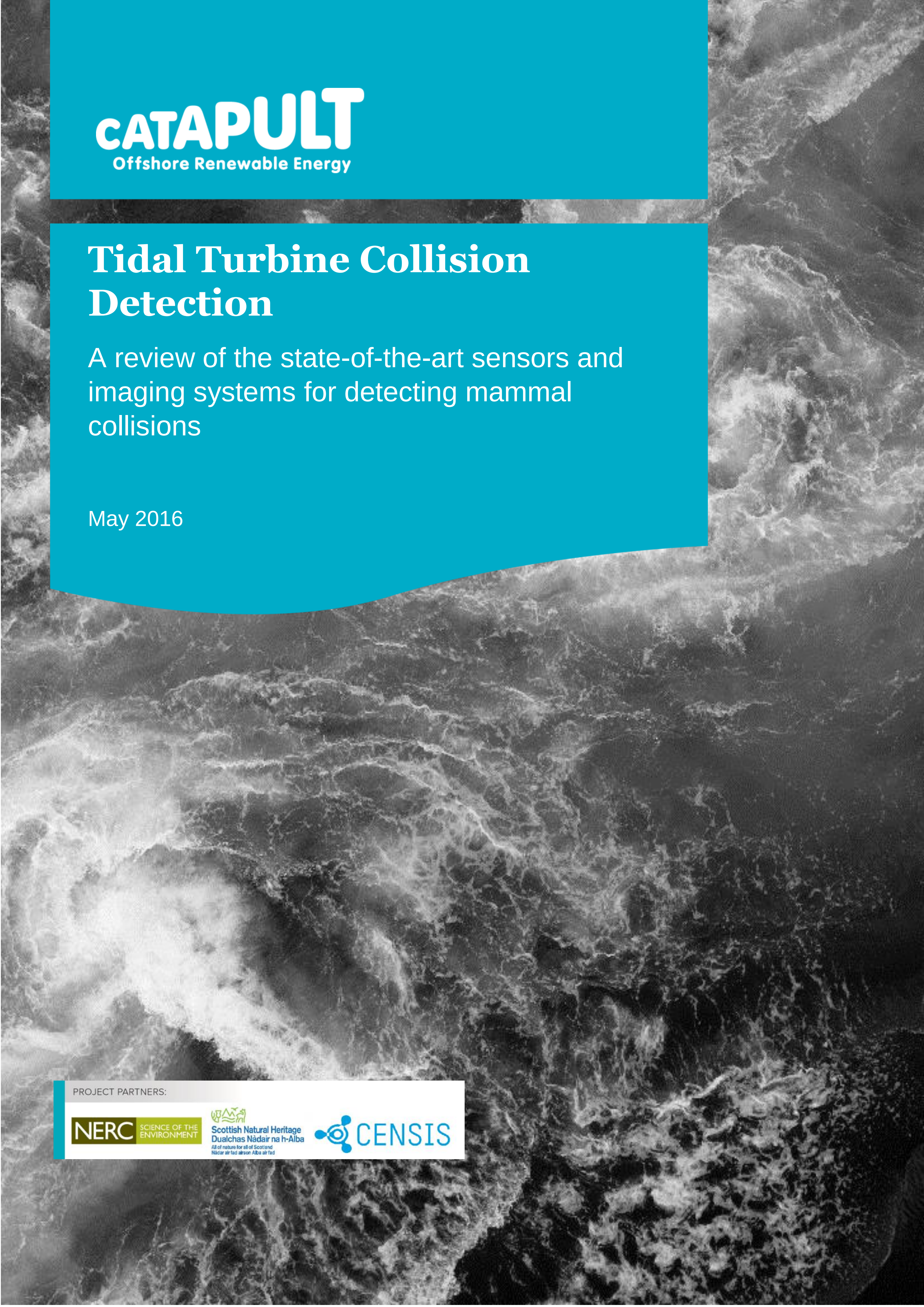

Catapult
Offshore Renewable Energy

Tidal Turbine Collision Detection

A review of the state-of-the-art sensors and imaging systems for detecting mammal collisions

May 2016

PROJECT PARTNERS:
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Disclaimer

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Abbreviations

ADCP	Acoustic Doppler Current Profiler
CENSIS	Centre for Sensor and Imaging Systems
DFKI	Deutsche Forschungszentrum fur Kunstliche Intelligenz
DNV	Det Norske Veritas
EIA	Environmental Impact Assessment
EM	Electromagnetic
EMF	Electromagnetic Field
EMEC	European Marine Energy Centre
ER	Environmental Requirement
EU	European Union
FAST	Fundy Advanced Sensor Technology
FLOWBEC	Flow and Benthic Ecology 4D
FP7	Seventh Framework Programme for Research
FR	Functional Requirement
GUI	Graphical User Interface
HD	High Definition
HDD	Hard Disk Drive
HRA	Habitats Regulations Appraisal
IR	Infrared
LED	Light Emitting Diode
MEMS	Microelectromechanical Systems
NERC	Natural Environment Research Council
NOAA	National Oceanic and Atmospheric Administration

NPL	National Physical Laboratory
OEM	Original Equipment Manufacturer
ORJIP	Offshore Renewables Joint Industry Programme
QTC	Quantum Tunnelling Composites
ReDAPT	Reliable Data Acquisition Platform for Tidal
SAMS	Scottish Association for Marine Science
SIS	Sensor and Imaging Systems
SMRU	Sea Mammal Research Unit
SONAR	Sound Navigation And Ranging
SpORRAn	Scottish Offshore Renewables Research Framework
SSD	Solid State Drive
TEL	Tidal Energy Ltd
TRL	Technology Readiness Level
TTCD	Tidal Turbine Collision Detection
TVL	Television Lines
UTOFIA	Underwater Time of Flight Image Acquisition
UV	Ultra Violet
WTKN	Wave and Tidal Knowledge Network

1 Executive Summary

This report presents the findings from a review of state-of-the-art sensing and imaging (SIS) technologies relevant to Tidal Turbine Collision Detection (TTCD) application. The study includes an assessment of the approximate technology readiness and the applicability of marine animal collision detection technologies and devices being proposed, in testing and development or already deployed in prototype tidal turbine projects.

There are a number of challenges in collecting the supporting evidence of marine animal collision events; the principal challenge is the monitoring environment and the deployment and operation of sensor systems in this. Highly energetic tidal flows are characterised by high levels of noise from the turbine and from the moving water, variable levels of water turbidity and abrasive materials moving at high velocities. Another challenge is the low maturity of some applicable sensor technologies and the need in each case to collect a sufficient body of data in a short time span to validate the technology design, conclude an optimal system and determine with high certainty that a turbine blade has collided with, or nearly collided with a marine animal.

This report attempts to identify benefits, constraints, barriers to implementation, technology readiness level (TRL[1]) and recommendations on the next steps to further development. The report describes available and emerging sensor technologies against the following stated TTCD detection needs:

- proximity/collision warning
- collision detection: object striking tidal turbine blade
- post-event condition monitoring: identify and warn of structural damage to turbine blade (e.g. hairline fracture)
- post-event object identification: differentiate between animal or debris following impact

The SIS technologies explored in this report include hydrophones active sound navigation and ranging (sonar), video camera and optical imaging, blade mounted strain gauges, blade-mounted accelerometers, electromagnetic field sensors and tactile sensing technologies. Also addressed are approaches to system architecture. The principal knowledge gap area is SIS to monitor post collision events. The principal evidence gaps are data for sonar imaging and tracking and blade collision impact. A collaborative mechanism to share relevant evidential SIS data would be helpful in progressing the closure of some of these gaps. Seven areas for further study have been suggested including the identified knowledge and evidence gaps, and also suggests feasibility studies to explore emerging technologies that may have additional value in TTCD. Financial resources remain a barrier to progression, with some tidal developments reaching the point of implementation but lacking sufficient funding to deploy and run

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[1] The measure of technology readiness used in this report: high TRL (7-9; system test, launch and operations), medium TRL (4-6; development of demonstrator to demonstration), low TRL (1-3; basic research to proof of feasibility)

comprehensive trials with the application. A common test and development site that implements some of the SIS that require further data input may help standardise experimental results and provide an economically viable opportunity to trial new approaches and technologies..

2 Introduction

Tidal turbine renewable energy developments require an Environmental Impact Assessment (EIA) and also a Habitats Regulations Appraisal (HRA) before a Marine Licence and Section 36 (if the project is >1MW) are granted. Part of the consenting process includes the developer taking measures to gather scientific evidence to identify the probability of marine mammals colliding with their turbines. Evidence from tidal turbine deployment completed to date indicates there are no known mammal collisions with a tidal device. The need for marine mammal collision detection is identified as a priority by the Offshore Renewables Joint Industry Programme (ORJIP) Ocean Energy[2] in order for offshore marine energy array consenting to become a viable proposition at scale.

Monitoring requirements vary from site-to-site, but can include:

- animal behaviour around turbine structures (e.g. can they detect turbines, do they avoid them, can they escape tidal stream, etc.),
- quantification of number of collisions and near misses (accuracy of assumed or modelled impact),
- outcome of animal collisions (injury/damage to animal, without evidence each collision assumed to be fatal),
- identification of object/species types (vs. behaviour and impact).

Working towards the accumulation of monitoring evidence a significant level of research and development of technologies for TTCD systems has been undertaken over the last decade. Academia, developers and manufacturers within the UK are leading contributors. This body of work has contributed to a number of TTCD system designs and approaches, which vary in complexity and which can include more than a dozen functional requirements. There is significant technology development on-going across a range of sensor technologies to meet these functional requirements.

The following sections describe and explore the TTCD approaches made to date, starting with the investigation approach adopted to capture information from relevant sources. What is clear is that developers have adopted or intend to adopt broadly similar approaches, some more comprehensive than others. Common to all is the assembly of a suite of TTCD devices that work in tandem within a system to track a sequence of events, namely the identification of an object of interest in the area, proximity of the object to the turbine and contact of the object with the turbine blade. To this end the common approach is use of a combination of acoustic sensors as proximity alerts (hydrophones and sonars) and imaging systems (imaging sonar and video camera) to evidence what type of object has triggered the proximity sensors.

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[2] http://www.orjip.org.uk/oceanenergy/about

3 Investigation Methodology

The starting point for this phase of the study was to take the findings of the Interim Report. The study sought to articulate key technical requirements and environmental factors or constraints for TTCD sensors systems.

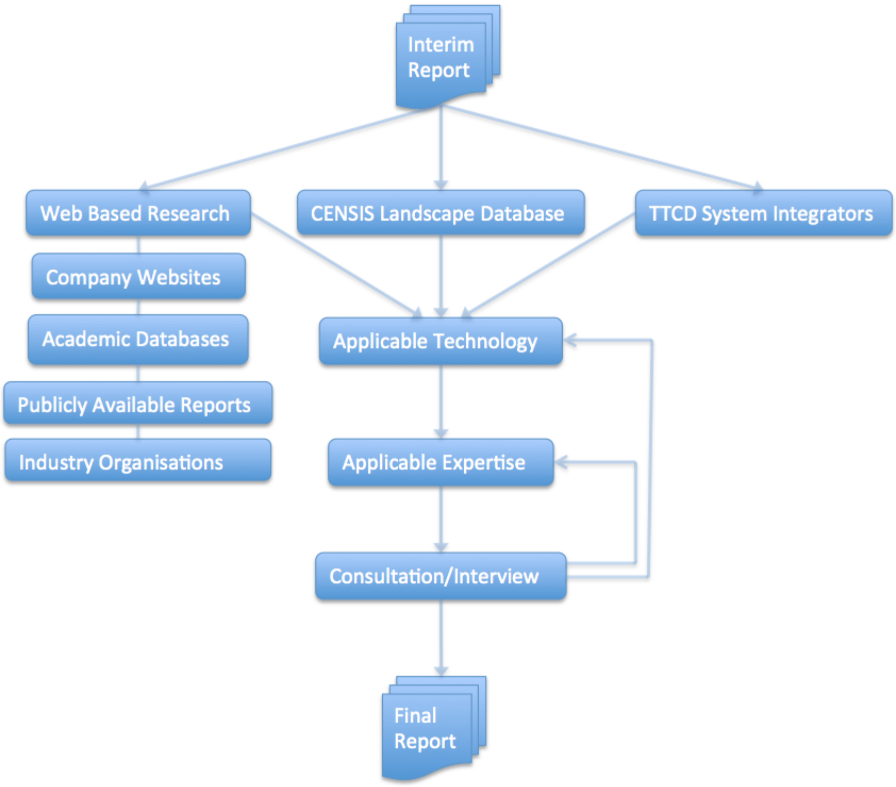

Figure 1 process flow of the investigation methodology

Figure 1 illustrates the activities undertaken to expand on the Interim Report. Three strands of investigation were pursued: (i) web-based research evaluated publicly available information sources to identify expertise and assess any knowledge gaps, interrogation of applicable or related technology company websites, search of databases of academic expertise and publications, review of related available reports and contact made with related industry organisations; (ii) internally at the Centre for Sensor and Imaging Systems (CENSIS) we reviewed our academic landscape database and industry capability; (iii) further discussion with TTCD system integrators explored initial technology ideas, their confidence in new technology suggested and any integration considerations.

The outputs of these investigation activities were combined to create a matrix of demonstrated or prospective technologies mapped against the four detection needs and their known maturity level and relevance. This matrix evolved with time and was updated as more information followed during interviews (section 6, Table 7).

The next stage was to identify and contact appropriate experts in each category of sensing technology, i.e sonar, optical camera, hydrophone etc. Experts were sought from academia (relevant research groups) and industry (operational/environmental experience). Appendix 1 summarises the technologies selected and the basis for selection of related experts. At least two individuals or organisations were identified against each technology category assuming not all those contacted would be able to support a discussion on this topic. Geographical location was not a constraint in this exercise; interviews included individuals and organisations in the UK, Europe, Canada and USA.

Those experts willing to contribute to this study were interviewed mostly via telephone conference calls but sometimes in face-to-face meetings or via email; Appendix 2 summarises the interviews and consultations held. Each interview was structured around a questionnaire; the questions were based upon technology applicability against one or more of the detection needs and the capability of the product or technology proposed as a solution. As far as the interviewees were willing to discuss, the consultation also captured any on-going improvements or developments being made to the products or technologies or any significant or potentially disruptive innovations. On concluding the discussions, interview notes were created and communicated back to respondents for cross-verification of facts and figures. On verbal agreement with the respondents these notes form a confidential aspect to this report. These interview notes and subsequent research and analysis form the basis of this report.

4 Requirements for TTCD Systems

4.1 System Description

4.1.1 Introduction

In order to provide evidence to help reduce uncertainty, supply chain partners in the marine energy industry are in the process of developing TTCD systems to be deployed alongside prototype turbines. Figure 2 is a representation of devices and approaches that have been adopted/proposed wholly or partly by developers in their TTCD systems. Some of the sensors are embedded in the turbine blades and others located around the turbine site. The typical detection needs are also presented graphically. The detection needs as well as the SIS technologies are elaborated in the following sections.

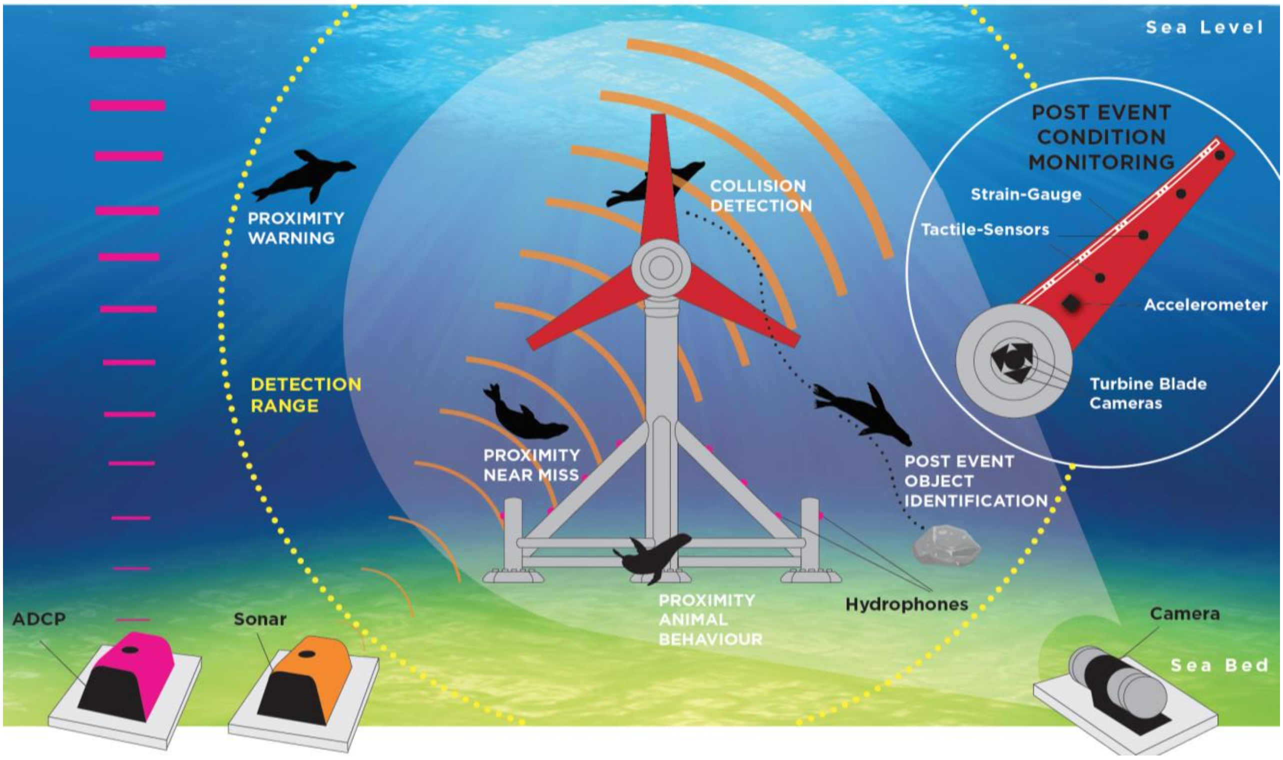

Figure 2 a representative diagram indicating tidal turbine collision detection requirements and sensors

4.1.2 Proximity Detection

Proximity is a relative term and during the course of the consultation this was used with respect to three different scenarios within the TTCD system:

i) Proximity Warning Using Instrumentation

The principal proximity warning device is active sonar, which is sometimes supported by passive sonar (hydrophones) and/or video camera. Ideally, a proximity sensor should provide an alert about collision risk, derived from understanding animal movement and the closest point to the blade where collision seems unavoidable. This ‘fine scale’ behaviour is not yet fully understood.

Proximity sensors have been used in different ways in TTCD. A signal that aligns with a set of preprogramed criteria can be used (and has been demonstrated operationally by the MCT project at Strangford Lough) to action a shut-down of the turbine to reduce the risk of mammals in the proximity colliding with blades. A second example is a warning can be used to automatically trigger a sequence of actions in other devices making up the TTCD system. An approach proposed for a deployment at a site off the coast of Pembrokeshire will use a proximity signal from an active sonar device to switch devices from standby/data re-write mode into record and store mode. The purpose of this approach is to optimise the opportunity to capture all available SIS data in context of a collision impact event.

The detection range of acoustic-based sensors and camera equipment limits the distance between object and turbine at which a proximity alert is effective. Furthermore, active sonar has to operate outwith the audible frequency ranges of marine animals to avoid altering the animals' behaviour (attraction or exclusion) or causing their distress. The frequency ranges permissible are not far ranging and range is further affected by water turbidity. In recognition of a potential new market, sonar hardware has been enhanced by some Original Equipment Manufacturer (OEMs) to deliver devices that meet the specific needs of TTCD. These have applied different operational modes and highly advanced signal interpretation methods to identify relevant objects.

As a general guide for active sonar the proximity range can be estimated as the volume of water within a sphere of between 30 and 60m radius depending on device, operational mode and water turbidity. The siting of the sonar device in the area is important, for example if the device is located at the base of the turbine looking outwards and has a minimal proximity threshold of 30m, for a marine animal moving at a speed of 10m/s a sonar at the base of the device would only have 3s to trigger an action; if that is the main function of the sonar. In this case they will need to be placed further away from the device.

Passive acoustic systems (hydrophones) can capture sounds from marine animals over the order of around 200m. However these are only useful for detecting some species during vocalisation. Furthermore the distance of, and the direction in which an animal is moving is challenging to pinpoint when they cease to vocalise. If the location of an animal is required, multiple hydrophones are required.

Optical video camera systems have been used in proximity alert but have limitations. Camera images are, like sonar, affected by water quality. Furthermore, artificial illumination is not permissible in TTCD so insufficient daylight also contributes to image quality. The best use of cameras is to observe the blades to capture an impact event, or deployed on the seabed to ground truth data from hydrophones and active sonar systems

ii) ***Proximity Animal Behaviour***

In relation to the question of whether marine animals are aware of and able to avoid turbine blades, developers and the scientific community agree that understanding animal behaviour (movement and vocalisation) within the proximity (10m to 60m) of the turbine is the most important, but as yet poorly understood area. Data from TTCD systems will contribute towards this broader understanding. In this task multi-directional (or 3D) hydrophone systems, imaging and tracking sonar and camera systems have been employed in for both species identification and location.

The individual devices making up a TTCD system need not work in isolation and information from tracking and imaging sonars, video and hydrophones can be combined to understand a sequence of events and movement of animals in the vicinity of the turbine. Tracking the animals will inform their general trajectory towards turbines with estimated velocities, and also if their movement might be related to foraging, feeding or other. These will all be helpful in improving understanding of behaviour.

iii) ***Proximity Near-Miss***

Close proximity is defined as a separation of less than a few metres from the turbine blade. An important gap in the tidal turbine field of knowledge is the understanding if marine mammals can navigate through and around the blades without colliding with them. Every device in a TTCD system is important in the determination of near miss. Imaging techniques, sonar, hydrophone and camera, can be helpful to inform a near-miss event but generally the current technology has difficulty to, or is unable to provide validation of it. This is where other parts of the TTCD system situated on the blades will contribute. An impact sensor installed in the turbine blade, a stress sensor at the root of the blade and video camera systems on the hub are approaches made by developers to capture and validate the near-miss/collision impact moment.

4.1.3 Collision Detection

Developers are exploring at least one of three, different approaches to detect blade impact; these are mechanical impact signatures, noise signatures and video image capture. Sonar imaging cannot be used closer than 3 m to the blade as the cavitation and bubbles affect the quality of the image.

The mechanical signatures of an impact event; for example a shock or a significant increase in the bend or flex in a blade outwith its expected operating range may be registered using accelerometer or strain gauge systems specifically designed for this purpose.

Hydrophones are being explored to detect the sound generated during an impact event that propagates through seawater. Similarly, microphones attached inside the turbine body, which may already be part of the condition are also being explored for the ability to capture the sound of an impact. The TTCD system of a near scale demonstrator turbine to be deployed off the Pembroke coast has been designed to integrate data from strain gauges at the blade root, vibration from impacts via blade-mounted accelerometers and any changes in the drive train operation that might be detectable during an impact event. Combined with data from camera systems and active sonar the approach aims to link the moment of collision with an identified object in the proximity, or by the same inference by the absence of an impact signal, a near miss event.

Arguably, while the corroborative mechanical and acoustic data is being accumulated by the various test TTCD systems, aside from human observer, the only SIS method at this time that can conclusively validate a near miss is video camera. However the developers and camera specialists consulted for this study were in general agreement that a video camera has too many limitations to work effectively over time as part of a TTCD system. Not all areas of the blade might be visible in the operating conditions. Biofouling and abrasive currents would eventually impair the lens, and to capture images at the required quality at night would require artificial illumination which is not permissible.

Alternatives to video camera, the most direct and unambiguous SIS to detect an impact event could be tactile sensing which detects physical contact between two objects. Although integration of tactile sensors within the turbine blades may be a challenge for blade manufacturers and OEMs, if strain gauge and accelerometer systems are found to be inadequate, a feasibility to test this type of technology could be of value. The potential of tactile sensing in TTCD is described in section 5.2.8.

4.1.4 Post-Event Object Identification

Few of the TTCD systems appear to incorporate a device to specifically identify a post collision object. Instead it is planned this be informed through the combination of sensory inputs across the entire TTCD system. Fast tidal flows, turbidity and turbulence generally mean that locating, tracking and analysing objects downstream of the turbine following an impact with the turbine is highly challenging and may be impossible with current technology. Human observation is likely the only reliable input that can confirm post impact status of an animal with any degree of confidence. However, by combining the information of movement detected by sonar, camera and hydrophone it is envisaged that confirming an impact with a species of interest can be determined with a high-level of confidence.

4.1.5 Post-impact Condition Monitoring

The condition monitoring of the turbine blade is one of the more mature technologies as it is of primary importance to the asset integrity and therefore high on the turbine developers' priorities. Technologies here are inherited and modified from wind turbines and include fibre-optic strain sensors embedded within the turbine blade and accelerometers at the base of the blade. These provide information on motion and loads experienced by the blades during service.

4.2 Monitoring Requirements Informing Consenting Needs

Based on the understanding gained of TTCD systems during consultation with regulators, researchers, OEMs and developers, Table 1 outlines the functional requirements and corresponding sensing and monitoring needs identified as being important to build a strong scientific evidence base to support future environmental consenting.

It is important to note that none of the developers consulted believed such requirements will/can remain as important in the longer term as the scientific knowledge grows to support and inform consenting. As the sector is nascent and in continuous development, there are as yet no standards imposed on technologies, operations or processes, hence any parameters or their values included in this report are indicative and not conclusive. Tables 1 and 2 outline the functional and environmental requirements (FR and ER respectively) that apply to TTCD devices. These have been identified from the SIS perspective of developers and technology providers consulted during the study. Automation of these FRs is critical, as data analysis is expensive and time consuming.

Ref.	**System Area**	**Functional Requirement (FR)**
FR1	Proximity (including behavioural response)	Detect and identify presence of the species of concern around locality of turbine (>60m)
FR2	Proximity (including behavioural response)	Identify protected species and track their motion to alarm their approach towards turbines (60-30m)
FR3	Proximity (including behavioural response)	Track and map movement of animals over time whilst close to turbine (<30m)
FR4	Proximity (including behavioural response)	Locate animals with a resolution of at least ~1m
FR5	Collision or impact detection	Confirm a physical contact between turbine blades and any objects or species
FR6	Collision or impact detection	Measure impact force on turbine blades from object or species collision
FR7	Collision or impact detection	Determine location of contact or collision on turbine blades
FR8	Collision or impact detection	Differentiate between object and species collision and identify marine animal to species level or colliding object properties (density, shape, mass)
FR9	Post-event object identification	Map movement of protected species post-collision over time within locality of turbine
FR10	Post-event object identification	Obtain image and video of object/species before, during and post event (resolution: >1.3MP; time scale need to be identified based on validation data)

Ref.	System Area	Functional Requirement (FR)
FR11	Post-event condition monitoring (animal)	Identify if animals suffer immediate fatal injury
FR12	Post-event condition monitoring (turbine)	Identify critical changes to turbine performance after collision event (e.g. bearing load) and health of sensors

Table 1 TTCD Functional requirements

Ref.	Parameter	Environmental Requirement (ER)
ER1	Ingress Protection	IP68, Submersible to depth of 50m
ER2	Operating Temperature	-10ºC to +40ºC (based on the typical operational range for shallow water electrical equipment although acceptable range is 4ºC to 20ºC)
ER3	Storage Temperature	-20ºC to +30ºC
ER4	Mechanical Shock	Critical for application
ER5	Vibration	Critical for application
ER6	Hydrostatic Pressure	Operates at twice submersible depth
ER7	Corrosion	Seawater operation for 5 years
ER8	Bio-fouling	Operation for 12 months without maintenance to remove bio-fouling
ER9	Maintenance	Minimum 12 month operation without preventative maintenance

Table 2 TTCD Environmental requirements

5 Technologies

5.1 Introduction

A TTCD system requires a number of complementary technologies to be employed to fulfil the detection and monitoring requirements identified. To date there has been a significant body of research and development that has contributed to approaches and device designs applicable for TTCD. This section 5 describes the SIS technologies developed, tested and deployed to date to fulfil some of the requirements described in Tables 1 and 2. These technologies can be considered state-of-the-art in TTCD.

Also described in this section are existing and emerging SIS technologies identified has having potential value in collision monitoring but which have not (knowingly) been explored in TTCD. How devices are designed to work together as part of a whole TTCD system ‘architecture’ are described in the last part of this section, together with a technology summary table.

5.2 State-of-the-art of Relevant SIS Technologies

5.2.1 Introduction

SIS technologies which have the capability to fulfil some of the TTCD requirements are introduced in this section. Technology categories that were considered are outlined in Appendix 1, and include hydrophones, sonars, video camera, strain gauge and accelerometers, magnetic and electric field sensing and tactile sensing. An introduction to each discusses capability against detection requirements, parameters measured, technology readiness level and remaining challenges or further improvements.

5.2.2 Hydrophone, microphone and use of sound data

Hydrophones are passive acoustic devices and used in TTCD to support marine mammal identification and to varying degrees of accuracy, locate and track. Validation of mammal presence near turbines is achieved by either/all of human observer, camera and sonar imaging. Hydrophones are also used in turbine noise level assessment and to record mechanical noise for health monitoring purposes. They may have the potential to pick up the noise of a blade colliding with an object.

Hydrophones are capable of detecting marine mammals across several hundreds of km, although the vocal range of most mammals is significantly less. OEMs and marine mammal researchers are developing specialised detection algorithms that aim to differentiate between different marine animal species. There is evidence these can also identify individuals from within a group. Recent advancements demonstrate the possibility to locate mammal position in real-time, used as part of a whale-tracking network off the west coast of Canada[3].

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[3] Ocean Networks Canada (www.oceannetworks.ca/)

Drifting hydrophones deployed from buoys are favoured for TTCD applications because tidal sites have high background noise. These drift with the tidal current so as to minimise flow noise around the sensor. High tidal noise may limit the application of mammal characterising and tracking analytics in TTCD, similarly, while the devices have the potential to pick up the noise of a blade colliding with an object, advanced signal filtering would be required to accommodate background noise. Deployed from buoys near the turbine and signal filtering, blade impacts might be 13iscernible. The higher frequency sound generated by wear of rotor bearings is quite distinctive and can provide supplementary data in turbine condition monitoring. Microphones situated inside the turbine housing are used to record the acoustic signals of the drive train. Furthermore changes to loading on the blades may translate into changes in noise patterns in the drive train. The potential to pick up blade collision events through changes in noise patterns is being explored by at least one developer consulted.

The principal areas of hydrophone technology developments include: improved system design, incorporation of processing power, user interfaces, and species identification algorithms with tracking capabilities. This meets requirements FR 1 and FR2 (Table 1). By employing an array of hydrophones accurate tracking of species to within 1m around the area close to the turbine appears to be possible, thus meeting FR4 (Table 1).

Table 3 provides a sample of hydrophone products that have either been tested in TTCD or used in marine mammal detection. Devices are generally built to the specifications of the application including requirements for directionality and detection range. An appropriate frequency range is just the most fundamental requirement, advanced signal processing adds value to the hardware and additional benefits include on-board processing and the capability to auto-adjust the system for optimal signal capture in real time.

Features including animal identification, classification and visualisation remain the niche areas in hydrophones. In the tidal turbine monitoring context, hydrophone hardware is high TRL (8-9) while animal classifying algorithms are still under development at medium TRL (3-5). Algorithms are not deterministic but rather provide an indicative current, sufficient validation data set.

The next generation of hydrophones is likely to be more compact and require less power along with the smart features. The miniature hydrophone array in Table 3 exemplifies this trend. Regarding maintenance, a period of two years or above is required which is generally achievable by the OEM. Of special note is the observation that Titanium housing appears to discourage the formation of bio-fouling which will otherwise impair signal quality over time.

Company	**Ocean Sonics**	**Teledyne RESON**	**Jasco**	**RTSYS**	**Jasco**
Product Model	icListen HF/HF(L)	TC4032	Ocean Sound Meter	EA SDA 1000	AMAR G3

Company	**Ocean Sonics**	**Teledyne RESON**	**Jasco**	**RTSYS**	**Jasco**
System Description	A smart digital hydrophone	Analog Hydrophone element	Customizable Hydrophone system	Hydrophone with embedded processor	Low power autonomous multichannel acoustic recorder with 1-4 devices
Validation or application in	National Physical Laboratory (NPL), Fundy Advanced Sensor Technology (FAST)	European Marine Energy Centre (EMEC) PODs	N/A	N/A	Tested in harsh conditions
Indicative lower frequency (Hz)	10/1	5	17	3	1
Indicative upper frequency (kHz)	200	120 (250; TC4034)	150	500	150
Communication interface	Ethernet	Analog	Analog	Ethernet	Ethernet, RS-232/485
Internal Battery life (h)	10	N/A	N/A	94-140	Optional
Internal Data Storage (GB)	128	N/A	N/A	128/256 solid state drive (SSD)	256 (SSD) – 1792 (hard disk drive)
Typical External Power (W)	1	1	2.5	0.6-2.5	50 – 100
Supporting Software	Yes (Lucy)	N/A	Yes	yes	AMARlink

Table 3 Typical specs of some TTCD relevant off-the-shelf hydrophone products

Summary

Hydrophones are used in TTCD to support marine mammal identification and to varying degrees of accuracy, locate and track their movement. Hydrophones and microphones are also used in condition monitoring. Drifting hydrophones deployed from buoys are favoured for TTCD applications because tidal sites have high background noise. Advanced signal filtering is required for data analytics. Technology development trends include improved system design, incorporation of processing power, user interfaces, and animal species identification algorithms with tracking capabilities

Devices are generally built to the specifications of the application including requirements for directionality and detection range. The next generation of hydrophones is likely to be more compact and require less power along with the smart features.

5.2.3 SONAR

Sound Navigation And Ranging (SONAR) is an active acoustic technique used for decades in underwater communications, navigation, object detection and imaging. Imaging sonar is a powerful technique for TTCD and is a key component in collision risk assessment. The technology continues to improve.

Imaging sonar works by generating pulses of sound waves (pings) at a desired frequency (from low <1Hz) to ultrasonic (>20kHz), which are then reflected (echoed) by objects in the water. The sonar device captures the reflections and interprets the signals into images. Resolution of an image depends on frequencies used and the angle of the beam. The time delay between a ping and an echo provides distance between the object and the detector. Multi-beam sonars are used for a wider spatial coverage and for this a larger number of beams will mean a better resolution.

There is an allowable frequency range imposed on sonar users. It is believed that sonar operation below 250kHz can impact on the behaviour and wellbeing of marine mammals. Thus all commercial sonar use is restricted to ranges in the order of 700KHz and above; much higher frequencies than the hearing range of marine species[4].

In TTCD applications sonar is primarily used to detect marine animals and objects larger than 1m in length at ranges of <60m in clear water to <15m in turbid water. The state-of-the-art sonar systems have emerged out of research and development pilot projects such as Reliable Data Acquisition Platform for Tidal (ReDAPT) and Flow and Benthic Ecology 4D (FLOWBEC). The device design and the site inform configuration of the devices around the turbine. Devices can be mounted on the main turbine structure looking outward, or on the seabed looking towards the turbine. Pilot projects have demonstrated it is not possible to image objects closer than 3m

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[4] Updated acoustic threshold levels are proposed in a guide produced by the National Oceanic and Atmospheric Administration (NOAA) Fisheries. They have compiled, interpreted, and synthesized the best available science to produce updated acoustic threshold levels for the onset of both temporary and permanent hearing threshold shifts. http://www.nmfs.noaa.gov/pr/acoustics/faq.htm

to the blades due to the high level of turbulence and cavitation in the area. This means sonar is not useful to validate a collision impact event.

State-of-the-art sonar in TTCD lies in advanced software that incorporates imaging and tracking algorithms working with optimised frequencies and beam configurations. Different types of marine animal are characterised by their shape and software to automate object identification is in development. The capability of the software has been validated by manual observation in 40m of water depth. Although diving birds are generally too small to detect with the same resolution, the approach is capable of identifying if they are present via the shape of the bubble trails they create. In this sonar meets requirement FR2 in Table 1.

The closer the object is to the sonar the more resolution can be applied and target identification is more probable. The mammal identification algorithms currently give prevalent false positives about objects detected in the 45-60m range, however the sonar OEMs will be able to improve this capability where they have opportunities to collect new data.

State-of-the-art tracking algorithms understand motion and can differentiate between inanimate and living objects. The algorithm applies acoustic Doppler current profiler (ADCP) data about current velocity and direction. Objects that move contrary to the current are identified as live animals while those drifting with the current are classed as inanimate objects.

The future of sonar is a monitoring process that combines fast, wide area scans at low resolution and small data packets and slower, narrow angle scans of higher volume data packets. The system will automatically switch between these scanning modes; the wide detection range will capture and live track a large number of objects at distance and the ADCP-informed tracking algorithm interpret object motion into inanimate and living objects. At this point the mode will switch to narrow angle to generate higher resolution image of a tracked object identified as an animal to which the automated image analysis is applied.

Active sonar hardware is high at TRL9 and certified for two years operation without maintenance. The object tracking and identification system is at medium TRL. More data, further testing and algorithm refinement to prove reliable use in this application. Increasing capability for on-board processing and machine learning is also important to create faster output and full automation. The specifications of relevant sonar systems are outlined in Table 4.

In summary. Imaging sonar is a powerful technique for TTCD and is a key component in collision risk assessment and primarily used to detect marine animals and objects larger than 1m. The detection range of sonar for TTCD applications is <60m in clear water to <15m in turbid water. It is not possible to image objects closer than 3m to the blades due to the high level of turbulence and cavitation in the area. This means sonar is not useful to validate a collision impact event. State-of-the-art sonar systems deploy advanced imaging and tracking algorithms and optimise frequencies and beam configurations. This approach can identify the type of marine animal including seals, porpoises and diving birds. More pilot projects are required to improve the reliability and accuracy of the imaging and tracking software. With more data sonar OEMs will be able to realise fully automated collision alert systems.

Company	**Tritech**	**Coda Octopus**	**DIDSON**
Product Model	Gemini 720i	Echoscope II	DIDSON 300 m
System Description	Sonar system with capability to detect and track species	Compact and real-time 3D acoustic system	Dual Frequency Sonar able to observe fish, mammal, and crustacean activity in turbid water
Application in	Tidal Energy Limited (TEL) Deltastream		EMEC
Frequency (kHz)	720	150/ 250/ 375/ 500	700 – 1800 (Dual)
Number of beams	256	128 × 128	48 or 96
Range Maximum (m)	120	250/200/200/150	30 – 90
Range Minimum (m)	0.2	1	1
Effective Angular resolution (°)	0.5	0.39, 0.39, 0.39, 0.23	0.4
Maximum Update/ping rate (Hz)	30	20	-
Angular Coverage (°)	120	50 × 50 or 30 × 30	29
Auxiliary Sensor for	Sound velocity	Tilt	-
Typical External Power (W)	35	150	30
Supporting Software	Gemini SeaTec Software (Species detection)	Windows-based, comprehensive real-time display and control software	Proprietary imaging software

Table 4 Typical specs of some TTCD relevant off-the-shelf SONAR systems

5.2.4 Video camera systems

Video footage has been used in TTCD to provide visual information of the turbine as part of a health monitoring system and to ground truth data received from sonar devices (e.g. the ReDAPT project). To capture the moment of contact the camera could be mounted on the blades of the turbine, the nacelle or the support structure and have a clear view of the surface of each blade along the whole length; a typical blade dimension is of the order of 10m length × 2m width.

Very high tidal flows create risk to static camera systems through impact and erosion from fast moving objects and sediments. Commercial underwater video camera equipment deployed in TTCD systems are typically sourced from the subsea oil and gas market which produces robust systems for low light, low contrast, highly turbid conditions. Other relevant expertise of OEMs in this sector lies in ‘marinisation’ of camera equipment, which means pressure-tested housings and lenses, wet connectors, power, and data management and communication protocols.

Artificial illumination is not permitted at tidal turbine sites as it can change the behaviour of marine mammals. This means image capture is limited to daylight and not possible at night. Tidal turbine sites are situated within the 200m depth sunlight zone of coastal waters and providing it is a bright day and the water is relatively clear, daylight illumination is sufficient. Using low light, high contrast video systems would help to maximise the available natural illumination.

From consultations with tidal turbine developers, video is used to monitor objects and animal species within visible range of the turbine. It can also be helpful to validate other sensor data or contribute to machine vision for sonar. Camera visibility ranges from up to 50m, or less than 10m depending on turbidity and light level. A significant barrier to the practical application of static, long term video cameras is biofouling of the lens. This can occur within days in some cases. Finding good antifouling solutions is still a challenge for the market, however of note is a recent, novel ultraviolet (UV)-based antifouling system[5] which could benefit TTCD.

Despite the limitations, camera and optical imaging is the only technique at the present that has the potential to provide clear visual evidence of the presence of animals in proximity, their identification, their number and their interaction with the turbines; during the day.

State-of-the-art digital cameras utilise advanced detectors that have improved pixel resolution, and higher data capture rates. Subsea camera OEMs are adopting these new technologies and have demonstrated ultra-low light image capture, and multispectral stereo imaging to provide depth perception and enhanced contrast for example, blue and green illumination/filtering. Ultraviolet wavelengths are used to detect fluorescent tracers and other UV luminous materials. The high absorption coefficient of infrared wavelengths in water limits the utility to close (a few cm distance) thermography applications.

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[5] http://www.oceannetworks.ca/innovation-centre/smart-ocean-systems/technology-demos/aml-oceanographic-uv-antifouling-system

For TTCD, it would be possible to develop systems that combine high resolution with ultra-low light monochrome to provide optimal long range views in turbid, low light conditions, combined with a high definition (HD) overlay clip when more detail is required.

Video generates large volumes of data. Cameras at tidal turbine sites are typically connected to shore via the project’s subsea multiplex cable or dedicated data cable. In terms of real time data retrieval, video data needs to be compressed as is too impractical to store. High efficiency compression codecs allow streaming and recording of footage at the appropriate times. If high definition video data needs to be sent continuously to shore, fibre-optic cables are the best solution. These can transmit typically at 1Gbit/sec.

The footage captured of an impact event may be a clip lasting a few seconds among thousands of hours of footage. A TTCD system that is able to predict a collision event can be used to timestamp the video footage, saving time in video analysis. The time stamp can be created either through proximity alerts or a risk alert calculated from analysing the trajectory of an animal in the area. An alternative approach is to have a video system in continual overwrite and only record during an alert trigger. This latter approach will be trialled as part of the TTCD system of a turbine device to be deployed off the Pembrokeshire coast. The developer of the site has designed a system architecture where a smart switching mechanism triggers the sequential operation of passive and active acoustic and video devices to capture the progress of an object throughout the monitoring zone from the first proximity alert to a confirmation of blade contact.

Video devices with a wireless capability would extend the areas on and around the turbine that could be monitored, allowing real time data to be communicated from very remote areas of the site. Underwater wireless solutions are emerging at a rapid pace. Live transmission of video images are possible through advanced data compression methods and signal modulation protocols to increase the bandwidth of acoustic and optical modems[6].

Notable developments in underwater imaging techniques emerging in the very near future are machine vision, which will be applicable in automatic species identification akin to what is being developed for sonar imaging. Also of note are time-of-flight and range gating methods applied to laser imaging to significantly improve image quality over distance. This method also provides positional data about an object[7]. This might be of benefit in blade impact monitoring however the effect of laser based imaging on marine animals is unknown and would require exploration.

Because of their limitations, cameras are viewed as an optional component in a monitoring system architecture. Primarily, they can meet the functional requirement FR10 in Table 1, and may be useful in providing supporting evidence in functional requirements FR2, FR4, FR7 and FR8. Underwater camera systems, which were noted used for tidal turbine monitoring, are listed along with some of their properties in Table 5. These cameras in context of environmental

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[6] http://www.applied-ocean.com/see-horse-modem.html; http://www.sonardyne.com/products/all-products/instruments/1148-bluecomm-underwater-optical-modem.html

[7] http://www.utofia.eu/?page_id=13207

monitoring are at high TRLs for camera technology and basic hardware, however algorithms and image processing remains at low TRLs.

Company	**GIGE Vision**	**ROVTECH Solutions**	**KONGSBERG**
Product Model	MANTA G-201 (POE)	Seacam	OE14-370/371
Application in	OpenHydro (EMEC)	EMEC Monitoring POD	Likely by a turbine manufacturer (anti biofouling)
System Description	Low cost GigE Vision cameras	Fixed focus underwater video camera	Underwater video camera with Zoom lens (36:1) & Graphical User Interface (GUI)
Features	Auto gain, exposure and white balance	21 high brightness white light emitting diode (LED) ring	Extended view angle, addressable serial control
Resolution	1624 × 1234	625 lines (400 television lines (TVL))	625 or 525 lines (PAL/NTSC) (550 TVL)
Minimum illumination (lux)	-	1	1.7
Website link to product information page or specification sheet	https://www.alliedvision.com/en/products/cameras/detail/g-201-30fps/action/pdf.html	http://www.rovtechsolutions.com/pdf/RSLfixedfocuscamera.pdf	http://www.bowtech.co.uk/iadmin/Uploads/productDocs/164/Explorer%20Pro.pdf

Table 5 Typical specs of the known off-the-shelf TTCD relevant camera products

Summary

Video footage is used in TTCD as part of a health monitoring system and to ground truth object detection data received from sonar devices. Optical systems are challenged in the high energy tidal sites from physical damage and low light conditions. Artificial illumination is not possible in TTCD and video footage cannot be taken at night. Despite the limitations, camera and optical imaging is the only technique presently available that can provide clear visual evidence of animals and their interaction with the turbines, including the validation of a blade collision event. State-of-the-art in underwater video camera include advances in improved pixel resolution, depth perception methods and wavelength filtering. Emerging technologies in laser imaging will improve imaging in turbid water and provide metrological data about an object. Advances in data compression codecs and underwater wireless technologies will enable live streaming from more remote sites, or areas difficult to cable. There is opportunity to generate systems capable of on-board, automatic image analysis, reducing the requirement to stream live video and optimising the capture of collision risk evidence.

5.2.5 Blade mounted strain gauge

Bending or flexing of a turbine blade can be measured by a strain gauge installed at the base of the blade to capture the bend moment or along the length of the blade. These sensors are used for condition monitoring purposes. Developers are exploring both as potential indicators of impact, used in conjunction with other sensors in the TTCD. Strain gauges can be electrical requiring wiring, or optical using fibre optic technology.

State-of-the-art of fibre optic strain sensors distribute the sensor system along a turbine blade. Every point along a single fibre can act as a sensor with a spatial resolution in the order of millimetres. A single fibre can capture strain information from the entire blade. In contrast, in an electrical strain sensor, every element will need a pair of connectors and cables. Fibre optic systems are ideal for a complex mechanical system like a turbine where blades are rotating and a minimal number of cables or wires is desired.

Out of all the TTCD requirements, the strain gauge can at best be helpful only for impact detection, delivering functional requirements FR5 and FR6, Table 1. When an object or an animal collides with a blade, a transient strain signal will be superimposed over the background signal in the strain sensor. Thus an impact event may have a characteristic strain signature. The sensor has most sensitivity to impacts in the horizontal direction than the in the vertical direction due to high blade stiffness and loading on the blade from water pressure. Bend moment at the base of the blade can provide additional data in this direction.

Frequency domain analysis is applied to identify impact signatures. Synchronously observing the signal from all the strain sensors in a particular blade may provide an indication of the possible impact location. It may also be possible to calculate the mass of an animal species or object that has struck the blade.

While the condition-monitoring application of a strain gauge system is considered a high TRL 7-9, application in impact detection is low-medium for tidal turbines as the approach is still being validated. Integration technology of strain gauge systems to turbine blade and rotor is estimated at medium TRL. Of note is a start-up delivering embedded fibre optic sensors within composites[8] and developing whole structure integration methods of an order of magnitude cheaper compared to current offerings. The value of fibre optic strain sensors for TTCD lies in structural integration and smart detection algorithms that require validated data.

Assuming an achievable fibre optics structural integration with composite material blades, as is being exemplified for wind turbines[9], major challenges remain for tidal applications in the delivery of power and telemetry and effective algorithms for ‘impact-signal’ extraction from the noisy background.

Summary

Developers are exploring the use of strain gauges as impact detectors in test prototypes, located at the root of the blade and along the length. Strain signals due to loading of the turbine in a tidal flow dominates any impact signature in magnitude, however developers will apply frequency domain analysis to identify the impact signature. Synchronously observing the signal from all the strain sensors in a particular blade may provide an indication of the possible impact location. It may also be possible to calculate the mass of an animal species or object that has struck the blade. These systems are under test and presently their effectiveness is unknown.

5.2.6 Accelerometers

An accelerometer measures physical acceleration of the object that hosts the sensor. Accelerometers can also be used to measure vibration in an object due to an impact. Micro-electro-mechanical-systems (MEMS) along with on chip processing have enabled development of extremely compact and robust accelerometer devices with a characteristic long life and reliable performance. Accelerometers are being explored to detect collision impact in both wind and tidal turbine blades. They appear to work well in wind turbine blades.

Accelerometers satisfy functional requirements FR5 and FR6, Table 1. Presently developers differ in their opinion on the capability of accelerometers to reliably record impact events. Until data begins to emerge from prototype devices with these sensors installed, the value of blade-mounted accelerometers remains undefined.

A manufacturer of custom accelerometers for TTCD system to be deployed off the Pembrokeshire coast was consulted as part of this study. The systems are presently at TRL 7-8 and once they can be validated in the working environment a TRL of 9 may be easily achieved. By intelligently analysing the synchronous signals from a set of devices embedded in each blade, and with intelligent processing in real time, the manufacturer and the developer expects

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[8] http://www.com-sens.eu
[9] http://www.smartfiber-fp7.eu/

these sensors will detect and register an impact event, and also provide information about the structural health of the blade.

Similar to the strain gauge, an accelerometer signal may contain extractable data about size and mass information about the objects colliding with the turbine blades. Furthermore, there may be sufficient differences in the impact signals of drifting hard inanimate objects like wood and the more flexible bulk of a live animal. Impact signatures may also be differentiated by body mass which could indicate different species. Providing the sensor works as expected, accelerometer based systems may provide high quality data of sufficient reliability to fulfil the consenting requirements.

Summary

Accelerometers are already successfully embedded in, and appear to work with blades rotating in air. If the accelerometer devices are successfully demonstrated in forthcoming prototype TTCD systems, the requirement for a technology that can validate a collision event will be met. One key point to note regarding accelerometers' capability for collision detection is that they require fewer sensing components and interconnections compared to camera and strain gauge systems.

5.2.7 Magnetic and Electromagnetic Field Sensors

Electromagnetic fields (EMFs) are a combination of electric and magnetic fields and are emitted by electrically charged objects including electronic devices. Living things generate EMFs by greater or smaller extents through the natural electrical impulses conveyed in the nervous system, static charge or the chemical reactions within the cells. Magnetic and EM field sensors have not been part of any TTCD development project to date, however they may have value in this application.

Magnetometers measure the minute disturbances in magnetic fields caused by the proximity of electrically conductive materials. Magnetometer arrays situated on the seabed are used to detect small underwater vessels, ROVs and divers or any objects that have detectable amounts of conductive metals in them. Device manufacturers consulted for this study describe arrays that can track the movement of an object; an example of the smallest object detectable by an array is a diver, who is traceable at a distance of 9 to 10 m.

Magnetometers will not detect a turbine blade unless it has a structural magnetic metallic frame. However if there is debris in the vicinity that lies within the detectability scope of a seabed array, then it could likely be detected and tracked. Providing the tracking is in sync with the movement of the blades and informed by ADCP data, a collision alert for relatively large, metal containing objects may be feasible. The arrays would need to be embedded in concrete (or other non-metallic matrix). Sensors on the market have Ethernet capability so can be wirelessly networked. They require an external power source.

Electric field (EF) sensors can differentiate between living and non-living objects and the view of a specialist consulted for this study is that an EF sensor would interpret a marine animal as a non-conducting object in the surrounding conducting sea water. It may be sensitive for animals the size of a porpoise and larger. The detection range would be much less than 10m. These assumptions would need to be tested.

EF sensors may be capable of detecting the EF signal pattern created by the rotating blades and by virtue of this, detect an anomaly in the signal caused by an object in the proximity. This could be an area worth further exploration.

EF systems can be passive or active. Active systems work by slightly electrifying the detection zone area of water around the sensor; however this is known to affect the behaviour of fish, the cause and types of marine species affected has not been fully investigated. EF providers suggest blade mounted EF sensors

Summary

Magnetometers in a seabed array are already commercially available for the detection of metal-containing objects. They may have some application in detecting non-living objects (that contain some metal) on collision paths to the turbine. EF sensors can detect living animals and there may be value in conducting a feasibility study to explore the sensitivity and specificity of these approaches. Both technologies can be readily retrofitted

5.2.8 Tactile sensors

Tactile sensors detect a direct physical contact (touch) between two objects or surfaces. A variety of different technologies have been adapted to tactile sensing. In TTCD, an appropriate type of tactile sensor integrated into blades may have the capability to detect contact between the blade and an object, including marine species.

Contact between objects can be measured by pressure sensors, sensors that detect optical reflectivity (typically in the infrared wavelengths), or electronic skins comprising capacitive cells which detect changes in small electric fields caused by two conductive objects coming into close or actual contact.

Tactile sensing may have value in TTCD as the only approach that could potentially satisfy, simultaneously the functional requirements FR5, FR6 and FR7, Table 1; i.e. demonstrate physical contact and determine the location of the contact on the blade. Depending on the technology used, it may also be possible to determine force at the point of contact.

Among the most relevant tactile sensing technologies for collision detection are the pressure sensors applied in manipulator arms of robotic marine systems. These are at high TRL and comprise a fibre optic detection method integrated with a fluid filled membrane that responds to a pressure difference between the two sides of the membrane. Discussion with a tactile system expert in subsea robotics confirmed a high confidence in the feasibility, capability and robustness of this technology in a TTCD application. This is based on existing success in developing a subsea robotic tactile grip.

Although the technology promise is high, there are clear challenges in the integration of such sensors within the turbine blade. Consultation with a turbine manufacturer on this issue confirmed there would be an appetite to explore tactile sensors and turbine blade design if other approaches currently being tested are unable to meet the functional requirements.

Alongside optical-pressure sensing, highly sensitive piezo-resistive/electric materials known as quantum tunnelling composites (QTC) may also have value in TTCD. These are designed to respond to a soft touch with a high sensitivity. A QTC manufacturer and device developer consulted for this study suggested that these may have value in TTCD assuming they can be developed for large magnitude impact forces.

Electronic skin, based on electric field sensing, is too immature to successfully integrate into turbine blades.

Transfer of any of the tactile sensing technologies into a TTCD application would require an initial desk study to indicate feasibility. However in the case of the optical sensor and pressure membrane, the technology has already been validated at a depth of 6km so some of the challenges may already be addressed[10]. There may be ways to optimise the viscosity of the fluid filling the membrane, or provide an array of differential viscosities to address variable pressures.

Summary

Tactile sensors may have value in TTCD, the pressure sensors used in robotic manipulator arms are closest applicable sensors to test for feasibility. Hardware TRL is low but detection algorithms developed for signal interpretation are medium to high TRL. The latter may be quickly adapted to meet the impact detection requirements. Potential blade integration solutions are unknown.

5.3 System architecture

System architecture describes how the different components of a TTCD system work and operate together in an integrated sensing and imaging TTCD system comprising technologies, electronic hardware and smart algorithms. The control centre of the system accepts and analyses inputs from the various devices and interprets and communicates actionable data to automated control systems or a human operator. The entire system may be called a ‘monitoring system’.

Monitoring systems could be further integrated with the turbine operation and control system creating an implementation path for precautionary actions such as shut down when mammals are exhibiting high collision risk behaviour or are in a high risk proximity. However, essentially

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[10] http://robotik.dfki-bremen.de/en/research/projects/seegrip-1.html

the monitoring system is not a part of the core turbine operational system; once the consenting requirements are fulfilled for a particular development project most developers expect to partly or wholly remove it.

Of the developer community consulted, there are fewer than 10 TTCD monitoring systems in development, either in early or in advanced phases, including a mature system waiting deployment by a leading developer in the UK. Many developers have adopted broadly similar approaches, some more comprehensive than others, but all acknowledge that different systems are required to work in tandem to track a certain sequence of events.

Further to devices and algorithms, a system can be designed in various ways to allow multiple functionalities, such as single or multiple alarm zones. One developer has used three levels of warning associating the animal size and behaviour with flow speed.

The physical configuration of TTCD devices relative to the turbine and blade plane also varies. Developers have included cameras alongside active sonar devices to monitor the blades from the seabed position and pointed in the direction of flow. Others have mounted cameras on the hub to monitor the blades in opposite direction. The former provides the opportunity to correlate the information from both sources and improve the identification algorithm.

Regarding the potential of a system architecture, it is worth considering the future benefits of designing a monitoring system that can evolve into machine learning platform which applies advanced pattern recognition to big data and has the ability to integrate new data streams as required. This opens up future opportunities to streamline inspection and maintenance schedules as this type of AI condition monitoring platform is continuously optimised and provides increasingly certain prognostics over time.

5.4 Summary of technologies reviewed

The TTCD system requirements outlined in Tables 1 and 2 are indicative only but do identify knowledge gaps. In general, most of the sensor and imaging devices are existing products, or have been modified from an existing commercial design and therefore high TRL, though the validation of the application in TTCD is ongoing in some cases, and therefore the specifications of the prototypes in relation to TTCD are not fully complete.

Modified products or prototypes are fit for purpose in TTCD, most if not all would be expected to meet the most commonly applied subsea technologies' standards (such as DNV A203, API 17N, or ISO 208D 2008) which are used by subsea OEMs as these are the most relevant also for TTCD devices. Certainly, those devices that have been developed in partnership with or sourced from subsea OEMs will have been built to these standards.

Table 6 outlines the functional requirement along with applicable technology category and estimated TRL of the most advanced example within that category that has been designed for TTCD. Technologies relevant to the detection needs are summarised in Table 7.

Sno	System Area	Requirement	Applicable Technologies	Estimated TRL
1.	Proximity (including behavioural response)	Detect and identify presence of the species of concern around locality of turbine (>60 meters)	hydrophone	high
2.	Proximity (including behavioural response)	Identify protected species and track their motion to alarm their approach towards turbines (60-30 meters)	sonar, camera, hydrophone	medium-high
3.	Proximity (including behavioural response)	Track and map movement of animals over time whilst close to turbine (<30m)	sonar, camera	high
4.	Proximity (including behavioural response)	Locate animals with a resolution of at least ~1 m	sonar, camera	high
5.	Collision or impact detection	Confirm a physical contact between turbine blades and any objects or species	accelerometer (tactile, proximity)	high (low)
6.	Collision or impact detection	Measure impact force on turbine blades from object or species collision	accelerometer, strain gauge	high
7.	Collision or impact detection	Determine location of contact or collision on turbine blades	accelerometer, strain gauge	low
8.	Collision or impact detection	Differentiate between object and species collision and identify: (a) marine animal to species level or (b) object properties (density, shape, mass)	a: sonar, camera b: accelerometer	a: medium b: low

Sno	System Area	Requirement	Applicable Technologies	Estimated TRL
9.	Post-event object identification	Map movement of protected species post-collision over time within locality of turbine	sonar, camera	low
10.	Post-event object identification	Obtain image and video of object/species before, during and post event (resolution: >1.3MP; time scale need to be identified based on validation data)	camera	medium-high
11.	Post-event condition monitoring (animal)	Identify if animals suffer immediate fatal injury	sonar, camera	low
12.	Post-event condition monitoring (turbine)	Identify critical changes to turbine performance after collision event (e.g. bearing load) and health of sensors	accelerometer, strain gauge, microphone	high

Table 6 TTCD requirements, relevant technologies and estimated TRL

6 Conclusions

The key conclusions drawn from this review are as follows:

The Need: A TTCD system addressing the detection requirements outlined in Table 6 is an essential mechanism through which the tidal energy sector will gather the necessary scientific evidence on which to base future commercial tidal turbine projects and to inform marine environment regulation.

Feasibility: Regulators are providing consent to a number of developers to explore, design and demonstrate in pilot tests a variety of approaches and technologies to assess collision risk.

System Evolution: Each developer requires a TTCD solution that is relevant and particular to the turbine design, the operating environment and the marine ecology of the proposed deployment site. There are common components in all TTCD approaches to date.

Typical Architecture: A comprehensive TTCD system will include a combination of acoustic sensors (hydrophones, and sonars incorporating ADCP data from the operational system), imaging systems (sonar and cameras) and blade-mounted sensors (strain sensors, accelerometers) and relevant condition monitoring data from the drive train. The integration of these systems is critical, as is the capability and robustness of the associated.

Standard Design: As of now, an optimised TTCD system architecture, or best practice cannot be determined until all data are interpreted from the different ongoing projects, and from the pilots about to be deployed. It might be possible to generalise on some aspects of system architecture and types of technologies used. Other aspects might need to remain site or device-specific either due to the type of turbine, its configuration or the nature of the tidal site and the animals that visit it.

Hydrophones: In comparison to active sonar devices, hydrophones have demonstrated less utility in proximity monitoring as they only detect species that vocalise. The perceived value of these devices lies in developing the signal interpretation capabilities to identify and locate, in real time, marine animals through their vocalisations. Following the development of signal interpretation capabilities, an estimation of population size in an area could potentially then be made. Unfortunately not all marine animals vocalise all the time.

Sonar Systems: the state-of-the-art in active sonars includes the capability, through motion tracking and advanced imaging algorithms, to identify with high certainty the presence of a seal or porpoise in the zone of interest. The device can collect sufficient data to assess and issue a “risk of collision” alert. Sonar hardware is mature and the most significant improvement to be made relevant to TTCD is in advancing the imaging and tracking software to realise a fully automated, intelligent system.

Future Sonars: It could be anticipated that, providing the amount of corroborating data will be of sufficient volume and diversity to train a machine vision package, sonar imaging is likely to become the primary long term collision proximity alert and risk assessment tool. More real data is required from different monitoring configurations and environments to improve the tracking and image analysis algorithms. Advances in tracking software can provide more accurate and earlier prognosis of collision risk. Sonar devices are certified for two years continuous use before maintenance.

Camera Systems: In at least one TTCD system yet to be deployed and tested, video cameras will be used to capture specific event-triggered information to support active and passive sonar data in object identification and/or to correlate accelerometer, strain gauge and drive train data with the blade making contact with an identified object. Time-of-flight and range gating methods could be applied in the future to improve images captured in turbid waters. Key barriers for optical systems in TTCD are the requirement for illumination in poor light or at night, and rapid rates of lens bio-fouling. A UV light-based treatment system has been identified as a potential, novel solution for the latter.

Blade Mounted/Embedded Sensors: Primarily for blade condition monitoring and secondarily as a direct measure of blade impact events, some developers have integrated fibre strain sensors and accelerometers embedded or mounted in blades. Strain gauges have been embedded at the root of the blade to capture bend moment and along the edge to capture flex along the length. A key challenge in blade mounted approaches like this will be the sensitivity range of the systems, which should be wide to capture the full range of velocity, size, mass and hardness to be representative of animal impact scenarios.

Accelerometers: Used as indicators of impact detection as well as turbine blade condition. Features in favour of accelerometers include their compact size and the feasibility of integration within blades. One sensor per blade is considered sufficient. For impact detection, the accelerometer hardware is mature, but the signal processing algorithms need to be further developed and validated as part of a TTCD system.

Tactile Sensing: An as yet unexplored technology within TTCD, but potentially of high relevance for validating blade contact. A system would need to be a blade-mounted or embedded and might worth exploring if accelerometers and strain gauges are found to not provide conclusive validation of impact.

Automated Detection Algorithms: There is opportunity to advance both sonar and video imaging systems by applying smart algorithms for image processing, including automated object detection leading to, species identification and target tracking in real-time. For sonar imaging, this is within reach, providing more data can be gathered to improve the machine learning software. For video cameras there is emerging technology that will enable machine vision underwater, the key components are fast capture of high resolution images and on-board processing of key features. On-board processing of images in both sonar and video systems is of benefit because the transmission of large data sets is no longer necessary, and instead actionable data is output real time, delivering an earlier risk alarm.

Historic Data: Faster development of an automated image processing system for sonar would be aided by expanding the sonar image library of identifiable species. This could be achievable through the collation of historic (and validated) data. This would require a diversity of data collected by a range of sonar-turbine configurations and from across a variety of tidal turbine sites. The same is also true about data collected from other sensor types.

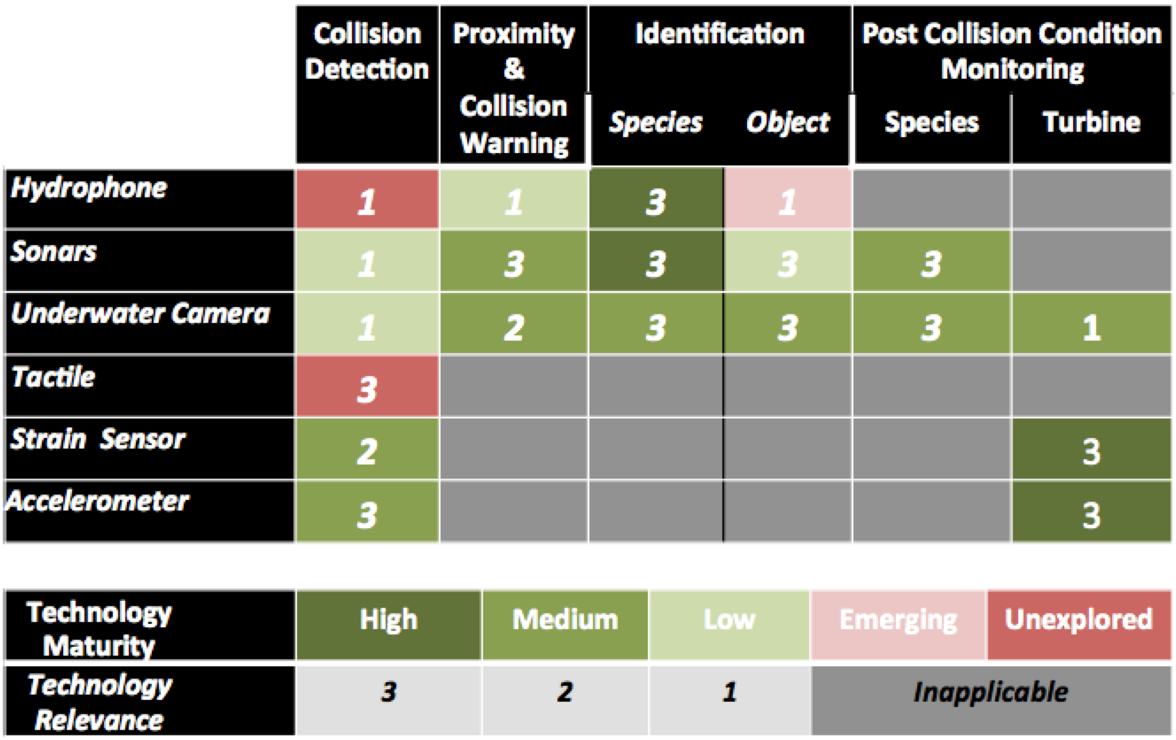
Data Validation: Validation in the tidal turbine operating environment remains the largest hurdle in further development of any applicable TTCD technology. However, there are financial factors delaying the build or deployment of many of the systems that have received deployment consent.

Future whole TTCD systems: Future architectures are likely to include advanced components and features in addition to those summarised in section 5.3. As an example, real-time acoustic data processing will be developed and integrated with the capability to extract acoustic impact signatures from hydrophone data. The implementation of real-time, improved contrast underwater imaging techniques is also likely. Automated target tracking can then be triggered with digital zoom and automated high resolution recording during a high collision risk event.

Table 7 concludes the outcome of this study and reflects the perceived knowledge gaps corresponding to relevant sensing technologies. The table also suggests the relevance of a technology for TTCD, while acknowledging the maturity for potential utility to deliver what is required in the TTCD operating environment. The following conclusions may be drawn from table 7:

- Sonars are highly relevant for proximity alerting, species and object identification, and there are opportunities to further develop sonar image tracking and analysis algorithms for this application.
- Blade mounted sensors (accelerometers and strain gauges) have potential to detect collisions. The approach is of medium to high maturity. Overlaying data with turbine condition monitoring data may provide corroborating data (high maturity). However, this capability needs to be validated for collision event detection in a TTCD application.
- Underwater video cameras are relevant to all of the detection needs providing visibility remains optimal and they are regularly maintained. There is capability for video to be further developed in TTCD applications.
- Tactile sensors are the most relevant method to detect a collision or touch event and are at high maturity in the context of underwater robotic manipulators. The value of tactile sensing in TTCD remains to be explored in the case where accelerometers and strain gauges are not successful for reliable identification of an impact event. A support system is required to determine what objects are detected.

It is important to note that monitoring systems for the first projects need to include capacity to address the first three columns in order to reduce uncertainty: detection ,proximity and identification.



	Collision Detection	Proximity & Collision Warning	Identification		Post Collision Condition Monitoring	
			Species	*Object*	Species	Turbine
Hydrophone	*1*	*1*	*3*	*1*		
Sonars	*1*	*3*	*3*	*3*	*3*	
Underwater Camera	*1*	*2*	*3*	*3*	*3*	1
Tactile	*3*					
Strain Sensor	*2*					3
Accelerometer	*3*					3

Technology Maturity	**High**	**Medium**	**Low**	**Emerging**	**Unexplored**
Technology Relevance	*3*	*2*	*1*	*Inapplicable*	

Table 7 Applicability and maturity of relevant sensor technologies for detection needs

7 Recommendations

In order to progress SIS technology development and also to close knowledge gaps in its adoption into the TTCD application, the following next steps are suggested:

- There are TTCD systems at different stages of development and with different capabilities aimed at deployment in approved projects. It would be helpful if there were an overarching, collaborative progress monitoring mechanism and historic data library to capture and store the output for all consented projects and to help inform best practice and contribute towards standardisation of a basic TTCD system. An open data library containing sensor data, test and validation methods, implementation methodologies as well as more detailed information on the sensing parameters, could improve or refine the general information accuracy and confidence in identification or classification algorithms. This could be facilitated by existing programmes including Ocean Energy Systems Annex IV[11] and ORJIP Ocean Energy. Data could be hosted on the Wave and Tidal Knowledge Network (WTKN).

- Identification of financial resources to support consented projects with TTCD systems. This could accelerate the system validation, first evidence collection and quick identification of unknowns which may then be helpful for other projects. It may be possible that this initial set of information is found to be sufficient to satisfy some of the key requirements and regulators could relax consenting requirements. Identification of funding resources for other TTCD oriented projects or systems will be helpful as well (EMEC pod, FLOWBEC platform). Full understanding of what has been attempted to date and what has worked well and what has not is also important.

- Facilitate the formation of a collaborative group consisting of stakeholders and experts across disciplines. There was a clear willingness from respondents consulted during this study to support and contribute to future collaborative activities to benefit TTCD. This would allow further pooling of knowledge and skills and encourage identification of technologies and best practice. The key outputs from this group would be: (i) confirmation of sector knowledge gaps, (ii) agreement on prioritisation of activities to close identified gaps; (iii) refinement and standardisation of technical and environmental requirements; (iv) facilitation of simpler engagement between experts across disciplines, for example between sensor experts and marine biologists, by promoting a common language across relevant disciplines. This could be facilitated under ORJIP Ocean Energy or Scottish Offshore Renewables Research Framework (SpORRAn).

- Electric field and magnetic field sensing technologies may have value in TTCD. Commercial systems exist for other underwater tracking applications and the transfer to TTCD would

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[11] http://tethys.pnnl.gov/about-annex-iv

require minimal development in hardware. Most effort would be required for signal analysis and building a test system to demonstrate its feasibility.

- There is a need for prototype TTCD or host turbine system that technology providers could use to verify the performance of sensor technology. The challenge here is that prototype systems will require deployment in a representative tidal environment where interaction with marine mammals can be assessed. This could be a test turbine on an existing tidal site or with other objects in test tank experimental research. The MeyGen Phase 1 project in the Pentland Firth and the TEL's Deltastream project in Ramsey Sound will both contribute to understanding sensor performance.

Knowledge gaps across disciplines relevant to tidal energy project development and consenting requirements have been investigated in the past decade and informed by different organisations globally (Appendix 3). Project plans addressing some aspects of the knowledge gaps are covered in available reviews. No evidence base or project plan exist that has successfully demonstrated the 'feasibility of collision detection' or 'verification of collision detection', while collision risk has consistently been identified as among the top priorities issues. Hence, projects specific to collision detection are suggested here in order of priority:

Project-1	Further development and validation of existing and mature collision detection and monitoring systems such as EMEC's pod, MeyGen's FLOWBEC and TEL's platforms
Objectives	*Push the next phase of development of evolving monitoring systems or mature systems ready for deployment and expand the initial evidence base*
Deliverables	● Upgrade/refine/deploy monitoring systems at existing/consented TTCD test tidal sites ● Expand data collected at tidal sites ● Comparison and correlation of datasets to identify agreements and or sources of errors ● Refine algorithms and improve system performance ● Identify best practice and mature technologies
Plan	Supported by ORJIP Ocean Energy, Catapult will plan a workshop with developers to understand how data collection could be expanded and with technology developers to identify best practices and potential system improvements.

Project-2	Further development and validation of advanced collision monitoring system methodologies and algorithms
Objectives	*Design future system architecture for highly accurate collision monitoring*
Deliverables	● Review the system architecture of existing monitoring systems down to subcomponent level in existing wind and tidal projects ● Identify common elements, need and scope of design standardisation within or across sectors ● Suggest design and protocols for standard standalone future system architectures ● Identify prospects for algorithm improvements and integration across projects ● Test and validate in suitable representative tidal site

Project-2	Further development and validation of advanced collision monitoring system methodologies and algorithms
Plan	A Catapult-led and ORJIP Ocean Energy-supported workshop with sector leaders is planned to determine where improvements can be made and what a test plan should contain and how it could be delivered.

Project-3	Further development and automation of tracking and image algorithms for sonar systems
Objectives	*Improve on current tracking and imaging software to realise a sonar proximity alert device capable of real time prognostic output of marine animal collision risk*
Deliverables	● Identify tidal turbine deployment sites suitable to obtain validated sonar data ● Identify existing suitable sonar data that could be shared ● Improve algorithms and software ● Deploy improved system and validate at site
Plan	Supported by ORJIP Ocean Energy, Catapult will plan a workshop with developers to understand the data that is being collected and can be made available and with technology developers to identify best practices and potential system improvements.

Project-4	Feasibility study of Range-gated Camera and Automated Image Analysis for Turbine Monitoring
Objectives	*Test value of range-gated technology in TTCD*
Deliverables	● Identify key performance parameters at tidal sites and estimate a range of values ● Develop or refine the range-gated camera system for delivering imaging range that is significantly better than standard cameras, by means of hardware improvements ● Develop real-time processing algorithms for automating the detection and inform the event of interest
Plan	This is planned to be an ORJIP Ocean Energy-supported call to complete a study into these technologies, delivered through the Catapult's Innovation Challenges.

Project-5	Tactile Impact Detection for Turbine Blade Integration
Objectives	*Extended development of the existing tactile sensors in underwater robotics for turbine collision detection application*
Deliverables	● Identify design specifications for the turbine blade integration and impact detection ● Design the tactile sensor cells for possible integration with blades ● Identify integration prospects with fibre optic sensors ● Explore issues and challenges regarding integration prospects with turbine blades made of different materials ● Test the system in controlled environment
Plan	This will form the basis of a Catapult Innovation Challenge to the market, which will be supported by the Catapult's proactive identification of relevant funding sources and calls. A project submission will then be made with market partners.

Project-6	Further development of blade-integrated accelerometer sensors as a standalone collision detector system
Objectives	Exploit the full potential of accelerometer technology to provide a standard standalone sensor module for application in any tidal turbine collision monitoring
Deliverables	● Review the existing knowledge base to best inform the accelerometer-specific detection parameters and their possible range at different sites ● Theoretical estimation of physical and or design parameters ● Identification of commercially available sensor elements ● Development of detection algorithm and hardware for sensor element ● Integration of the full standalone system and test in controlled environment ● Integration with turbine blade and test in controlled environment
Plan	This will form the basis of a Catapult Innovation Challenge to the market, which will be supported by the Catapult’s proactive identification of relevant funding sources and calls. A project submission will then be made with market partners.

Project-7	Sensitivity and specificity testing of magnetometers and electric field sensors
Objectives	*Explore the feasibility of magnetic and electric field sensing to provide complementary data to sonar imaging, tracking and blade collision events in a TTCD system.*
Deliverables	● Identify key performance parameters at tidal sites and estimate a range of values ● Design a scaled version of a magnetometer array test system and electric field test system including test protocols to validate sensitivity and specificity to track non-living and living objects, respectively ● Develop software and data processing approaches to link ADCP and turbine blade rotation data with magnetic tracking and electric field data
Plan	This will form the basis of a Catapult Innovation Challenge to the market, which will be supported by the Catapult’s proactive identification of relevant funding sources and calls. A project submission will then be made with market partners.

8 Acknowledgements

This feasibility study was undertaken and completed with funding support from Scottish Natural Heritage and the Natural Environmental Research Council.

Appendix 1 Technology Categories

Technologies	**Institutions**	**Relevance and Qualification**		
		Key Products, or research	Relevant Capabilities	Reference by (optional)
Hydrophone	Ocean Sonics	IC-Listen	Smart devices	SMRU
Sonar	Tritech	Gemini 720i	SeaTech detection software	Web research
	Coda-Octopus	Echoscope II	Compact and real-time 3D detection	CENSIS, web search
	Ultra-electronics	Devices and Detection algorithms	Advanced detection algorithms	EMEC (Participated in ReDAPT development)
Camera	Odos Imaging	TOF camera range	TOF & range-gating capabilities, Underwater Time of Flight Image Acquisition(UTOFIA) project partner	CENSIS
Tactile	DFKI Gmbh	Subsea robotics	Largest European expert, underwater tactile capabilities	Web research
	Peratech	QTC composites	Touch sensor applications	Personal knowledge
	GU - Ravinder Dahiya	Electronic skin	EU wise leading expertise	CENSIS research landscape
Strain Gauge	Com & Sense	Embedded composite sensors	Fibre-optic embedded strain sensors for wind turbines	Smart Fibre (FP7) project partner
Accelerometer	H-scientific	Smart hardware, and detection algorithms	Developed custom devices for TEL	TEL)
Monitoring System Integration	TEL	System integration	Custom design of monitoring system	EMEC, SMRU, web research
Turbine Condition Monitoring	Andritz	Turbines	Turbine system development	ORE Catapult

Appendix 2 List of Experts Consulted

Date	Interviewee Name	Professional Role (Technical Expertise)	Organization	Org Type	Location	Medium
01/09/15	Mark Wood	President (Electronic Product Innovation)	Ocean Sonics	C2	Nova Scotia, Canada	Phone
03/09/15	Dr Norbert Elkmann	Robotic Systems Business Unit Manager	Fraunhofer IFF	B	Magdeburg, Germany	Email
07/09/15	Dr Ravinder Dahiya	Reader (Tactile Skin)	University of Glasgow	A	Glasgow, UK	Face
09/09/15	Dr Pauline Jepp	Senior Software Development Engineer (Tracking Algorithm)	Tritech	C2	Aberdeen, UK	Face
	Allan Donaldson	Sales Engineer				
10/09/15	Peter Kampmann	Team Leader Hardware Architectures & Sensors (Subsea Tactile Sensor System)	Robotics Innovation Centre (DFKI)	B	Bremen, Germany	Phone
11/09/15	Dr Alex Reader	VP Business Development	Peratech	C2	Richmond, UK	Phone
15/09/15	Chris Williams	Development Director (Renewable Projects)	Tidal Energy Ltd	C1, C2	Cardiff, UK	Face
	Peter Bromley	Engineering Manager (Marine Engineer, Autonomous Systems)				
17/09/15	Dr Chris Yates	CEO (Thin Films, Optics, Programing)	Odos Imaging	C2	Edinburgh, UK	Phone
18/09/15	Dr Peter Dobbins	Principal Scientist (Sonar Systems)	Ultra Electronics	C2	Aberdeen, UK	Phone
21/09/15	Craig Love	Engineering Manager (Turbine System Engineer)	Andritz Hydro Hammerfest	C1	Glasgow, UK	Face
	Katrina Phillips	Turbine Layout Engineer				
22/09/15	Dr Michael Larsen	VP / General Manager	Information Systems Laboratories Inc.	C2	San Diego, USA	Phone
	Dr Jeff Ridgway	Research Scientist				
25/09/15	Dr Geert Luyckx	Managing Associate (Fibre Optics)	Com & Sense	C2	Ghent, Belgium	Phone
29/09/15	Dr Henry Robinson	Managing Director (Physicist, Engineer)	H-scientific	C2	Hampshire, UK	Phone
	Dr Alison Little	Senior Project Engineer				

Organisation Type

A: Academic

B: Research Organisation

C1: Developer (Turbine)

C2: Developer (Sensor)

Appendix 3 Knowledge Gap Study

Existing Reports (Title)	**Relevant Topical Coverage**	**Owner Agency**	**Authors**	**Release Date**
Collision risks between marine renewable energy devices and mammals, fish and diving birds - Report to the Scottish Executive	*Collision risk, mitigations - Ecology and Marine Biology perspectives*	Natural Environment Research Council *(NERC)*	*Ben Wilson et al)*Scottish Association for Marine Science *(SAMS))*	*03/2007*
Marine Mammal Impacts (Wave & Tidal Consenting Position Paper Series)	*Key Issues and status*	*NERC*	C Sparling et al (Sea Mammal Research Unit (SMRU))	*2013*
Review of current knowledge of underwater noise emissions from wave and tidal stream energy devices (Pentland Firth and Orkney Waters Enabling Actions Report)	*Sub Sea Operational Noise*	*The Crown Estate*	SP Robinson & PA Lepper (NPL)	*08/2013*
Report of the Workshop on Interactions between Marine Renewable Projects and Cetaceans Worldwide	*Collision Risk and Management Worldwide*	*Convention on Biological diversity, UN*	*Misc.*	*01/2014*
Evaluating and Assessing the Relative Effectiveness of Acoustic Deterrent Devices and other Non-Lethal Measures on Marine Mammals (Report to MS, Scottish Govt.)	*Active acoustics as deterrent, mammal impact with vessels*	*Marine Scotland*	Alex Coram et al (SMRU)	*2014*

Consolidation of wave and tidal EIA/HRA issues and research priorities (Technical Report to The Crown Estate)	Key EIA/HRA issues and the current research gaps	*The Crown Estate*	Ian Hutchison (Aquatera Ltd)	*01/2014*

Appendix 4 Interview Notes

Confidential; held by the ORE Catapult.

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