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Adapting sonar systems for monitoring ocean energy technologies

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Abstract

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The global energy sector is under profound reforms aiming towards renewable energy sources, clean technologies and expansion of smart grids, all with the additional aim of providing affordable and dependable electricity for everyone. A reduction of carbon dioxide emissions is a priority on the global agenda, and to achieve that, cleaner energy technologies has to be more integrated into the energy mix. This thesis focus on a sustainable implementation of wave, tidal and offshore wind power, wherefore there is a need to investigate more about the prerequisites and consequences ocean energy can have on the marine environment. For that, reliable, cost effective and continuous environmental monitoring framework is necessary in order to support and safeguard ocean energy operations.

The main objectives of the research presented in this thesis are to develop a multifunctional environmental monitoring platform based on sonar systems for ocean energy applications, by adapting high resolution multibeam, dual beam and split beam sonar systems and also underwater cameras; Propose data acquisition and processing protocols capable of decipher sonar data in order to provide continuous environmental monitoring and reporting; Conduct qualitative and quantitative observations of fish and marine mammals using the built monitoring platform; And investigate the feasibility of utilizing the Uppsala University wave energy converter technology to generate electricity worldwide. As a result, a multifunctional platform was designed, built and tested. This included the hardware, the data acquisition system, and a data analysis framework comprising new algorithms necessary to process the new acoustic data. The multibeam, dual beam, and split beam sonar systems and underwater cameras produced both qualitative and quantitative data of biomass, occurrence and behavior of fish and marine mammals in the vicinity of ocean energy devices. With this platform, it was also possible to conduct seabed and structural inspections within ocean energy devices, observe cavitating flows, etc. One of the most important results of this research was the possibility of extracting visual signatures of fish and marine mammals through acoustic images. This can be valuable for training algorithms for manual or automatic identification and classification of underwater targets through imaging sonar systems, a technique that can be widely used in the offshore activities. Regarding feasibility studies and wave power resource assessment, this study concluded that mild wave climates can provide enough energy to run reverse osmosis desalination systems as well as produce sufficient electricity to integrate into a national grid.

In summary, this thesis concludes that the implementation of ocean energy can be facilitated by creating environmental monitoring, risk and resource assessment frameworks such as the presented research work that contribute to lowering the risks associated with subsea work and thereby costs of ocean energy projects.

Keywords: Ocean energy, sonar systems, monitoring technologies, marine environment, wave power

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"Every morning, in Africa a gazelle wakes up. It knows it must run faster than the fastest lion, else will be a meet.
Every morning, a lion wakes up. It knows that must outrun the slowest gazelle or will starve to a premature end.
It does not matter if you are a lion or a gazelle. When the sun comes up, you had better be running"

-- an African proverb--

to my parents Fatima and Albino,
you made it possible!

List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I Parwal. A., Remouit. F., Hong. Y., **Francisco. F**., Castellucci. V., Hai. L., Ulvgård. L., Li. W., Lejerskog. E., Baudoin. A., Nasir. M., Chatzigiannakou. M., Haikonen. K., Ekström. R., Boström. C., Göteman. M., Waters. R., Svensson. O., Sundberg. J., Rahm. M., Strömstedt. E., Engström. J., Savin. J., Leijon. M. (2015). Wave Energy Research at Uppsala University and the Lysekil Research Site, Sweden. A Status Update. *Proceedings of the 11th European Wave and Tidal Energy Conference (EWTEC), Nantes, France, 6-11th Sept 2015*.

II Bender. A., **Francisco. F**., Sundberg. J. (2017) Methods and Models for Environmental Monitoring of Marine Renewable Energy. *Proceedings of the 12th European Wave and Tidal Energy Conference (EWTEC) 27th Aug -1st Sept 2017, Cork, Ireland, 2017.*

III **Francisco. F**., Sundberg, J. (2015). Sonar for Environmental Monitoring. Initial Setup of an Active Acoustic Platform. *The Twenty-fifth (2015) International Ocean and Polar Engineering Conference Kona, Big Island, Hawaii, USA, June 21-26, 2015*.

IV **Francisco. F**., Sundberg, J. (2015). Sonar for Environmental Monitoring. Understanding the Functionality of Active Acoustics as a Method for Monitoring Marine Renewable Energy Devices. *Proceedings of the 11th European Wave and Tidal Energy Conference (EWTEC), Nantes, France, 6-11th Sept 2015.*

V **Francisco. F**., Sundberg, J. Sonar for Environmental Monitoring: Sonar for environmental monitoring: Configuration of a multifunctional active acoustics platform applied for marine renewables. *Manuscript*

VI **Francisco. F** Carpman. N., Dolguntseva. I., Sundberg. J. (2017) Use of Multibeam and Dual-Beam Sonar Systems to Observe Cavitating Flow Produced by Ferryboats: In A Marine Renewable Energy Perspective. *MDPI, Journal of Marine Sciences and Engineering, 2017, 5, 30.*

VII **Francisco. F**., Sundberg. J. Detection of Visual Signatures of Marine Mammals and Fish within Marine Renewable Energy Farms Using Multibeam Imaging Sonar. *Submitted to MDPI, Journal of Marine Sciences and Engineering (2018).*

VIII **Francisco. F**., Bender. A., Sundberg. J. Use of Multibeam Imaging Sonar for Observation of Marine Mammals and Fish on a Marine Renewable Energy Site. *Manuscript (2018)*.

IX **Francisco. F**., Sundberg. J. Evaluation of Underwater Acoustic and Optical Imaging for Structural Inspections for Marine Renewables. *Submitted to IEEE, Journal of Oceanic Engineering (2018)*.

X **Francisco. F**., Sundberg. J. An Alternative Technique for Ultra-High Resolution Bathymetry and Seabed Inspection for Marine Renewables. *Manuscript (2018)*.

XI **Francisco. F**., Leijon. J., Boström. C., Engström. J., Sundberg. J. (2018) Wave power as solution for off-grid water desalination systems: Resource characterization for Kilifi-Kenya. *Published in MDPI, Energies, 2018 (11) 4.*

XII **Francisco. F**., Sundberg. J., Ekergård. B., Leijon. M. Wave Power in the Electricity Generation Mix: a Case Study of Ghana. *Manuscript*.

Contents

Abbreviations

ADCP	Acoustic Doppler Current Profiler
AVM	Acoustic visibility measure
DBS	Dual-beam Sonar
ECMWF	European Centre for Medium-Range Weather Forecasts
FOV	Field of View
GSM	Global System for Mobile Communication
MBS	Multibeam Sonar
HEC	Hydrokinetic energy converter
PV-SP	Photovoltaic Solar Panel
RADAR	Radio Detection And Ranging
SBS	Split-beam Sonar
SONAR	Sound Navigation And Raging
TVG	Time varied gain
UU	Uppsala University
UWC	Underwater Camera
WEC	Wave Energy Converter

Nomenclature

Symbol	**Unit**	**Entity**
ρ	Kg/m^3	Density
t	s	Time
x	m	Horizontal displacement
λ	m	Wave length
f	Hz	Linear frequency
ϕ	m/s	Phase speed
C	m/s	Speed of sound
Z	m	Depth
I	dB re 1 μPa	Intensity of Sound
k		Absorption coefficient
R	m	Radius of a sphere
TL	dB re 1 μPa	Transmission Loss
A	m	Amplitude of the sound wave
T	°C	Temperature
DI	dB re 1 μPa	Directive index
SL	dB re 1 μPa	Target source level
N	dB re 1 μPa	Noise
NL	dB re 1 μPa	Ambient Noise
TS	dB re 1 μPa	Target strength
v	m/s	Radial velocity
θ	π rad	polar angle
F_e	kW/m	Wave energy flux
H_{m0}	M	Significant wave height
T_{m0}	S	Wave mean period
Dir	° in geo-reference	Wave mean direction

Introduction

The energy sector is currently experiencing profound reforms and progressing towards clean and new renewable technologies and expansion of smart grids that will replace the already out-of-date energy systems. The world economy growth is rising, ca. 6% by year 2017, and accompanied by high growth in electricity demand of ca. 2 % in developed economies, and up to 12% in developing countries [1], [2]. In order to meet the actual energy demand, the exploration of all available renewable and non-renewable energy sources have also been rising. However, the world's electricity demand is still mainly met by fossil fuels (65%), followed by renewables (25%) and nuclear (10%) [2]. Although the implementation of renewable energy sources for electricity generation has increased substantially, the global energy related CO_2 emissions also increased by ca. 1.4% in 2017 [1], [2], possible due to a steep economic growth, weaker energy efficient systems and low fossil fuel prices [2]. In contrast with the goal of rapidly decreasing carbon emissions, the actual energy framework, which is mainly based on fossil fuels, might sustain the current CO_2 emission levels. However, the way forward is to bring cleaner i.e. nuclear and hydropower and newer i.e. solar, wind and ocean energy conversion technologies into the energy mix. The focus of this thesis is on the implementation of ocean energy, i.e wave and tidal power.

The implementation of marine renewable energy technologies follow the regional and local available resources, energy demand, environmental and socioeconomic conditions. For example, wave and offshore wind power resource are mostly available in oceanic coastlines, while tidal power is also available in several areas across the globe where the tidal range is considerable high. Therefore wave energy converters (WECs), offshore wind and tidal turbines have the potential to be integrated in the electrical generation mix in many countries worldwide. Wave and tidal power has an enormous potential in terms of energy density and global availability. The global extractable resource of combined tidal power is estimate do be ca. 1000 TWh/year [3], [4] and ca of 100 000 TWh/year of offshore wind power [5], [6]. Wind power already is an established technology and contributed with approximately 36% of the total renewable energy growth in 2017 [2].

Several concepts for wave and tidal power have been developed over the past decades with the view to deliver reliable electricity to the grid. However, very few of them has made into the commercial phase [7]. The relative low commercialization rate compared to offshore wind, might be associated with technical and environmental issues, higher development and operational costs aggravated by poor reliability and survivability of power take-off systems. Therefore, it is important that researchers, technology developers, financers, and police makers have a holistic view and make collective actions towards an accelerated and robust implementation of wave and tidal power.

The framework for ocean energy implementation consists of phases such as resource assessment, numeric modelling, development of power take off and control systems, grid connection, environmental monitoring, deployments, manufacturing, and marketing. This thesis focus on environmental monitoring and resource assessment which are determinant aspects of ocean energy projects. Resource assessment is needed in order to establish the feasibility of a specific energy conversion technology in relation to the local conditions. Environmental monitoring is important in order to obtain permits and licenses to harvest energy at a specific area as well as important for sustainable development.

Worldwide, history has shown that lack of reliable environmental data can be a barrier for consenting permits for renewable energy projects. For example, the European Union requires rigorous environmental monitoring frameworks throughout an entire project period [8]. In order to meet these consenting requirements, reliable and long-term environmental data is needed. Environmental monitoring is also needed in order to provide multivariable data to researchers, technology developers, energy utilities and to the general public. For that, modern and contextualized environmental monitoring techniques have to be evolved from the already dated monitoring techniques which are mostly limited by high costs, high risks, harsh weather conditions, and reliability [9] to modern, affordable and robust monitoring frameworks. The author believe that the overall costs of commissioning wave and tidal power projects can also be substantially lowered by adopting modern and effective environmental monitoring frameworks. The present thesis brings this vision to life through the development of simplified hardware and data processing and analysis techniques based on modern sonar systems, adapted for monitoring the physical environmental including fish and marine mammals surrounding ocean energy devices.

1.1 Importance of physical and biological environmental monitoring and energy resource assessment

Ocean energy have the potential of providing clean electricity to millions of people globally, if technical and economic conditions are favourable. Today, most of the new projects are started by SMEs or educational institutions with limited budgets. Therefore, all efforts channelled to minimize costs of ocean energy projects would be of great value for the sector. For example, some of the inevitable phases that involve substantial high costs are the pre-deployment activities related to site specific resource characterization, site specific seabed inspections and bathymetry, overall risk assessment and environmental monitoring. Most of today's standard procedures in marine operations were inherited from the rather wealthy defence, naval, oil and gas industries. The offshore wind sector has already begun to implement their own specific solutions such as jacking vessels, etc [10]–[12]. Unfortunately, the reality is that the ocean energy sector especially wave and tidal power, is still immature and incapable of sustaining the demanding costs of offshore operations. An approach to facilitate the implementation of ocean energy projects is to reduce survey costs by adapting and developing alternative techniques and tools based on existent components and procedures. The research leading to this thesis addresses part of this issue, for this, off the shelf sonar systems, cameras, etc., were integrated into a multifunctional platform, designed with the vision of monitoring the subsea environment surrounding ocean energy devices (Figure 1.1). Sonar systems are becoming indispensable tools for gathering data of physical, geological and biological properties of the hydrosphere e.g. [13]–[16].

Today, the accessibility of environmental data is still focused on regional and global scale, despite the existence of sophisticated data centres and data acquisition platforms such satellites, data buoys, etc. The current data framework favours weather forecasting, climate studies and other large and mesoscale phenomena. For example, wave data is mostly available at global and regional scales, commonly from 50 km to 14 km of spatial resolution and at four to eight hours of time resolution e.g. [17], which is not enough for site specific resource assessment. There are only few areas, such the Bay of Biscay and the English Channel where the wave data is available at spatial resolution of 2 km down to 200 m [18], which is very suitable for wave power resource assessment. There are also private databases able to provide high resolution environmental data, but at high purchasing costs. It is very important to work towards the acquisition of high resolution and reliable environmental data and make it available at accessible costs, in order to support the wave and tidal power sectors.

1.2 Environmental issues related to marine renewables

Human activity in the oceans can positively or negatively affect the marine environment. With the ever increasing use of the oceans, newly deployed technologies such as wind, wave and tidal power devices, new stressors are introduced into the marine environment of which the possible impacts are still beyond our common understanding [9]. Today, the quantity of environment data being acquired from offshore wind power (e.g. [4]), surpasses those from wave and tidal power, which is logical because offshore wind power is well spread across Europe. Less is known about the short and long term effects of wave and tidal power on the environment. In general, during the installation phase of an ocean energy project, the common effects are related to alteration of benthic zone instigated by laying of foundations and submarine export cables [19], [20]. The water quality can be affected by dispersion of sediments resultant from drilling, dredging and cable trenching [9], [21]. Vibrations and loud sound emitted during deployments also affects the marine environment, e.g. pile driving can produce loud impulsive sounds in order of 240 dB re 1 μPa at 1 m, which is almost the double over the ambient noise [22], [23]. Probable effects during the operational phase of an ocean energy project, are alterations of local hydrodynamics, emissions of loud sounds, propagation of electromagnetic fields from submarine export cables, collisions, colonization, artificial reef effects, leakage of fluids and contaminants, etc [19], [21], [24]. Positive or negative environmental effects during the decommissioning phase are likely to be reoccurring from the installation phase, but the impacts may be greater with the removal of devices [9]. For example, during 15 to 25 years in which an energy converter is permitted to be in the water, marine organisms may form great colonies within the devices, and the removal of such structures may trigger a combination of environmental effects. Marine ecosystems are complex and dynamic, thus prediction and forecasting of anthropogenic driven ecosystem changes can occur at different temporal and spatial scales [22], [25], [26]. Unidentified cumulative effects are the greatest uncertainties regarding the implementation of ocean energy. Therefore, reliable, cost effective and continuous environmental monitoring is necessary in order to support and improve the offshore operations.

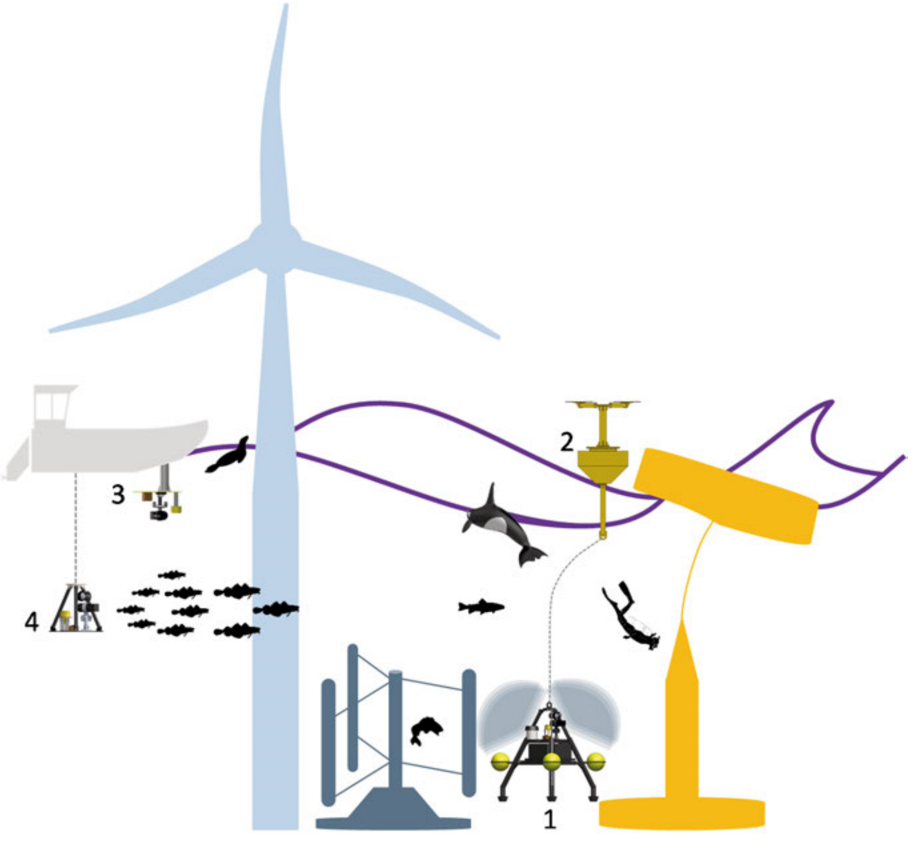

Figure 1.1. The vison of a multifunctional environmental monitoring platform based on sonar systems and applied for ocean energy. 1 – 2 represents a standalone configuration for long term surveys; 3 – 4 represents portable configurations for scouting surveys. The goal is to produce high resolution environmental data make it available at accessible costs, in order to support the offshore wind, wave and tidal power sectors.

2. Scope of the thesis

The work presented in thesis is part of the marine and hydrokinetic-riverine renewable energy projects undertaken on the Division of Electricity, Department of Engineering Sciences at Uppsala University (UU). Offshore tests were conducted at Lysekil research site, and riverine tests were conducted at Dal River in Söderfors. This research work also complements other studies such as the automation and robotization of underwater tasks [27]; experimental approach to onshore testing and offshore deployments of offshore monitoring of UU WECs [28]; underwater radiated noise from the UU WECs [29]; possible environmental effects of point absorbers wave energy converters [23], [30], [31]; study of colonization patterns and habitat dynamics related to operation of the Lysekil wave power research site [23], [30], [31]; study of buoy and generator interactions of the UU WEC [32], among other related studies. The presented work also contributes to the operation, installation and maintenance of the WECs and HECs as a whole.

2.1 The Lysekil project

The Lysekil research project is operated by the Div. of Electricity at Uppsala University. It comprises the design, construction, deployment and monitoring of full scale direct-driven point absorbers. The Lysekil research site is situated on the west coast of Sweden (58º11’42’’ N, 11º 22’ 50’’ E), approximately 5 NM south of the town of Lysekil. The research site has been operating since 2004, and since then, more than 10 different WECs, 2 submarine substations, 30 dummy WECs for environmental studies, submarine power and communications cables and a wave measuring buoy has been deployed. At this site, the common sea states occur with average wave power values of ca. 4 kW/m, significant wave heights of 1.2 m to 2.7 m and energy periods of 5 s to 7 s. More and detailed information about the Lysekil project can be assessed on [33], [34].

The UU WEC technology (Figure 2.1a), comprises of linear generators moored on a baseplate and connected to a heaving buoy e.g. [34], [35]. Wave energy is converted from the reactive force between the generator and the heaving buoy trough a reciprocating movement of the translator relative to the stator. The electricity produced by each generator is transmitted to a submarine substation and then exported to land via 1 kV electric cable. The UU

WECs have capacity of between 10 kW to 100 kW, at ca. 450 V, depending on the construction [33], [34]. Environmental studies conducted on the past [23], [29]–[31] have found that the UU WEC technology have limited effects to the marine environment. Underwater radiated noise, and artificial reef effects are among the subjects so far studied during the operational phase. However, more studies need to be done, as it is also required by the authorities. An overview of the Lysekil project is presented in Paper I and e.g., [33], [34].

2.2 The Söderfors project

Similar to the Lysekil project, the Söderfors project also involves the design, construction, installation, operation and environmental monitoring of a full scale direct-driven hydrokinetic turbine (UU HEC), deployed in the River Dal in Söderfors (60°23.26 N, 17°14.90 E), ca. 60 km north of Uppsala. The UU HEC technology tested in Söderfors measure 3.5 m of height and 6.0 m of width, it comprises five straight blades connected to a direct-driven permanent generator encapsulated in a steel hub on top of a steel made tripod gravity-foundation (Figure 2.1b) [36]. The site has a bottom depth of ca. 7 m, water speed of ca. 0.5 m/s to 1.5 m/s and discharges of 300 m^3/s – 1100 m^3/s. The riverbed is generally composed by hard subtracts (small rocks), in a clear conduit geometry within the excavated outlet of the hydro power plant. Deployed on the site are an energy converter, three acoustic Doppler current profilers (ADCP), export cable and marking buoys. Little is known about the environmental effects of this particular HEC. More about the Söderfors Project can be found in e.g. [36]–[38].

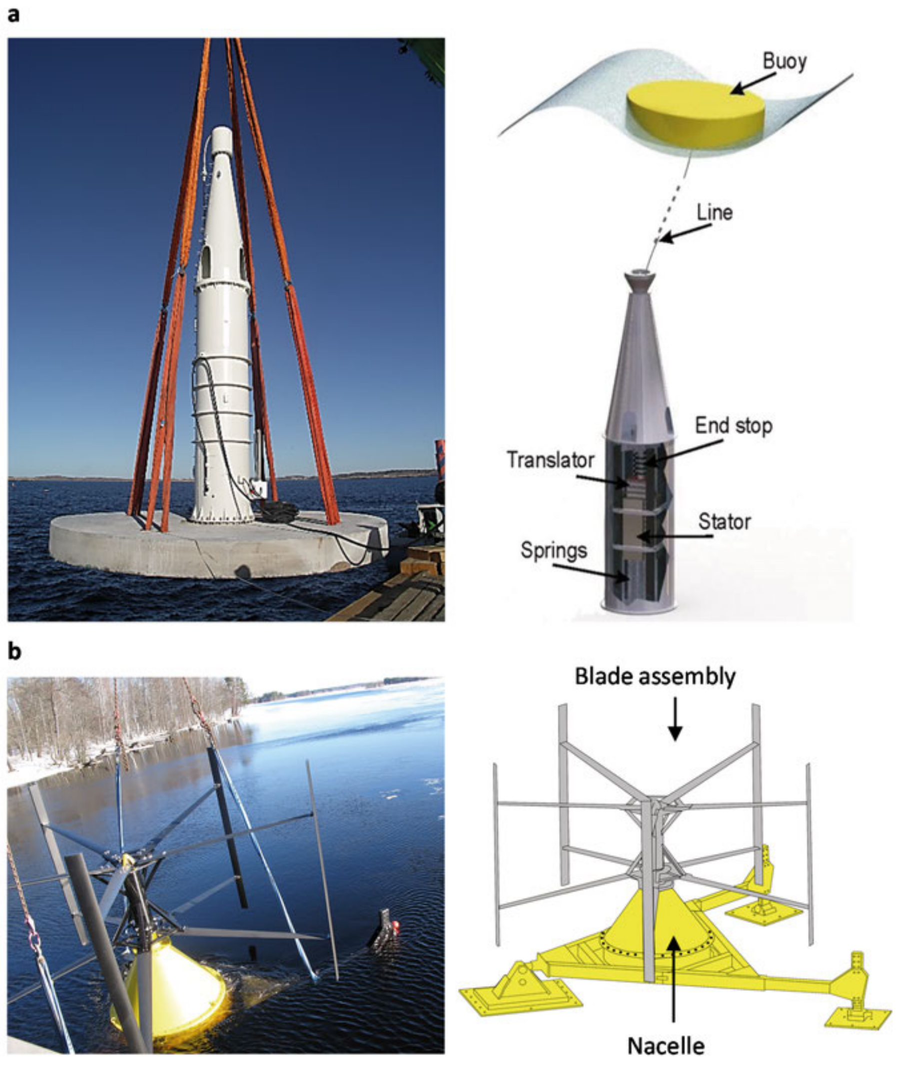

Figure 2.1. Overview of the (a) wave power and (b) hydrokinetic power converters developed by the Division of Electricity at Uppsala University.

2.3 Research hypothesis and aim

This thesis addresses the following hypothesis:

- High resolution sonar systems can be effectively used for monitoring ocean and riverine energy devices and the surrounding environment, especially in murky, deep and harsh marine environments where conventional monitoring methods are costly and risky.

- Marine renewable energy technologies may affect the marine environment in unforeseen and unpredictable manners, beyond our current knowledge.
- The feasibility of ocean energy projects can be brought to favourable and competitive standards if effective environmental monitoring of physical parameters and resource assessment frameworks become widely available.

Based on the above listed hypothesis and with the vision to minimize the costs and risks associated with subsea operations, this PhD work aims the following tasks:

- To develop an environmental monitoring platform based on sonar systems for ocean energy applications, by adapting standardized hardware such as high resolution multibeam (MBS), dual beam (DBS) and split beam (SBS) sonar systems and underwater cameras (UWCs) and integrate them into a multifunctional monitoring platform;
- To propose standardized data acquisition and processing protocols capable of decipher and analyse sonar data for a continuous environmental monitoring and reporting;
- The study of occurrence and behaviour of marine mammals and fish within wave and tidal power farms, using the built monitoring platform;
- To investigate the wave power resource and the feasibility of utilizing UU WEC technology to generate electricity worldwide.

2.4 Outline of the thesis

The research carried put within this thesis has been focused in three parallel paths:

- Designing, building and testing of hardware for the monitoring platform in order to evaluate the effectiveness of sonar systems for subsea surveying of ocean energy sites;
- Quantitative and qualitative analyses of the acquired data;
- The resource assessment and wave power characterisation of potential wave power projects.

The following Chapter 3 provides the theoretical background of sonar systems. The experimental setup describing the construction of the platform, auxiliary systems and the data processing framework are described in Chapter 4. The summary of results and conclusions are presented in Chapter 5. Future work is in Chapter 6.

3. Theory

Adaptation of sonar systems to monitor marine renewables is the centre of this thesis. Sonar (Sound Navigation And Ranging) are by definition, underwater echo ranging devices operating with radiated acoustic energy. This chapter outlines a general theory of sonar systems.

3.1 Sonar systems

Sonar is an echo ranging technology which uses sound energy to locate and survey objects within a water column [39]–[43]. In atmospheric conditions, sonar systems were used before the existence of RADAR (Radio Detection And Ranging) and are still being used for navigation, atmospheric studies, etc. Sonar can be used in several frequencies, depending on the objective of the survey. For example, ultra-low frequencies (< 0.1 Hz) are used for sub bottom profiling and hydrocarbons prospection. Low to mid frequencies (e.g. 0.1 – 100 kHz) are normally used for underwater communication, navigation, depth measurements and biomass estimation. And high (> 100 kHz) to ultra-high (> 1000 kHz) frequencies are used for acoustic imaging acquisition [43]–[45]. Commonly, a sonar system comprises a transducer that convert sound into electric signals, a set of electronics that control the excitation of the transducer, and a signal output or display unit [9], [43], [46] (Figure 3.1). An echogram consists of a series of echoes representing a real time signal, visually encoded by intensity or colour [43], [47]. While, an acoustic image consists of several echoes from multiple beams which are spatially distinct, and each is generally encoded by intensity, range or colour [43], [47], [48].

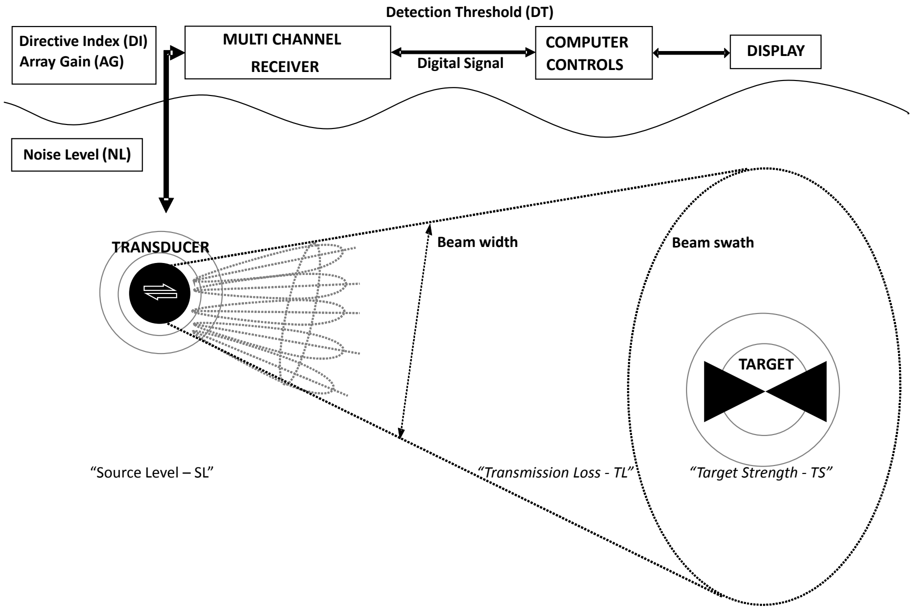

Figure 3.1. Overview of the working principle and the main components of a modern sonar system.

3.2 Underwater sound propagation

In order to evaluate the large variety of existent sonar systems, it is essential to first understand the sound-carrying medium, water, and the physical processes behind the sound propagation [9]. Sound are acoustic waves which propagates as a mechanical disturbance in a medium [42], [49]. Sound is associated with pressure and density fluctuations carried by particle motions, therefore related with distortion of the medium [42], [49]. The equation of sound is given as a function of pressure $p = p(x_1, x_2, x_3, t)$, speed of sound $c = c(x_1, x_2, x_3)$, amplitude of the pressure disturbance p_0, wavelength λ, frequency f, and phase speed ϕ (Equation 3.1). The speed of sound in water is a function of temperature, salinity and pressure, and the typical values a range of 1450 m/s to 1550 m/s [42], [49].

$$p(x,t) = p_0 \sin(\frac{2\pi x}{\lambda} - 2\pi f t + \phi) \qquad \text{Equation 3.1}$$

Acoustic waves are composed by kinetic and potential energy, referent to particle motion, and work done by elastic pressure forces. The acoustic intensity I, is the average energy flux per unit of surface and time, and for a plane wave is given in Watts per square meter $[{}^{W}/_{m^2}]$ (Equation 3.2) [42], [49].

$$I = \frac{p_0^2}{2\rho c} = \frac{p_{rms}^2}{\rho c} \qquad \text{Equation 3.2}$$

Sound in water is greatly absorbed by viscosity, ionic relaxation of boric acid ($B(OH)_3$) and magnesium sulphate ($Mg(SO)_4$) and loses at the fluid boundaries, surface (bubbles and ice) and bottom (sediments) [50], [51]. Acoustic absorption per unit distance *x* depends on the intensity I_0 before and *I* after absorption of sound, and also depend of coefficient *k* due to frequency of propagation (Equation 3.3) [52]. The coefficient k is given in decibels (dB) per kilometre as: 0.08 dB/km at 1000 Hz, 50 dB/km at 100 kHz, $1dB = 10\log(I/I_0)$. Low frequencies are much less attenuated than higher frequencies [50], [51].

$$I = I_0 \exp(-kx) \qquad \text{Equation 3.3}$$

Isolated targets, the water surface and the sea bottom reflect and scatter sound. At the surface, the ocean-atmosphere boundary layer reflects sound because the impedance difference is pronounced and little acoustic energy can cross this boundary [51]. For high acoustic frequencies the coefficient of reflection has a magnitude less than one and depends on the acoustic wave amplitude *A*, absorption coefficient k and root mean square of the acoustic wave height h (Equation 3.4) [53].

$$R = -e^{-2k^2h^2sin^2A} \qquad \text{Equation 3. 4}$$

In addition to the frequency of the sound, waves and roughness of the sea surface, factors such as wind generated bubbles, living organisms, biomass and fish occurring close to the surface, all interfere on the reflection and scattering of the sound waves [54]. The contrast of acoustic impedance between the water and seabed is less than at the sea surface, even if the reflection and diffraction processes are more complex on the seabed due to bottom composition [9]. The propagation of sound on benthic layers is further explained in *Biot* and *Buckingham* theory [55]. The reflection of sound at a given target larger than the incident acoustic wavelength depends on the size and shape of the target in respect to the surrounding environment. The complexity of target shapes can be approximated by interpolation or extrapolation and combination of simple target shapes [56].

Geometric spreading losses occur when the amplitude of an acoustic wave decay with increase of the distance from the source, resulting that energy content at a far offset is smaller than at a near offset [56]. The losses in spherical and cylindrical geometric spreading are expressed in terms of dB per doubling of distance from the source, and are independent of the acoustic wave frequency [56]. Underwater sound are spherical waves, the decrease in acoustic intensities (I_1 and I_2) between two targets is inversely proportional the radios (R_1 *and* R_2) of the sphere or range (Equation 3.5).

$$\frac{I_2}{I_1} = \left(\frac{R_1}{R_2}\right)^2 \qquad \text{Equation 3.5}$$

Transmission Loss (*TL*) compares the intensity of a signal at a specific range from the source to the source intensity at reference unit distance ($R_{1m} = 1\ m$) and is given in dB or as *TL* = 20log*R*, without unit [9], [53], [56]. Transmission loss mostly is a result of geometrical spread and absorption and emphasises that each frequency have a specific maximum range (Equation 3.6). Therefore, the frequency is a critical design parameter of sonar systems [9]. Here, the absorption coefficient *k* is a function of temperature (*T*) and depends on boric acid, magnesium sulphate and pure water (Equation 3.7), which is further explained by the *Model of Francois-Garrison* [56].

$$2TL = 40logR + 2kR \qquad \text{Equation 3.6}$$

$$k = (0.17 \times 10^{-3} f^{-})/(T + 18) \qquad \text{Equation 3.7}$$

3.2.1 The sonar equation

A sonar uses an acoustic transmitter and a receiver. The transmitter generates a pulse, or ping, transmitted towards a target, which is then reflected to the receiver as an echo. Additionally from calculating the range of targets by measuring the round trip time of pulses, sonar can also measure the bearing of each pulse. This is done by using several hydrophones to measure the relative time of each pulse in a process designated by beamforming [9], [53], [56]. Beam-formers are used to concentrate the acoustic power into beams that are swept to cover the chosen search angles [9], [56]. The sonar equation (Equation 3.8) is associated with the characteristics of the noise present at the receiver when an echo is detected. The ambient noise is described as isotropic if echoes arrive in one direction or several directions; or described as reverberation if the echoes returns primarily from the same direction as the signal [9], [56].

$$SL - 2TL + TS - NL + DI \geq DT \qquad \text{Equation 3.8}$$

A list of underwater acoustic parameters levelled in decibels relative to the standard reference intensity of a 1 µPa of plane wave are shown Table 3.1, and a diagram of the working principle of a sonar system is shown in Figure 3.1.

Table 3.1. Summary of acoustic and sonar parameters [9], [51], [53], [57]

Source Parameters	Symbol	Definition
Source Level	SL	10log10*(source intensity / reference intensity)
Source Directivity Index	Dis	10log10*(intensity of a directional source in the source-to-target direction / intensity of an omni-directional source of equal power)
Medium Parameters		
Transmission Loss	TL	10log10*(signal intensity @ source / signal intensity @ target or receiver)
Noise Level	NL	10log10*(noise intensity / reference intensity)
Target Parameters		
Target Strength	TS	10log10*(echo intensity / incident intensity)
Receiver Parameters		
Received Level	RL	10log10*(received intensity / reference intensity)
Receiver Directivity Index	DIr	10log10*(intensity measured by an omni-directional receiver / intensity of a directional receiver in the same isotropic sound field)
Detection Threshold (signal-to-noise ratio)	DT	10log10*(signal intensity / noise intensity) @ threshold

3.3 Sonar systems utilized in this research

After evaluating 19 different sonar systems, among 200 or more types available in the market, a multibeam imaging sonar, a dual beam sonar, and split beam sonar were chosen.

3.3.1 The multibeam sonar system

In multibeam sonar systems (MBS), the acoustic signals are irradiated and received in multiple angles across the track swath and typically in fan shapes [53]. Transmitting and receiving components i.e. transducer and hydrophone, are arranged in a 2-dimensiconal arrays, each component transmits pulses individually in a crescent order, and the echo is received simultaneously by all receivers [53]. Each signal (echo) is processed discretely enabling several beams to be formed by combining the outputs of the several arrays of transducers operating with different phase functions [9], [53]. This arrangement steers the beams in several directions at the same time creating spiral patterns that fill an entire the field of view (FOV). With this setup, the angular resolution increases if the beams are aligned side by side in the same plane, reaching up to 1500 beams in angular sectors up to 180° of FOV [46], [58]. Furthermore, the use of several narrow beams with a short pulses can maximize the effectiveness of the sampling volume covered by the entire swath in a single ping. Today, multibeam sonar systems can operate in frequencies up to 3 MHz at refresh rates up to 50 Hz, with range resolution of ca. 1 cm and beam spacing of ca. 0.2° [9], [53], [59], [60]. The limitations of multibeam sonar systems are mainly the short range which is limited to less than 100 m; the background noise generated by seabed, which affects the signal, mainly when the target is located at longer distance than the bottom depth [43], [59]; the presence of bubbles within the swath that can cause intense noise, mainly if the sonar is operating with high frequencies [43], [59]; the data processing of multibeam sonar systems is complex, time consuming and large volume of data are generated [9]. On the other hand, multibeam sonar systems are useful for bathymetry surveys, seabed mapping and inspection, fishery, underwater navigation, inspection of underwater structures, underwater surveillance etc., [9].

3.3.2 The dual beam sonar system

The transducer of dual beam sonar systems (DBS) are composed by two arrays of single frequencies, a narrow and wide beam transmitters and receivers, respectively. Echoes are received simultaneously by the two arrays and the resulting effect is a coaxial beam pattern featuring a core beam within a relatively broad beam [61], [62]. Beam patterns can be pre-determinate by comparing the two output signals of a target. And a direct measurement of backscattering cross section is obtained by removing the beam pattern [61], [62]. Dual beam sonar only utilizes signal intensity without the phase. Consequently, among the three parameters of the spherical coordinate system (r, θ, φ), a dual beam sonar can only determine two parameters (r, θ) [61], [62]. Dual beam sonar systems can operate with frequencies up to 1 MHz and beam width of up to 60° [61], [62]. This type of sonar are normally used for navigation, scientific, recreational and fishing surveys [9].

3.3.3 The split beam sonar system

In a split beam sonar system (SBS), the transducer is divided in four quadrants that work simultaneously, but receive echo independently, forming four beams arranged perpendicularly two by two [47], [59]. Split beam sonar systems uses both amplitude and phase of an acoustic signals to determine the position of targets within the spherical coordinates (r, θ, φ), using interferometer technique, i.e. use of phase differences between adjacent quadrants [46], [47], [59], [63]. Split beam sonar can also operate in frequencies up to 1 MHz, and have superior performance comparing to dual beam systems, mainly due to higher SGN (signal to noise ratio), and phase angle, but the spatial resolution can be limited [9]. Split beam sonar systems are commonly used as a standard technology in fisheries surveys [59].

In the present thesis, the MBS was used to acquire acoustic images at mid-range up to 100 m. The DBS and SBS were utilized to detect and track targets at longer range and provide a 3-dimensional information of targets. Underwater cameras (UWCs) were used to acquire near-range optical images of the underwater environment. A summary of specific environmental monitoring objectives for each sensor is given in Table 3.2.

Table 3.2. Environmental monitoring objectives for each deployed sensor integrated in the monitoring platform

	MBS	DBS	SBS	UWC
Monitoring objective	structural inspection	bathymetry	biomass	structural inspection
	seabed inspection	biomass	fish	seabed inspection
	biomass	fish	marine mammals	marine mammals and fish
	marine mammals and fish	suspended bubbles	benthic habitat	benthic habitat
	benthic habitat	benthic habitat	bathymetry	
	suspended bubbles		suspended bubbles	

4. The study setup

This research focused on developing hardware for monitoring the subsea environment surrounding ocean energy converting devices. To achieve this goal, a multifunctional platform was designed, built and tested. There was also a need to develop new protocols to process and analyse the collected data. Both the hardware and the data processing protocols were tested and the results were presented in Papers III – X.

The main instruments integrated into platform were a MBS, DBS, SBS, UWCs (Figure 4), and the main features are portability, versatility and autonomy. This section describes how this multifunctional environmental monitoring platform based on sonar systems was built.

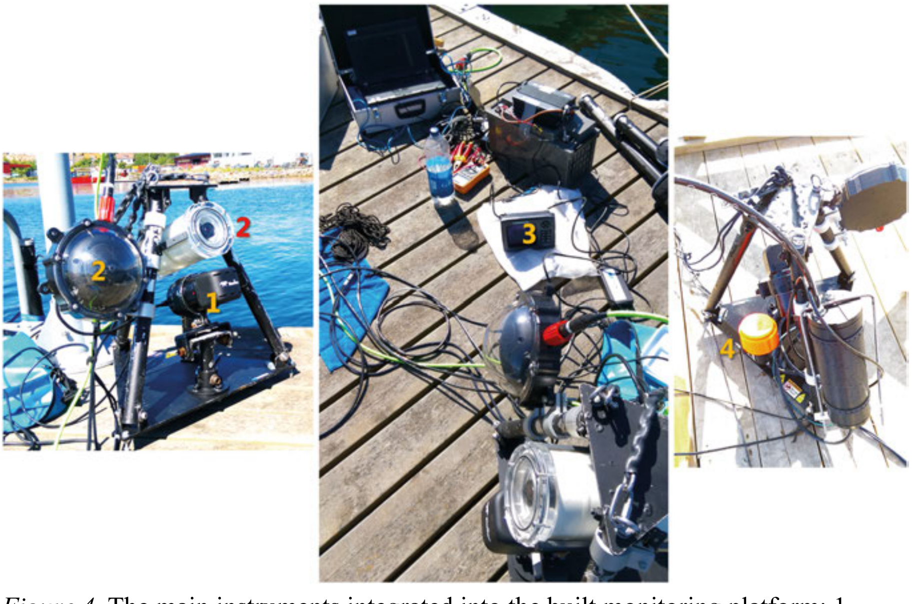

Figure 4. The main instruments integrated into the built monitoring platform: 1-multibeam sonar (MBS), 2-underwater cameras (UWCs), 3-dual beam sonar (DBS), and 4-splitbeam sonar (SBS).

4.1 Hardware development

The hardware included a portable pole mount, a tripod and the entire standalone platform (Figure 4.1). The portable mount system was designed for scouting surveys. The tripod was designed to be deployed is scouting surveys as well as integrated into the standalone platform. The standalone platform was designed to operate autonomously as well as remotely controlled in order to perform long term surveys. The conceptual design included a tripod deployable on the seabed and linked to a communication buoy on the surface. However the buoy was not built due to time and cost constrains. The conceptual design had two phases, the first phase involved a “sophisticated”, compact and easy to assembly model (Figure 4.1a, Paper III). Because of construction constrains this model evolved into a more straightforward and easy to build concept but difficult to assembly on site (Fig. 4.1b, Paper V).

4.1.1 Portable mount system

Technically the portable mount system comprises a pole mount made of reinforced materials, with variable length of 1 m to 5 m attached to a thin aluminium baseplate (Figure 4.1c). The baseplate houses the instruments (MBS, DBS, SBS, and UWCs) and acts as a hydrodynamic stabilizer on scouting surveys. The entire portable mount system was designed to be lightweight ca. 3 kg, and easy to deploy from a surface platform (e.g. vessel, bridge, dock).

4.1.2 Tripod

The tripod is made of the same thin aluminium baseplate used on the portable mount system that can be reassembled to form a stable pyramid structure (top part of Figure 4.1b). It measures 630 mm of width, 560 mm of height, and weight ca. 7 kg. The tripod houses the MBS, SBS and UWCs, but could also include an acoustic Doppler current profiler (ADCP), hydrophones, sediment trapper, among other devices.

4.1.3 The standalone platform

The standalone platform comprises a steal chassis, coupled with the tripod and watertight aluminium-made containers. The entire platform measures 1800 mm of width, 1700 mm of height, and have gross weight of ca. 250 kg (Figure 4.1b). Instruments that were submerged with this platform are the MBS, SBS and UWCs. Inside the water tight containers were the on-board computer, switch, a router, timer, power-supply circuit and batteries. The on-board computer controls all the devices and stores the data. The battery pack comprised a set of five deep cycle gel batteries with a total output power of 7.8 kWh. Initially, the conceptual design allowed a power-efficient plan that included the recharging of the batteries using a set of solar panels placed on the communication buoy. Technical specifications of all the allocated devices are listed in Table 4.1.

4.1.4 Conceptual communication buoy

The conceptual communication buoy was designed with ca. 1000 mm of diameter, and 1700 mm of height (Figure 4.1d). This buoy would house solar panels, batteries, modem and a router. The purpose of this unity was to establish a remote wireless connection between the tripod and a user as well as recharge the batteries of the submerged tripod. This buoy could also be used as a docking station where a user could stablish a direct connection with the submerged instruments without the need of retrieving the platform.

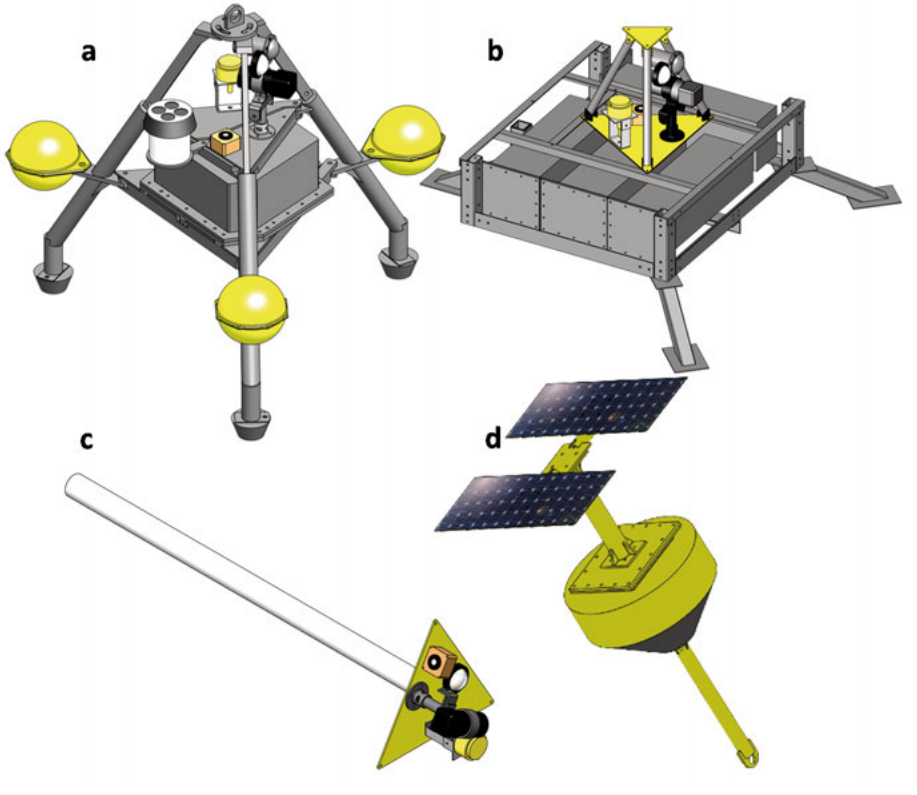

Figure 4.1. Computer rendering of the hardware for a subsea environmental monitoring platform. (a) The first conceptual design of the standalone platform with a sophisticated structure; (b) The second and actual concept of the standalone platform, aimed to save time and costs of construction; (c) The pole mount system; And (d) the conceptual communication buoy.

Table 4.1. Technical specifications of main instruments allocated to the monitoring platform.

Component	Specification	Component	Specification
Computer *VIA Artigo A1200*	Clock: 1.0 GHz RAM: 4GB DDR3 HDD: 2TB (storage memory) VGA: FULL HD 3D Input Voltage: 12 VDC	Battery bank	12 V, 7.8 kWh Deep cycle gel
DBS	Frequency: 50/200 KHz No. Beams: 2 FOV: conic, 29°/12° Maximum range: 762 m Input Voltage: 10 – 19 VDC	Multibeam imaging sonar (MBS) *BlueView M900-130-S-MKS-VSDL*	Frequency: 0.9 MHz (operational) Number of Beams: 768 Refresh rate: up to 50 Hz FOV: 130°x20° (field of view) Resolution: 0.18° / 2.54 cm Max. range: 100 m Input Voltage: 12 – 48 VDC Power consumption: 13 W
SBS *Simrad EK 80*	Frequency: 200 KHz No. Beams: 4 FOV: conic, 12° Max. range: 550 m Input Voltage: 12 – 48 VDC	UWC 1 *Mobotix AG*	FOV: Hemispherical, 180° Sensitivity: 0,05 lux Max. resolution: 2048x1536 (3MP) Refresh rate: M-JPEVGA: 22 fps Video stream: (MxPEG) 30 fps
UWC 2 *Axis 2880CS*	Lense: 2.8 – 8 mm / F1.2 FOV: 92°-32° Sensitivity: 0.04 lux Max. resolution: 2592x1944 (5 MP) Max. frame rate (M-JPEG): 30 fps Video stream (MxPEG): H.264	UWC 3 *Sony AS200V*	Lense: 2.8 – 11 mm / F17.1 FOV: 170° Sensitivity: 6 lux Max. resolution: 3952x2224 (8.8 MP) Max. frame rate H.264: 240 fps Video stream MP4 / XAVC S H.264

4.2 Deployment setup

The platform was designed to be portable, versatile and autonomous, allowing it to be deployed in four configurations (Figure 4.2, Paper V). The pole mount system was deployed from a scouting vessel (Figure 4.2a) or from a fixed structure (Figure 4.2b) for downwards looking surveys. The tripod was down and upcasted from a vessel (Figure 4.2c) or a fixed structure (Figure 4.2d) in order to observe targets throughout the entire water column. The focus of this research was a standalone configuration (Figure 4.2e) with an autonomous operation was used for long term surveys.

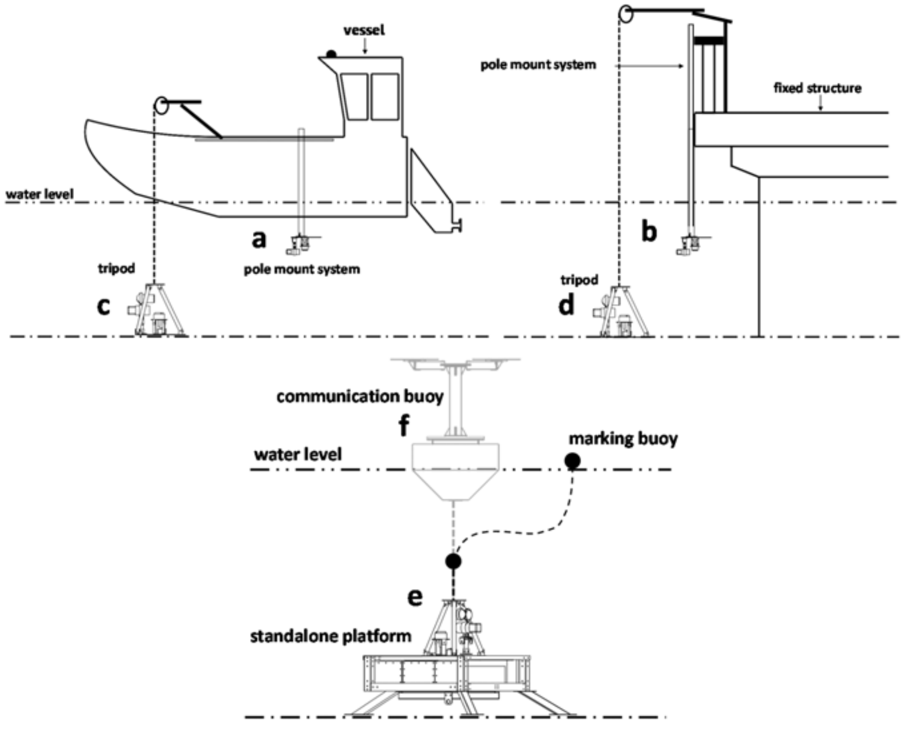

Figure 4.2. Deployment configurations. (a) Pole mount system deployed from a vessel or (b) from a fixed structure. (c) Tripod deployed from a vessel, or (d) from fixed structure. Deployment of the standalone configuration for long term surveys (e) the actual setup, (f) the conceptual setup including the communication buoy.

4.3 Auxiliary systems

The design and construction of auxiliary systems were also part of this research work. A robust quick release mechanism was built to be used to release the standalone platform from the seabed; and a model of the Söderfors hydrokinetic turbine has also been designed and built for environmental studies involving fish in a test tank.

4.3.1 A model of hydrokinetic turbine

A hydrokinetic 1:10 model turbine of the Söderfors HEC was designed and built to be primarily used in testing tanks for fish behaviour studies. This model turbine was built with only three blades instead of five (Figure 4.3a), but design and construction are still in progress and the final device will be versatile allowing both vertical and horizontal axes configurations. Experiments with living fish were conducted in a hydrokinetic test tank in Älvkarleby (Paper IX).

4.3.2 A robust quick-release mechanism prototype

The initial idea was to attach floaters to the tripod (Figure 4.1a), and anchor it to the seabed through a quick release device (Figure 4.3b). With a coded signal from the surface, the releasing device would detach from the anchor, allowing the entire tripod to surface. However, with changing of the concept design of the platform, the quick release mechanism was left to work with the conceptual communication buoy, therefore it was built but never tested or used. The main section of this device that comprise the releasing hook and was made of reinforced steel capable of sustaining large dynamic loads. The two lateral containers houses batteries, control electronics and a robust actuator.

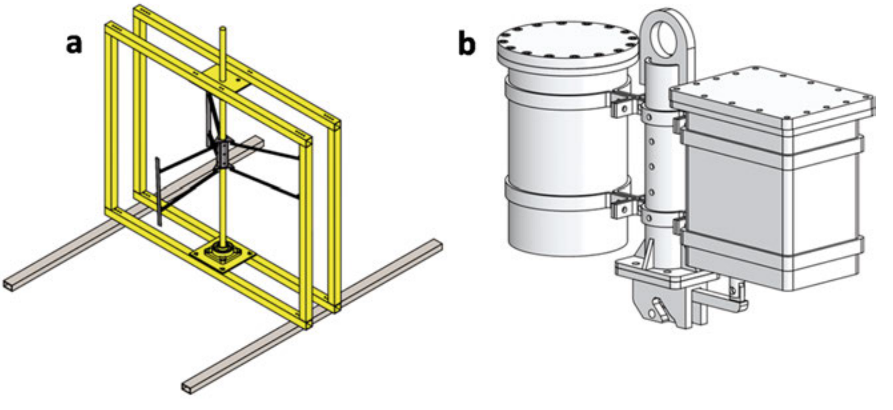

Figure 4.3. Computer rendering of (a) 1:10 model of the Söderfors hydrokinetic turbine, but restricted to three blades instead of five; (b) robust quick release mechanism to be used with the standalone platform and communication buoy.

4.4 The built hardware

Images of the actual built hardware are shown in Figure 4.4. Several tests were conducted in marine, and riverine environments in order to calibrate the instruments and improve the chassis and deployment setup. The construction of the platform took ca. nine months including a six month delay that triggered the change of conceptual designs as mentioned in Section 4.1. Critical components such as the water tight containers (Figure 4.4a) were extensively tested prior to deployment. Each instruments were also extensively tested and recalibrated several times. System integration tests were conducted in the laboratory as well as in real marine and riverine conditions (Figure 4.4 b, c). These tests were critical in order to set the optimal operational parameters such as memory and power management, burst timings, and automation routines for the long term deployment.

The platform was easy to deploy from a vessel or a fixed structure (Figure 4.4d). However, the standalone configuration required substantial work to set up (Figure 4.4e – h). Compromises on the design made it difficult to assemble the batteries. The start-up procedure (Figure 4.4e) was lengthy as it required manual entry of an ICMP (internet control message protocol) via suit of IPs (internet protocols): TCP (transport control protocol) UDP (user datagram protocol/internet protocol), and RTP (real-time transport protocols). The standalone platform was deployed using a vessel equipped with a crane and a winch (Figure 4.4f) which lowered the platform to the seabed. At the end of each survey, the platform was retrieved, opened, and the data was downloaded and the batteries recharged (Figure 4.4h).
Deployments in riverine environments used both the pole mount system (Figure 4.4i – m) and the tripod for long term surveys in Söderfors, where a UU HEC is deployed. In in Söderfors, the MBS was deployed on the pole mount attached to a bridge pillar and directed to the HEC (Figure 4.4j), while the SBS was deployed on the tripod with and upward looking configuration (Figure 4.4k). All instruments were interconnected in the data acquisition station placed on the bridge (rectangle in Figure 4.4m). This data acquisition station is accessible via internet protocols from a nearby measurement cabin as well as from the Angstrom Laboratory in Uppsala.
The 1:10 model HEC was also built by the author at Angstrom Laboratory (Figure 4.4n) and transported to a hydrokinetic test tank for experiments with fish (Figure 4.4o) in Älvkarleby, ca. 80 km north of Uppsala.

Part of the quick release mechanism is shown if Figure 4.4p, this is the main section that comprise a robust hook designed to hold large static and dynamic loads.

Figure 4.4a-p. Compilation of images taken during construction and deployment of the monitoring platform.

5. System integration and data acquisition framework

This multifunctional environmental monitoring platform is electrically divided in three segments: the instruments, power supply, and communications (Figure 5.1). Each instrument is connected to the computer through a switch or router. The on-board computer store data and controls all instruments. The power supply consists of batteries, timers, inverter-circuit, and chargers. Conceptually, if a power cable exists, the inverters would turn AC to DC power and feed the entire system [9]. The communication segment on the buoy includes switch, router, a wideband GSM antenna, photovoltaic solar panels (PV) batteries and a multipurpose plug [9]. The battery bank on the conceptual buoy would be recharged by a PV and supply power to the router and antenna, as well as recharge the batteries located in the standalone platform. A multipurpose plug comprising power and data connectors to could be fitted in order to stablish a direct wire connection between the submerged standalone platform and a user on the surface. The plug would work as a docking station where data can be downloaded and a direct charging of the batteries can be effectuated.

The on-board computer controls the data acquisition of all the devices integrated on the monitoring platform. Then, software is used to process the data. Each instrument had its own routine and subroutines such as illustrated in Figure 5.2. However, specific algorithms were developed to address specific research questions, such as detection of cavitation using MBS and DBS (Paper VI), detection visual signatures retrieved from acoustic images (Paper VII), ultra-high resolution seabed inspections (Paper X).

The MBS uses the *BlueView SDK 3.6* and *ProViwer4* software [64] for data acquisition and processing. Data was acquired as a sequence of pings, each contains echoes from 768 beams that combined formed acoustic images. The MBS data contains information of backscatter intensity of, range and two-dimensional positioning (r, θ) including velocity of targets. Further data analysis and image processing was conducted using *Matlab, FIJI* [65], [66].

DBS data was processed and analysed using *Sonar Viewer* and *Matlab* [16], and the SBS uses *Simrad EK80* software for data acquisition and analysis. Data of both DBS and SBS comprised acoustic backscatter intensity and range of targets within the acoustic swath. However, the SBS provides three-dimensional positioning (r, θ, φ) of targets, instead of two (r, θ), provided by the

DBS. Acoustic data and echograms were further processed and analysed using *Matlab*. The raw data of all sonar systems (MBS, DBS and SBS) were automatically compensated with time-varied-gain (TVG) in order to remove the effects of transmission loss on the acquired acoustic data. The data acquired by UWCs had a simple structure of an optical image, which were submitted to further image processing using *Matlab*.

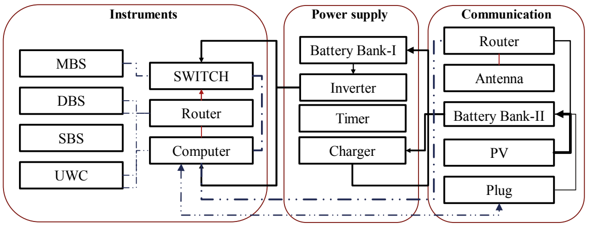

Figure 5.1. The system integration architecture showing how the instruments are interconnected. The dashed line represents data link and the full line represents the power supply.

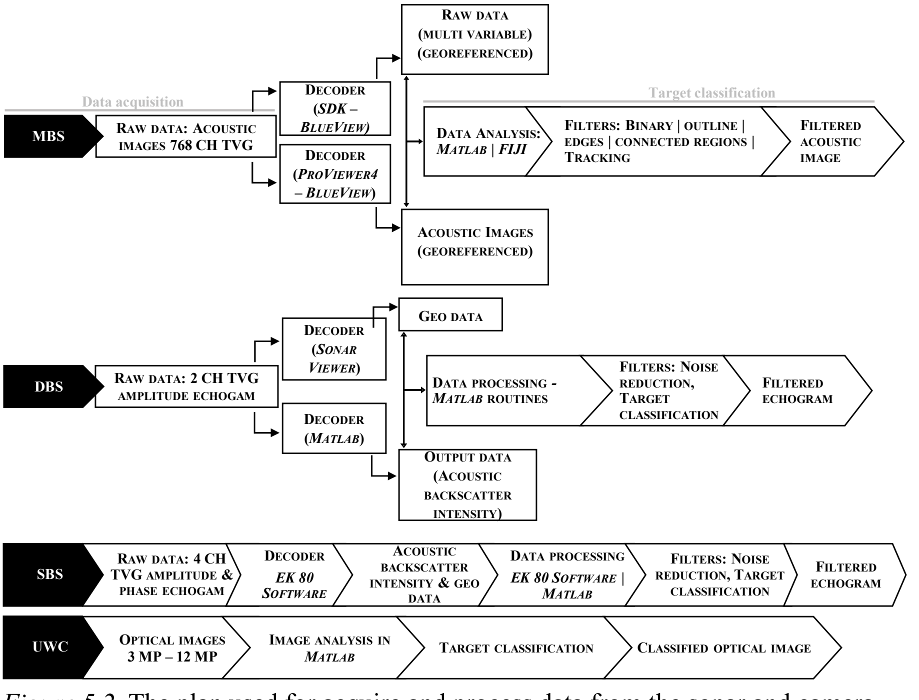

Figure 5.2. The plan used for acquire and process data from the sonar and camera systems. The multibeam imaging sonar (MBS) acquired acoustic images; the dual beam sonar (DBS) acquired depth data and produced echograms; the split beam sonar (SBS) acquired positioning and biomass data and produced echograms; and the underwater cameras (UWC) captured optical images during the survey.

6. Summary of results and conclusions

This Chapter provide a summary of results and conclusions from the papers on which this research work was based. It is divided into three parts, each refers to a specific research objective: hardware design and performance; quantitative and qualitative data analysis; and wave power resource assessment.

Paper I was described in Section 2.1, and Paper V is extensively described across the entire thesis, therefore not further discussed in this Chapter.

6.1 Hardware design and performance tests

6.1.1 Today's monitoring systems and their limitations – Paper II

There are several technologies and techniques designed to monitor the marine environment, which are mostly adjusted for offshore activities such as marine transportation, oil and gas prospection, military, safety and rescue, biology and oceanographic research, etc [9]. But, regarding the ocean energy sector, there is a need for new and adaptive environmental monitoring techniques and attuned technologies. For example, high resolution and modern sonar systems, can be adapted for the monitoring of ocean energy devices and its surroundings, especially in murky, deep and harsh water conditions.

Conventional and traditional environmental monitoring techniques, e.g. quantitative sampling, visual observations, diving etc, are costly, risky and limited by variety of factors [67]–[70]. On the other hand, modern techniques do not require direct observations, therefore it only uses quantitative sampling and diving for calibration and installation of instruments, if needed. Such unmanned monitoring frameworks can be deployable in fixed or moving platforms, such as standalone underwater monitoring stations (submerged platforms or data buoys), remote operated vehicle (ROV) or autonomous underwater vehicles (AUV), towed underwater vehicles, airplanes and satellites [16], [27], [68], [71], [72]. Several non-invasive monitoring instruments can be integrated into these platforms and attuned to gather environmental data at predetermined space and time. Comprehensive information about today's monitoring systems and its limitations is provided in Paper II.

6.1.2 Initial tests and calibration of sonar systems – Paper III, IV

Initial calibration tests were conducted in order to learn the MBS and DBS functionalities and capabilities. The aim was also to evaluate if the sonar systems were affected by water velocity, turbulence, temperature, salinity, turbidity, stratification, etc. Therefore, tests were conducted at different locations with different aquatic environmental characteristics e.g. marine-sheltered, marine-energetic, riverine-sheltered, and riverine-rapid. Specific targets such as UU WECs, the Söderfors turbine (UU HEC), bridge structures, hull of boats, fish shaped dummies, and live fish trapped in test nets, among other targets were studied.

An example of initial calibration results using MBS and DBS systems is the biomass estimation with test fishing nets, which evaluated the instrumentation capabilities of tracking and classify fish in terms of size and shape. In this case, five test fishing nets were deployed longitudinally and in parallel to the river flow on River Fyris in Uppsala, and River Dal in Söderfors near the test site location [73]. The nets with and without live fish, were insonified at near-range. The resultant acoustic images (Figure 6.1a) and echograms (Figure 6.1b) show fish trapped in the nets as bright arcs.

At this phase of the research, the main finding was that the MBS and DBS could produce clear acoustic images and echograms in all four types of aquatic environments, respectively. However, suspended sediments in stratified water layers and the surface turbulence caused noise to acoustic images and also affected the upper part of the DBS echograms. The MBS acoustic images were affected by the surface turbulence, and suspended bubbles within the water column. The dimensions of targets that were measured using the MBS embedded ruler, had errors of accuracy of approximately 10 mm, and these errors might have been associated with visual limitations, screen resolution, Doppler effects that might have distorted the images, the geometric shape and composition of targets. The geometric shape and composition of targets were later addressed with further observations and analyses of a variety of different targets, e.g. Papers VII and VIII.

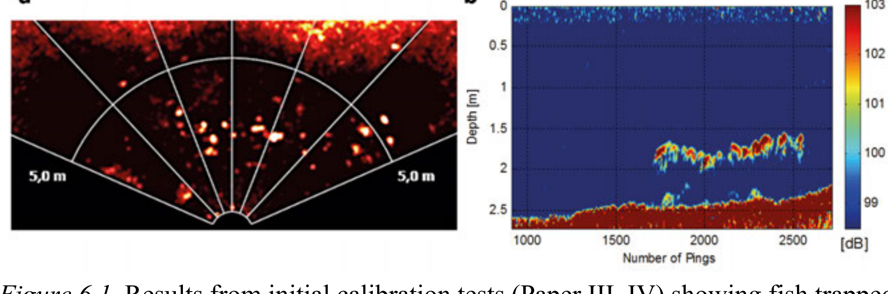

Figure 6.1. Results from initial calibration tests (Paper III, IV) showing fish trapped in a test fishing net represented by the red arcs, (a) MBS acoustic image, (b) DBS echogram from.

6.2 Quantitative and qualitative data analysis

6.2.1 Observation of cavitation flows using MBS and DBS systems – Paper VI

Since hydrokinetic resources commonly occur in rivers, narrow channels and in coastal bends with tidal currents [4], [74], in the future, totally submerged HECs might be deployable in areas with boat traffic. Assuming that strong and deep wakes produced by transiting vessels may contain cavitating flows or can trigger cavitation that would directly or indirectly affect the optimum operation of HECs deployed in areas with intense boat traffic. A study was conducted to access the range of wake produced by two transiting vessels in a narrow channel located in Finnham Island – Stockholm archipelago. A MBS and a DBS were used to observe the wake and measure the depth of the cavitating flow left by a vessel with propeller versus a vessel with waterjet thrusters.

The results show the vessel with propellers thruster had a wide and intense cavitating flow which reached 12 m of depth, and lasted approximately 90 s (Figure 6.2a). While, the vessel with waterjet thrusters produced a narrower and less intense cavitating flow, reaching depths of approximately 10 m and also lasting approximately 90 s (Figure 6.2b). The local bottom depth profile within the surveyed area reached between 12 m and 33 m.

This study concluded that the vessel with propellers produce more intense cavitating flows compared to the vessel with waterjet thrusters, this when considering mid-size passenger ferries with carrying capacity of ca. 350 passengers. It was also concluded that depending on the bottom depth of the site, the cavitating flow in the wake of ferryboats or similar vessels may have an impact on HECs placed in areas where boat traffic is prominent. This finding implies that it may be important to consider and investigate further cavitating flows, prior to deployments of HECs.

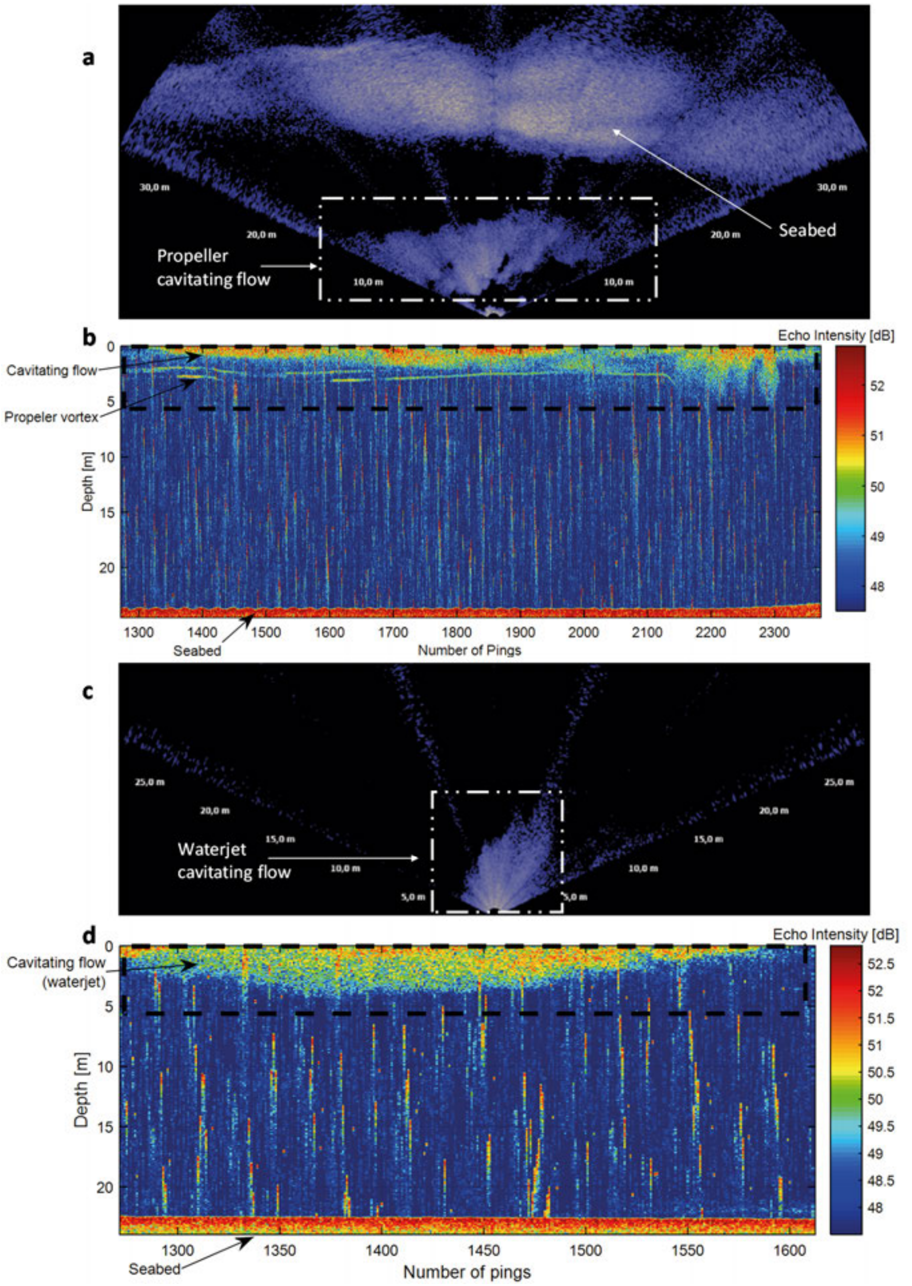

Figure 6.2. Cavitating flow of vessels with propeller and waterjet thrusters: (a, c) acoustic images, (b, d) filtered echogram (Paper VI). Both flows reached depths close to 10 m and lasted ca. 90 s but the propeller induced a more intensive and large flow. The filtered echograms show flows reaching 6 m of depth but raw echogram showed that the actual flow reached ca. 8 m of depth for the propeller vessel.

6.2.2 Echo intensity analysis – Papers V, VI

Identification and classification of targets could be improved by utilizing K-means clustering, supervised and unsupervised classification of values of acoustic backscattering intensity (Papers V, VI). The K-means clustering is a method that separates data into sets, so that each set of acoustic backscattering intensity values are clustered with the nearest mean [75]. This technique can separate targets of interest from the background noise, benthic zone, and water surface. For example, Figure 6.3a shows acoustic intensity values of an UU WEC and its surroundings. Here, four clusters were identified, the cluster with red dots refers to echoes from a WEC, the blue-dots cluster represents the seabed; the cluster with black dots represents background noise and surface turbulence; and the cluster with cyan dots contains the most frequent echoes of the entire acoustic backscattering intensity data. In this case, the most frequent values of echo intensity (Figure 6.3b) were between -98 dB and -102 dB, the water surface and riverbed reflected echoes above -100 dB of intensity, suspended targets and noise had values between -65 dB and -96 dB.

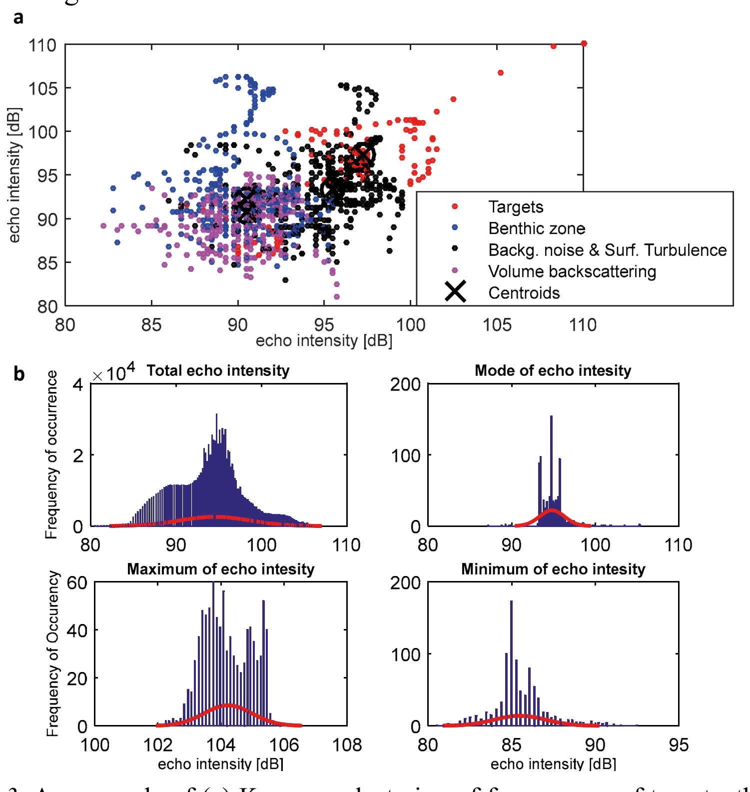

Figure 6.3. An example of (a) K-means clustering of four groups of targets, the red dots: an UU WEC, blue dots: seabed, black dots: background noise and surface turbulence, cyan dots: entire volume backscattering of targets with low echo intensity. (b) Distribution of the acoustic backscattering (echo) intensity: the mode of echo intensity represents background noise, the maximum represents a WEC, and minimum of echo intensity that represents both a WEC and background noise. (Papers V, VI)

6.2.3 Detection of visual signatures of marine mammals and fish using acoustic images – Paper VII

Ocean energy is mostly harvested in deep, murky and highly energetic areas in which conventional data acquisition techniques are impractical. However, the present research has shown that high resolution and high frequency sonar systems can be an alternative technology for monitoring ocean energy sites. The information about the occurrence, size and behaviour of fish, diving birds, marine mammals, occurring within ocean energy sites can also be collected using imaging sonar systems. However, the use of imaging sonar systems is still new and the interpretation of acoustic images remains difficult. For this reason, and in order to facilitate the classification of underwater targets using acoustic images, this research resulted in the development of a technique to extract visual features of targets such as fish and marine mammals. And proposed the use of such visual features as unique target signatures that can be used for automatic or aided target classification. Therefore, a new quantity entitled as Acoustic Visibility Measure, AVM, was invented as an indirect technique of identification and classification of targets by comparing the observed size (R_o) with the standard value (R_e), $AVM = R_o/R_e$ (Paper VII).

The AVM data can be utilized to train algorithms for manual or automatic identification and classification of underwater targets detected by imaging sonar systems. Software such as *ProViwer4* [64] and *FIJI* [65] were used to process acoustic images acquired using the MBS, and extract the size and shape of marine animals. And the visual signatures were extrapolated using *Solidworks* software [76].

This study found that acoustic images can be used to classify underwater targets such as harbour and grey seals, large marine mammals, cod and schools of fish, according to their size, shape and swimming behaviour. For example, the results show that harbour seals occurred as bright torpedo-like and fast moving targets (Figure 6.4a). Whereas grey seals occurred as bulky-ellipsoidal targets displaying serpentine movements (Figure 6.4b). Cod occurred as bright, 0.9 m long, ellipsoidal targets shoaling in groups of up to 50 fish (Figure 6.4c). Larger marine mammals most likely orcas, occurred with relatively low visibility compared to their body size, measuring between 4 m and 7 m (Figure 6.4d).

The AVM technique has the potential of providing a new window of both qualitative and quantitative observations of underwater targets. With further improvements, this technique can be useful for environmental impact studies within marine renewable energy sites as well as in other applications.

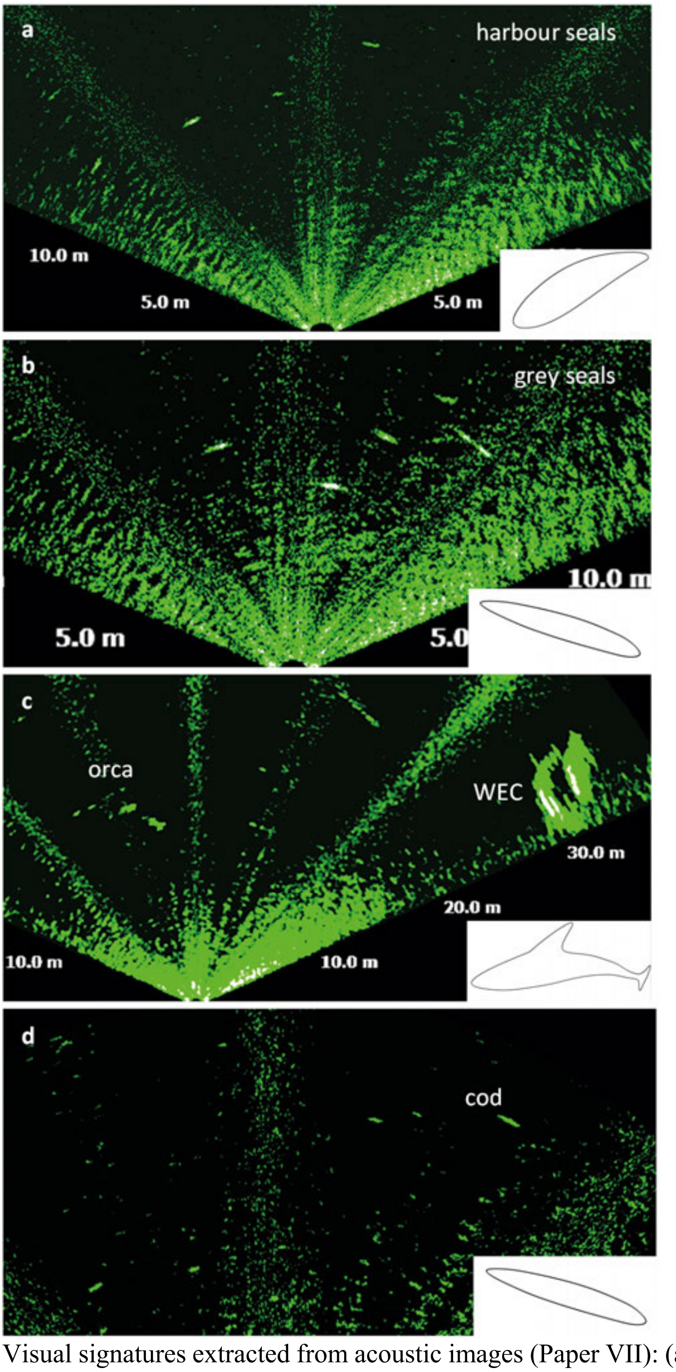

Figure 6.4. Visual signatures extracted from acoustic images (Paper VII): (a) harbour seals with length: 1.2 m to 2 m; range of ca. 11 m (b) grey seals with length: 1.6 m to 2.6 m, range of ca. 10 m; (c) orcas with length of 7 m, dorsal fin of 1.3 m, at range of 15 m; and (d) cod with length of 0.6 m to 0.9 m, range of 10 to 20 m. The shape was obtained from several acoustic images processed *ProViwer4* and *FIJI*, and then re-constructed by extrapolation using *Solidworks*.

6.2.4 Observation of marine mammals and fish at Lysekil wave power research site – Paper VIII

The aim of this study was to observe the occurrence of fish and marine mammals at the Lysekil wave power test site. For that, the MBS was integrated into a standalone monitoring platform (Figure 4.2e) and used for gathering acoustic images of the environment surrounding UU WECs. The MBS was orientated upwards with a pitch angle of 10°. The survey was conducted between the 23rd of August and the 1st of September 2016 and during this period, the automatically conducted 260 observations of underwater targets. Each observation comprised 1199 acoustic images acquired at 1.25 Hz within a time-lap of 16 minutes, and with intervals between observations of 47 minutes. The data was processed using *ProViwer4* [64] and *Matlab* [66], in which acoustic images were submitted to supervised classification. Sample of well visible targets were selected as training data for the image processing framework. Reading errors were estimated to be ±0.5 cm of the measured length and range. There was a lack of true or expected (reference) values to compare with the observations, therefore the measurement accuracy was estimated through bootstrapping and taking into account omission, coordination and double-counting errors.

This study found that occurrence of marine mammals and fish was distributed across distinct time and space domains (Figure 6.5). Seals occurred periodically with 1 to 2 hours of intervals, and the most frequent were harbour seals measuring between 1 m and 2 m, followed by grey seals with lengths of ca. 2 m to 4 m. Larger targets measuring 4 m to 7 m were most likely orcas and were detected at night time. Three different categories of fish were distinguished, large fish [>0.4 m] occurred exclusively at night-time and near the benthic zone, mid-size fish [20 cm – 40 cm] and small-size fish [< 20 cm]. Mid and small-size fish were frequently observed during daylight within the pelagic and semi pelagic zones and in schools of 5 m to 14 m of length (Figure 6.6).

In conclusion, a standalone environmental monitoring platform equipped with a multibeam imaging sonar can be a reliable technique for qualitative and quantitative observations of marine mammals and fish in ocean energy sites.

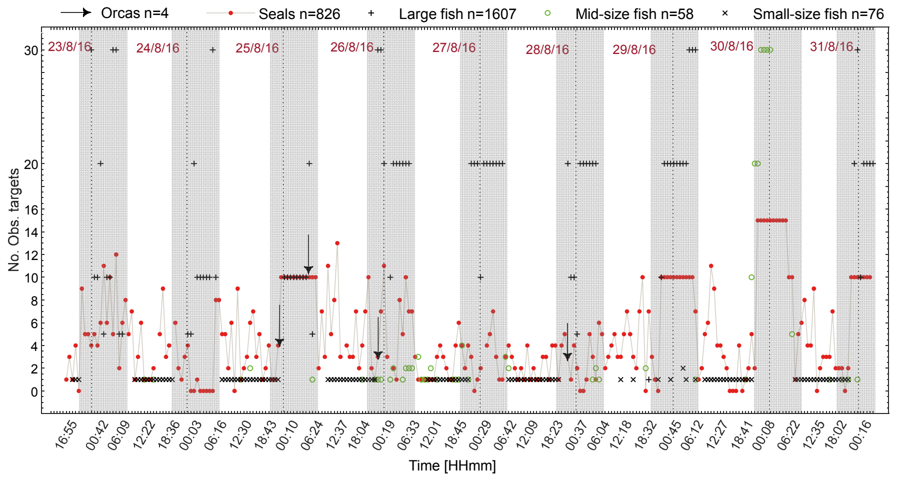

Figure 6.5. Survey time series beginning on 23-08-2016 and ending on 01-09-2016 at the Lysekil research site (Paper VIII). Small and mid-size fish were counted in schools and had diurnal occurrences. Large fish was individually counted, and had nocturnal occurrences. Seals and large mammals (orca) occurred periodically along the time. The grey shaded areas represent the nigh-time.

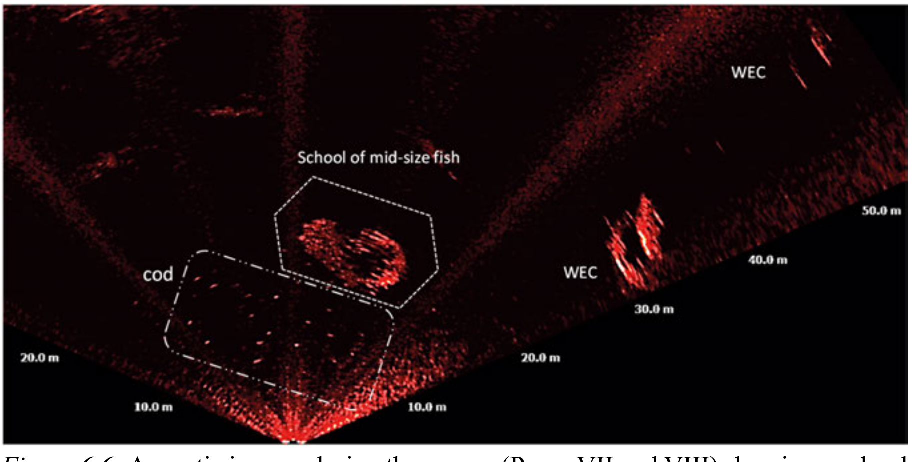

Figure 6.6. Acoustic images during the survey (Paper VII and VIII) showing a school of mid-size fish measuring 12 m of diagonal length, and at least 20 large-size fish/cod, measuring 0.4 m to 0.9 m, at ranges of 10 to 20 m, time 19:26 UTC.

6.2.5 Acoustic versus optical imaging for structural inspections – Paper IX

A practical way of identifying and classifying objects is through direct or indirect visualisation. Cameras operating in the visible and a near-visible spectra, provide a more authentic image of the natural environment, therefore are common tools to observe objects. But, this is only possible when the environment is favourable to electromagnetic wave propagation. In the hydrosphere, light and other electromagnetic radiation are largely attenuated by water, dissolved matter and suspended particles [77]–[80]. This limited the use of electromagnetic instruments such as cameras and Lidar (light detection and ranging) to investigate the aquatic environment, in dark and deep waters. On the other hand, sound propagates considerably further than light in water [42], [48], [81], [82], reaching longer ranges than any electromagnetic wave. This justifies the use of sonar systems and other acoustic instruments for remote sensing, communication and navigation in the hydrosphere. The underlying assumptions of this study were that UWCs function well if the water is clear and illuminated; a MBS is suitable for murky and turbid waters where UWCs are unfeasible. The resolution of UWCs is mostly affected by turbidity and the range of a MBS is dependent of the operating frequency. Since both UWCs and MBS can be used to acquire underwater images, Paper IX aimed to find the optimal ranges and ambient conditions in which optical and acoustic images can be acquired. For that, a MBS and four different UWCs were used to acquire underwater images of the UU WECs, Söderfors HEC and its 1:10 model HEC, and the surroundings of a floating dock.

The results (e.g., Figure 6.7) show that optical images were significantly affected by decreasing of luminosity, increasing depth and water celerity. And acoustic images were mostly affected by increasing range, surface turbulence and bubbles, reverberation and water column stratification.

In summary, optical cameras had superior performance for nearfield and high accuracy image acquisition, while imaging sonar provided superior performance at acquiring images at mid to long range (Figure 6.8).

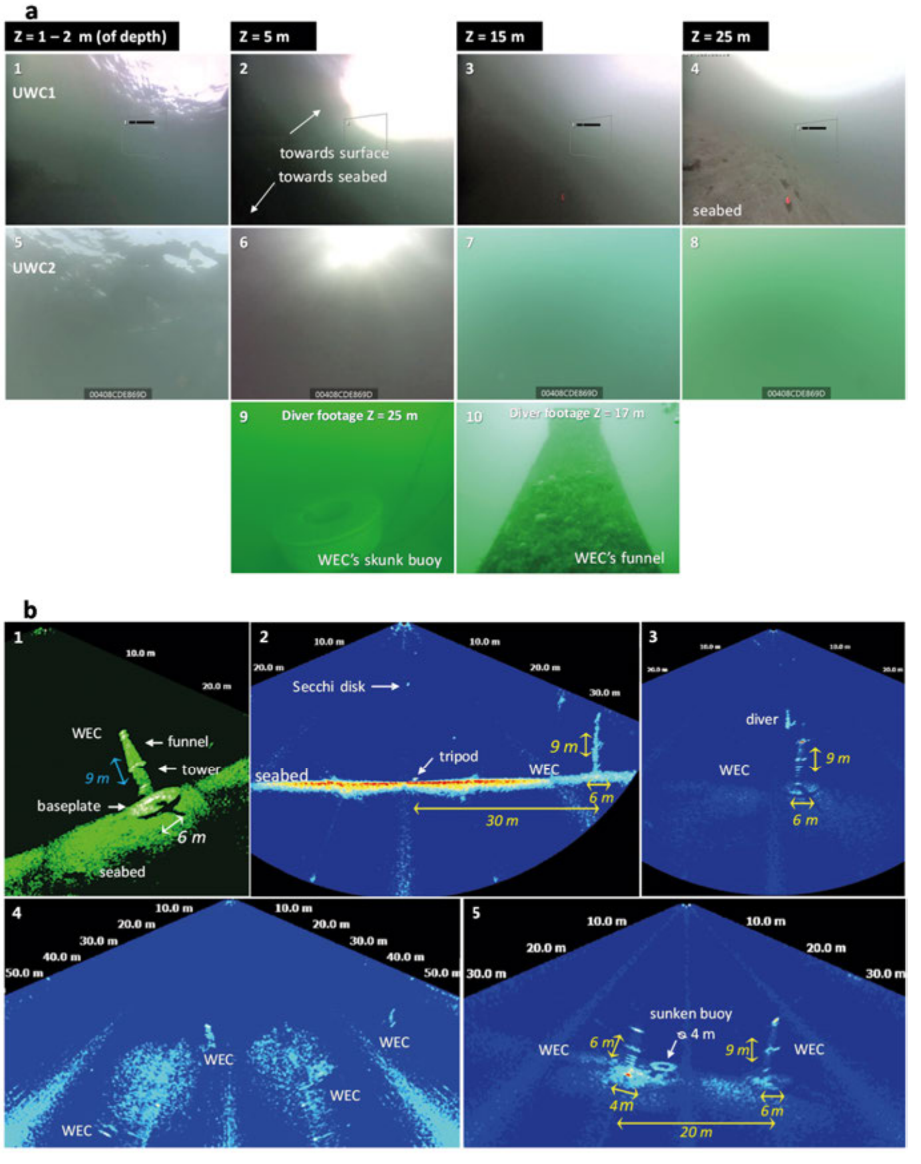

Figure 6.7. Evaluation of images in relation to increasing depth (Z) at Lysekil wave power research site (Paper IX): (a) Comparison of optical images from underwater cameras UWC1, UWC2, no target was detected except the seabed. Optical images 9 and 10 a sunk heaving buoy and the funnel of a WEC were taken by divers. (b) Acoustic images from the MBS showing WECs, a Secchi disk, the tripod, a diver and a sunk buoy.

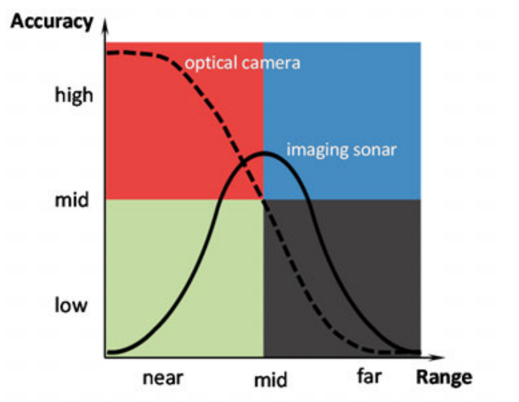

Figure 6.8. Empirically drawn diagram showing possible characteristic performance curves of optical and acoustic images as a function of range. (Paper IX)

6.2.6 Ultra-high resolution bathymetry and seabed inspection – Paper X

One of the areas of ocean energy involving substantial costs is the meticulous seabed inspection that has to be conducted prior to deployment of ocean energy devices. Detailed seabed inspections and bathymetry can reduce the risk of bad landing, structural damages, and negative environmental impacts to the benthic habitats. With focus on marine renewable energy projects, this study proposes a cost and time effective technique of surveying the seabed. It involves the use of high precision and inexpensive DBS and MBS systems and UWCs integrated into a monitoring platform (Figures 4.2a, 4.2c) to gather data. With the assumption that errors caused by pitch and roll of the survey vessel were small enough to be and auto-corrected by the sonar computers, the depth measurements data was analysed using a simplified algorithm $Z = z_{eco} \pm z_{heave} - z_{tide} + z_{draft}$. Where z_{eco} is the instantaneous height of the sonar in relation to the seabed, z_{heave} is the heave component derived from instantaneous height (h) measured by a global positioning system (GPS), z_{tide} is the tidal height and z_{draft} is the draft of the transducers.

The results show that the MBS coupled with DBS and UWCs produced seabed inspection and bathymetry maps with spatial resolutions of ca. 0.075 m. For example, a harbour located ca. 6 NM from the Lysekil research site was surveyed (Figure 6.9a), and the results show that the seabed is generally flat with the $\overline{AB}$ inclination of ca. 2.3° and mean depth of 5.5 m, while the $\overline{CD}$ inclination is ca. 2° with a mean depth of 5 m, becoming deeper towards the entrance of the harbour $(\overline{D})$, with ca. 9 m of depth (Figure 6.9b). The seabed inspection of the same area, revelled several artefacts with the approximate sizes varying from 0.4 m^2 to 2.3 m^2 (Figure 6.9c). Artefact 1 could be an upside-down object such as a table or a ladder, the dock wall covered by metal was also visible (artefact 2), artefacts 3 and 4 could be barrels. The seabed appears to be made of a top layer of soft substrate which is the general characteristics of the seabed in this area.

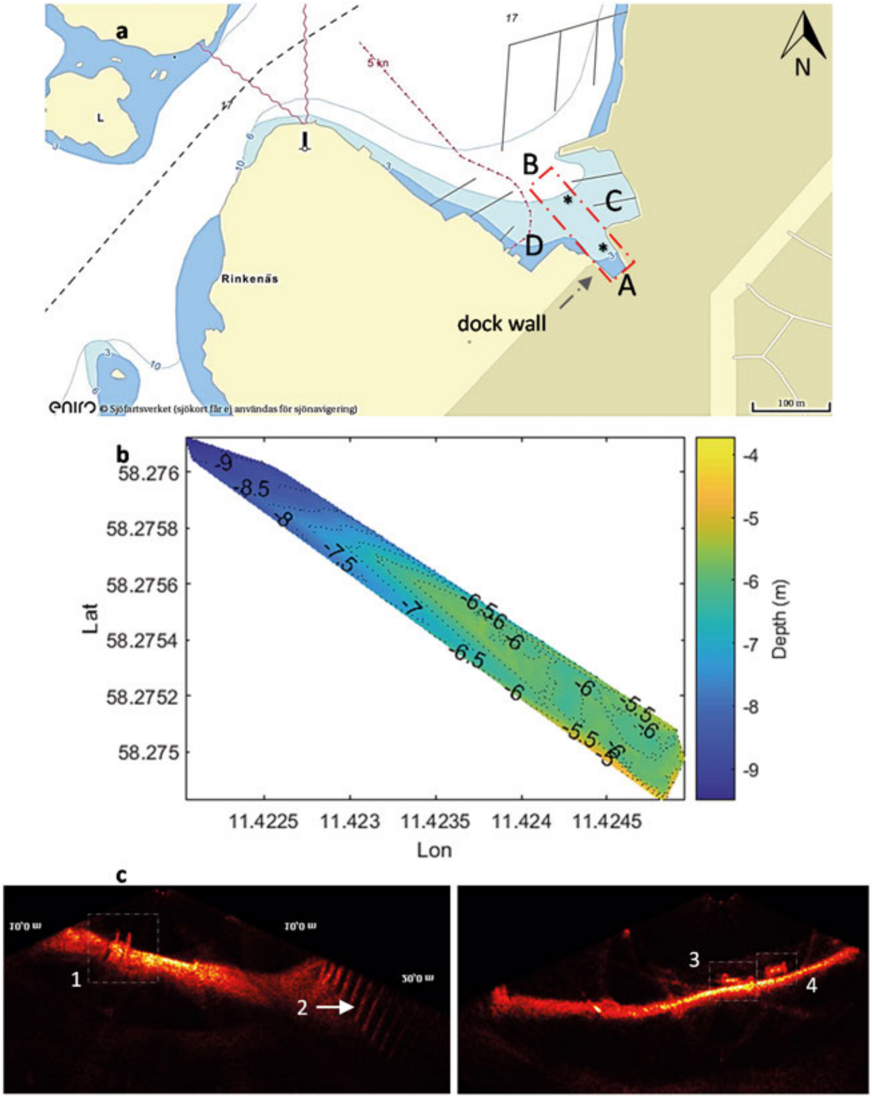

Figure 6.9. (a) Example of a surveyed area of a harbour located in Lysekil, (58.275038° N, 11.424705° E). (b) Ultra-high resolution bathymetric map with spatial resolution of ca. 0.075 m. (c) Acoustic image of sunken artefacts lying on the bottom: artefact 1 with 1.5 m x 1.5 m, artefact 2 is a harbour steel wall, artefact 3 measured approximately 0.7 m x 0.6 m and artefact 4 measured 0.8 m x 0.5 m. (Papers V, X)

6.3 Wave power resource assessment

6.3.1 Use of wave power for off-grid water desalination systems – Paper XI

Seawater can be desalinated through reverse osmosis and transformed into freshwater for human use in coastal areas [83]. Wave power has the potential of being combined with reverse osmosis to power desalination systems in coastal areas with sufficient wave power resource. The objective of this study was to analyse the wave power resource availability of a coastal area in Kilifi, Kenya and to evaluate the possibility of using the UU WEC technology to power desalination plants.

The wave power resource (P_w) was estimated using data provided by *Fugr*o [84] covering a period from 01-01-1997 to 31-12-2015, with temporal resolution of 6 hours and was based on analysis of the *World Waves* data source of the *European Centre for Medium-range Weather Forecasts* wave model. Reanalysed provided by *Fugro Oceanor*, was a combination of buoy and multi-satellite altimeter data, by transformed from offshore grid points to a nearshore point (3.815° S, 39.846° E) using *Simulating Wave Nearshore* (*SWAN*) model. Wave power can be defined as the average transport rate of energy per meter of wave front, and here it was estimated as $P_w \cong 0.5\, H_s^2 T_e$. Where H_s is the significant wave height and T_e is the energy period [85]–[87]. The possible use of wave energy for desalination plants through reverse osmosis was estimated by finding the number or WECs (X_{wec}) necessary to meet the water demand of the local inhabitants at daily basis (X_p) as a function of the number of inhabitants that can be supplied of freshwater from a single WEC ($X_{p.wec}$), i.e. $X_{wec} = X_p / X_{p.wec}$.

The results of this study show that the mean wave power value in Kilifi for the period between 01-01-1997 to 31-12-2015 was 7 kW/m, the median value was 5 kW/m, the mode was 5 kW/m, and the minimum and maximum were 0.2 kW/m and 53 kW/m respectively. The typical sea sates were determined by values of T_e rather than H_s leading to frequently occurring wave power values in the interval between 5 kW/m to 25 kW/m (Figure 6.10). The seasonal cycle was mostly influenced by the East African monsoons and was characterised by a maximum in August–September with mean of 10.5 kW/m, and a minimum in January–May with mean values of ca. 4 kW/m. The hourly difference between midday and mid-night mean values was ca. 0.3 kW/m. This diurnal variability of wave power may be related to the coastal wind dynamics, such as offshore and sea breezes triggered by pressure gradients resultant from uneven heating and cooling of the land and sea masses.

Regarding wave powered desalination, the estimative results (Figure 6.11) were reached assuming that wave power has an annual capacity factor near 30%, with a fixed energy consumption of 3 kW/m^3, and daily water use of 0.02 m^3 (20 l) per person. However, the number of WECs rated at 20 kW, required for a daily supply of freshwater to 5000 inhabitants would vary as a function of the capacity factor. Moreover, the capacity factor would vary seasonally, being lower during summer months and higher during winter. The number of required WECs would also vary according to the efficiency of the desalination system in terms of energy consumption.

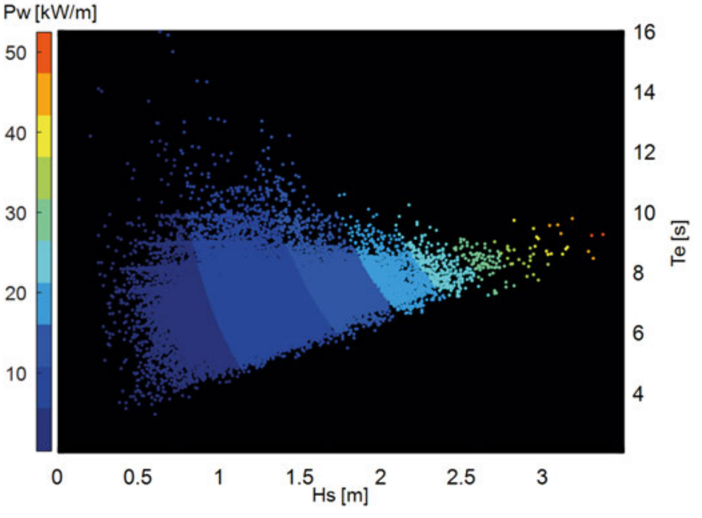

Figure 6.10. Combined scatter plot showing the occurrence of significant wave height - *Hs*, energy period - *Te* and wave power - *Pw* in Kilifi. Frequently occurring wave power values were within 5 and 25 Kw/m. (Paper XI)

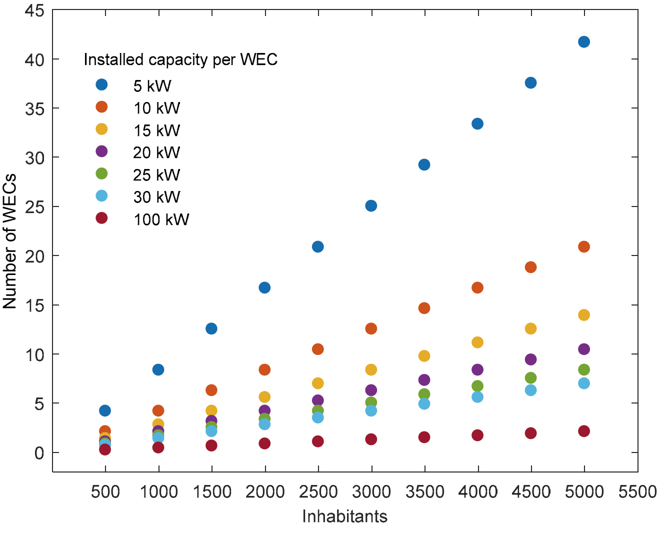

Figure 6.11. Estimated number of WECs necessary for daily freshwater production as a function of number of inhabitants and installed capacity per WEC (Paper XI). A capacity factor of 30% and fixed energy consumption of 3 kWh/m^3 was considered.

6.3.2 Integrating wave power in the electricity generation mix – Paper XII

The access and quality of electricity are key factors for sustainable development. Yet there are still ca. 13 % of the world population without access to electricity. An estimated investments of ca. 43 billion € per year until 2030 [1], are urgently needed in order to expand the grid and provide reliable and affordable electricity for everyone. To reach this goal further reforms in the energy sector need to be seriously implemented. Technically this may include diversification of the electricity generation, expansion of central-grids, implementation of mini (micro)-grids, and proliferation of renewable energy technologies such as wave power at lower costs as well as the establishment of smart grid systems. For example, Ghana has an electrification rate of approximately 79 % and to improve the current situation, different renewable energy systems should be brought into the power generation mix. In this light, this study aimed to assess the wave power resource availability in Ada, Ghana, and to estimate the volume of electricity that a 100 MW wave power farm can generate using the UU WEC technology, taking into consideration different capacity factors.

Wave data was used to investigate the local wave power resource availability and based on this information, four capacity factors were used to estimate the electricity generation. The wave data set covered the period between 1979 and 2014, with temporal resolution of 6 h. This data was retrieved from an *Interim Re-analysis* database provided by the *European Centre for Medium-range Weather Forecasts* [17]. The estimated capacity factor (CF_i) is dependent on the power loses (*LS*), downtime (*DT*) and wave power availability (*AV*). The other three capacity factors (*CF*) of 25%, 35% and 45% were obtained from the literature which are also used in wind and wave power industries. An annual electricity generation (P_G) was estimated as a function of the installed capacity (P_T) and as a function of the capacity factors CF_i and (*CF*).

The results showed that the annual mean wave power in Ghana has values of ca. 10 kW/m. The most occurring sea state (with ca. 50%) had values between 7 kW/m and 10 kW/m. The second dominant sea state, with 22% of frequency of occurrence, had values of ca. 14 kW/m. The third dominant sea state (20%) had values between 3 kW/m and 5 kW/m. The remaining sea states, with 8% of frequency of occurrence, had values equal or higher than 16 kW/m. The availability and capacity factors were estimated to be high during the most of the year with exceptions for May, November and December (Figure 8 on Paper XII). Estimated annual electricity generation was between 175 GWh and 610 GWh, for capacity factors in the range of 25% - 70%, respectively (Figure 6.12).

In conclusion, the annual resource availability factor for the period between 1979 and 2014 was ca. 80%, suggesting that a wave power farm would be able to produce electricity during the entire annual cycle. If these results were to be confirmed, wave power will be considered a dependable technology for electricity generation in countries such as Ghana and possible qualify as base-load in the electricity generation mix in Africa and similar locations.

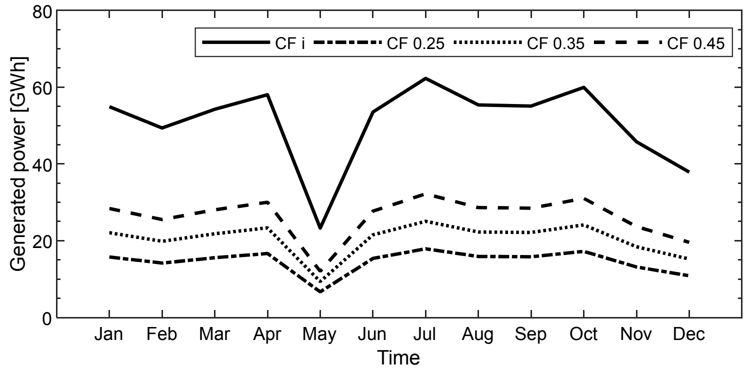

Figure 5. Estimation of electricity generation considering different capacity factors (CF_i and CF) for a wave power site in Ada, Ghana. CF_i is an estimated capacity factor dependent of power loses (3 %), downtime (10 %) and a variable monthly wave power availability (Paper XII).

6.4 Conclusions

In summary, the main conclusions of this thesis are the following:

- Multibeam imaging sonar systems can provide perceptible images of the underwater environment.
- The multibeam sonar used in this research work was able to detect targets as small as 30 mm at near ranges, and was also able to acquire images of targets close to the distortive benthic water surface zones.
- The combination of the multibeam sonar, dual and split beam sonar systems produced qualitative and quantitative estimation of biomass.
- A multibeam imaging sonar and a dual beam sonar system can detect cavitating flows in wakes produced by ferryboats in real conditions and with high enough resolution to extract features such as the geometry and propagation patterns.
- A combination of a multibeam imaging sonar and underwater camera systems can be used to inspect ocean energy devices and study the composition of seabed including objects that can pose risk to the deployment of ocean energy devices.
- The standalone monitoring platform equipped with a multibeam imaging sonar produced both qualitative and quantitative data of occurrence and behavior of fish and marine mammals in the vicinity of UU WECs deployed at the Lysekil wave power research site.

- Bathymetry data can be obtained at the finest spatial and temporal resolutions using inexpensive dual or split beam sonar systems, and survey time can be shortened by conducting adaptive scouting survey designs.

New data analysis protocols were introduced in order to interpret the acquired acoustic data, and from the performance results it can be concluded that:

- K-means clustering, supervised and unsupervised classification techniques can be adapted to specifically process acoustic backscattering intensity data so that targets of interest can be effectively separated from the fore and background noise.
- Identification and classification of underwater targets using acoustic images can be done using the newly introduced parameter designated as acoustic visibility measure (*AVM*). *AVM* is an indirect technique of identifying and classifying underwater targets by comparing observed sizes or shapes with a standard value and a known shape.
- Adaptive and well defined depth measurements using dual or split beams sonar systems, can be converted into ultra-high resolution bathymetry maps by applying a simplified data processing algorithm.

Regarding feasibility studies and wave power resource assessment, it can be concluded that:

- Many locations worldwide where wave power can be harvested, have mild wave climates, for example Sweden with values ca. 2.5 kW/m to 5 kW/m, Kenya with ca. 7 kW/m, and with Ghana with ca. 10 kW/m.
- In areas such as Kilifi in Kenya, wave power technology can be combined with reverse osmosis desalination systems, or any other type of electric water treatment system, to produce fresh water for coastal communities.
- Assuming capacity factors in the interval between 25 % and 70 %, the estimated annual electricity generation of a 100 MW wave power farm located in Ada, Ghana, can reach ca.175 GWh to 610 GWh, respectively.
- These studies suggest that wave power can be a dependable technology for electricity generation worldwide and can be included into the electricity generation mix in near future.

As a whole, this thesis concludes that risks associated with subsea work and elevated costs of ocean energy projects can be lowered by creating and implementing holistic environmental monitoring, risk and resource assessment frameworks, adapted specifically for the new ocean energy industry.

7. Future Work

Multifunctional environmental monitoring frameworks will continue to be very important in ocean energy sector. Building such tools can be challenging especially when the objective is to conduct surveys in harsh conditions where ocean energy sites are normally located. The author's ultimate goal with this thesis is to facilitate the implementation of ocean energy projects. Therefore, a multifunctional monitoring platform was designed and built. But, given the large scope of this task, there are several other steps needing to be accomplished, e.g.:

- Improve the electrical installation in order to make the system faultless and easier to interconnect the devices. This will make the system robust and quick to deploy.
- Redesign the standalone chassis to improve versatility.
- Upgrade the on-board computer and integrate a redundancy data acquisition system for the standalone deployment configuration.
- Build an all-in-all data acquisition and pre-processing software using graphic user interfaces. This would simultaneously control all integrated devices.
- Avoid the use of UDP (user datagram protocol) without redundancy protocols. This may cause timeout and interruption of communication between the on-board computer and the instruments.

Working in the sea is challenging in all aspects, and "what can go wrong will eventually go wrong". In order to avoid the loss of time and other resources, the author recommends conducting extensive tests of components and procedures before the full deployment of offshore platforms or devices. ”A long checklist is better than a shortened experiment”.

Regarding resource assessment, the main recommendation is that more cooperative work is conducted in order to make the small-scale, high resolution and environmental data widely and affordably available. This would facilitate the fast implementation of renewable energy projects worldwide.

8. Summary of papers

Paper I

Uppsala University Research, Lysekil Research Site, Sweden: A Status Update

This summarizes the research work on wave power that the Uppsala University has especially done in the period between 2013 and 2015. Experimental results such as grid connections, modelling of wave power farms, power production from the generators connected to different buoys and environmental studies are presented in this paper. The author contribution to this paper was field work and the writing of *Section H* referent to environmental studies, plus general check.

Published in Proceedings of the 11th European Wave and Tidal Energy Conference, EWTEC15, Nantes, France, pages 09A2-3-1–8, September 2015.

Paper II

A review of Technologies for Examining the Environmental Impact from Wave and Tidal Power Installations

This paper provides an overview of the state of the art of environmental monitoring methods and technologies that are commonly used to evaluate the impact of wave and tidal power to the marine environment. The author contribution to this paper was the overall conception of the manuscript, and mainly the writing of *Chapter III* referent to unmanned monitoring tools and the compilation of *Table III*.

Published in Proceedings of the 12th European Wave and Tidal Energy Conference, EWTEC15, Cork, Ireland, pages 1092:1-10, August 2017.

Paper III

Sonar for Environmental Monitoring. Initial Setup of an Active Acoustic Platform

This paper refers to technical aspects regarding the hardware and software design of an environmental monitoring platform based on active acoustics. The author did most of the work in this paper: design, construction, testing of

components, writing the manuscript, and presented it orally at the ISOPE 2015 Conference.
Published in Proceedings of the 25th International Ocean and Polar Engineering Conference Kona, Big Island, Hawaii, USA, June 21-26, 2015. ISOPE-2015 Kona.

Paper IV

Sonar for Environmental Monitoring: Understanding the Functionality of Active Acoustics as a Method for Monitoring Marine Renewable Energy Devices
This paper provides the calibration results from tests conducted using multibeam and dual-beam sonar systems. The objective was to learn how to interpret acoustic images of WECs and TECs, as well as to learn the limitations of sonar systems sampling in different aquatic environment taking turbidity, water velocity, and stratification, among other factors into account. The author did most of the work in this paper: design, construction, testing of components, writing the manuscript, and presented the content in a poster at the EWTEC 2015 Conference.
Published in Proceedings of the 11th European Wave and Tidal Energy Conference, EWTEC15, Nantes, France, pages 09A2-3-1–8, September 2015.

Paper V

Sonar for environmental monitoring: Configuration of a multifunctional active acoustics platform applied for marine renewables
This paper describes with details how an environmental monitoring platform based on sonar systems was build, how it is been developed and deployed. The paper also presents results from initial deployments that were performed using a downward looking configuration. The author did most of the work in this paper: design, construction, testing of components, writing the manuscript.
Manuscript.

Paper VI

Use of Multibeam and Dual-Beam Sonar Systems to Observe Cavitating Flow Produced by Ferryboats: In a Marine Renewable Energy Perspective

With the prospectus to deploy energy converters in areas with heavy boat traffic, we investigated the depth range of cavitating flow produced by transiting ferry boats in narrow channels. This work demonstrated that the dual beam and multibeam sonar systems can be used to observe and measure cavitating flows. The author did most of the work in this paper: design, construction, testing of components, field work and writing the manuscript.
Published in the MDPI, Journal of Marine Sciences and Engineering, 2017, 5, 30.

Paper VII

Detection of Visual Signatures of Marine Mammals and Fish within Marine Renewable Energy Farms Using Multibeam Imaging Sonar
With the vision of facilitating the classification of underwater targets using acoustic images, this paper prepared a technique to extract visual features of targets such as fish and marine mammals, and propose to use it as unique signatures. A new quantity designated by acoustic visibility measure (*AVM*) was introduced comparing the observed target size with a standard value. The author did most of the work in this paper: design, construction, testing of components, field work and writing the manuscript.
Submitted to the MDPI, Journal of Marine Sciences and Engineering

Paper VIII

Use of Multibeam Imaging Sonar for Observation of Marine Mammals and Fish on a Marine Renewable Energy Site
This study aimed to observe the occurrence of fish, seals and larger marine mammals at the Lysekil wave power test site, using a multibeam sonar system integrated into a standalone monitoring platform. The author did most of the work in this paper: design, construction, testing of components, field work and writing the manuscript.
Manuscript.

Paper IX

Evaluation of Underwater Acoustic and Optical Imaging for Structural Inspections for Marine Renewables
In this paper, the authors compared the performance of optical and acoustic imaging on underwater structural inspection in order to find optimal ranges and ambient conditions in which underwater cameras and sonar systems can operate. The studied targets were the UU WECs, the Söderfors HEC, a 1:10

model HEC, and the surroundings of a floating dock. The author did most of the work in this paper.
Submitted to the IEEE, Journal of Oceanic Engineering

Paper X

An Alternative Technique for Ultra-High Resolution Bathymetry and Seabed Inspection for Marine Renewables
This paper proposes an alternative technique for detailed seabed inspections and bathymetric surveys that can reduce costs and risks associated with deployment of marine renewable energy devices. It involves the use of modern dual beam and multibeam sonar systems and underwater cameras. The author did most of the work in this paper: design, construction, testing of components, field work and writing the manuscript.
Manuscript.

Paper XI

Wave Power as Solution for Off-Grid Water Desalination Systems: Resource Characterization for Kilifi-Kenya
The authors believe that WECs have the potential of being combined with reverse osmosis to power desalination systems in coastal areas with sufficient wave power resource. In this paper the wave power resource of a coastal area in Kilifi, Kenya was characterised and a possible use of WECs to power desalination plants was evaluated. The author contributed with data analysis, study conception and writing of the manuscript.
Published in the MDPI, Energies, 2018, 11, 4.

Paper XII

Wave Power in the Electricity Generation Mix: a Case Study of Ghana
With the conviction that renewable energy should be brought into the power generation mix. This paper investigated the wave power resource availability in Ada, Ghana, and estimate the volume of electricity that a 100 MW wave power farm can generate using the *Seabased* or UU WEC technology, taking into consideration different capacity factors. The author contributed with data analysis, study conception and writing of the manuscript.
Manuscript.

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A luta continua…

10. Svensk sammanfattning

Energisektorn genomgår för närvarande stora reformer och utvecklas mot renare, koldioxidfri teknik baserat på förnybara energikällor, som med en kombination av en utbyggnad av smarta nät ersätter redan utdaterade energisystemen. Haven har potential att bidra till energiförsörjningen för miljontals människor världen över. Implementeringen av system för marin energi består av flera faser. Detta inkludera till exempel resursbedömning, numerisk modellering, utveckling av energiomvandlings- och styrsystem, nätanslutning, miljöövervakning, marknadsföring, tillverkning och projektgenomförande. Denna avhandling fokuserar på resursbedömning och miljöövervakning, två moment som är avgörande faktorer för marina energiprojekt. Resursbedömning, till exempel mängden vågenergi, behövs för att bekräfta genomförbarheten av ett specifikt projekt och val av energiomvandlingsteknik, i förhållande till de lokala förutsättningar och förhållandena. Miljöövervakning och uppföljning är också en viktig del - för de tillstånds som krävs för att utvinna energi i ett visst område och för att tekniken allmänt ska bidra till en hållbar utveckling.

Forskningen som presenterades i denna avhandling bekräftar antagandena att högupplösta sonarsystem (ekolod) kan anpassas för övervakning av marina energiprojekt och den omgivande miljön, speciellt i mörka, djupa och fysiskt hårda miljöer där konventionella övervakningsmetoder är kostsamma och riskabla. Omvandlingen av energi kan påverka havsmiljön på oförutsedda sätt och genomförbarheten av marina energiprojekt kan förbättras och göras mer konkurrenskraftiga om det finns allmänt tillgängliga standarder för effektiv miljöövervakning och resursbedömning.

För att verifiera dessa antaganden och samtidigt minska risken och kostnaderna vid undervattensarbeten så konstruerades, byggdes och testades en multifunktionell miljöövervakningsplattform (Figur 11). Denna plattform var baserad på sonarsystem och undervattenskameror som anpassades, integrerades och programmerades för att kontinuerligt kunna övervaka havsenergisystem och dess omgivande miljöer. Den nya övervakningsplattformen kompletterades vidare med nya databehandlings- och analystekniker för att dechiffrera akustiska data med hög upplösning för vidare tolkningar.

Från detta forsknings- och utvecklingsarbete slutsatsen dras att ett så kallat ”multibeam” sonarsystem kan ge detaljerad och ändamålsenliga data över undervattensmiljön. Sonaren som användes kunde upptäcka mål så små som 30 mm inom ett relativt närområde. Det var också möjligt att analysera olika typer av mål nära såväl havsbotten som vid vattenytan. Genom att kombinera olika sonarer, som en ”multibeam-”, en ”dualbeam-”, en ”splitbeam-sonar”, och kopplat till ett undervattenskamerasystem, kunde både kvalitativ och kvantitativ data samlas in om bland annat biomassa, förekomst och beteende hos fisk och marina däggdjur, samt fysiska data som turbulens, detaljerade mätningar om havsdjup samt undersökningar av olika strukturer på havsbotten.

Nya protokoll för dataanalys togs fram för att tolka insamlad akustisk data. En så kallad ”K-medelkluster” och en autonom klassificering anpassades för att detektera akustisk ”backscatteringsanalys”, så att intressanta mål effektivt kunde separeras från oönskat för- och bakgrundsbrus. För att ytterligare underlätta identifiering och klassificering av undervattenmål, med hjälp av akustiska bilder, infördes måttet akustisk synlighet (*AVM*). Detta är ett indirekt sätt att identifiera och klassificera undervattensmål genom att jämföra observerade storlekar, eller former, med standardvärden och kända former. *AVM* har potential att användas för att träna algoritmer för manuell eller automatisk identifiering och klassificering av undervattensmål, som till exempel att urskilja olika marina djurarter under vatten.

Denna avhandling behandlar också möjligheten att använda Uppsala universitets (UU) vågkraftteknik för att generera elektricitet på flera områden över i världen. Till exempel genomfördes vågresursbedömning för att utvärdera möjligheten att använda ”omvänd osmos” i ett avsaltningssystem i Kenya, östra Afrika. Slutsatsen är att UU’s teknik kan kombineras med omvänd osmos för avsaltningssystem, eller någon annan typ av elektriska vattenreningssystem, för att producera färskvatten för kustsamhällen. Även förutsättningar för vågkraft i Ghana, västra Afrika, analyserades. Även om vågenergiresursen var relativt liten var den mycket konstanta över ett år varför Ghana har möjlighet att använda vågkraft som ett substantiellt bidrag i sin elenergiproduktion, givet en anpassad vågkraftsteknik som den utvecklad vid UU. En slutsats är att vågkraft kan bli en pålitlig teknik med potential att globalt bidra till den framtida elmixen.

11. Sumário em Português

O setor energético está atualmente passando por profundas reformas e avançando em direção a tecnologias limpas e renováveis, e tambem à expansão de redes inteligentes (smart grids) que substituirão os já obsoletos sistemas de energia. O oceano tem o potencial de garantir energia para milhões de pessoas em todo o mundo, e a estrutura para implementação de tecnologias de energia oceânica consiste em várias fases. Começando pela avaliação de recursos energetiocs, modelagem numérica, desenvolvimento de sistemas de controle e tomada de força, conexão à rede eléctrica, monitoria ambiental, fabricação, instalações offshore, e marketing. A presente Tese de Doutoramento foca o monitoramento ambiental e a avaliação de recursos energéticos, pois estes são aspectos determinantes em projetos de energia oceânica. A avaliação de recursos é necessária para estabelecer a viabilidade de uma tecnologia específica de conversão de energia em relação às condições locais. O monitoramento ambiental é importante para obter permissõs e licenças para a exploração de energia em locais específicos, bem como é importante para um desenvolvimento sustentável em geral.

Em resumeo, a pesquisa apresentada nesta tese confirmou as hipóteses de que sistemas de sonar de alta resolução podem ser adaptados para monitorar dispositivos de energia oceânica e o ambiente circundante, especialmente em ambientes escuros, profundos e hostis, onde os métodos de monitoramento convencionais são caros e arriscados; a colheita de energia oceânica pode afetar o ambiente marinho de maneiras imprevistas; e a viabilidade de projetos de energia oceânica podem ser levados a padrões favoráveis e competitivos, se estruturas eficazes de monitoramento ambiental e avaliação de recursos estiverem amplamente disponíveis.

Com o objetivo de reduzir o risco associado ao trabalho submarino e validar essas premissas, a plataforma de monitoria ambiental multifuncional foi projetada, construída e testada. Esta plataforma foi baseada em sistemas de sonar adaptados e em câmeras subaquáticas que foram integradas e afinadas para monitorar dispositivos de energia oceânica e seus arredores. Essa nova plataforma de monitoria teve que ser complementada com novas técnicas de processamento e análise de dados para decifrar os dados acústicos de alta resolução.Este trabalho de pesquisa conclui que os sistemas de imagens multifeixe fornecem imagens perceptíveis do ambiente subaquático. O sonar de imagens multifeixe utilizado neste trabalho foi capaz de detectar alvos tão pequenos quanto 30 mm de comprient, em curto a medo alcance. Também foi possível adquirir imagens de alvos próximos à zona bêntica de alta refletividade acústica, bem como alvos próximos à superfície da água. A combinação de um sonar de multifeixe, sonar de feixe duplo, soanr de feixe dividido e sistemas de câmeras subaquáticas produziu amostragem qualitativa e quantitativa de biomassa, ocorrência e comportamento de peixes e mamíferos marinhos, medições de turbulência subaquática, batimetria, fundo do mar e inspeções estruturais. Novos protocolos de análise de dados foram introduzidos para interpretar os dados acústicos adquiridos. Por exemplo, o agrupamento K-means e o metodos de classificação supervisionada e não supervisionada foram adaptados para o processamento da intesidade acústica, de modo que os alvos de interesse possam ser efetivamente separados do ruído frontal e de fundo.

A fim de facilitar ainda mais a identificação e classificação de alvos subaquáticos usando imagens acústicas, a medida de visibilidade acústica (*AVM*) foi primeiramente introduzida. Essa é uma maneira indireta de identificar e classificar alvos subaquáticos, comparando o tamanho ou a forma observada com um valor padrão e uma forma conhecida. A medida acústica da visibilidade tem o potencial de ser usada para treinar algoritmos para identificação manual ou automática e classificação de alvos subaquáticos por meio de sonar de imagens multifeixe.

O autor também compartilha a visão de facilitar a implementação de projetos de energia oceânica. Assim, esta tese também investigou a viabildade de utilizar a tecnologia do conversor de energia das ondas da Universidade de Uppsala (UU WEC) para gerar eletricidade em diversas áreas em todo o mundo. Por exemplo, a avaliação do recurso de energia das ondas foi conduzida para avaliar a viabilidade de combinar sistemas de dessalinização por osmose reversa com tecnologia conversor de energia das onda no Quênia, e a conclusão é que ésses despositivos podem ser combinados com sistemas de dessalinização por osmose reversa ou qualquer outro tipo sistema eléctrico de tratamento de água, que possa produzir água potável para as comunidades costeiras. Também foi concluído que a energia das ondas pode ser uma tecnologia confiável e ter o potencial de se integrar a reder de geração de eletricidade.

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