University of Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/ Specialization: Offshore Technology/ Asset Management	Spring semester, 2015 Open
Writer: Ole Fredrik Frafjord	…………………………………………… (Writer's signature)
Faculty supervisor: Knut Erik Bang External supervisor(s): Bjarte Langeland (Stinger Technology)	
Thesis title: Subsea Inspection and Monitoring Challenges	
Credits (ECTS): 30	
Key words: Subsea, Inspection, Monitoring	Pages: 89 + enclosure: 37 Stavanger, 15 June 2015

Abstract

This paper uncovers and suggests solutions for the challenges to control change over time more reliable and cost effective.
Front-end concept engineering, design, inspection and monitoring strategies, technologies, systems and methods for Life-of-Field are recommended.
Autonomous underwater vehicles (AUV) are identified as a possible cost-efficient opportunity to reduce cost of inspections and monitoring operations while safeguarding asset integrity.
A recognized design spiral methodology is used to perform a front-end concept evaluation of an AUV system. Investigation of key technological limitations and new developments within underwater communication, energy storage and wireless power transmission is performed. It further enables opportunities such as AUV recharging station on the seafloor for better utilization.
One major learning point is through the use of numerical models and the outcome being a better and more hydro effective hull design.
One expectation from this paper may be the aid to collaborating partners in their design work.

List of figures:

List of tables:

1 Introduction

General subsea operations are faced with excessive cost challenges. As the oil price plummeted by end of 2014, it has even further underlined the critical need to deploy new technology and utilize man-hours more efficient.
The industry may need to boost their continuous search for autonomous and cost efficient solutions, balancing safe quality and reasonable budget. Innovation and streamlining are key factors the process to go deeper and further underwater.

Throughout the entire operational life cycle of subsea field, structures, pipelines, seabed settlement and the environment need to be consistently monitored to ensure safe extraction of oil and gas. Reliable subsea inspection and condition monitoring is an important piece of the puzzle to succeed. Future subsea production systems in deeper and more remote locations are depending upon further cost efficient solutions. The current fulfilment of the seabed factory vision is to further move the process plant sub-surface. Increasing cost and complexity, as well as reaching longer, deeper and colder, call for more use of inventive remote advanced technology to acquire the data necessary. The challenges to control change over time more reliable and cost effective is assessed in this paper.

Company Stinger Technology operates within underwater research and technology product applications. This thesis is developed together with Stinger Technology. They are specialist in tailoring solutions to problems posed by working subsea. They cover the whole process of creating a product or service from design to implementation. They like to do simple things well, and complex ones even better.
Cooperation with Stinger Technology has been beneficial. Through a Stinger workshop survey, first hand impression of advanced underwater technology was

acquired. Their detection and early warning products has also provided valuable inputs. Part of their research work includes product durability testing through long termed deployment of their remotely operated vehicle (ROV). This test marks the longest continuous deployment of an ROV without requiring maintenance.
Last year the University of Stavanger (UiS) invested in new research facility with pool. It is used by the UiS Subsea organization, made up of B.Sc. and M.Sc. students aiming to use their research and development of underwater vehicle in international competitions such as MATE ROV. Part of this thesis is inspired from this year's autonomous underwater vehicle (AUV) project. Knowledge gained from surveys at UiS Subsea is used to build an understanding of the challenges that subsea inspection and monitoring faces.

A motivating factor to develop this thesis is the fascinating and important subsea underwater vehicle use. To fill in and contribute to further cost efficient methods, models and design of underwater vehicles is both valuable and interesting. An inspiration it the fact later years UAV drones have developed and exploded in popularity both within military, commercial and private use. It is expected that this development will also occur underwater. The Hunter-Killer AUV (Figure 1) is an example of cutting edge military technology with transferable abilities to commercial subsea activities.

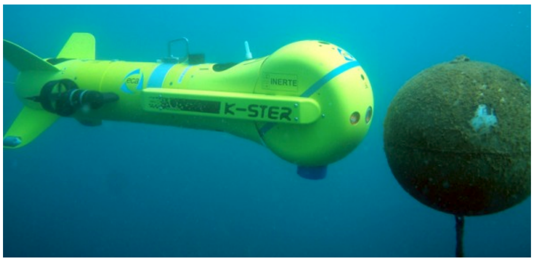


Figure 1: Hunter-Killer AUV (ECA Robotics)

Only the imagination put limits into the development and use of a wireless vehicle. With recession of oil and gas investments, continuous military spending within drone technology both above and underwater is likely to make the commercial AUV market more dependent upon harvesting and collaborating within their industry.

The main focus areas in this thesis are subsea inspection and monitoring in search for improvements and opportunities. It covers some of the challenges, available methods and involves design evaluations of cost-efficient solutions.

1.1 Scope and objectives

The main focus areas and objectives are further targeted as follows:

- Maintenance strategy and planning
- Investigation into different technologies and challenges related to monitoring and inspection
- Evaluation and suggestion current available detection technologies used in subsea inspection and monitoring, their application, system requirements, function and limits.
- Investigate operational requirements and research how to utilize state-of-art tools to improve subsea condition monitoring.
- Extract features and benefits, by observing UiS Subsea and Stinger Technology AS efforts to develop remote and durable applications for subsea inspection and monitoring.
- Present opportunities for improved condition monitoring solution through a review and utilization of cutting edge technology.
- Carry a general attention throughout the thesis regarding cost-efficiency and safe environment within the task.
- Use of a design methodology to perform a front-end concept evaluation
- Investigate key technological limitations and new developments within underwater communication, energy storage and wireless power transmission is performed
- Design optimization process
- Analyse and simulate the hydrodynamic drag forces acting on a new AUV design using computational fluid dynamics.
- Investigate opportunities for organizations

2 Maintenance approach

This chapter seeks to provide an understanding of the purpose and mission of subsea inspection and monitoring. Life-of-Field concept will always incorporate this kind of activities in order to identify subsea challenges. This concept is captured in word by subsea7 as follow:

- *"Assurance of asset integrity throughout the operational life cycle, enabled by a suite of services including integrity management, survey, inspection, repair, maintenance and field extension.*
- *Delivering maximum operational functionality whilst protecting health, safety and the environment."*

It includes a consideration of different maintenance approaches of subsea assets in order to evaluate and measure the merit between different inspection and monitoring (IM) solutions covered in this paper.
Threats and failure modes for subsea production system are presented through a life-cycle analysis to review maintenance strategies and inspection requirements.

Subsea inspection and monitoring is an integral part of asset integrity management. Structural and environmental IM programme in combination with a suitable maintenance strategy enables assets to be evaluated for functionality, condition and safety. This process allows for timely planning of repair and replacement activities to increase revenue due to higher uptime and operating results. It may also provide valuable information used to develop an understanding of failure mechanisms and damaging trends (CIRIA et al. 2007). The flow chart (Figure 2) shows an overview of maintenance best-practices and strategies that various IM programme is a part of:

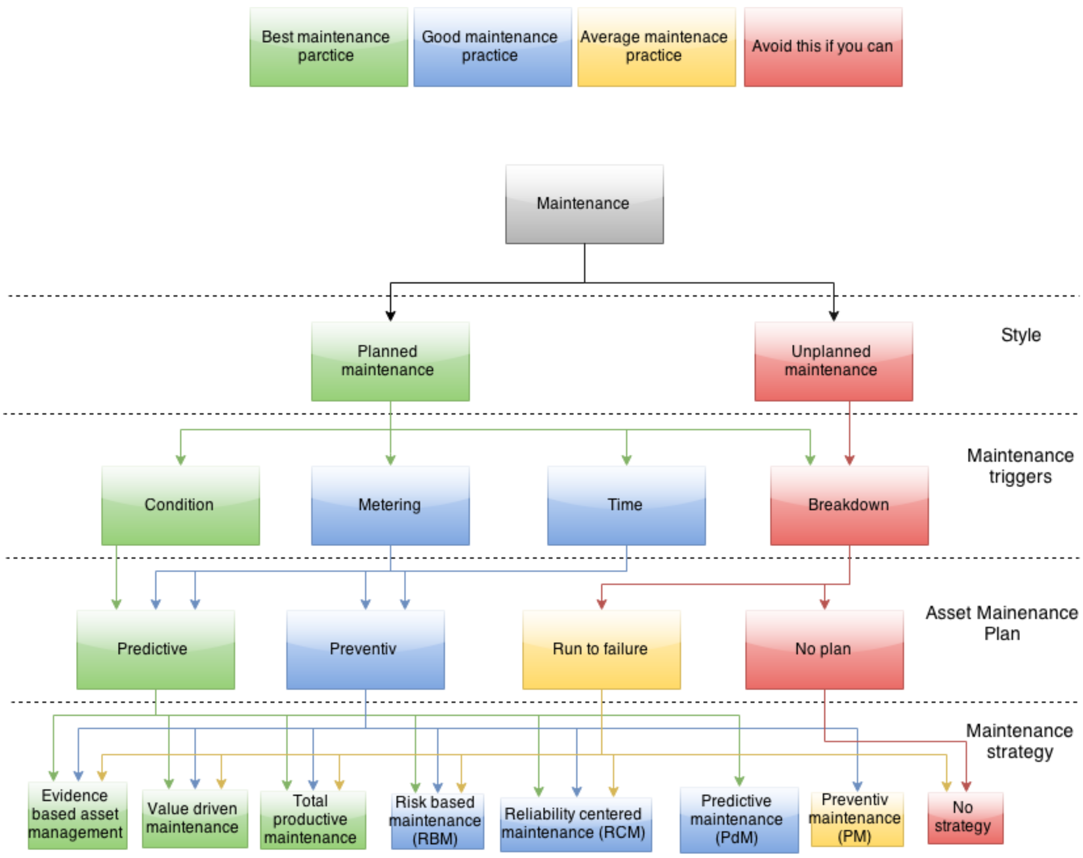


Figure 2: Maintenance strategies flowchart

2.1 Unplanned maintenance

Unplanned maintenance will always occurs, since it is impossible to anticipate all failures that can occur. It includes reactive maintenance, corrective maintenance, emergency maintenance, breakdown maintenance and run-to-failure maintenance. It is considered as an "avoid if you can" style in the flowchart above. Because involves both unplanned and unscheduled maintenance, which require more time and resources to perform. Unplanned inspection is needed to investigate and determine the problem and further develop a maintenance plan. These unplanned failures can pose a high risk and effect production. The first generation of subsea production systems presented significant failures such as material problems and leakages, which caused long downtime and high costs. Table 1 present two of the subsea failure that British petroleum´s experienced.

Table 1: British petroleum´s early experience of subsea failures (Uyiomendo & Markeset 2010)

Project	Failure mode	Direct cost	Downtime
Foinaven	Super duplex (steel pipe) cracking	55 USD/m	10 months
Foinaven	(Valve) Stem seal leakage	30 USD/m	4 months

Improved solutions are continuously being developed in response to expensive maintenance tasks such as these. It includes reduction of response time of unscheduled inspection and maintenance with permanently deployed IMR vessel, stock retention, and more modular and standard designs. It has led maintenance to be completed in days or weeks instead of months (Uyiomendo & Markeset 2010). Operational cost of an IMR vessel is very high, thus more cost-efficient solutions are needed to achieve high availability. Increasing the probability of early detection before an initial failure progresses into a larger problem.

2.2 Planned maintenance

Planned maintenance involves planning, documenting and developing maintenance plan before a breakdown occurs. This include mapping of potential threats, failure modes and effects. It allows maintenance technicians to perform maintenance more efficiently, because they know what to do in advance and can make prior arrangement for spare parts and resources.
Asset inspection and maintenance requirements change depending on the component's life-cycle failure pattern, criticality, safety risks and costs associated with failure. Observed failure rates in subsea assets follow the bathtub curve (Uyiomendo & Markeset 2010). The bathtub curve (Figure 3) is often used for life-cycle analysis. It can describe the relative failure rate of a component or an entire population of components in a system in relation to time. Where planning of maintenance action depends on where on the bathtub the component is located (Soares 2010). The Weibull distribution model can be used to describe each section of the bathtub curve with the failure rate:

$$z(t) = \lambda^{\beta} \beta t^{\beta - 1} \quad (1)$$

Where $\beta<1$ in first section, $\beta=1$ in second section and $\beta>1$ in third section.

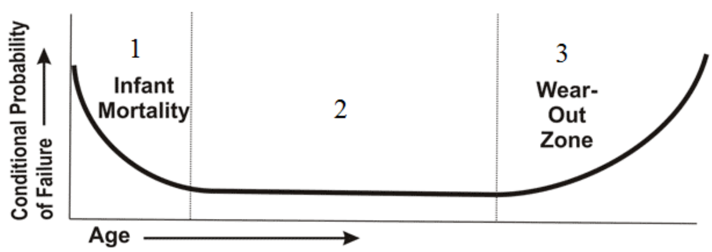


Figure 3: The bath-tub curve (Aven T, 2014, Lecture notes UiS)

2.2.1 Infant mortality

The first section of the bath-tub curve where $\beta<1$ is the early failure period, due to infant mortality. The shape indicates a decreasing failure rate, where no preventive maintenance is recommends. Any preventive replacement or repair will only increase the failure rate. However, the failure rate is initially high and requires more frequently inspection and monitoring. These high failures rates are addressed through warranties and testing before and during commissioning under representative conditions (Uyiomendo & Markeset 2010). Table 2 present threats during design, manufacturing and installation of subsea production system, which might incur the high initial failure rate.

Table 2: Early life threats to subsea facilities (DNV GL 2014, Subsea Facilities - Technology Developments, Incidents and Future Trends) ***(U) = only relevant for umbilical***

Threat - Examples	Threat description – Examples	Failure mode
Design	• Lack of understanding of relevant design standards • Details of interfaces not ready during design • Lack of experience/ Newcomer in the market • Lack of knowledge • *Stretching of technology, different interpretation of qualified design (U)* • Improper/Unfortunate design • Unfamiliar with project specific design requirements • Basis of deign incomplete, inconsistent or subjected to late changes • Incorrect materials selection • *Inability to capture effect of bitumen on armour stress (U)* • Design shortcoming • *Incomplete 3rd party verification (not able to pick-up failure or shortcomings in design due to splitting of verification scope between various suppliers(U)* • Lack of analysis tools	Burst Metal loss Leak Cracking Yielding Collapse Loss of function Material ageing
Manufacturing	• Newcomer in the market • New materials with unknown performance for the application in question • Lack of resources for manufacturing follow-up • Construction yards with lack of experience with relevant authority regulation and project specific specifications and standards • Challenges implementing project specific regulations and requirements • Smaller deliveries – less focus from fabrication yard • Culture awareness • Lack of qualification of manufacturer • Lack of traceability of raw materials • Use of inexperienced personnel due to high activity • Shortcoming and damage during manufacturing	
Fabrication	• Newcomer in the market, inexperienced personnel • Lack of resources for fabrication follow-up • Fabrication yards with lack of experience with authority regulations and standards for design • Welding shortcoming • Damage or shortcoming during assembly (e.g. Bolt torque or physical damage) • Lack of or insufficient FAT	
Coating application	• Newcomer in the market • Lack of resources for follow-up during coating application • Lack of knowledge • Coating shortcoming • *Perforation of umbilical plastic outer sheat causing damage to internals (U)*	
Testing	• Failure during pressure testing, system integration testing, control system testing • *Incorrect tensioner grip force for umbilical(U)* • Risk of not capturing relevant failure modes during testing	Leak Burst Cracking Yielding Collapse Loss of function
Temporary storage	• UV radiation • Internal corrosion	Material ageing Metal loss
Installation	• Transportation • Mechanical damages, overload, fatigue, deformation, HISC • Assembly shortcomings (e.g. incorrect bolt torque) • *Jointing of umbilical causing fatigue/compression (U)*	Yielding Collapse Cracking Loss of function

2.2.2 Normal operation

The second phase is often called the useful life. Here the Weibull distribution model is reduced to an exponential distribution (β=1), with random failures at a constant rate. Components that have an exponential distributions are memory-less, thus preventive maintenance would be waste of money. Either an increased probability of failure would be introduced, by replacing a functioning unit with a defect unit or a unit that might fail after a short time as a result of infant mortality. Thus no preventive maintenance is recommended and the subsea production systems are run to failure in this phase. However, the risk of failure (production, cost and HSE) must be within the limits of standards and regulations such as Norsok Z-008 (Uyiomendo & Markeset 2010). This includes safety and redundancy features, which must be regularly tested and inspected. A plan for corrective maintenance should be specified before a failure occurs, to allow the asset to be quickly repaired or replaced while causing minimal effect on production. Since SPS control modules are run to failure with a constant failure rate and the failure rate of electronic and hydraulic components are extremely rare (Uyiomendo & Markeset 2010). It might indicate that the majority of failures are due to random external events such as incorrect operation and third party mechanical damaged on hoses, cables, etc. by fishing trawlers, ROVs and other impact or water ingress (Uyiomendo & Markeset 2010). These threats are presented in Table 3. They are also responsible for some of the most serious leakages that has occurred on the Norwegian and UK continental shelf (DNV GL 2014):

- (2013) Bleed valve set in the open position by a mistake: 2.5 tonnes oil
- (07.2002 – 01.2003) Wrong operation of a valve on manifold: 30 m^3 oil
- (1996) Dropped object caused XT leakage: 41.6 tonnes gas

Table 3: Constant threats to subsea facilities in it´s useful life (DNV GL 2014, Subsea Facilities - Technology Developments, Incidents and Future Trends) *(U) = Only relevant for umbilical*

Threat group	Threat - Examples	Threat description – Examples	Failure mode
Third party	Trawling	• Trawl board impact • Trawl line snag	Burst Yielding Leak Cracking Collapse Loss of function
	Anchoring	• Ship traffic	
	Dropped object		
	Mechanical impacts	• By intervention tools or ROV	
	Vessel impact		
	Vandalism/terrorism		
	Traffic	• Vehicle impact, vibration	
Natural hazard	Extreme weather	• Depends on location of the system	Burst Leak Cracking Loss of function
	Earthquake		
	Landslides		
	Ice loads		
	Volcanic activity		
Operational	Incorrect operation	• Out of spec. operation, promotes wax and hydrate formation , increased risk for erosion due to sand, out of spec. flow, pressure, temperature, blow down, oxygen content • *Excessive pressure, insufficient cooling topside (U)*	Clogging Metal loss Yielding Collapse Loss of function Material ageing
	Incorrect procedures	• Procedures not updated according to changes in operation	
	Human errors	• Overfamiliarity (e.g. ignored alarms), lack of training, lack of experience transfer	

Although subsea production systems are run to failure in the second phase of the bathtub curve, external threats in table 3 and historical accidents indicate the need for regular inspection and condition monitoring of subsea assets, beyond the yearly general visual inspections by ROVs.

2.2.3 Wear-out zone

In the third section called wear-out zone, the failure rate of SPS increases due to material degradation and structural deterioration presented in table 4. These threats require more complex asset maintenance plans such as preventive or predictive maintenance to reduce the probability of failure and extend service life (Figure 4).

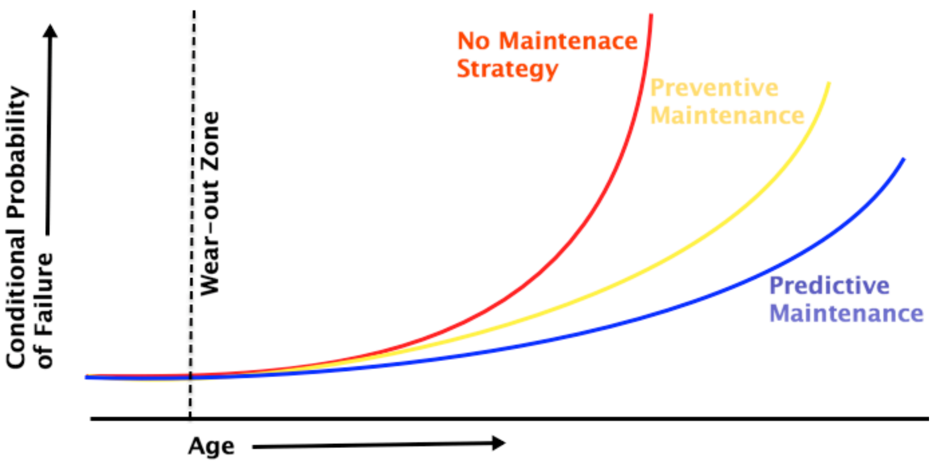


Figure 4 Extended service life with preventive maintenance and predictive maintenance

Table 4: Wear-out threats to subsea facilities. (DNV GL 2014, Subsea Facilities - Technology Developments, Incidents and Future Trends) ***(U) = Only relevant for umbilical***

Threat group	Threat - Examples	Threat description – Examples	Failure mode
Material degradation	Corrosion	• Internal uniform corrosion • Environmental cracking • External corrosion due to CP system failure, lack of CP (loss of electrical continuity), excessive anode consumption causing lack of CP capacity • Galvanic corrosion • Flow induced corrosion • *Crevice corrosion due to seawater ingress unintentionally or intentionally (U)* • *Corrosion impact on steel armours when removing bitumen in umbilical (U)*	Metal loss Leak Burst Cracking Loss of function
	Coating degradation	• Formation of cold spots causing internal corrosion • Causing lack of CP capacity	Metal loss
	HISC	• Combination of excessive load, hydrogen and susceptible material	Crack Burst
	Material Ageing (degradation)	• Elastomeric seal ageing • Plastic creep • Faulty materials selection • Lack of UV resistance • Embrittlement of plastic materials having low resistance to UV-radiation • *Thermal ageing of umbilical internals caused by integrated high voltage cable (U)* • Embrittlement of materials exposed to low temperatures	Material ageing Leak Loss of function Collapse Cracking
	Erosion	• Presence of sand • Flow condition	Metal loss Leak Burst Loss of function
	Wear	• High friction • Change of friction on hard faced seal surfaces • Galling e.g. due to incorrect torque of bolts • Loss of sealing • *Wear of umbilical tubes and outer protective sheath (U)*	Leak Loss of function Metal loss
	Cavitation	• Implosion of gas bubbles	Metal loss Leak
Internal medium	Change in fluid composition	• Impurities or contaminations in hydraulic fluid • Fluid incompatibility with materials • Use of incorrect hydraulic fluid Internal leaks (leak between systems) (e.g. control system leak	Metal loss Cracking Loss of function
	Change in reservoir condition	• Changes in well fluid composition (e.g. well souring, gas/water/oil composition changing production environment)	
	Injection chemicals	• Compatibility fluid/material,	
	Fluid incompatibility	• Hydraulic, compatibility fluid/material.	
	Well stimulation chemicals	• Compatibility fluid/material, ingress of fluid	
Structural	Fatigue	• Due to VIV caused by waves, process variations, fluid hammer, slugging etc.	Burst Leak Cracking Collapse Yielding Loss of function Metal loss
	Excessive mechanical loads	• Due to pipeline/riser expansion, drilling, intervention, subsidence, well growth, scouring settlement, vibrations, over-torqueing, new tie-ins, XT retrieval, BOP loads, installation tolerances not accounted for in design	
	Excessive pressure loads	• Related to operation, fluid hammer	
	Excessive thermal loads	• Related to operation • *Axial tension (U)*	
	Temperature variations	• Temperature variations causing cyclic thermal expansion /retraction	
	Vibrations	• Promote fatigue	
	Loss of bolt tension	• e.g. Hang off arrangement for umbilical	
	Calcareous layer	• Unable to install or retract equipment, high resistance in electrical connections	
	Marine growth	• Unable to inspect equipment, increased load, installation delay, • *Excessive tension and increased dynamic behaviour (U)*	
	Local buckling	• *E.g. Umbilical excessive bending (U), axial compression (U)*	
	On bottom stability	• *Outer sheath damage (U)*	
	Twist	• *Outer sheath damage, excessive bending and axial compression (U)*	
	Burial	• *Insufficient burial depth or coverage of umbilical (U)*	
	Freespan	• *Frees pans due to sea currents, VIV (U)*	
Control system threats	Loss of power (electrical, hydraulic)	• Due to material degradation, low insulation resistance, water ingress (diffusion) resulting in short circuit, calcareous formation on mating surfaces, contamination on contact surfaces, cooling system failure	Loss of function Leak

2.2.4 Preventive maintenance

Preventive maintenance is suitable for components critical to operation with an increasing probability of failure, where regular maintenance can prevent or reduce failure modes. It allows collective planning of inspection, upgrade, replacement and repair tasks in periods where the execution has the least impact on production or the availability of subsea production systems. Required resources are made available prior to the execution, which is performed while components are still working to avoid unexpected failure. Scheduled preventive maintenance can be time-based or usage-based. A typical example of usage-based is replacement of wet-mate connectors after x mate/de-mate cycles. Times-based preventive maintenance can be performed after a predetermined running time, Mean Time Before Failure (MTBF), calendar time, etc. These intervals are generated based on a component criticality, expected failure and cost of maintenance, which usual result in too early or too late replacement.
Too early replacement is often the consequence of preventive maintenance, due to safety limits, which is unprofitable. Failure can also occur as a result of preventive maintenance, by replacing a functioning unit with a defect unit or a unit that fails after a short time as a result of infant mortality.
Too late replacement can result in failure, with more costly maintenance and downtime. Optimal maintenance intervals can be achieved with the use maintenance policies such as age replacement, block replacement or minimal repair block replacement (Soares et al. 2010).

2.2.5 Predictive maintenance

Predictive maintenance (PdM) is suitable for components or systems critical to operation, with failure modes that can be cost-effectively predicted with regular condition monitoring. It includes inspecting equipment, components or structures on a regular basis to monitor their condition and identify the level of degradation.
The maintenance frequency of a successful predictive maintenance program is as low as possible to prevent unplanned reactive maintenance, without performing

unprofitable repair or replacement and incurring more faults associated with doing too much preventative maintenance. PdM is more complex to coordinate and require more resources to perform than preventive maintenance (MA CMMS 2014). However, many of the issues related to scheduled preventive maintenance are avoided through comprehensive interpretation of data gathered with condition monitoring techniques. Condition monitoring is a generalized method for establishing equipment's health using measured parameters, which reflect changes in the equipment's mechanical state.
The main objective of the predictive maintenance is to (Markeset 2014):

- Predict failures in advance
- Prevent occurrence of the failure by performing condition-based maintenance
- Allow planning for scheduled maintenance as economically as possible at a time convenient to management, technicians, weather, etc.
- Minimize operational risks and unscheduled interruption of the production system

Some of the main challenges with this strategy involve determining which parameters to monitor, how to monitor them and setting baselines/alert levels to reflect the actual condition. Measurements can be collected through regular inspection by manual or automatic systems covered in Chapter 3. Measurement data should then be communicated to a control system for diagnosis, such as a SCADA (supervisory Control/Data Acquisition System) or PCDA (Process Control and Data Acquisition).

Facilitating for condition monitoring of subsea production system and processes is today a customarily approach to ensure safe operation and optimize performance of assets throughout its serviceable life. The present of subsea operational and environmental challenges, has led to sensors for monitoring of subsea equipment and processes being build-in or mounted directly on equipment as non-remote sensors. This is especially true for traditional sensors used for performance monitoring such temperature, pressure and flow rate, as well sensors for direct vibration measurement. Although, these sensors provide reliable and accurate measurements, they also require structural interfaces and cabling, which may introduce technical challenges or too high cost to justify the need. Further technical challenges and expenditures related to performing maintenance and installation of these structure-mounted sensors are also limiting factors. In combination with the industry´s lack of confidence in condition monitoring as an optimization tool (Midtun 2011), these costly and technical challenging tasks appear to have led engineers to resolve the matter by pricey custom designed subsea production systems with more redundancy and conservative material selection to improve reliability, availability, maintainability and serviceability (RAMS). Thus, subsea installations have not experienced the same amount of emphasize on condition monitoring as observed on topside equipment.

However, recent developments have pushed for more modular designed to enable developed of smaller field as subsea satellites tie back to exciting offshore infrastructure. While more complex equipment is being installed subsea for enhanced oil recovery, require more sophisticated monitoring systems.

As well as in light of accidents such as the Macondo accident experienced by BP in the Gulf of Mexico in April 2010 and the recent oil spill in Santa Barbara, has amplified environmental concern, operator's effort to appease public opinion, improve safety and their reputation. Consequently supporting with incentives to develop better and more cost-efficient solution to monitor subsea production systems.

2.2.6 Planned inspection

Observed failures and appropriate maintenance approaches on subsea production systems are well illustrated by the bathtub curve. But in reality the bathtub curve (Figure 5) is comprised of:

- Decreasing probability of "early-life" failures
- Increasing probability of failures related to the threats that dominate during the wear-out phase
- Constant random failure rates

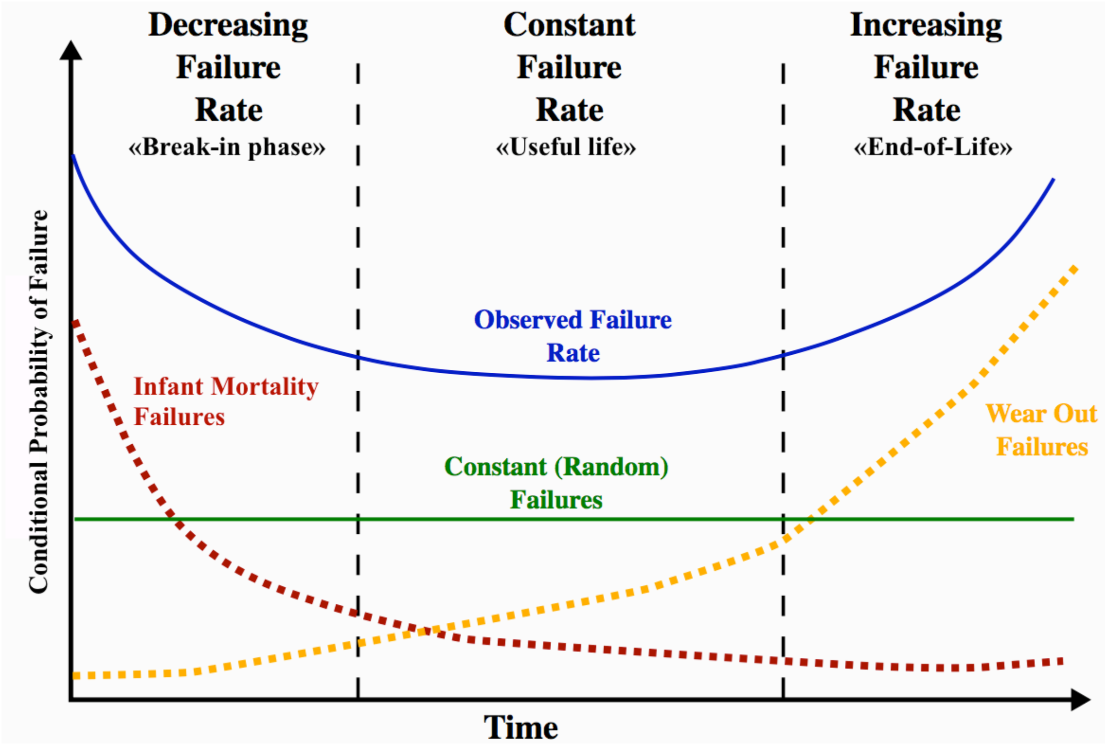


Figure 5: Detailed bathtub curve (Adopted from the U.S Army)

Hendelsesdatabasen is a database established by Petroleum Safety Authority Norway, which includes information about 80 reported leaks of hydrocarbons and control fluids on the NCS between 1999 and 2013(DNV GL 2014).
This show that subsea production system will always be subjected to threats, which require more regular inspection and monitoring to ensure the safety of assets and the environment. The main purpose of the inspection is usually to look for major damages and leaks. Other tasks may include cleaning, cathodic protection measurements (potential recordings), visual inspection of remaining anode mass, wall/coating/marine growth thickness measurements, vibration measurements and visual inspection of scouring. If a leakage is detected, additional rate measurements and sampling to reveal its origin might be required (DNV GL 2014). Special equipment might be needed, especially to perform internal inspection of wall thickness due to corrosion or erosion. Thus a more comprehensive inspection is generally performed every five-year. This includes Non-destructive testing (NDT) tools to provide quality assurance in compliance with regulations and defect management benefits (Uyiomendo & Markeset 2010). Traditional inspection with ROV is often limited to the yearly

scheduled inspection program and high costs. More effort should be used to develop cost efficient solutions to monitor the actual condition of equipment in accordance to relevant degradation mechanisms throughout the service life. At the same time adapt the inspection program to the criticality of components to the operation of the subsea production system while considering where, what, when and how to inspect. (Soares et al. 2010):

Development of residential underwater inspection vehicle, readily available at the seafloor, without the weather constrains and high vessel costs might be solution to support a more dynamic way of scheduling maintenance activities. An autonomous system with a condition-based approach such as a risk-based inspection, may provide a sufficient framework to fulfil environmental risk acceptance criteria and minimize cost consequences with failure (Soares et al. 2010).

3 Subsea inspection and condition monitoring systems

The incentives and need for better inspection, condition monitoring and leak detection system, especially as O&G operators are seeking more cost-efficient solutions to make new and excising developments profitable with current low oil prices. While pursuing oil and gas exploration in deeper waters and further north, which increase the difficulty and cost related to retrieving subsea equipment to perform maintenance or replacement. It has accelerated the development and stipulated advances in the way subsea production system are monitored and inspected. It includes remote controlled and autonomous solutions for subsea leak detection and condition monitoring systems to ensure safe operation of the subsea production system while protecting the sensitive environment.

3.1 Resident monitoring units

These custom made underwater monitoring units, referred to as landers in this thesis can be designed with a cone shaped or tripod structure, as shown in figure 6 and 7. Landers are usually stationed near subsea assets for leak detection and condition monitoring. They can be equipped with a variety of environmental and condition monitoring sensors such as:

- Active acoustic sensors - Leak detection
- Methane sniffers - Leak detection
- Capacitance sensors – Leak detection
- Passive acoustic sensor - Leak detection and condition monitoring
- Bio sensors – Leak detection
- Fluorescent detectors - Leak detection
- Electromagnetic sensors - Condition monitoring

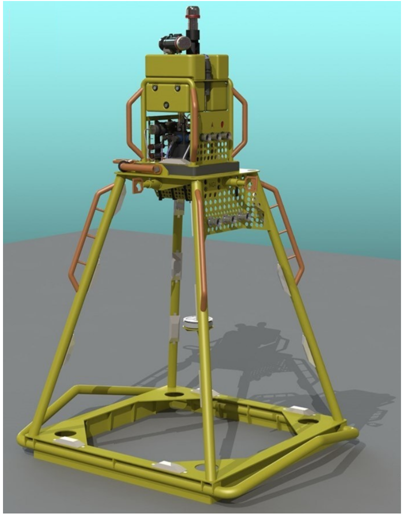


Figure 6: Seabed Leak Detection system (Stinger Technology 2015)

Figure 7: Subsea acoustic leak detection and condition monitoring unit (NAXYS 2015)

3.1.1 Active acoustic detector

Common sensing solution often includes acoustic monitoring system for leak detection, providing operators with valuable data, which can be converted into images for further analysis and localization of leakage. The sensitivity range is from 100 to 500 meters, thus several units must be linked to an intelligent network to control a larger area. Non-retrievable resident installed sensor units are usually designed with up to 25 years of design life, providing cost-efficient and high sensitive leak detection.

Figure 6 shows a seabed leak detection system from Stinger Technology, equipped with active sonar for detection of large leaks and a methane sensor for smaller leaks. The active sonar can detect bubble plumes by scanning an area with acoustic signals. Gas bubbles reflect acoustic waves effectively due to impedance difference between water and gas. The scanned sonar image can then be processed with intelligent algorithms for automatic analysis and leak detection by filter out irrelevant signals such as structures and marine life. Detection of crude oil is limited due to lower impedance difference between water and crude oil. Leak detection with active sonar may also be sensitive to acoustic shadowing effects by subsea structures, thus more than one unit might be needed (NGI, Stinger Technology 2015). Better algorithms for leak detection and autonomous recognition of gas plumes in acoustic pictures will further improve this method.

3.1.2 Methane sniffer

The methane sensor, called "sniffer" can detect smaller gas leaks by measuring the amount of dissolved methane in the seawater, diffusing over a membrane and into a sensor chamber. This method can be very sensitive to small leaks depending on the distance and drift of the leaking medium, thus this method can be limited if the leaking medium is flowing away from the sensor. A methane sniffer is a point sensor, which make positioning of the leak relative to the sensor not possible (DNV 2010). This paper concurs with Stinger´s commercial approach to utilize CFD techniques in order to enable positioning of leakage. Solved by simulating measurement data from more than one detector combined with current meters (Stinger Technology 2015)

3.1.3 Capacitive sensors

Subsea leak detection systems based on capacitive sensors is the most common method used in the NCS. The capacitive sensors consist of two electrodes that measure the change of dielectric constant of the separating medium, which is proportional to the capacitance. Since the dielectric constant of water is very different from hydrocarbon, a change will appear to the capacitance when hydrocarbons get in direct contact with the sensor. This is a point sensing method, which make positioning of the leak relative to the sensor not possible. Seawater currents and buoyancy effects that carry the leaking medium away from the sensor are limiting capacitance methods. But the buoyancy effect of hydrocarbons in seawater can be utilized by collecting hydrocarbons with the template protective covers. The sensor can then mounted on the collector and when in direct contact with the leaking medium it is very sensitive (DNV 2010). This method should be further improved by developing more efficient collectors.

3.1.4 Passive acoustic detector

Figure 7 show NAXYS´s subsea acoustic leak detection and condition monitoring system. It is equipped with passive acoustic hydrophones, capable of detecting oil and gas leaks within 500 meters. In contrast to the active sonar, these hydrophones only listen for the discrete sound signatures of leaks and filter out noise from other sources and performs as “ears” on the seabed. Leak positioning can be achieved by using more than two sensors.
Because passive hydrophones only listens to the sound generated by a leak, it can detect leaks regardless of the chemical composition of the leaking medium. Passive hydrophones are thus capable of detecting gas, crude oil and control fluids, as long as the pressure difference of the leakage is sufficient enough to generate strong pressure waves, which can be detected by the hydrophones. To avoid shadowing of acoustic waves, it is recommended to use multiple hydrophones. Passive hydrophones can also be used for condition monitoring of valve and choke operations, structural integrity and analysis of subsea machinery by measuring acoustic emission caused by stress waves in vibrating structures and misaligned shafts (Midtun 2011).

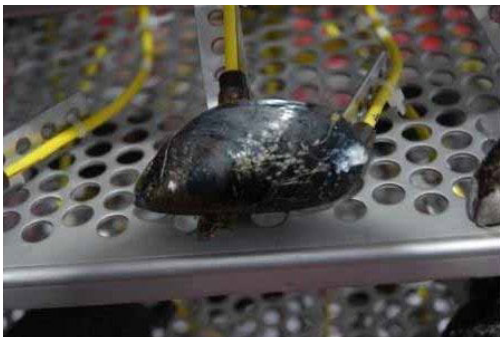


Figure 8: Instrumented blue mussels as biosensors for leak detection (Biota Guard 2015)

Figure 9: Fluorescence detectors (Bowtech 2015)

3.1.5 Biosensors

Biosensors are another promising technology used for real-time environmental monitoring and leak detection related to subsea productions. Figure 8 show Biota Guard´s blue mussel biosensors mounted in a sensors rack, instrumented with sensors to measure hearth rhythm and activity. Information from mussel’s health and activity has proven to be up to 1400 times more sensitive than convectional sensors to detect oil in water. Recordings of mussel's heath and activity can also be used to document the environmental footprint of O&G operations. Biosensors are point sensors and affected by local current or drift, thus more than one sensor is required to cover a larger area (Biota Guard 2015). This energy efficient sensor type should compliment and improve sensoring underwater.

3.1.6 Fluorescent methods

Fluorescent detectors such as Bowtech´s leak detection system (Figure 9) include LED light that emits a certain wavelength for excitation of fluorescent tracer dye in the leaking medium. A camera fitted with a narrowband filter is then used to detect the emitting light from the fluorescent marker. This method is commonly used to detect leakage of control fluids and since hydraulic fluids do not naturally fluoresce, fluorescent marker is often added as standard. Crude oil however has significant natural fluorescence. Within a limiting range of a few meters, these fluorescent detectors can efficiently detect and locate small leaks (DNV 2010). This may be a preferred method for inspection use with ROV or AUV.

3.1.7 Electromagnetic sensor

Resident monitoring units such as NAXYS´s system in figure 7 can also be equipped with sensors for electromagnetic condition monitoring of electric machines, cables and equipment such as subsea transformer.
This method use low frequency antennas or underwater electric potential sensors to measuring emerging electromagnetic stray fields from electric equipment to detect unique electromagnetic signatures used for diagnostics. Failure and faults can then be identified with proper algorithms and signal analyser (Barzegaran & Mohammed 2014). Electromagnetic condition monitoring can also be used along with passive acoustic monitor systems to

determining load, torque and general performance of rotating equipment by calculating slip ratio (Midtun 2015).

3.2 Unmanned underwater vehicle

While resident installed monitoring units can offer reliable and accurate measurements, their limiting range and need for grid connection, promote more adaptable solutions for inspection and monitoring of subsea production systems.

Underwater operations within the O&G industry can present great danger and risk to human saturation diver. Subsea production systems are also usually located in harsh and deep waters, where professional diving operations are not feasible, thus remote controlled or autonomous solutions are required. The use of remotely operated vehicle (ROV) for regular inspections and maintenance activities greatly reduce the risk factors for personnel.
However, these IMR operations are expensive, as they require a support vessel and operators to control the ROV. It has resulted in developments of AUVs as a more cost-efficient solution to perform predefined survey and inspection missions.

3.2.1 ROV

Remotely operated vehicle (ROV) is the workhorse of subsea operations. It is basically a robot, which is controlled by an operator from a surface host facility via umbilical cable. It allows ROV pilots to perform subsea tasks in a hazardous environment, while safely situated in a comfortable environment at a support vessel. The ROV is connected with the umbilical for power and data transmission providing live video for high definition camera, position and other senor data. The industry use ROVs to support underwater operations in all lifecycles of offshore O&G fields, such as exploration drilling support, completions and work-over support, installation and construction support of subsea infrastructure and equipment, inspection and surveys of pipelines, platform and subsea structures, decommissioning and subsea infrastructure removal.

Depending on the application and required capabilities, ROV companies usually offer work class, intermediate class and observation class ROVs customized for different operations. Ranging from big and powerful weighing 4 tonnes as in Figure 10 with hydraulic manipulators to perform heavy intervention tasks, to smaller inspection micro ROV (MROV) weighing under 10 kg such as in Figure 11.

Figure 10: Heavy work class ROV (Oceaneering 2015)

Figure 11: MROV (Stinger 2015)

ROVs are highly manoeuvrable and versatile vehicles, offering hovering and station keeping capabilities. Horizontal and vertical thrusters are used to move the vehicle in any direction and can be controlled manually with joysticks or with an automatic control system for station keeping, allowing operators to concentrate on other tasks. ROVs are constrained by their tether, thus the range depends on the length of the umbilical cable and depth rating for the vehicle. They can be operated in rough weather conditions, however the deployment phase can be sensitive to waves and wind. A support vessel with moonpool can offer more reliable launch of ROVs and tether management systems even in demanding weather conditions. Support vessels with ROVs are usual readily available for an emergency response and the time from notification to having the ROV in place at the seabed is proportional to the travel distance for the vessel and water depth to lower the ROV. ROV operations should be detailed planned in advance to ensure that the vehicle is capable of performing and equipped with the appropriate tools for the mission, as any unplanned or new operational demands may require a time-consuming recovery and re-launch. Depending on the size and available thrust capacity, the ROV can be equipped with various sensors and tools for inspection and monitoring, including leak detection system, sonars, CP measurement, fluorescent detectors, cleaning tools and more specific NDT inspection tools such as ultrasonic and eddy scanners for corrosion mapping, etc. ROV are highly technical and require careful maintenance to minimize software and hardware failure, and operators are dependent on the control systems and communication running smoothly.

The major limiting factor of ROV operations is high costs. Oceaneering´s service rates in 2012, was over 6,000$ per day for the standard Millennium ROV with heavy-duty capabilities. In addition come required personnel of minimum two pilots and supervisor at 6,000$ per 12-hour day operations, thus total of 18,000$ for a 24-hour operations. Additional cost of the support vessel Siem Daya 2 at a reduced rate is 55,000$ due to current market situation (Marketnews 2015). Total cost per day for performing basic subsea inspection with a reliable work-class ROV is then 73,000$, which underlines the high costs.
More reasonable ROV solutions are available, however the cost of support vessels prepared for rough waters and labour costs predominates total expenses.

Stinger Technology has various solutions to reduce some these expensive subsea inspection and monitoring costs. They have permanently deployed a Micro ROV (Figure 11) on the seafloor off the coast of Stavanger, Norway. This is part of a durability test and has so far lasted 20 months underwater. The resident MROV is accommodated by a protective crate, which aids to minimize biological fouling and inhibit marine intruders.
By following the test conducted by Stinger, the concept of having a resident ROV readily available at the seafloor has proved to be feasible. In addition, they have integrated the ROV system with a client network, allowing operators to remotely control the MROV over a partly wireless network. It enables remote pilot and control functions from onshore facilities. This reduces the cost of having onsite

personnel while supporting integrated onshore operation of inspection and monitoring activities in the North Sea. The system lets oil companies play a more active part of subsea inspection and monitoring operations, without having to spend a lot of money on sending personnel out in the field. Instead of waiting until an operator is onsite, the resident ROV can be immediately deployed from an onshore control room with multiple experts present for real-time operations. This is a cost-efficient solution to involve multiple experts in subsea inspection operations to ensure the integrity of subsea assets.
Stinger´s resident MROV solution can also offer improved emergency preparedness by removing transit time of a conventional ROV system and personnel, and launch/dive procedures (Stinger Technology, VideoRay 2015).

3.2.2 AUV

Autonomous underwater vehicle (AUV) is an untethered, underwater robot that can carry out pre-programmed missions and tasks independently from an operator or ship. It is usually deployed from a support vessel and by sophisticated system integration of artificial intelligence that exploits underwater navigation, obstacle detection and identification techniques, it can perform predefined missions without operator control. When the mission is completed, it returns to a pre-programmed location and where data can be retrieved.
A global AUV market mapping by Dormer in 2014 showed that the military made up 50% of the AUV demand, scientific and environmental research 47% and only 3% was represented commercial activities. Commercial use of AUV is forecasted to increase from 3% to 8% by 2018. Over 400 AUVs was produced by 2007 (Philips 2010), while the global AUV fleet is expected to be over 800 units by 2018.

The Navy are successfully using AUV for underwater surveys. They are typically locating lost wrecks, missing airplanes and explosives. Just like recent years of drones developed and military use, it proven that the AUV is capable to carry and place explosives and disarm them with products like the AMDV (Figure 12) or

SAMDIS system (Miller 2015). They are continuously investigating application and use, where such a system would also offer great benefits both economical and in performance.

Figure 12: Autonomous Mine Disposal Vehicles (BAE systems 2015)

Scientific and environmental organizations have along with increasing eco awareness been a driver for AUV development (Dormer 2014). Equipped with environmental sensing and research mapping AUVs are used to discover dumping sites with environmental hazards. They may be in form of wrecks, large amounts of ammunition and toxic waste (Snøfugl 2013). Without the AUV technology and the sensing solutions, these sites could have been undetected. Now scientists and engineers have a chance to monitor these sites in order to avoid uncontrolled pollution.

Commercial activities are conducting underwater surveys, mapping of seabed and pipeline inspection using AUV. The worldwide AUV demand is expected to rapidly expand its market share. Low energy density of batteries and computer processing power were limiting factors for further development. But the rapid growth of digital technology has contributed with multiple advances for these limiting factors. With the recent advancements in areas such as sensing, battery endurance and tracking stability, AUVs may now offer great opportunities for oil and gas companies. It should provide a cost-efficient "eyeball" solution for subsea operations such as offshore pipeline construction and drilling operations, inspection and monitoring of assets, in addition to perform life-of-field and pipeline condition monitoring and inspections.

4 Conceptual design for an AUV monitoring system

The oil and gas industry experiences a higher demand for more autonomous systems to perform complex tasks. By looking at the development within the automobile industry, it is clear that major improvements can be achieved with automation. The technological advances and practices they have implemented have not only increased the productivity of their factories, but also improved RAMS of their production. Together with state-of-the-art space and military technology, the oil and gas industry can benefit from further adopting some of these intelligent systems and transform the technology to develop better subsea production systems. Automation is one of the foremost promising areas, as more remote located oil and gas fields are pursued. A more autonomous subsea inspection and monitoring system can lower the OPEX of exiting O&G fields and help realize development plans for remote challenging and marginal O&G fields. With the potential to fulfil the operators need for a more cost-efficient, faster, reliable and more continuous assessment of subsea infrastructure.

This chapter discuss the design process of an AUV in order to reach an optimized solution at reasonable costs. A basic concept design phase is performed and a solution based on the challenges in subsea condition monitoring and inspection is presented.

4.1 AUV design process

The graph in Figure 13 illustrates how rapid the product costs become committed, as the product design progresses from a specification stage to conceptualization. Thus, tools and methods that can ensure an optimized design early in the process are highly valuable. Computational fluid dynamics and the design spiral are efficient engineering tools and methods, which will be presented and used in this thesis.

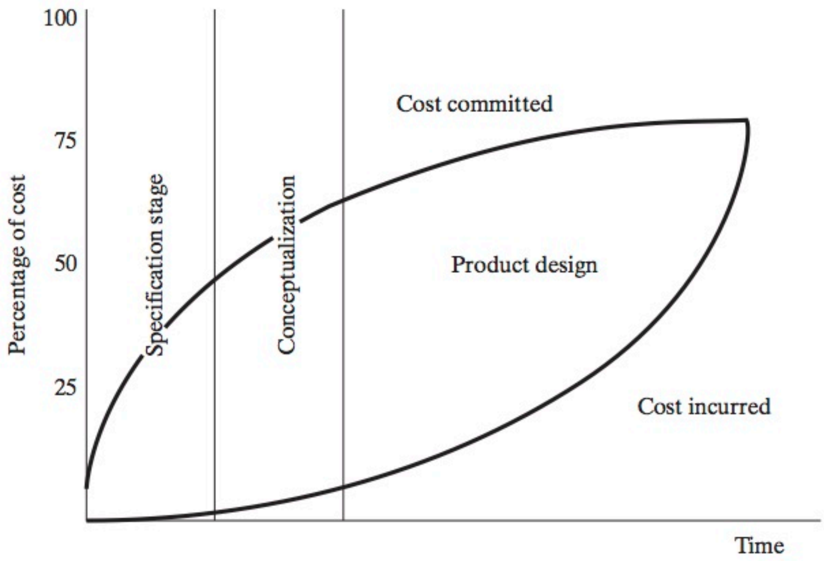


Figure 13: Costs committed vs. cost incurred in typical design process (Cengage, 2011)

Most AUVs have been developed in research programmes with an ad-hoc design process with no official rules or standards from international certifications organizations or classification societies to work from or meet (Phillips et al. 2013). However, the AUV design process may benefit from more structured ship design procedures and models developed by researchers over the last 60 years. They traditionally involve three general design phases: concept design, engineering design and production design.

These phases are often illustrated with the Design Spiral of Evans (Figure 14). Evans spiral methodology describes an efficient design process, by considering the highly interdependent complex systems in an iterative refinement process through a sequence of design activities.

As each design step progresses through the recurring activities, the increasing complexity and design fidelity of simulations are approaching realistic in-field operations.

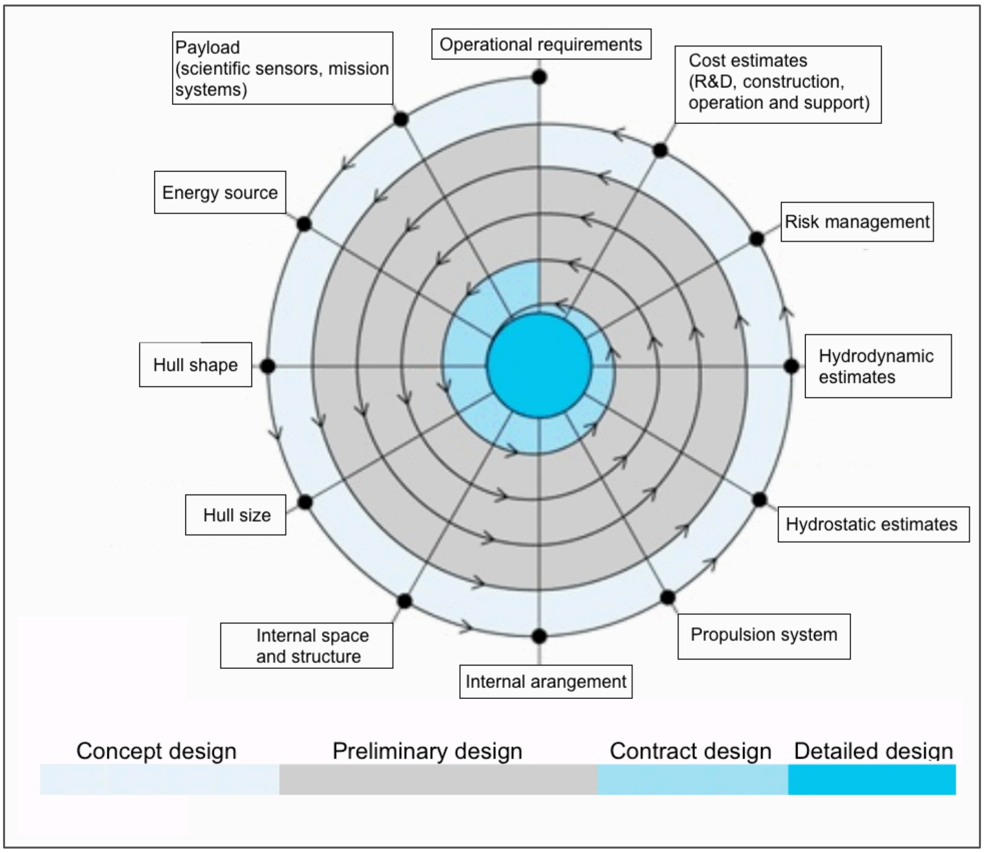


Figure 13: AUV iterative design spiral (model adopted from Gale & Slutsyky 2014)

The overall design spiral process and the use of modern computer-aided design and engineering tools was described by Stephen M. Hollister in 1994:

The first design phase progresses through the specific design steps including rough-order-of-magnitude (ROM) design, technology assessment, analysis of alternatives (AoA) and feasibility study to develop a conceptual design.
The initial step involves describing the purpose of the vehicle and defining operational requirements. A list of the major design features and measures for missions can be included.
The process may start with a rough-order-of-magnitude (ROM) estimate since there are little or no previously design information available for the concept.

This step is based on approximations, where estimators look at similar existing solutions and costs to predict future products or developments by applying proportional coefficients fore these estimates (Okray 2015). Specialists can be brought in to support with expert knowledge, experience and judgement to appropriately evaluate historical values and recommend rules of thumb.
As the concept design phase progress, the feasibility of the proposed vehicle design should be determined. Any necessary adjustments to the operational requirements should be evaluated to reach an optimized design and best meet the overall mission goals. Various payload, powering options, principle dimensions, general layout and capabilities are evaluated. Simple simulations to optimize the principal dimensions of the vehicle and state of art investigation can be performed to assess different alternatives.
The concept design process should lead to decisions on basic parameters, such as power source, hull type and produce one or two concept drawings for further evaluation.

Second phase include preliminary design (PD) and contract design (CD), where a more comprehensive and rigorous analysis of the concept design is performed. It involves identification of conflicting components, selection of parameter values, overall structure, hull shape and general arrangement. More exact calculations and simulations are performed, including hydrostatic, hydrodynamic and structural calculations. The AUV design should be conceptualized to a suitable level of detail in order for sub-contractors to quote equipment, packages and systems.

The final production design phase include detailed design and construction. It involves the creation of final arrangement drawings, structural drawings, assembly drawings and specification leading to production drawings used to physically build the vehicle.

Each cycle produces a new baseline with more information and a new iteration process re-evaluates the design. The design spiral shows the overall process, but each activity has also an internal spiral, where different engineering groups iterate their own area up against the current baseline.

Design activities used in this conceptual design is shown in Figure 14. Some of the challenges within these areas are evaluated in the next sections and chapters as follow:

• Operational requirements	**4.2 Operational requirements**
• Communication and Navigation	**4.3 Underwater telecommunication techniques**
• Power source	**4.4 Power source**
	4.5 Underwater wireless power transfer
	4.6 Recharge station energy source
• Payload	**4.7.1 Payload**
• Hull shape	**4.7.3 Hull and communication challenges**
• Hull size	**4.7.4 Hull geometry**
• Internal space and structure	**4.7.5 Internal space and structure**
• Internal arrangements	**4.7.6 Internal arrangement**
• Propulsion system	**4.7.7 Propulsion system**
• Hydrostatic and	**4.8 Optimization process**
hydrodynamic estimates	**5 Utilization of CFD as a cost-efficient design tool**

4.2 Operational requirements

The operational requirements should outline operator´s requirements of the system. It may only be a short document that includes the purpose and goals of the vehicle. Although it might seem insignificant, it contains essential information that maintains the focus of the project and guides decision-makers to chose between design trade-offs during the design process. The operational requirements may include of the following sections (Hollister 1994).

4.2.1 The purpose of the system

This part should be a short paragraph or sentence containing a simple and clear purpose of the system. If the description of the purpose or mission of the system is too long or vague, it might hinder the development of a successful design.
A system designed to perform too many tasks may end up inadequate and not achieve the purpose sufficiently (Hollister 1994).

A simple and short purpose of an AUV monitoring system:

"The vehicle should operate autonomous and inspect subsea infrastructure regularly in a safe, cost efficient and reliable manner that will increase the integrity of subsea assets."

A more general purpose for inspection and monitoring system could be:

"A system that will increase the integrity of subsea assets by monitoring and inspect subsea infrastructure regularly in a safe, cost efficient and reliable manner to detect early faults and leakages."

4.2.2 Measure of merit

This part is used to compare alternative designs by converting complete designs into a number, which expresses if system design "A" is better than system design "B". It further guides decision-makers to select between major design trade-offs.
A specific measure of merits can be to minimize corrective maintenance of subsea assets, where the vehicle design is converted into a formula, based on the downtime of subsea assets, which can be predicted and reflected by the vehicle availability. A stationed vehicle at the sea bottom may provide higher availability with a better chance of detecting faults. If the vehicle operates autonomously, it might offer even higher availability and chance of detecting faults.
There are a various weighting factors (Table 5) that can be define for the major design requirements and assigned to each design to rate different alternatives with only a single number. They may also to simulate different strategies to find

the optimal solution for condition monitoring, inspection and maintenance intervals. A suggested simulation approach is presented in Appendix B. In case there are no applicable historical data, the weighted rating techniques rely on subjective design evaluation, which are subjected to larger uncertainties. However, this approach may help to better evaluate different design trade-offs (Hollister 1994).

Table 5: Design weighting factors of a subsea condition monitoring system

Design Measures	*Weighting factors*
Economic	1. $\frac{\text{Total Maintenace Cost}}{\text{Asset Replacement Value}}$ 2. $\frac{\text{Average Inventory Value of Maintenace Material}}{\text{Asset Replacement Value}}$ 3. $\frac{\text{Corrective Maintenace Cost}}{\text{Total Maintenace Cost}}$ 4. $\frac{\textit{Condition Based Maintenance}\text{ Cost}}{\text{Total Maintenace Cost}}$
Technical	5. $\frac{\text{Total Operational Time}}{\text{Total Operational Time + Downtime due to Maintenance}}$ 6. $\frac{\textit{Uptime}}{\text{Required Time}}$ 7. $\frac{\text{Total Operational Time}}{\text{Total Operational Time + Downtime related to failures}}$ 8. $\frac{\text{Preventive Maint time causing downtime}}{\text{Total downtime related to maintenance}}$

The mathematical equations used as weighting factors in table 5 may be difficult to calculate with insufficient information. However a simple attribute weight rating weighted rating presented by Hollister (1994) can be performed. Where a set of important design attributes is determined with their weightings and ratings. It involves the following steps:

1 Select a list of major design attributes, such as operating speed, range, ease of operation, cost, safety, reliability, etc.

2 Determine a weighting number for the attribute, which relates to the relative importance of that attribute compared to other attributes.

3 For each concept design alternative, assign each attribute one of the following ratings:
Excellent, Very Good, Good, Satisfactory, Poor or Unacceptable

4 Apply a percentage value to each rating:
Excellent (100%), Very Good (75%), Good (62.5%), Satisfactory (50%), Poor (25%), Very Poor(12.5%) Unacceptable (0%)

5 Multiply the rating percent times the weighting factor for each attribute and sum the result.
This single sum value is the measure of merit of the solution.

The following inspection and condition monitoring solutions are evaluated with this *Attribute Weight Rating Weighted Rating* approach in Table 6. Ratings and values are assigned according to author´s accumulated knowledge and subjective opinion.

Table 6 ***Attribute Weight Rating Weighted Rating of inspection and*** **condition monitoring solutions**

Design Attribute	**Weighting number (0-250)**	**Design A:** ROV operation from vessel	**Design B:** ROV operation from seabed facility	**Design C:** Residential Lander Monitoring unit	**Design D:** AUV operation from seabed facility
Operational cost	250	Poor (25%)	Satisfactory (50%)	Excellent (100%)	Very Good (75%)
Acquisition cost	200	Satisfactory (50%)	Poor (25%)	Very Good (75%)	Satisfactory (50%)
Maintenance cost	200	Good (62.5%)	Very Good (75%)	Excellent (100%)	Excellent (100%)
Availability	250	Good (62.5%)	Excellent (100%)	Excellent (100%)	Excellent (100%)
Operational range	200	Excellent (100%)	Satisfactory (50%)	Very Poor (12.5%)	Very Good (75%)
Inspection excellence	200	Excellent (100%)	Very Good (75%)	Good (62.5%)	Very Good (75%)
Environmental	150	Satisfactory (50%)	Very Good (75%)	Excellent (100%)	Excellent (100%)
TOTAL SCORE:		**918,75**	**987,5**	**1150**	**1187,5**

AUV operation from a seafloor facility has the highest score (Design D). This design concept is selected for further considered in the next sections.

4.2.3 Operator´s design requirements

This part may consist of a list of design requirements with assigned significance or range such as:

- A list of chosen design requirements of a specific concept, shown in table 7.

- A checklist of design options can be developed and presented to the operators for review and assigned with a desirability factor. Different design attributes can be assign values between, shown in table 8:
  1. Must Have (MH)
  2. Very Desirable (VD)
  3. Desirable (D)
  4. Desirable, if there is Enough Room (DER)
  5. Desirable, if there is Enough Money (DEM)

- A description by the operators on what, where and how exactly the vehicle will be used.

Table 7: Operators list of AUV concept design requirements

1	Length	≈ 1m
2	Width	≈ 1m
3	Height	≈ 1m
4	Inspection range	< 1m
5	Station keeping	< 3 knots current
6	Operational speed	> 3 knots
7	Cruising range	> 7.5km

Table 8: Operators checklist of AUV design attributes with desirability factors

Design attributes	MH	VD	D	DER	DEM
Target detection	X				
Target tracking	X				
Obstacle avoidance	X				
Target identification	X				
(<10m)	X				
(<25m)		X			
(<50)			X		
3D Structure rendering		X			
O&G leakage detection		X			
Methane sensor				X	X
Mass spectrometer		X			
Cathode protection sensor				X	
Current profiler		X			
Operation monitoring		X			
Turbidity sensor		X			
Recharge at seafloor		X			
Upload data from seafloor		X			
Real-time data transmission		X			
< 10bit/s	X				
< 100bit/s		X			
< 1mbit/s		X			
> 1mbit/s			X		
Manipulator					X

4.2.4 Design constraints

This final part of the operational requirements may include fixed design constrains such as:

- Limited crane lifting capacity and space of the host facility
- Maximum vehicle size, weight for specific inspection tasks
- Rules and regulations constrains

4.3 Underwater telecommunication techniques

In terrestrial applications, wireless communication is mainly achieved using electromagnetic (EM) communication technology. EM waves have the advantages of high propagation speed, which as enable use to transmit large amount of data wireless for long distances. Unfortunately, EM waves do not propagate well through water, which have left commercial wireless communication technology such as GPS, Wi-Fi and mobile telecommunication unfeasible for underwater communication (Brundage 2010).
After many years of research, there are still few sufficient wireless communication options; although technological advances and the increasing demand for wireless transmission of data underwater has accelerated this development. Where optical, acoustic and radio frequency RF-EM wave technology are the three major underwater communication technologies.

4.3.1 Underwater acoustic communication

Acoustic waves can travel up to tens of kilometres and has dominated underwater communication for decades. Although acoustic waves travel much faster in water than air, the propagation speed in water (1500 m/s) provide low data rates for a communication systems, compared to optical and RF-EM waves. The limited bandwidth is around 0 b/s – 20 kb/s (Che et al. 2010). Acoustic propagation is also very difficult to predict because the waves are influenced by several parameter such as temperature, pressure and salinity, which can vary greatly with depth. Acoustic waves are also affected by ambient noise, thus noisy intervention work and other sources of vibration may distort the original signal. Complex signal processing and filtering is needed to account for the occurrence of shadowing, fading, multipath and Doppler spread (Kok 2011). There are also environmental concerns of acoustic technology, which can have a negative affect on marine life. Although acoustic communication includes several challenges, it is still the most feasible solution for long-distance communication underwater (Che et al. 2010).

4.3.2 Underwater electromagnetic communication

Although scientist have been investigating underwater EM communication since the early days of radio, they still struggle to cope with the challenge of EM wave attenuation in water, due to high permittivity and electrical conductivity.
The Extreme Low Frequency (ELF) submarine communication system has been considered as the only successfully deployed application. With limited one-way communication, it was capable of transmitting a few characters per minutes across the globe using huge antennas (Rhodes 2006).
Though radio frequency (RF) EM signalling experience limited transmission range in water and electromagnetic interference from power cables and motors, it also include some valuable features that differ from acoustic and optical technologies. It certainly benefits from high EM wave propagation speed and small Doppler shifts since it is inversely proportional to the speed (Rhodes 2006). Allowing high bandwidth (<100Mb/s) at very close range. RF-EM signalling also inherits useful EM transmission properties through water/air and water/earth boundaries shown in figure 15 (Che et al. 2010).

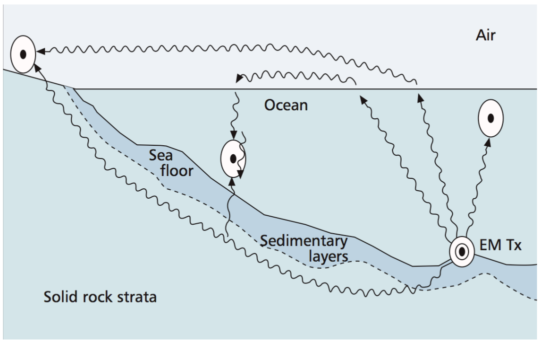


Figure 15 RF multi-path propagation underwater

These smooth interface transmissions make it possible for RF-EM signals to travel the path of least resistance, thus extending communication range for close-to-surface or seabed applications. This advantage can be utilized to create more feasible wireless communication networks.
Solutions for pure water propagation with Radio frequency (RF) conduction antennas have been proven to transmit high-speed communication at 1Mb/s up

to 1m distances and lower bandwidth (<25b/s) up to 200m (Che et al. 2010). By generating an electric field in the water using a pair of electrodes with opposite current and detect changes in this field with another pair of receiving electrodes (Zoksimovski et al. 2012).
Wireless Fibre Systems (WFS) Technologies is a company that have successfully developed different short-range underwater electromagnetic communication systems, called Seatooth. It supports data transmission rates from 10b/s to 100Mb/s. However, high data rates require very small distances (0-10cm), thus only feasible as a wireless contact. For distances up to 5 meters, the S300 can transmit data at 156kb/s. A large antenna is also required for longer range.

4.3.3 Underwater optical communication

Within the electromagnetic spectrum, visible light, especially blue light is less affected by the attenuation in seawater (Kok 2011). Scientists have managed to exploit the benefits of using optical waves from light emitting diodes (LEDs) and lasers to transmit data information, with ultra-high bandwidth potential.
Optical wave technology has gained more attention lately, due to lower costs and more energy efficient off-the-shelf LEDs.
Woods Hole Oceanographic institution is amongst those how have successfully demonstrated an optical systems offering high data rates up to 1Mbit/s within 100 meters. This can be achieved because of the high propagation speed of blue light (speed of light ≈ 299 792 458 m/s). However, the technology is subjected to range limitations due to relative high scattering and absorption of optical waves. Optical wave technology is also dependent on line of sight, with the nodes closely aligned. Making it unfeasible in very turbid and dirty waters. Further marine growth and fouling is also a problem.

4.3.4 Summary

There are many challenges and advantages by choosing to transmit data wireless underwater. Finding the most effective technique and configuration requires an iterative process. Wireless applications do not only dependent on the operational requirement but also on the site, such as depth, distance from shore, marine environment. The three major technologies offer various benefits and limitation, which in many configurations can compliment each other.

Acoustic signalling technology is a mature technique in contrast to optical and RF-EM wireless underwater technology, thus significant improvement can be expected in the near future. These two up-and-coming technologies already offer great advantages, such as being immune to acoustic noise and high data rate capacity. Wireless optical communication system has proven to support high wireless data transmission underwater to efficiently upload video and large amount of sensor data. Equipped with a long-range acoustic communication for activation and navigation and a protecting mechanism for marine fouling. These optical units would be an economical and well suited to be stationed at different monitoring sites. This communication method can then be utilized during AUV surveys of subsea infrastructure, to efficiently gather valuable measurement data from different sites.

As a result the AUV and upload stations can be equipped with RF-EM technology, which can offer the required reliability being immune to marine growth, acoustic noise and turbidity.

Landers can be use as upload station and be further connected to a network utilizing the extended range capability of RF-EM propagation through the seabed ground.

4.4 AUV power source

One of the main limitations of AUV operations is the amount of energy the AUV can carry to run the propulsion system and payload. Mobile energy sources are heavy and use a lot of space in these small bodies. Thus designing the AUV with the desired range is one of the main challenges and requires an iterative process. The range (L) of the AUV is dependent on the vehicle´s speed (V), propulsion power (P_P), payload power (P_L) to operate all the equipment and the energy (E) stored in the vehicle (Phillips et al. 2009). It can be calculated in kilometres by:

$$L = \frac{EV}{\left(P_p + P_L\right) * 10^3} \qquad (2)$$

Where E is in joule, P_P and P_L is in watts, L is in kilometres and V in metres per second. They are all closely affected by each other, resulting in a challenging iterative design process. The velocity of the vehicle is influenced by the drag force and thrust power. If the propulsion efficiency is overestimated and the drag force is underestimated in the design phase, it can result in an underestimation of the necessary proportional power and energy for the required operational range. In order to safely assure that these parameters are correctly estimated, CFD simulations should be performed early in the design phase as a cost-efficient design tool. It should involve optimization of the hydrodynamic performance of the AUV to reduce and correctly assess the necessary thrust power and stored energy. Since most AUV operations are restricted to the amount of energy that can be stored in the vehicle, due to the confined space in the AUV and limited energy density of the power source. It is important to select the most efficient and suitable power source. The process of evaluating alternative power sources must consider various factors such as:

- Application of the AUV (hovering capabilities, agility, long-range pipeline tracking, operational depth)
- Service time (recharging/replenishing)
- Facility requirements (logistic support, operator skill level)
- Cost constraints
- Acceptable safety level and environmental impact (noise, emission, recycle)
- Complexity, weight and volume
- Temperature
- Reliability

4.4.1 Electrochemical power source

Electrochemical power sources may be classified into four different groups (Størkersen and Hasvold 2004):

1. Batteries inside a rigid pressure container discharging at atmospheric pressure.
2. Pressure compensated batteries discharging at ambient pressure
3. Seawater batteries
4. Fuel cells

First group include conventional rechargeable lead acid, nickel-metal and lithium-ion batteries. Also non-reachable alkaline and lithium batteries could be considered, but the cost of changing them during continuous operation is too high. Rechargeable lead acid and nickel-based batteries are low cost batteries, but the performance is poor.
Rechargeable lithium-ion batteries have become the new standard in industrial application. The topic of using energy stored in rechargeable batteries to power vehicles are hotter than ever. It is not only environmental benefits that come with the use of clean energy. But Elon Musk, CEO of Tesla has delivered an electrical driven car that accelerates faster than a Ferrari, for less than half price. This is much thanks to the development of lithium-ion battery technology that has brought a great leap to the performance of energy storage. Elon Musk has accelerated a technological trend that might revolutionize battery technology and its applications, in similar manner to what Steve Jobs managed to revolutionize the world. An important part of the strategy is to build a battery Gigafactory to minimize cost of production and offer the high performance lithium-ion technology as everyday commodities, storing renewable energy in cars and homes. It is difficult to compliment the innovate effort done by Elon Musk and Tesla without mention their strategy, opening up their patents to the world. Further increasing the competition, which in turn continues to push for more innovation and development. An investigation of the 85kWh lithium-ion

battery pack in a Tesla Model S might offer a good perceptive on the commercial sate-of-art battery technology today and what might be the next thing. A teardown of the 85kWh Tesla Model S performed by Jason Hughes in 2014 reveals 7104 cylindrical Panasonic NCR18650B (Table 9) lithium-ion batteries in 96 groups connected in parallel, with each 74 cells wired in series. Each cell according to Panasonic has a power density of remarkable 260Wh/kg. Thus, a very simple AUV battery pack with 8S30P configuration could provide 30V and 3kWh at 2,400$ with an approximately weight of 11kg. However, additional housing, controllers and protection are needed, which adds to the total weight and volume of the battery packs.

Nominal Voltage	Nominal Capacity	Dimensions (Diameter*Height)	Weight	Price
3.6V	3400mAh	18*65mm	47g	10$

Table 9: Panasonic NCR18650B Lithium-ion Battery

The cost per kilowatt-hour of $800 is based on of-the-shelf price. The cost per kWh based on the price difference between Tesla´s 60kWh and 85kWh models give $400 per kWh. However, people associated with Tesla say the cost are probably below $200. The consulting firm Mckinsey also speculated in 2012 of cost down to $200 per kWh within 2020 (Ingram 2012). Recently studies now indicate that these predictions are accurate as the cost as drop below $300 per kilowatt-hour (Voelcker 2015).

SubCTech is a company that offer similar lithium-ion battery packs for AUVs, where a 4kWh power block weight 30kg. This gives an energy density of 133Wh/kg, which is half of the Panasonic NCR18650 cell value. A large part of this come from the additional weight of housing, safety and control systems. Oil pressure compensated housing made of high strength titanium, maintain atmospheric pressure and protect against corrosion.

Part of the second battery group working at ambient pressure is the lithium-ion polymer battery. Lithium polymer batteries can be manufactured in various soft package or pouch shapes, which is useful for the confined space in AUVs. It has similar performance as lithium-ion cells, but the soft package has the additional advantage of being lighter and insensitive to operational water depth.

Both lithium-ion and lithium polymer are widely used in the industry and AUVs today and offer the highest available energy density. However, these batteries degrade over time, which is one of the major downside of this technology, thus requiring new battery pack after approximately 1000 full cycles. Extra cells may also be needed to compensate for this loss.

A new and promising technology with improved cycle durability is the Lithium-Sulphur battery. It has received a lot of attention lately and might become the next generation battery technology. By replacing one of the electrodes in the Li-ion battery with a sulphur-based electrode, the theoretical energy potential reach up to 5 times higher than Li-ion.
OXIS Energy is a company that achieved 300Wh/kg cell level in 2014 and expects to develop 400Wh/kg cell level in 2016, which can maintain 80% capacity after 2000 cycles. Their expectation of the Lithium-Sulphur battery can be viewed in figure 16 and compared other known battery technologies. However, these high energy density in figure 16 do not include the additional weight and volume required to operate in AUVs.

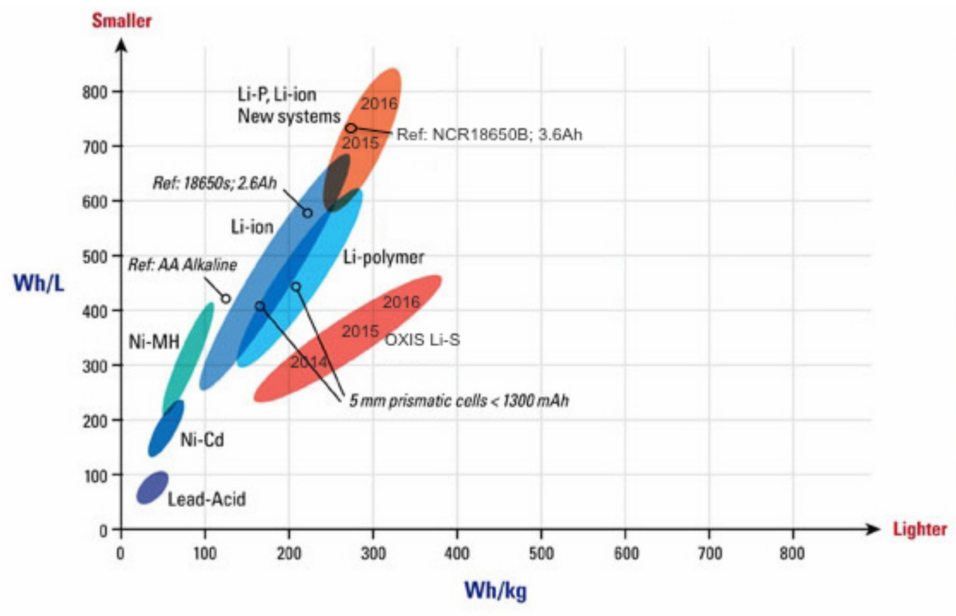


Figure 16 Comparison of conventional battery technology and OXIS future prediction of Lithium-Sulphur batteries.

Aluminium-oxygen semi fuel cells are also part of the second battery group working at ambient pressure, thus very attractive to deep-water operations. These batteries can only be recharged mechanically by replacing consumed anode and electrolytes, thus requiring support vessel and skilled service personnel. It has been used in HUGIN AUVs developed by Kongsberg since 1998 and produce around 100Wh/kg, which is high compared to the Li-ion battery SubCtech offers today (Størkersen & Hasvold 2004).

Seawater batteries use the ocean as electrolyte and can offer high energy density as the electrolyte is not technically part of battery mass. A major disadvantage of seawater batteries is very low power output, which makes them only suitable for low power sensors (Størkersen & Hasvold 2004).

Hydrogen-oxygen fuel cells generate electricity from a chemical reaction between oxygen and hydrogen, which must be stored in the vehicle. The energy density of the reactants alone is approximate 2000Wh/kg and can be stored as compressed gas in lightweight containers with net positive buoyancy (Hasvold & Størkersen 2000). Hydrogen-oxygen fuel cells have been developed by Siemens since 1985 and are used in many submarines today. Several space applications have also utilized fuel cell power. Although the hydrogen-oxygen fuel technology has matured over the years, there are no commercial AUVs powered by it. JAMSTEC and Mitsubishi began to develop an experimental AUV power by fuel cells combined with lithium-ion batteries and in 2005, this 10 meter long AUV called URASHIMA took the world record with a 317km long distance dive using fuel cells (Mendez el at. 2006). Further AUV prototypes have been limited due to high associated cost with fuel cells and large space requirements. However, recent development geared towards commercial use might bring down the cost and provide more compact solutions to power AUVs in the future.
In 2016, the Toyota Mira will be one of the first commercially available fuel cell powered automobile. More compact fuel cell systems has also been developed for unmanned areal vehicles (UAVs) and set new endurance records. EnergyOR is a company that develop small fuel cells. In March 2015 they demonstrated the first fuel cell powered quad-copter with a 2 hours endurance flight record. This

is impressive compared to the record holder of a similar lithium-ion battery powered quad-copter developed by Frantz in 2014, which managed to fly for 1.5 hours. It can be expected that small fuel cells will allow greater endurance for as AUVs in the future.

4.4.2 Alternative power source

Besides electrochemical power sources, nuclear and combustion power sources have also been investigated. Nuclear reactors systems have the benefit of using highly energy rich materials with almost no emissions. However, the complexity and size requirements to deal with issues such as shielding from the radioactivity has limited nuclear power source to larger submarines and space applications.

Combustion systems combined with a turbine to generate power have been successfully used in AUVs, such as the closed-cycle diesel engine in R-One Robot developed by the University of Tokyo in 1998. It was designed for slow speed and long-range surveys, equipped with liquid oxygen tanks it could operate for 12 hours, producing 5kW. However, even small closed-cycle diesel engine like this one are relative large and complex for AUVs. The R-One Robot weight of 4.35 tonnes and the closed-cycle diesel engine demand for fuel and oxygen refilling and carbon dioxide absorbent replacement, has limited further feasible development compared to battery systems. Although alternative metal-fuelled combustion systems that use seawater as oxidizer has been developed for submarines, and could offer more compacted solutions for AUVs. It offers the advantages of higher energy density, as using seawater eliminate the need for liquid oxygen tanks allowing more capacity for fuel (Miller 2002). Simulations have illustrated that operations length could be more than doubled compared to batteries. However, power output and efficiency issues related to friction and thermal losses must be improved to provide a viable solution (Eagle et al. 2012). These open-cycle systems also need additional buoyancy measures to compensate for the ejection of reaction products.

4.4.3 Summary

Although great leaps have been made in the performance of different AUV power sources, the capacity and size is still a critical factor in the design process. The limiting energy density is holding back a number of operations and technologies, which require less cumbersome and expensive procedures to recharge and replenish energy.

Improved battery and alternative power source technology have been successfully developed in laboratories. But it usually can take 10 years until it is fully tested, validated and put into mass-production.

The current state of AUV power sources require support vessels. It is further necessary to make compromises between larger AUV power source suitable for long-endurance with more comprehensive logistic on-board the support vessel or simpler short-range AUV with rechargeable batteries. A underwater recharging station may provide sufficient power for an AUV equipped Panasonic NCR18650B Lithium-ion 3kWh battery pack. However, this solution relies particularly on a simple and robust power transfer connection between the underwater recharged station and the AUV.

4.5 Underwater wireless power transfer

Today, AUVs operations require support vessel to conduct cumbersome recovery and disassembling procedures to recharge or change batteries. It is also time consuming and inefficient to ascend from the deep-sea bottom.

Thus better options are needed in order to facilitate for cost-efficient AUV subsea inspection operations in the O&G sectors. One method is to allowing the AUV to recharge the batteries at the seabed. A means to easily connect to a power source is then necessary and this is where wireless power transfer may come in use.

It is not only data transmission that benefit from wireless technology.

An increasing interest in wireless power transfer can also be observed in our daily life. Making the hassle of damaged and worn mobile connectors

disappearing. Even IKEA is now offering inexpensive wireless solutions to recharge electronic equipment at home (Howarth 2015).
Wireless charging has even more advantages underwater, as wet-mate connectors are vulnerable to the harsh subsea environment and use by underwater vehicles. It can be a tricky operation to align and make a clean connection with an AUV or ROV. Problems may occur from misalignment, excessive wear from multiple connection cycles, water ingress, corrosion and marine growth. Wireless connection may offer a more reliable alternative to avoid these issues and efficiently deliver power unaffected by turbidity and contaminants.
Based on electromagnetic field to transfer energy, it is possible to wireless charge underwater application.
Contactless power transmission can be divided into two main regions, based on the physical phenomena of EM field propagation: far-field and near-field (Valtchev 2012).

4.5.1 Far-field energy transmission techniques

Far-field, also called radiative technology use EM wave propagation methods to transfer power over longer distances. It typically involves transmission of beamed EM radiation such as optical waves, microwaves and radio waves. These techniques are dependent on thigh alignment between the transmitter and receiver. The beams of EM waves that are absorbed by the receiver are converted to electrical energy and if it misses the receiver, the energy is lost. Optical techniques transmit power to a remote detector with optical waves focused in a laser beam. Similar to the wireless data transmission, this technology is vulnerable to objects that can interrupt the transmission, such as turbid water, marine fouling and growth. There are also some low efficiency drawback associated with optical wave propagation in water and the conversion of light into electricity using photovoltaic cells with efficiency of 40%-50% (Hecht 2006). Strong laser beams can also be hazardous to marine life as is can burn through tissue.

Microwave power transmission use similar techniques by directing a concentrated beam of microwaves to a receiving unit called rectenna, which convert microwave energy into direct current electricity (Valtchev 2012). With similar alignment, efficiency and safety issues as optical transmission, this technology is still limited to research application. Although further exploration, might provide feasible wireless transmission in the furfure.

4.5.2 Near-field Energy transmission techniques

Near-field also known as non-radiative technology use magnetic fields and inductive techniques to transfer power over shorter distances. Feasible methods that can be useful in subsea application include electromagnetic induction (inductive coupling) and electrodynamic induction (resonant inductive coupling). Both methods are based on the transformer principle in which power is transferred between coils through a time-varying magnetic field (MacLean & Collins 2013).

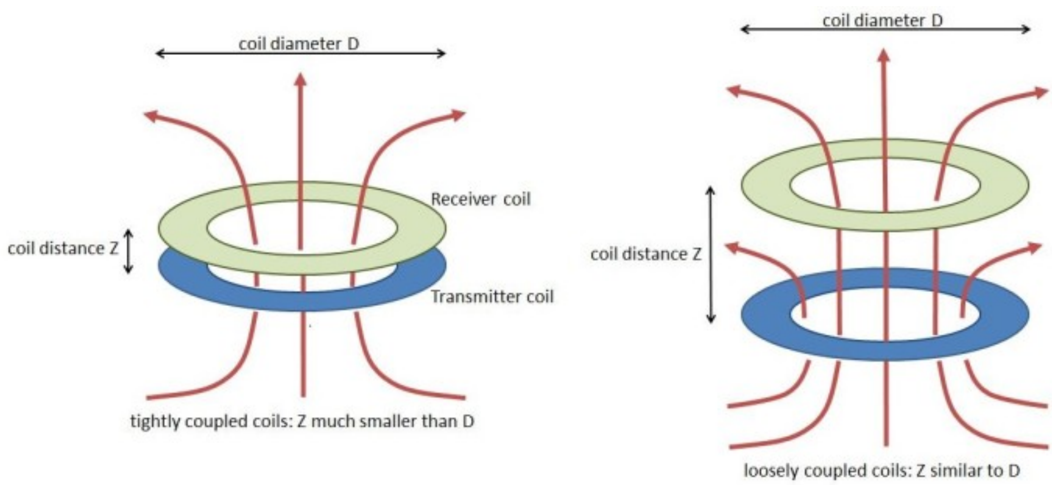


Figure 17: Inductive coupling on the left and resonant inductive coupling on the right (Qi Wireless Power, 2015)

The inductive coupling in figure 17 (left) use tightly coupled coils that are operating at slightly "off-resonance" frequency. This method provides highest power transmission efficiency for very close distances, but it is highly dependent on coil alignment. WPS is a company that can offer this technology for subsea applications, with the ability to deliver power up to 3kW within 10cm. If the system is optimally aligned it can operate at 90% efficiency.

The more loosely coupled coils in figure 17 (right) operate at resonant frequency (resonant inductive coupling) in order to minimize energy losses to the non-resonant environment. (Gopinath A. 2013). This method extends the range in which power can be efficiently transferred wirelessly between two coils. It is also less sensitive to coil alignment and can support multiple receiver coils. However, these benefits come at the cost of lower power transmission efficiency.
Both techniques induce an alternating current in the secondary coil that can be used to charge batteries.
WPS and WiTricity are amongst those who have developed commercial wireless power transmission systems for terrestrial use based on resonant inductive coupling. In 2013, Kesler and McCarthy performed a test with a WiTricity system through a 15cm water column. The experiment proved that 3 kilowatts of power could be transferred at 80% efficiency without precision alignment. They further believe that efficiency improvements can be achieved with resonators specially designed for subsea application for a specific operating range.

4.5.3 Summary

Since conventional wireless technology used in terrestrial and space applications have very poor performance in water. The subsea industry has relied on physical connection when transmitting large amount of data between subsea applications and up to the water surface. Although fiber optical tether provide a reliable and high-speed communication, it includes range limitations and greatly affect manoeuvrability of underwater vehicles. Tetherless AUV have thus got more attention last couple of years to survey deeper and more remote water than before. Having the AUV stationed at the sea floor is essential in deep waters, to achieve economical and asset integrity benefits that come through utilization of an AUV. Thus a practical and reliable subsea recharge solution is needed to realize this envisioned concept. It should involve a simple procedure, which the AUV can manage to preform in various conditions and include a method to transfer data and recharge batteries. The cheapest and quickest method that might come to mind is to establish a physical connection between the recharge station and the AUV. However, such dock-in solution requiring a wet-mateable connector are exposed to threatening deterioration after being reconnected numerous times. Further extreme pressure, marine growth and the corrosive environment may require wireless technology to offer a more shielded solution.

It is proven that it is possible to transmit power using inductive coupling at high efficiency through water. Commercial available systems operate at a limited range of 10cm and are highly sensitive to misalignment. However, it is believed that further research and development within energy transmission technology based on resonance inductive coupling techniques is likely to improve the performance.
It is safe to say that a wireless power transfer system is feasible to integrate onto a recharge station to recharge the AUV.
The AUV would be able to recharge the batteries wirelessly with the use of wireless power transfer (WPS) technology. A WPS system based on induction is considered as the most optimal solution to integrated in the recharge station.

As a result the proposed concept will involve an AUV coupled with a residential installed lander. The lander would provide a recharge station and a communication link to the AUV. One of the main reasons of having the AUV permanently available at the sea bottom is to reduce deployment time and perform more frequently inspection of the subsea infrastructure at a reduced cost compared to a ROV system. The AUV would be equipped with various sensors to capture high quality measurements during regular inspections and remotely executed detailed inspections.
Since the AUV can only operate within a limited range, additional landers can be deployed in a network to support the AUV with a recharge station and allow transfer information onshore.
Whereas permanently installed monitoring systems alone, may provide limited information to verify faults or provide incomplete information, leading to an initial response with limited or no intervention capabilities. A more detailed inspection from an AUV may provide critical information to address failures before more comprehensive intervention is needed. Thus onshore personnel can

obtain information more quickly to mobilize necessary assets and carry out required response.

Compared to a similar ROV solution, the integration of AUV with a recharge system for on-shore operations would reduce the need for support vessels, offshore personnel and space requirements on the host facility (Watson 2013).

4.6 Recharge station energy source

It might present circumstances where the option for grid connection to previously subsea network or surface facility is not feasible or non-existent.

In this case, the envisioned system would require an alternative source of power and communication link to an on-shore facility.

The recharge station would need to transmit data through optical fiber to a surface-based satellite, linked with an on-shore facility.

Underwater wireless communication technology does not have the capacity to transfer high amount of data for long distances. However, EM wave technology might provide high-speed solution to the nearest network link for long-range data transmission through the seabed-ground in the near future.

Wind and wave may provide feasible renewable energy sources that can provide enough power to the recharge station and the communication system. Among the recent development is Statoil´s Hywind wind turbine, which has proven to withstand harsh offshore environment. Another option is the OTP´s wave energy harvester, which generates electricity from the relative heave motion between the buoy and a submerged heave plate. Spare generated energy can be stored in batteries large enough to power the recharge station during low wind or wave generation (Watson 2013).

4.7 AUV geometry and module configuration

Previous sections have considered “High-concept” inspection and condition monitoring system to meet operator´s requirements and technological developments critical to success. The AUV concept supported by a recharge station is considered both feasible and best solution to increase subsea asset integrity. This section considers the development of principal dimensions, hull shape design, arrangements, and performance goals for the AUV.
Key components and steps involved in the process to achieve a feasible design and further optimization aspects are discussed in this chapter.
Potential design constrain indicated in red in Figure 1, are part of the many design trade-offs, which should be considered early during the concept design phase. The design spiral may suggest the following trade-offs listed below in a descending order of importance to be considered in a step-by-step procedure to create a feasible design:

1. Payload vs. Volume
2. Energy (Volume, Weight) vs. Range
3. Hull geometry vs. Power, Speed
4. Arrangement vs. Volume, Hull shape
5. Hydrodynamic stability vs. Hull shape
6. Cost vs. Weight

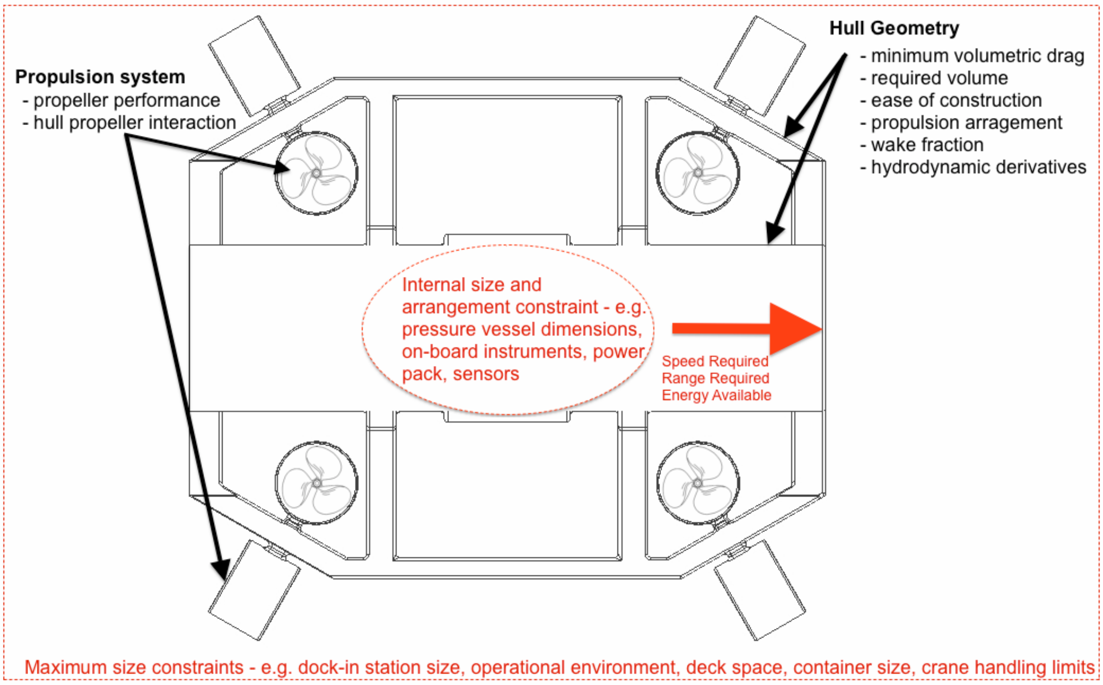


Figure 18: Hydrodynamic aspects of AUV design in black and potential constraints in red (derived from Phillips et al. 2009)

Although the design process may appear like simple step-by-step process, it might not be that straightforward as the interactions between these design trade-offs are complex and interrelated. Any changes in the weight or volume may initiate a chain of reactions, affecting the displacement, performance and cost of the vehicle. An increase of the weight requires additional buoyancy material to maintain the displacement of the vehicle, which adds to the volume and more thrust is needed to move the vehicle at the desired speed. To achieve desired speed and range, larger motors and more energy are needed, which in turn adds to the weight and cost of the vehicle. These changes may require new arrangement drawings, which may further increase resistance and drag force. Hence accurate weight estimates and tracking are essential to minimize iteration time.

A redefined measure of merit for the chosen concept can be used in the step-by-step procedure, to guide the design process and evaluate design trade-offs from the following components.

4.7.1 Payload

The payload is considered the most important module of the system, thus selected first to ensure adequate free space and weight capacity of AUV hull. It includes scientific sensors, cameras, on-board computer and instruments required for automatic control and navigation to conduct desired inspection and monitoring tasks.

4.7.2 Energy source

Energy storage has been identified as one of AUV´s main operational constraints. It requires a significant proportion of the vessel volume and weight, thus it is considered as the second step in the design process. The evaluation of current available energy sources indicated that secondary lithium-ion battery technology might be the most feasible solution for energy storage for an AUV.

4.7.3 Hull and communication challenges

As the environment we are dealing with mainly consists of fluid, it is essential that designers understand how the subsea environment affects performance of underwater equipment and vehicles. Based on numerical simulations, it possible to study the behaviour of such complex flows in order to predict underwater vehicle performance.

While oil and gas fields in deep-waters are increasing, more cutting edge technology and cost-efficient solutions are needed to achieve higher revenues. These systems must endure extreme forces as the pressure increases roughly with 1 bar for every 10m in depth, which at 2000m below the sea surface, give engineers a challenging pressure of 2000 tonnes per square meter. To get a sense of the forces in play, imaging stacking 8 locomotives on a single square meter (Parodi 2014). Underwater equipment is therefore often located in spherical or tube-shaped protective housing (Figure 19) typically made of titanium, to withstand high pressures.

Figure 19: Pressure vessel for subsea instruments (OceanWorks 2015)

By considering a fluid parcel of seawater in thermodynamic equilibrium, the density can be described:

$$\boldsymbol{\rho} = \boldsymbol{\rho}\,(T, p, s). \qquad (3)$$

T = temperature, p = pressure and s = salinity (kg salt/kg sea water).

The density of seawater increases by decreasing temperature. Additionally an increase of salinity also increases the seawater density, although seawater density is mostly affected by the changes of pressure.

The temperature of seawater is ultimately controlled by the activity of molecules and atoms. An increase in the activity (energy), results in higher temperature. This thermodynamic property of fluid is a measure of heat content, which is related to the specific heat of the fluid.

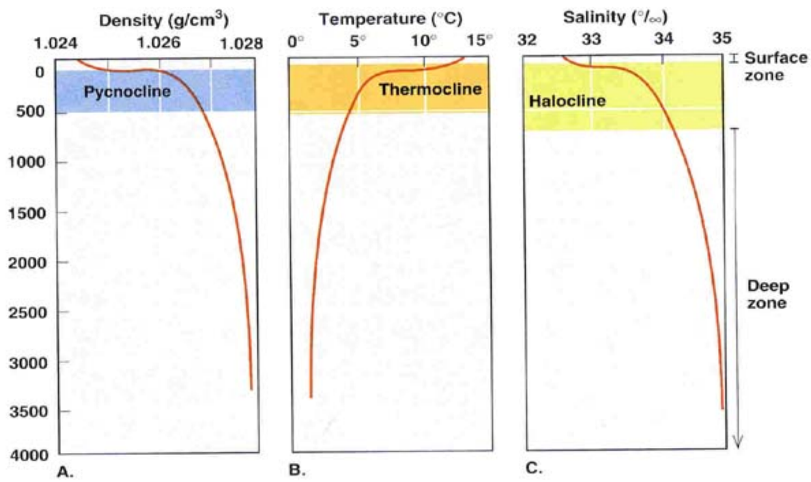


Figure 20: Underwater changes of density, temperature and salinity (Darin W. Toohey)

As shown in Figure 20, the pycnocline, thermocline and halocline represent different area of rapidly changes within density, temperature and salinity respectively. This relation between pressure, temperature and salinity plays an important role for subsea engineers to understand underwater currents, which must be accounted for when performing operations on the seabed. As the salinity levels are quit stable in deep waters, small changes can cause huge impact on water movements as the denser water can sink several hundred meters. It may develop strong underwater currents that ROVs and AUVs must endure to allow for station keeping. An increase in seawater density will also increase the drag on underwater vehicle. Because the propagation of acoustic waves underwater depended on the density of fluid, subsea engineers must also study these variations in order to successfully communicate acoustically in seawater.

4.7.3.1 Energy consumption from hydrodynamic drag

Drag is the summation of all forces that a fluid exerts on a body against its motion. This force is undesirable in most application and engineers use a lot of resources to minimize and predict this effect. The drag force that resists the movement of a deeply submerged UV can be divided into skin friction drag and pressure drag.

Skin friction drag is directly related to the wall shear stress $\tau_{w,}$ due to no-slip condition caused by viscous effects. This friction force can be obtained by integrating the tangential component of the shear force over the surface of the body, in the direction of the fluid flow.
Since this friction force is proportional to the surface area, efficient reduction involves maximizing the ratio between body volume and surface area. However, the pressure drag is proportional to the frontal area and the pressure differences along the body. Consequently, these two forces change opposite of each other when engineers modify the design. Thus to minimize the total drag, both effects should be weighted and balanced early in the design phase. (Cengel & Cimbala 2006)

4.7.4 Hull geometry

Size and arrangement of the internal payload and power source are the main constraints of the hull size. While the hull shape is mainly constraint by the desired hydrodynamic attributes, which partially determines the energy requirements, dynamic stability and manoeuvrability of the AUV. The hull shape may also be constrained by necessary launch, recovery and docking capabilities. Ease of construction, maintenance and accessibility to internal components are also among important design attributes that determine the hull shape (Phillips 2010). An optimal compromise between long endurance and speed has been a shared goal amongst survey AUV designers. It has lead engineers to develop various streamlined hull shapes ranging from the torpedo shaped REMUS (Kongsberg, Norway) and laminar shaped HUGIN (Kongsberg, Norway) to the streamlined rectangular shaped Sabertooth (Saab Seaeye), Sentry (Woods Hole Oceanographic Institution) and the new innovative hull shape of Subsea 7´s autonomous inspection vehicle (AIV). Each vehicle and hull shape is optimized to fulfil a specific purpose or missions.

Basic design attributes and geometry constrains used for this concept are:

- Stations keeping in 3 knots current
- Close to structure operations
- Subsea recharge capabilities
- Operation speed up to 1.5 m/s
- Length of the AUV must be less than 1.0 m
- Width of the AUV must be no more than 1.0 m
- Height of the AUV must be no more than 1.0 m

Figure 18 shows the outline for a concept AUV considered in this study and illustrates some of design challenges associated with hydrodynamic design and module configuration.

4.7.5 Internal space and structure

The first steps involving on-board components initially determine required space for internal components. The space is then further allocated while designing the hull size and shape. It includes design of internal structure and pressure container to protect sensitive components against the hydrostatic pressure acting on the AUV. As identified for hull challenges, the high pressure imposes great challenges. It requires spherical or tube-shaped pressure vessels in order to efficiently protect components and fit them into streamlined hull forms, thus present additional space constrains.

Although lightweight materials for hull structure and pressure vessel are often used for deep underwater vehicles, the total weight of the vehicle ends up heavy and requires additional buoyancy material to achieve slight positive buoyancy. Hence in the event of failure, the vehicle will slowly ascent to the surface (Philips 2010).

4.7.6 Internal arrangement

Arrangement preferences should be considered during the hull design. Although principally hydrodynamic aspects often determine the hull shape of AUVs, the optimization process may benefit from using a framework capable of generating optimal design of AUVs, by consider both internal arrangements and hydrodynamic aspects. It involving development of arrangement strategies to optimally place internal components in order to minimize wasted volume and ensure optimal hydrodynamic stability, such as centre of gravity (CG) and centre of buoyancy (CB) (Alam et al. 2012).

4.7.7 Propulsion system

Most AUVs use conventional propellers to move the vehicle forward, with thrusters or hydroplanes for manoeuvring. Other available propulsion system includes buoyancy thrust (glider) and jet-pumps. Researchers are also experimenting with biomimetic propulsion system for AUV, such as the BIOswimmer developed by Boston Engineering.

Control surfaces such as hydroplanes are very energy efficient, but the vehicle needs to move in order to manoeuvre. Propelled thrusters offer high manoeuvre capabilities, such as station keeping and hovering. Ballast systems may also be used for vertical movement.

4.8 AUV optimization process

Methods of solving design trade-offs may involve iterative optimization processes, such as a parametric analysis within specified design limits. Where all design variables except one, are held constant to measure the change in performance and develop a set of feasible designs.
The need to predict hydrodynamic aspects of different designs early in the design process to optimize and minimize iteration time, leads engineers to use such analytical method to estimate forces acting on the AUV hull form. But this approach is limited and can only give exact solutions to simple geometries. It is a simple theoretical method using mathematics to solve physical problems. Hence, experimental methods are used to achieve accurate results of these complex geometries. It involves constructing physical prototypes, wind tunnels or water pools to create the external environment. This approach can produce very realistic data, however it is normally an expensive and time consuming method. Hence, in order to perform accurate predictions early in the design process at low costs, engineer can use numerical methods to simulate hydrodynamic forces such as the drag force acting on the hull form. This numerical approach with the use of computational fluid dynamics (CFD) is used to predict and analyse systems containing fluid flow, gas flow, heat transfer and coupled phenomena such as acoustic movement and chemical reactions. These predictions are solved and analysed with the use of numerical methods and algorithms through computer-based simulation.

Figure 21 further illustrates an iterative AUV design process in a flowchart with a hydrodynamic optimization outlined early in the development. The optimization framework use CFD modelling for cost efficient hydrodynamic consideration such as minimization of drag force action on the AUV hull. Further spins in the iterative design spiral, refines the hull form through hull faring. It involves minimizing drag force and unnecessary volume while attaining optimal hydrodynamic stabilities and manoeuvrability. This includes simulating various hull designs and propellers early in the design process, without have to physically build any prototypes. Arising issues concerning arrangements are also continuously addressed in this optimization process:

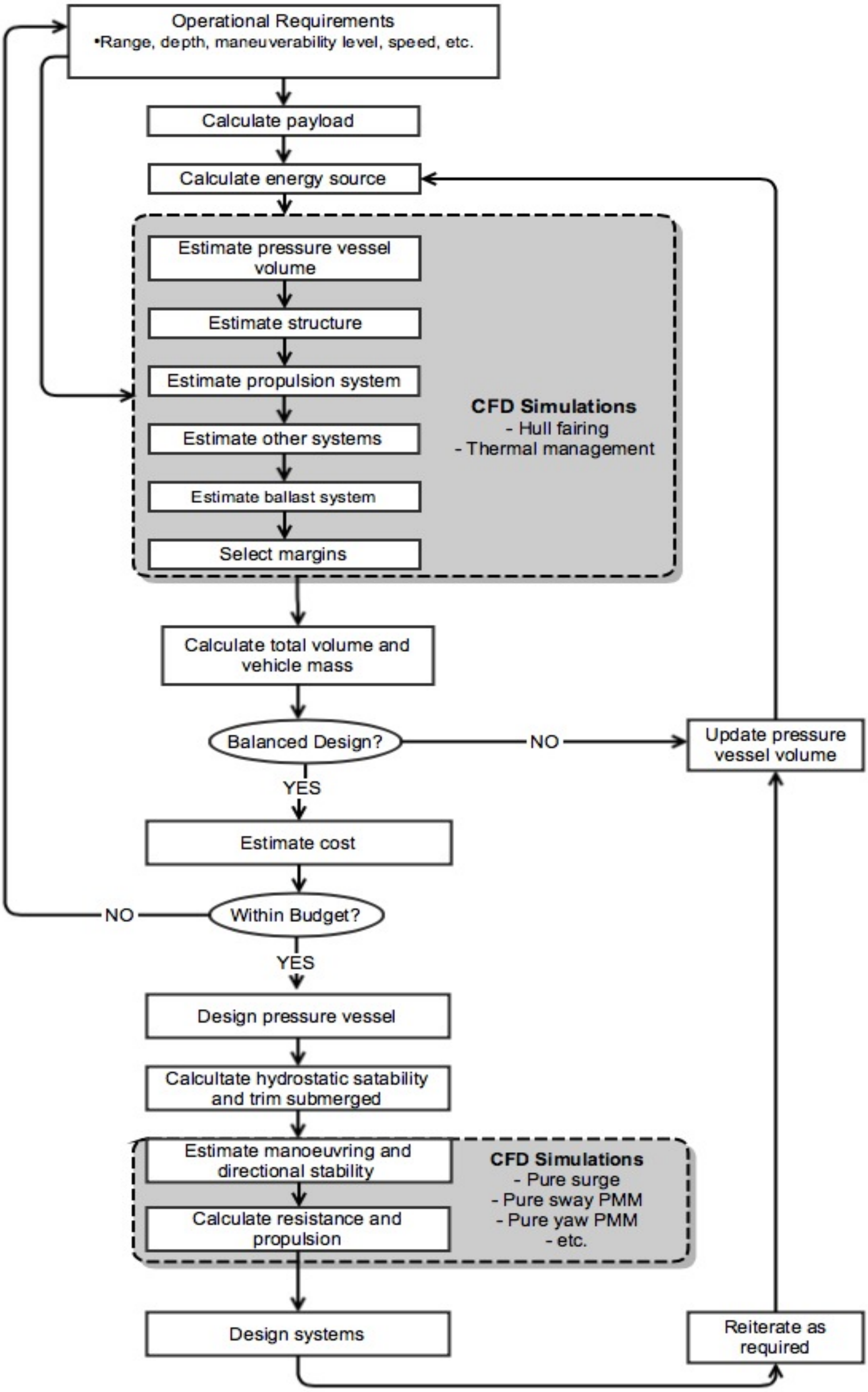


Figure 21: AUV design process (derived from Phillips et al. 2009)

5 Utilization of CFD as a cost-efficient design tool

Computational Fluid Dynamics (CFD) contains powerful techniques with a wide range of physical modelling capabilities, which can be applied to various industrial application areas (Versteeg & Malalasekera 2007). For instance, aerodynamic simulation on cars to find the drag and lift coefficients, hydrodynamic modelling of ships to predict wave motion and pressure on the hull or to simulate the reaction flow in a gas turbine combustor.

Computational Fluid Dynamics, CFD can offer many great features and it is applicable to various technical problems. One of its greatest advantages is that instead of building prototypes or test products, the use of CFD can provide information of the performance of the product early in the design process. Making it possible to analyse the performance of different designs, without any physical product testing.

Today, CFD techniques are often an integral part of the design, R&D processes to achieve optimized products. The automotive, aerospace and shipbuilding industry extensively run CFD analysis on their designs to reduce drag forces, thus increasing the fuel efficiency and resolving environmental issues (Takamura & Saito 2010).

CFD analysis compared with experimental based methods, reveal some of its great value to fluid systems design. Instead of performing time consuming test in wind tunnels and build different prototypes. Car manufacturer can use CFD to analyse multiple design profiles and parameters in a short time interval, reducing lead times and total cost of new products. In very large system such as the shipbuilding industry, experimental testing is done with scaled down prototypes, which may underestimate the actual forces. However, CFD analysis has the capability to simulate large systems under a controlled environment, where accurate experimental testing would be very difficult or even impossible to perform. Furthermore, CFD analysis can provide useful information beyond normal operation limits and analyse under high-risk conditions. The cost of experiments greatly varies with the number of configurations tested and the quantity and quality of measurement data. While a CFD analysis can produce large amount of results in high level of details for different configuration at low costs. Although performing CFD appears to be very feasible, more frequently use by smaller companies are limited because of high computational requirements and insufficient amount of qualified people with the necessary knowledge to understand these complex codes (Versteeg & Malalasekera 2007).

In this thesis, CFD is used for a subsea application to simulate the hydrodynamic forces on an AUV and investigate the flow environment around the hull surface. The goal is to estimate the drag coefficients in order to assess the thrust requirements to move the vehicle at 1.5m/s and achieve operators desired range of the vehicle. Based on the simulation and analysis, an improvement design is suggested.

5.1 Numerical methods

Appendix A present basic theory behind the CFD code to provide an insight to how the numerical simulation are used to solve and analyse problems that involve fluid flows.

In order to solve all the partial differential equations that describe the application, a discretization method such as the Finite Method (FVM) can be used. The method can obtain an approximate solution of the flow, by integrating the governing equations over small control volumes in space and/or time.
The sizes of the control volumes are specified in the grid generation and greatly affect the quality of the solution. Finer grid distribution, result in higher accuracy. Thus, in order to obtain realistic results numerically, the discretization process becomes very comprehensive and requires CFD programs.
The result of the discretization process is a system of algebraic equations, which can be solved by the computer. This can be done with the Tri-Diagonal Matrix Algorithm (TDMA), which is a technique that can solve higher dimensional sets

of equations iteratively. It uses the method of forward elimination and back substitution. (Versteeg & Malalasekera 2007).

5.2 Software

In this thesis, OpenFOAM is used to perform CFD analysis. It is an open source, Linux based, CFD software package. Since it is free, it offers great economical advantages to smaller companies as the cost of computational power reduces. The OpenFOAM software package does not include any graphical user interface. In order to build a case, input parameters can be specified in text files called dictionaries and a basic file structure of a case include:

System

- **controlDict** contain run control parameters such as start time, end time and time step.
- **fvSchemes** contain the discretisation schemes.
- **fvSolution** contain equations solvers, tolerances, etc.

Constant

- **transportProperties** contain specific physical properties of the case
- **polyMesh** contain specifications for the case mesh

"0"

- "0", is the initializing "time" directory if the case starts at t=0. It contains initial values and boundary conditions. Further "time" directories represents the simulated time and contain the result written to file by OpenFOAM (Nabla Ltd., 2007).

5.3 Pre-processing

The purpose of the analysis is to calculate the thrust force required to move the AUV at 1,5 m/s and evaluate additional hydrodynamic forces acting on the AUV.

The design of the AUV is derived from the work done by UiS Subsea. The AUV geometry is 0.26m high, 0.754m wide and 0.76m long and was created in Autodesk Inventor, and exported as an STL file.

An open source program called HelyxOS, which offers a Graphical user interface for OpenFOAM is used for setting up the case. HelyxOS uses snappyHexMesh to create detailed meshes.

5.3.1 Mesh generation

First, the base mesh at "level 0" is specified and created by blockMesh. The base mesh is a 2.0x1.2x4.5m-bounding box that can be considered as a section from the sea bottom or a test water pool, depending on the boundary condition. The six faces of this rectangle will define the patches inlet, outlet, side1, and side2, top and ground walls. The volume is split into 11844 regular hexahedron cells (21x12x47), resulting in 1mm^3 cell volume, as shown in the formula 19.

$$\frac{2 * 1,2 * 4,5}{21 * 12 * 47} m^3 = \frac{10,8}{11844} m^3 \approx 1mm^3 \qquad (4)$$

The STL file of the geometry is then imported into the base mesh and will define the AUV Patch.

Further refinements are added to the STL surface and the volume around, to improve the result. HelyxOS uses snappyHexMesh to refine the base mesh by splitting the initial block cells. Figure 22 show how the mesh has been refined at different distances from the STL surface.

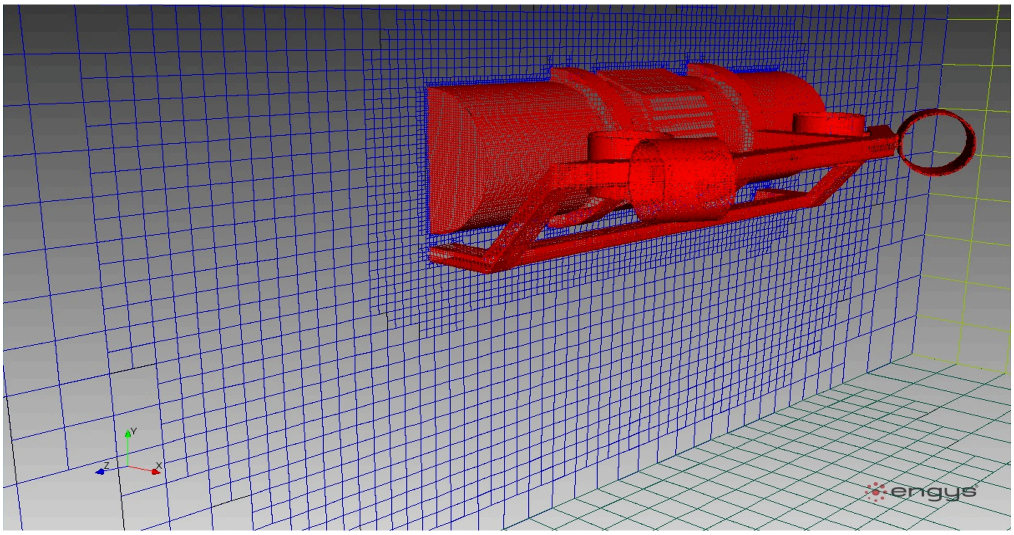


Figure 22: Base and AUV mesh

Settings for the volumetric refinements at different distances from the STL surface can be found in figure 23. The cell volume at "level 5", closet to the STL surface is 0.003mm^3, which should capture a good quality of the flow near the STL surface. An extra volumetric refinement box at "level 2" is added to give a better result of the flow further behind the STL surface.

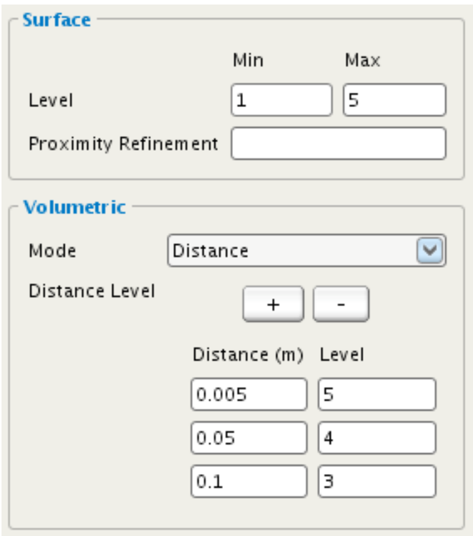


Figure 23: Settings for surface and volumetric refinements

Figure 23 show also the surface refinement, which is set to minimum "level 1" and maximum "level 5" to efficiently capture surface features. This can be seen in the figure 24, where cells on the surface of the STL have different sizes.

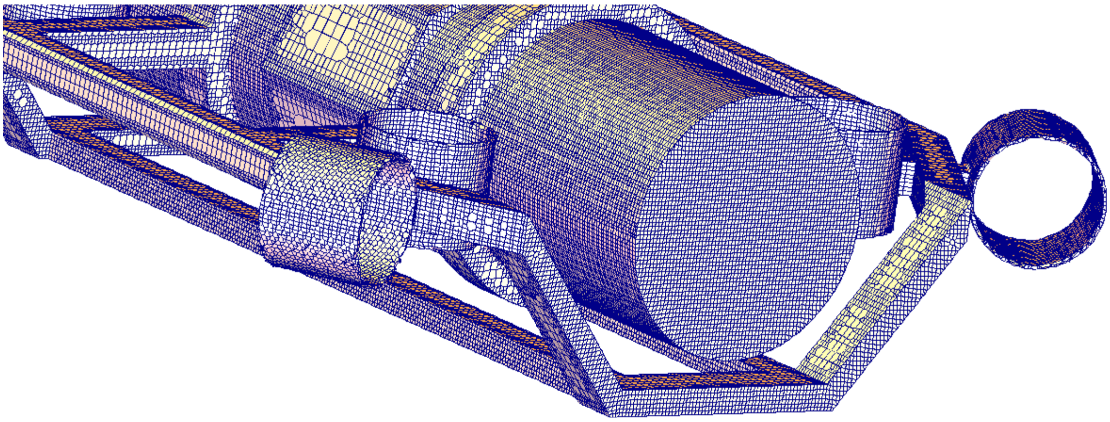


Figure 24: AUV mesh

The complete generated mesh consists of 1,11 million cells, with defined boundary patches shown in figure 25.

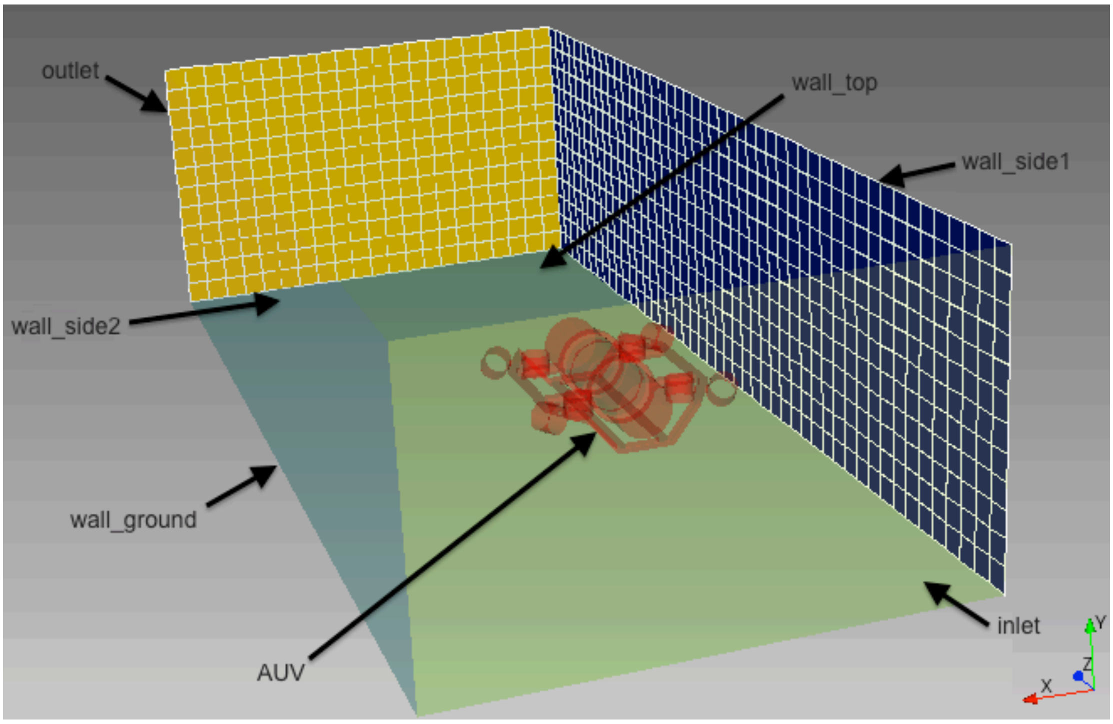


Figure 25: Defined boundary patches

5.3.2 Solver setup

This case is studied under a steady-state simulation and the flow is assumed to be incompressible. In OpenFoam the simpleFoam solver is chosen with k- ω SST turbulence model. In order to solve the CFD problem, initial and boundary conditions are required. They should define the flow condition that the AUV would experience underwater, moving at 1,5m/s over the seabed.

Table 10 show an overview of the patches and some of their properties.

Table 10: Patches and some of their properties

Name:	Patch type:	Boundary type:	
inlet	Inlet	See Table 11	
outlet	Outlet	See Table 11	
wall_side1	Wall	Fixed-wall	Slip
wall_side2	Wall	Fixed-wall	Slip
wall_top	Wall	Fixed-wall	Slip
wall_ground	Wall	Moving-wall	1,5 m/s – in +Z direction
AUVok1	Wall	Fixed-wall	No-Slip

Table 11: Inlet and outlet properties

Boundary:	Boundary type:			
	U	P	k	ω
inlet	fixedValue	zeroGradient	turbulent-Intensity-KineticEnergy-Inlet	turbulentMixing-LengthFrequency-Inlet
outlet	inletOutlet	fixedValue	inletOutlet	inletOutlet

The fluid velocity for the inlet boundary conditions is assumed constant and set to a fixed velocity U= (0, 0, 1.5) m/s.

For incompressible flow where the velocity is given, the inlet boundary condition for pressure is set to zero gradient for consistency (Nabla Ltd., 2014).

Since this is an outline design calculation, there are no measured inlet values of k and ω. They are instead defined with a rough approximation based on turbulence intensity (T_i) and a specific mixing length (L). The turbulence intensity (T_i) is set to 1% and the mixing length (L) is set 0,084 (7% of the water pool height) (Versteeg & Malalasekera 2007). The turbulent kinetic energy (k) and turbulence specific dissipation (ω) are then derived from eq. 5 and eq. 6:

$$k = \frac{2}{3}(U_{ref} * T_i)^2 \quad (5)$$

$$\omega = \frac{k^{0.5}}{C_\mu^{0.25}\, L} \quad (6)$$

The coefficient C_μ=0.09 (OpenFOAM, 2014)
Outlet boundary conditions are mostly defined by inletOutlet, which basically defines the boundary condition as a fixed value if the flux is pointing inwards, or zeroGradient if the flux is pointing outwards. (Höpken J., 2014)
Outlet boundary condition for pressure is defined by a fixed value p = 0 Pa.

Wall boundary conditions for U is set to slip, except for the AUV and gound-wall. Slip condition enables flow to pass along the walls. The no-slip boundary condition for the AUV defines the flow velocity as fixed value to zero in all directions (Ekedahl E., 2008). The ground wall is set to a moving wall in 1.5 m/s in positive z direction, to simulate the relative moving seafloor at the same speed as the AUV.
Seawater density is set to 1027,3 kg/m^3, with salinity of 35 psu at 100m depths. Further information is interpolated from seawater properties tables published by MIT University, and can be found in Appendix C (transportPropeties).

5.4 Post-processing

The post-processing is performed in the terminal with OpenFoam commandos and ParaView 4.1.0(Figure 26). These tools process numerical results and present data in a more convenient way for analysis.
Figure 26 shows the front projection area (A≈0.0815m^2) of the AUV design.

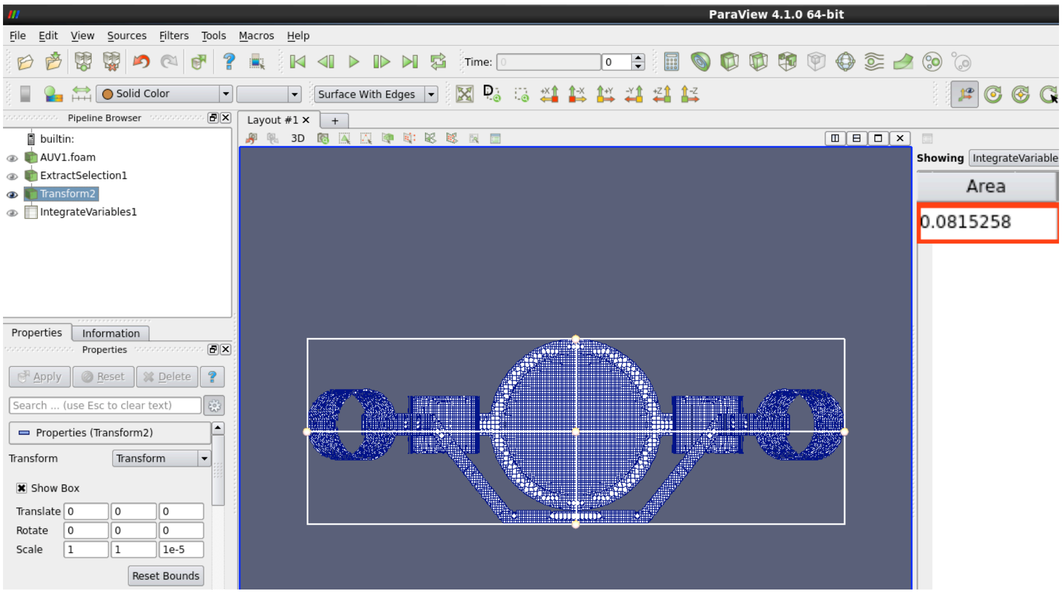


Figure 26: Front projecting area of the AUV

The hull surface shear stress of the last time step is computed with OpenFoam, by running the commando *"wallSearStress –latestTime"* in the terminal.

5.5 Result

Wall shear stress and static pressure are significant factors for an efficient movement. When the AUV moves through water, development of negative pressure gradients and turbulent zones may occur around the hull, due to a separation of the boundary layer may. Practically in areas where the hull shape is non-uniform or presents complex surface shape such as sharp edges, curves and aft of the vehicle, as shown in Figure 27.

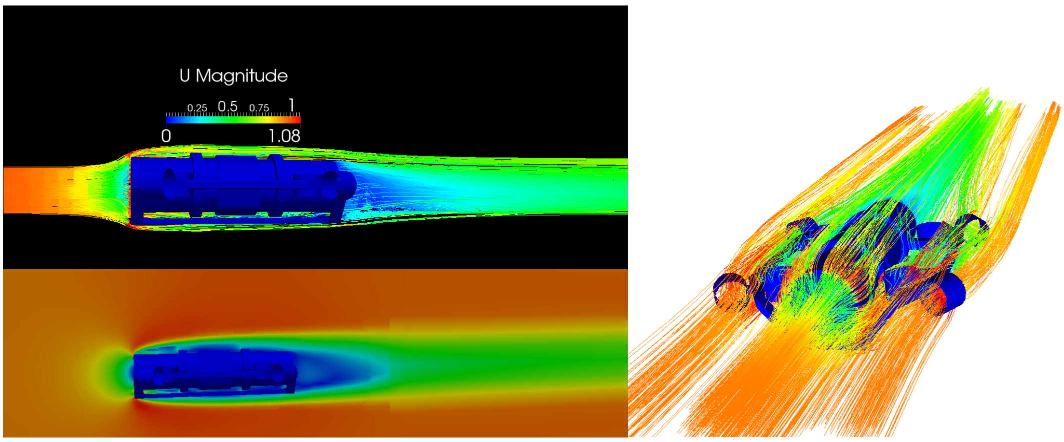


Figure 27: Streamline patterns and separation zone of the boundary layer

Figure 28 show a turbulent zone behind the vehicle and eddies that occur due to separation of the boundary layer. The separation is induced by the disk back-geometry that prevents the flow to recover in the rear part of the hull, which result in larger pressure drag. An effort should be made to minimize this turbulent zone.

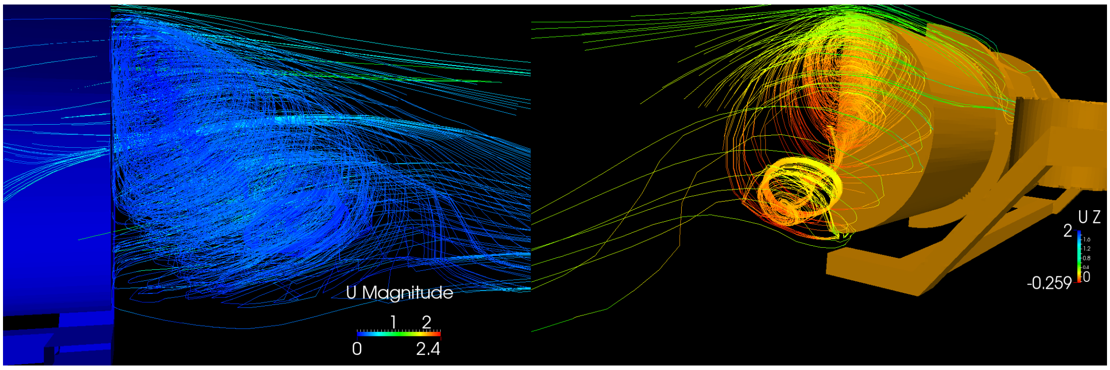


Figure 28: Turbulent zones aft of the vehicle

The surface shear stress distribution on the hull is presented in Figure 29. Higher wall shear stress can be observed where the body shape presents complex surface geometries, such as sharp edges the front and back disk and on skew nozzles faces. These high shear stress zones contribute to excessive skin friction coefficient shown in figure 30.

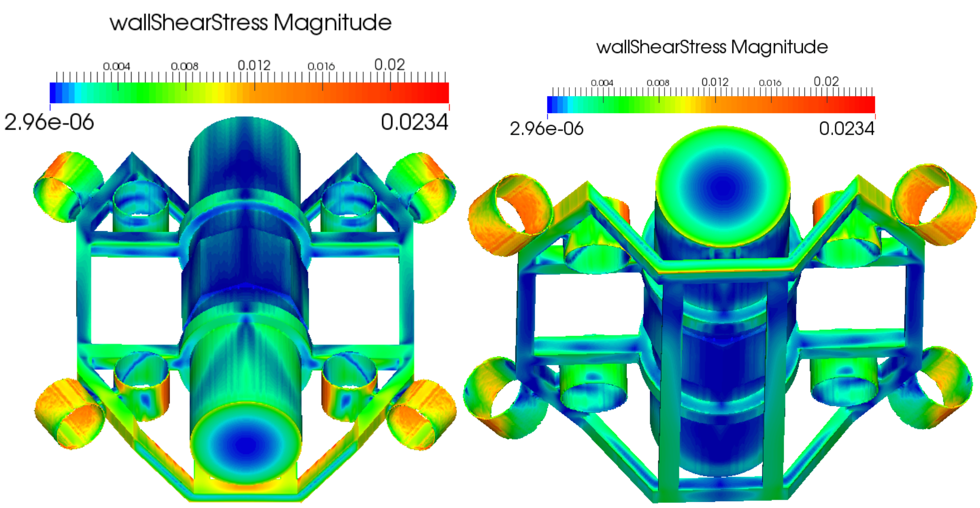


Figure 29: Top-fore (Left) and bottom-aft (Right) view of the wall shear stress distribution on the AUV hull

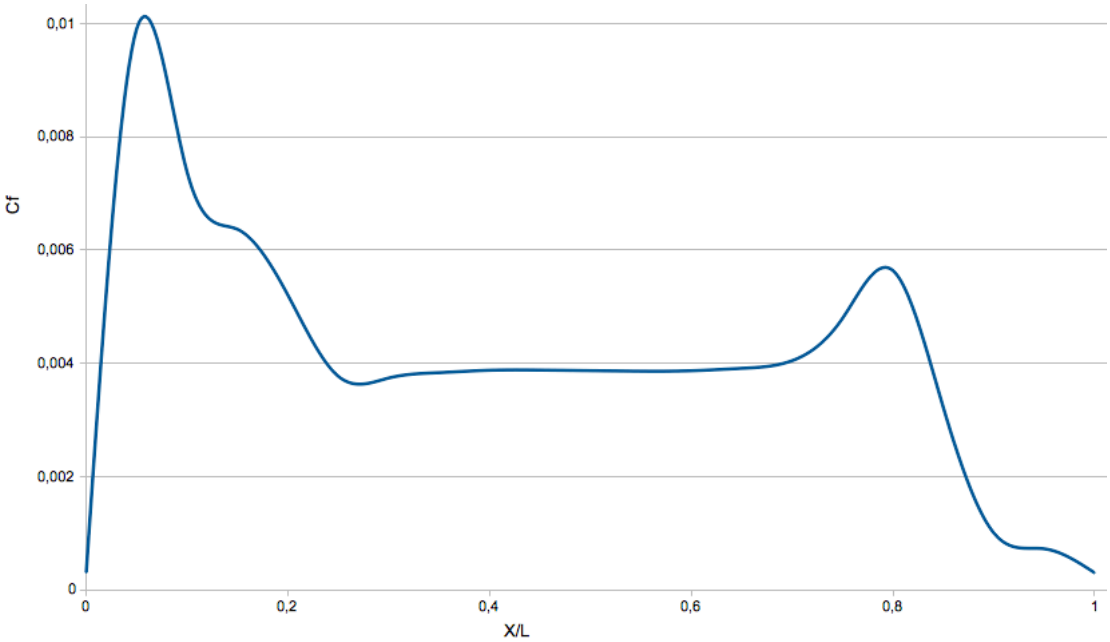


Figure 30: Longitudinal distribution of skin friction (C_f) coefficient

Figure 31 shows the pressure field on the AUV hull. One may observe negative pressure gradients in areas behind sharp edges and curves, which confirms separation of the boundary layer in these zones. These undesirable pressure differences will induce drag force.

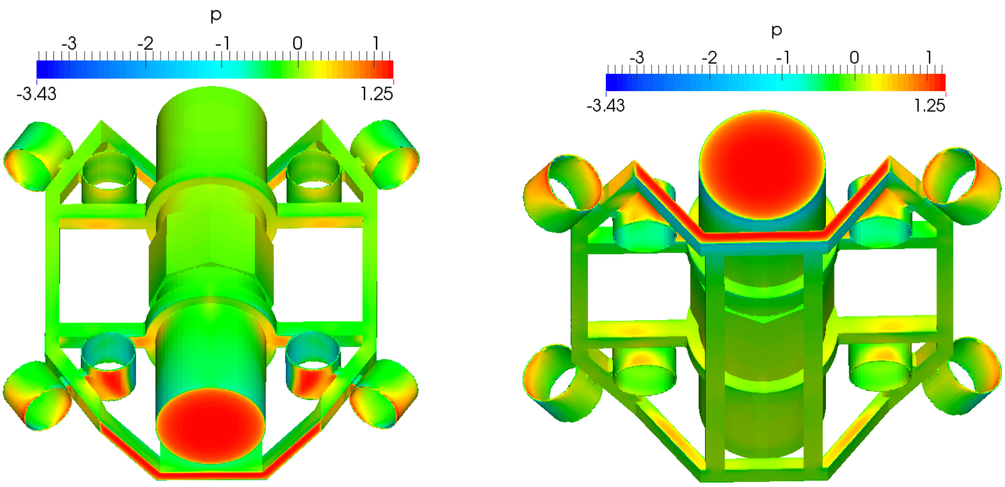


Figure 31: Top-fore (left) and bottom-fore view of the pressure field on the AUV hull

Pressure gradients observed between different zones on the hull (Figure 32) generates a drag force that act perpendicular to the hull surface, which slows down the vehicle movement. Flow separations occur in the religion after high pressure is observed, such as in front of the vehicle and the pressure decreases sharply. An effort should be made to even these rapid negative pressure gradients.

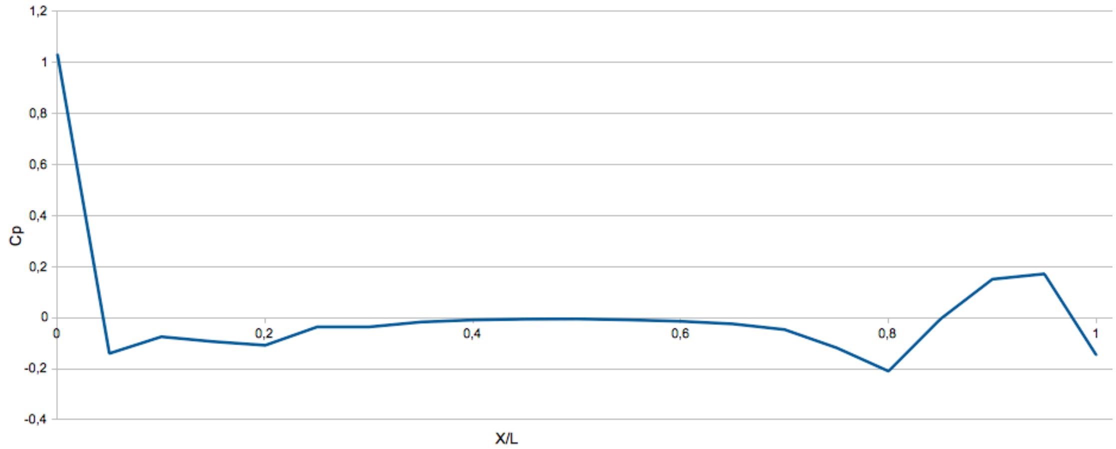


Figure 32: Longitudinal distribution of pressure (Cd) coefficient

5.5.1 Drag and thrust estimate

Figure 33 show the simulated total drag coefficient versus accumulated time steps. One may observe the simulation is stabilizing after 200 iterations with a drag coefficient of Cd=1.1 (Figure 34)

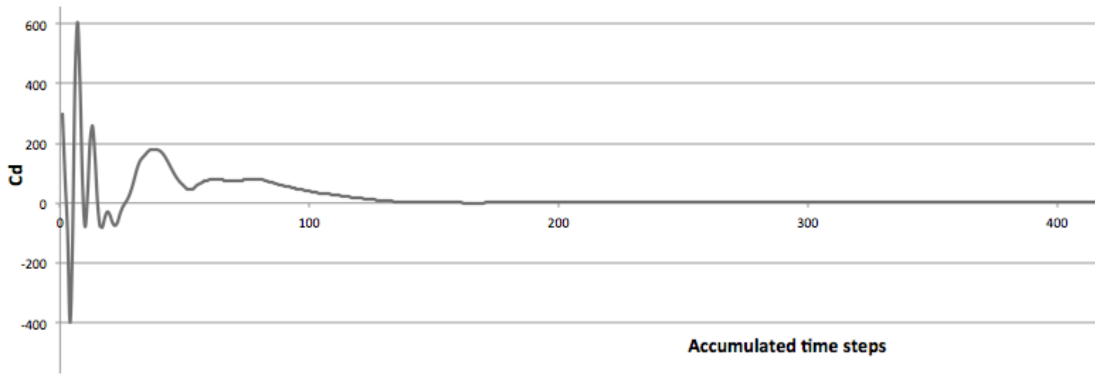


Figure 33: Total drag coefficient versus accumulated time steps

It is now possible to calculate the drag force using the drag coefficient from the simulation:

$$F_D = 0.5\rho C_d A v^2 = \mathbf{103.6N} = 10{,}56 \text{ kg force} \qquad (7)$$

$$\textit{Where, } \rho = 1027.3\frac{kg}{m^3},\ C_d = 1.1\ \ A = 0.0815m^2,\ v = 1.5\frac{m}{s}$$

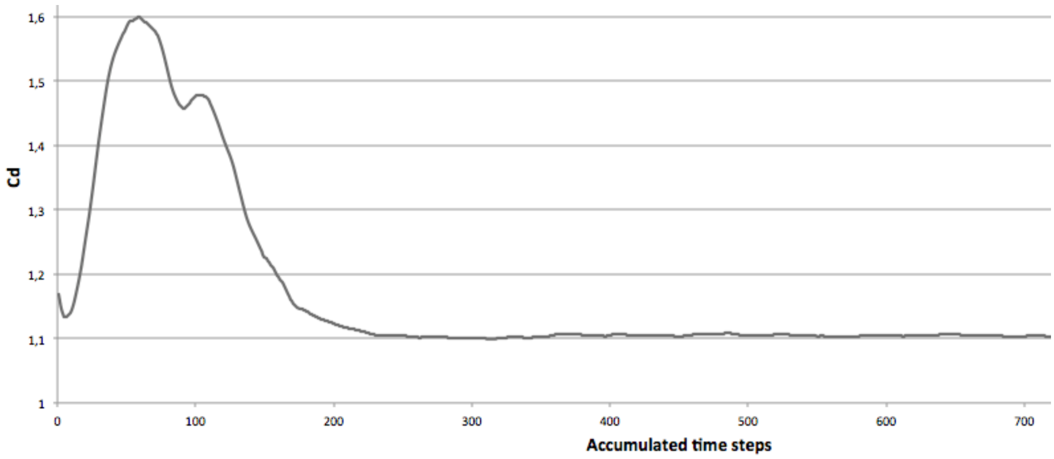


Figure 34: Total drag coefficient versus accumulated time steps

Based on the force coefficient extracted from the simulation, the AUV will have a drag force of 10,6kg when moving in seawater at 1.5m/s. This AUV design must therefore be equipped with a propulsion system that can produce at least 10,6 kg thrust at 1.5m/s. Thrusters, propellers and other propulsion systems experience a thrust degradation or loss as they move faster and faster in water. Thrusters for underwater vehicles are often designed to produce maximum thrust at Bollard. Thrust at Bollard is the conventional measure of for the push or pull power exerted by a stationary thruster. Practical measurement tests are performed in stationary water, and it may require multiple prototypes to find the optimal size and shape of the propellers. CFD simulation can be used for more cost-efficient testing of different propel sizes and shapes. CFD simulation also allow for consistent testing in more realistic conditions.

Required thrust estimates must consider the loss factor for thrusters as the AUV move trough the water. It is assumed a 20% performance drop of the maximum Bollard thrust for every 1m/s. Thus the AUV with a 10,6kg of drag moving in 1.5m/s through the water require thrusters with a Bollard thrust of:

$$F_B = \frac{F_D}{0.9^v} = \frac{\mathbf{10.56}}{\mathbf{0.9^{1.5}}} = 12{,}37 \text{ kg of Bollard thrust} \qquad (8)$$

Since the four horizontal thrusters (k=4) are angled with 30° in the horizontal plane (Figure 35), the required Bollard thrust for each thruster is:

$$F_T = \frac{F_B}{k*Cos(\alpha)} = \frac{12.37}{4*Cos(30)} = 3.57 \text{ kgf } = \mathbf{7.87lbf} \qquad (9)$$

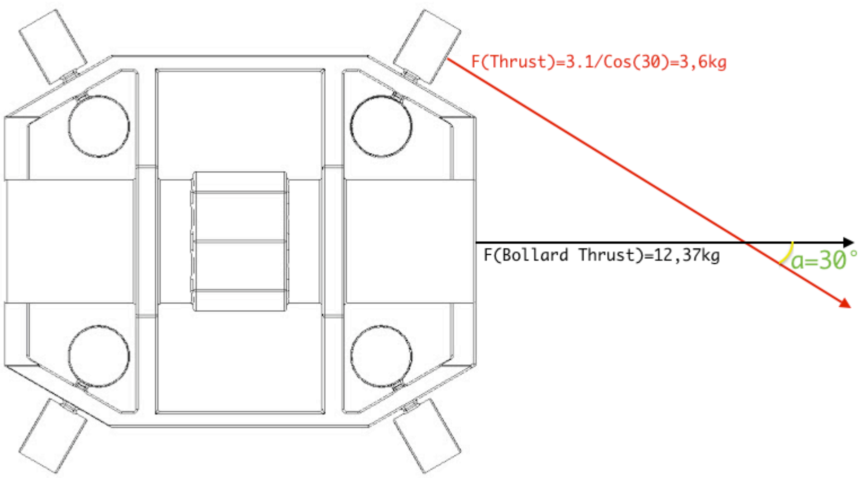


Figure 35: Angled horizontal thrusters

The Tecnadyne thruster model 150 with 5.4kg Bollard thrust forward, may be a suitable choice. The thrust performance of this thuster in Figure 36, show the input power (P_e =4*195Watts) while producing 7.87lbf with four propeller 1950 RPM, while moving at 1.5m/s. This confirms the assumption of 10% thrust degradation per knot speed reasonable and this thruster is suitable.

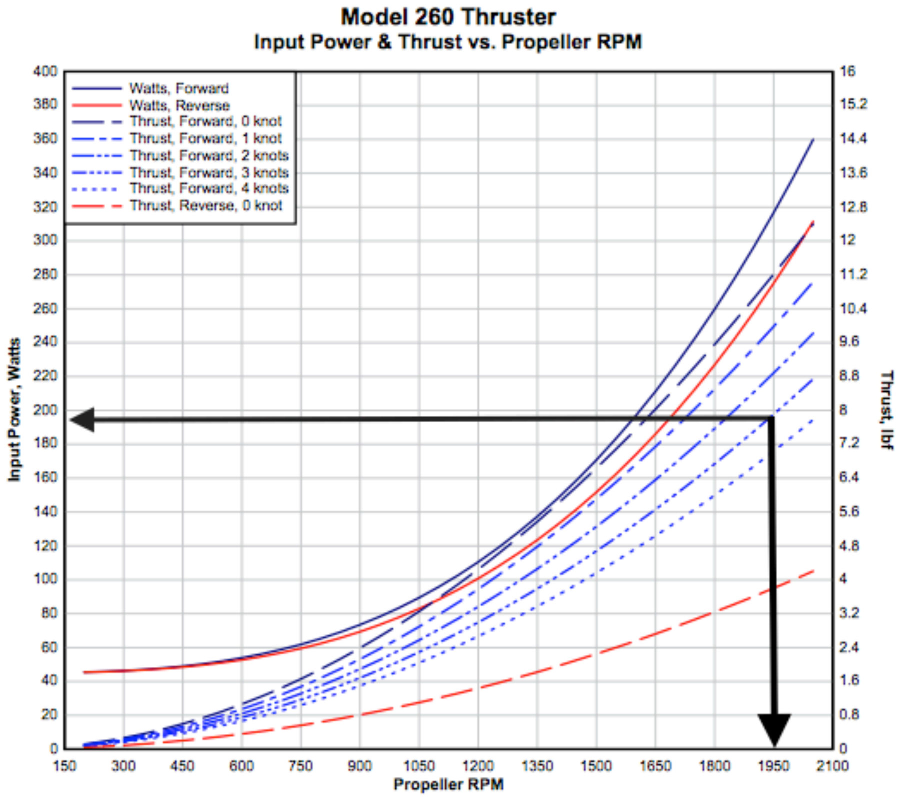


Figure 36: Tecnadyne Model 260 thrust performance curve (Tecnadyne 2015)

A hotel load (P_h =250 watts) and battery capacity (B =3000 watt-hour) is assumed in order to calculate a rough estimate for endurance of the AUV:

$$Endurance = \frac{B}{(P_e+P_h)} = \frac{\mathbf{3000}}{((\mathbf{195*4})+\mathbf{250})} = \mathbf{2.9\ hours} \tag{10}$$

$$Range = Endurance * Speed = 2.9h * 1.5\frac{m}{s} = \mathbf{15.7km} \tag{11}$$

5.6 Summary and derived optimized design results

The initial AUV design has an endurance of 2.9 hours and a range of 15.7km at 1.5m/s. This means that the AUV can travel a distance of 7km and then return to the recharge station. The result is consistent with operators desired range for this inspection system, but with limited spare capacity of only 0.7km. Additional protruding sensors and other equipment will also induce higher drag force on the hull, which requires higher safety factors, iterations and simulations to meet the realistic drag coefficient. Other changes such as hotel load, battery capacity and thrusters will also further adjust the result.

Simulation of this design revealed strong negative and positive pressure gradients along the hull surface, which occur from flow separation and turbulent zones near sharp edges and curves. Theses pressure differences should be minimized and distributed more evenly along the hull. A more efficient design is suggested in figure 37, as part of the iterative hydrodynamic optimization process.

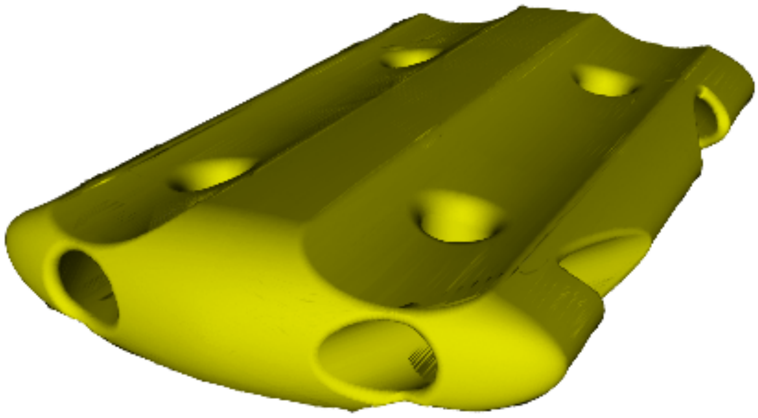


Figure 37: Optimized AUV design

A new simulation performed based on the new optimized AUV design. The same parameters where used as the previous simulation. The mesh counted 2.2 million cells. Further information about the simulation set-up and run time control can be found in the previous section and Appendix C.

The simulated drag force coefficient (C_{dnew}=0.38) for this new design showed major improvement at form the initial design (C_d=1.1). With this reduced drag coefficient the total required bollard drag from one thruster is:

$$F_{Dnew} = 0.5\rho C_d A v^2 = \mathbf{50N} \approx 5 \text{ kg force} \quad (12)$$

$$Where,\ \rho = 1027.3\frac{kg}{m^3},\ C_{dnew} = 0.38\ \ A(new) = 0.11m^2,\ v = 1.5\frac{m}{s}$$

$$F_{Bnew} = \frac{F_{Dnew}}{0.9^{v}} = \frac{\mathbf{5}}{\mathbf{0.9^{1.5}}} = 5{,}9 \text{ kg of Bollard thrust} \tag{13}$$

$$F_{Tnew} = \frac{F_{Bnew}}{k * Cos(\alpha)} = \frac{5{,}9}{4 * Cos(30)} = 1.7 \text{ kgf} = \mathbf{3.75lbf} \tag{14}$$

The same thrusters are used, as on the previous section. From figure 36 the thurster power input can be find for vehicle speed of 1.5m/s and 3.75lbf is 90watts. The endurance and range for the same hotel load (P_h =250 watts) and battery capacity (B =3000 watt-hour) is then:

$$Endurance = \frac{B}{(P_e + P_h)} = \frac{\mathbf{3000}}{((\mathbf{90} * \mathbf{4}) + \mathbf{250})} = \mathbf{4.9\ hours} \tag{15}$$

$$Range = Endurance * Speed = 4.9h * 1.5\frac{m}{s} = \mathbf{26.6km} \tag{16}$$

With the new drag optimized AUV design, the AUV can now travel 13.3km and then return to the recharge station. This is concurring with operators range requirements and sufficient spare capacity.

An improvement of 69 % in operational range was achieved with the new design through this optimization process.

5.7 Discussion

These simulations are performed with the simplest upwind scheme possible, the first-order upwind scheme. This means that upon discretisation of the governing equations, numerical diffusion easily occurs as a numerical roundoff. This is similar to the concept of how diffusion works in fluids. Instead a second order upwind scheme should be used to reduce numerical diffusion. Second order upwind scheme requires more process power.

The snappyHexMesh refinement process used to create detailed meshes for these simulations is limited by available random-access memory and process power of the author's student laptop. Higher mesh size for snappyHexMEsh should be used to achieve better results. blockMesh may provide a more a efficient mesh, with lower mesh size requirements as it allows more opportunities for users to define suitable mesh refinements in specific regions.

Although these simulations may lack of accuracy due to limitation of the author´s laptop computer, they clearly prove the concept of utilization computational fluid dynamics as a cost efficient design tool.

6 Organizational opportunities

In this high-risk industry, reliability is one of the main concerns. Thus it is vital to continuously monitor and inspect subsea systems to ensure the integrity of the system throughout the entire lifecycle of subsea equipment. With even more remotely operated O&G fields, it is becoming more challenging to successfully implement new and improved integrity monitoring or leak detection systems. John G. Bomba at the MT Society conference in 2014 pointed out some of the organizational challenges that have been identified in previous subsea monitoring projects. Implying that past experience and solutions show that improvement should especially be considered for contracting, reliability, deployment, accessibility and utilization of data.

- **Contracting**

One of the subjects was to ensure higher reliability and more cost-effective solutions for contracting. Past projects have been contracted as a complete package, which has limited the owner's influence on the configuration and qualification testing. The practices of monitoring vendors could be more motivating by better incentivize for long-term reliability.

- **Reliability**

Reliability requirements should be provided to vendors more efficient and well defined. Vendors should improve their quality systems, in order to stimulate efficient and sustainable utilization of their resources.
Monitoring systems are often designed with custom components and configurations. More standard available equipment can provide more robust and flexible systems with higher availability.

- **Deployment**

Design teams should increase their consideration of the deployment phase by including installation team, to ensure better contingencies for damages related to installation. More cost-efficient and reliable solutions for in-service quality assurance of equipment are needed.
In order for the equipment to sustain more remote operational environment, improved marinisation is needed. For all the different sensing technologies and solutions available, there has been a lack of sensing quality and system integration. More sufficient management plans to account for measurement uncertainties are needed to minimize false alarms and provide more accurate sensing information.

- **Accessibility and Utilization of Data**

The subsea industry has experienced false alarms and undetected fault, which require improved monitoring system health management. The monitoring system can be better managed by integrating it into the inspection and monitoring strategy, thus more efficient planning of maintenance. Installed monitoring systems produce huge amount of measurement data. More comprehensive barrier analysis should be carried out to exploit the potential of measurement information. Poor data analysis and utilization has resulted in valuable data not being made available in a useful way, underutilized or lost. This can be improved by better qualification of measurement data and analysis.

- **Integrated operations**

Oil and gas industry in Norway have experienced major changes in the last year. Statoil recognized excessive cost issues on the NCS due to previous high oil price and activity resulted in rapid growth with creeping inefficiency. They have demanded cost reductions and initiated several joint improvement agendas to increase efficiency and cut costs. How Statoil interact with service providers and vendors is one of many bottlenecks that have been identified. It has led to a closer integration of service companies and subcontractors into Statoil's organization, to allow for better resource management and time control. While more standardized operations with requirements for more frequently follow-up and reporting may improve collaboration and efficiency of operations. It may also enable new methods of conducting operations and led to breakthrough of new technology to performing tasks such as integrated inspection and monitoring solutions. Which in turn can reduce time and money spent on expensive support vessels and onsite personnel.

- **Simple, while but still robust solutions**

High oil prices may have led the industry to invest in "amazing" technology and equipment, which later suggested that they could have managed without, but at the time tempted with higher, more robust and reliable performance. However the first generation of subsea production systems presented several faults and lack of utilizing the collected data. Hence, a collective understanding of the principle called KISS "Keep it Stupid Simple" have emerged and resulted in operators crossing out several requirements and demands on vendor´s lists. Instead of working through cumbersome procedures, integrated operations and closer collaboration may be the ultimate solution in response to vendor's discontent of Statoil´s many special rules and requirements. And at the time giving more confidence to subcontractor's competence in order to further reduce costs and achieve more cost-efficient solutions.

- **Do it right the first time to avoid future unexpected expenses**

Operators have learned that shortcuts, poor decisions without considering the life cycle cost and future requirement has led to major modifications costs in the NCS. It may suggest why the industry today use larger amounts of engineering hours in offshore projects, since operators now prioritize to do it right the first time to avoid future unexpected costs. While offshore field developments are becoming more challenging and require more complex solutions, it has also led to more engineering hours to ensure that the projects do not awry before it even starts. However, new and enhanced software, and hardware can provide efficient tools to meet the increased demanding engineer work with computer simulation and modelling capability to ensure that it is done right the first time.

The oil and gas industry in Norway has proven that with a collective effort they have been capable of achieving good results with its excellent low HSE statistics of serious accidents. Today, the industry must reduce costs, while continuing to ensure safe operations to allow for further field developments in more exposed and sensitive environments.

7 Conclusion

The challenges were to address controlled change over time more reliable and cost effective. This has been achieved through the paper evaluation and recommendations within each subject. Added up it contributes to further cost efficient methods, models and design of underwater vehicles is both valuable and interesting.

Subsea inspection and monitoring was the main focus area in search for improvements and opportunities. The paper has covered some of the challenges, available methods and involved design evaluations of cost-efficient solutions.

Further findings, statements and recommendation within each topic are as follows:

- *Maintenance strategy and planning*

Maintenance strategy and planning are essential to avoid expensive unplanned maintenance of subsea production systems. A suitable plan for inspection and maintenance intervals should reflect the probability of failures and anticipate degradation mechanisms. The bathtub curve provided an intuitive and simple illustration of observed failures in each operational phase for subsea production system. No preventive maintenance is recommended in the early failure period and the "useful life" phase, due to random and unpredicted failures. However, regular inspection and condition monitoring should be used for early detection of failure mechanisms, to allow for improved planning of maintenance activities. This means that repair or replacement can be performed in periods, more convenient for operators and sub-contractors such as in the spring or summer with calmer weathers. As the time past, subsea production systems are increasingly subjected to wear-out threats such as material degradation and structural fatigue. These hazards require more comprehensive inspection programmes, such as risk-based inspection performed by ROV or AUV. The goal is to successfully predicted failures in advance by monitoring the condition of subsea production systems and use measurement data to trend for timely inspection and maintenance activities. Preventive maintenance is recognized as a suitable maintenance strategy for components critical to operation with an increased probability of failure, where condition monitoring is either not feasible or economical. Predictive maintenance is the superior maintenance strategy, however it requires more resources and the cost frequently exceeds the benefits. Thus more cost-effective solutions to monitor and inspect subsea assets should be continuously looked-for.

- *Investigation into different technologies and challenges related to monitoring and inspection*
- *Evaluation and suggestion current available detection technologies used in subsea inspection and monitoring, their application, system requirements, function and limits.*
- *Investigate operational requirements and research how to utilize state-of-art tools to improve subsea condition monitoring.*
- *Extract features and benefits, by observing UiS Subsea and Stinger Technology AS efforts to develop remote and durable applications for subsea inspection and monitoring.*
- *Present opportunities for improved condition monitoring solution through a review and utilization of cutting edge technology.*

The conclusions for the above objectives are as follows:

To break the cost curve related to monitoring and inspection activities, more sophisticated and autonomous systems have been developed in recent years. In addition to increasing environmental incentives that push for development of improved leak detection systems. Sensors used to inspect or monitor subsea production systems, such as electromagnetic sensors and hydrophones provide impressive capabilities, but they also present significant limitations. However, together they can be used to determining load, torque and general performance of rotating equipment. An effort by innovative companies and collaboration across the industry, have augmented this revolutionary trend to combine different sensors to achieve better monitoring solution. Stinger´s permanently installed leak detection system is a great example of a pioneering solution that combines complementing technologies and sensors to further improve the ability for leak detection. Better algorithms for leak detection and autonomous recognition of gas plumes in acoustic pictures will further improve this method. Stinger´s commercial approach to utilize CFD techniques in order to enable positioning of leakage, may further provide a viable solution to complement other point sensors such as capacitors and biosensors. This approach should be further improved with more effective and faster simulations to allow further real-time detection. Computational process power is still a limiting factor, but with declining hardware prices along with the rapid growth of cheaper and more convenient cloud services, this limitation will soon be solved.

- *Investigation of key technological limitations and new developments within underwater communication, energy storage and wireless power transmission was performed*

The recognized design spiral methodology was used to evaluate the measure of merit. It led to recommended opportunities such as AUV recharging station on the seafloor for better utilization.

- *Design optimization process*
- *Analyse and simulate the hydrodynamic drag force acting on a new AUV design using computational fluid dynamics*

Numerical simulations of the initial AUV design revealed strong negative and positive pressure gradients along the hull surface, which occurred from the flow separation and turbulent zones near sharp edges and curves. These pressure differences were minimized and distributed more evenly along the hull. The result was a more efficient design. With the new drag optimized AUV design, the AUV can now travel 13.3km and then return to a recharge station. This concurred with chosen operators range requirements and gave excellent spare capacity. An improvement of 69 % in operational range with a new design was achieved through this optimization process. Further work should be to continue the design spiral to accomplish a better product.

Stinger´s innovative approach for resident ROV deployment was partly implemented in the design consideration in this paper. Both commercial operators and organizational support to UiS Subsea should be further developed and maintained to further stimulate study work of underwater vehicles. As with drones, the explosion in versatile use is expected to also affect underwater vehicles. Commercial AUV developer should be ready to capitalize this on coming growth. Military and environmental organizations are likely to piggyback into this evolution. In addition it like to assume that the military are secretly developing their own strategies, design and utilization of AUV even as a weapons. Perhaps military technology will also float back.

Throughout this thesis a cost-efficient and environmental though was kept evident and live.

Abbreviations

AUV - Autonomous underwater vehicle

CFD - Computational fluid dynamics

EM - Electromagnetic

HSE - Health, safety and environment

IM - Inspection and monitoring

IMR - Inspection, maintenance and repair

MROV - micro remotely operated vehicle

MTBF - Mean time before failure

NDT - Non-destructive testing

O&G - Oil and Gas

PdM - Predictive maintenance

RAMS - Reliability, availability, maintainability and serviceability

RF - Radio frequency

ROV - Remotely operated vehicle

SPS - Subsea production systems

References

Alam K., Ray T., Anavatti S. G. (2012), An Evolutionary Approach for the Design of Autonomous Underwater Vehicles, Published in AI 2012: Advances in Artificial Intelligence: 25th International Australasian Joint Conference, Sydney, Australia, December 4-7, 2012, p. 279-290

Ando K., A. Takamura, I. Saito, 2010, Retrieved 22. January 2015: <http://www.esteco.com/modefrontier/automotive-aerodynamic-design-exploration-employing-new-optimization-methodology-based>

Aven T. (2014) Reliability Analysis, Lecture notes University of Stavanger

BAE Systems, Autonomous Mine Disposal Vehicles, Retrieved 23 March 2015: <http://www.baesystems.com/what-we-do-rzz/products-&-services>

Barzegaran M. R., Mohammed O. A. (2014) Condition monitoring of electrical machines for extreme environments using electromagnetic stray fields, Florida International University, Published in Electrical Machines (ICEM), 2014 International Conference, 10.1109

BIOSwimmer, Boston Engineering, Retrieved 13. April 2015: <https://www.boston-engineering.com/impact/our-work/bioswimmer-2/>

Biota Guard, Bio sensor, Retrieved 13. April 2015: <http://www.biotaguard.no>

Bomba J. G. (2014) Mtsociety conference, Genesis, Retrieved 19. March 2015: <https://www.mtsociety.org/pdf/conferences/2014%20Subsea%20Leak%20Detection%20Symposium/14SLDS_Bomba_John.pdf>

Brundage H. (2010) Designing a wireless underwater optical communication system, M.Sc. Thesis, Massachusetts Institute of Technology

Campbell M. Loh T., Chediak M. (2015) Battery Hackers Are Building the Future in the Garage, Blommberg Business News, Retrieved 16. March 2015: <http://www.bloomberg.com/news/features/2015-03-11/battery-hackers-are-building-the-future-in-the-garage>

Che X., Wells I., Dickers G., Kear P., Gong X. (2010) Re-Evaluation of RF Electromagnetic Communication in Underwater Sensor Networks, Swansea Metropolitan University, Published in: Communications Magazine, IEEE (Volume: 48, Issue: 12)

CIRIA, CUR, CETMEF (2007) The Rock Manual. The use of rock in hydraulic engineering (second edition)

DNV (2010) SELECTION AND USE OF SUBSEA LEAK DETECTION SYSTEMS, RECOMMENDED PRACTICE DNV-RP-F302

DNV GL (2014) Subsea Facilities - Technology Developments, Incidents and Future Trends, Petroleumstilsynet, March 2014,

Dormer M. (2014) AUV–Global Market Prospects, Douglas Westwood, UUV OI London 13 March 2014

Eagle E. W., Walters D. F., Cadou C. P. (2012) System Modeling of a Novel Aluminum Fueled UUV Power System, American Institute of Aeronautics and Astronautics, March 12, 2015: <http://deepblue.lib.umich.edu/bitstream/handle/2027.42/97073/AIAA2012-1135.pdf?sequence=1>

EnergyOR, World First Fuel Cell Multirotor, Retrieved 12. March 2015: http://energyor.com

Evans J. (1959) Basic Design Concepts, Naval Engineers Journal

Ferziger J. H. ,Peric M. (2002) Computational methods for fluid dynamics(3rd Edition), Published by Springer, 2002.

Frantz F. (2014) World Record Flight Achieved Using 3DR Electronics and Tiger Rotors , DIY Drones, Retrieved 1. March 2015: <http://diydrones.com/profiles/blogs/world-record-flight-achieved-using-3dr-electronics-and-tiger>

Gale P. A., Slutsky J. (2014) Naval architecture, AccessScience McGraw-Hill Education

GE MCS (2013) GE Introduces Subsea Leak Detection and Multi-Domain Condition Monitoring, Retrieved 12. February 2015: <http://www.ge-mcs.com/de/news-and-press/76-press-releases/2967-ge-introduces-subsea-leak-detection-and-multi-domain-condition-monitoring.html>

Gopinath A. (2013) All About Transferring Power Wirelessly, EFYmag Online, Retrieved 15. February 2015: <http://www.efymagonline.com/pdf/52_Wireless%20Power%20Transfer_EFY%20August%202013.pdf>

Hecht J. (2006) PHOTONIC FRONTIERS: Photonic power delivery: Photonic power conversion delivers power via laser beams, Laser Focus World, Retrieved 12. February 2015: <http://www.laserfocusworld.com/articles/print/volume-42/issue-1/features/photonic-frontiers-photonic-power-delivery-photonic-power-conversion-delivers-power-via-laser-beams.html>

Hollister S. M. (1994), The Design Spiral for Computer-Aided Boat Design, N.A., P.E., Retrieved 12. April 2015: <http://www.newavesys.com/spiral.htm>

Howarth D., (2015) Ikea launches furniture that wirelessly charges smartphones and tablets, De Zeen Magazine, 1 March 2015

Hughes J. (2014) Inside the battery pack, Tesla Motors Club, Retrieved 3. April

2015: <http://www.teslamotorsclub.com/showthread.php/34934-Pics-Info-Inside-the-battery-pack>

Ingram A. (2012) Electric-Car Battery Costs To Decline To $200/kWh In 2020, Green Car Reports, Retrieved 4. April 2015: <http://www.greencarreports.com/news/1077804_electric-car-battery-costs-to-decline-to-200-kwh-in-2020-mckinsey-says>

Jelen F. C., Black J. H. (1983) Cost and Optimization Engineering, 3th ed. McGraw-Hill Book Company, p. 324

K. Ando, A. Takamura, I. Saito (2010) Automotive aerodynamic design exploration employing new optimization methodology based on CFD, Retrieved 9. March 2015: <http://www.esteco.com/modefrontier/automotive-aerodynamic-design-exploration-employing-new-optimization-methodology-based->

Kesler M., McCarthy C. (2013) Highly Resonant Wireless Power Transfer In Subsea Applica Tions, WiTricity White Paper, Retrieved 15. February 2015: <http://www.witricity.com/assets/HRWPT-in-Subsea-Applications.pdf>

Kok S. (2011) A multi-lag/multi-scale receiver for underwater acoustic communications, M.Sc. Thesis, Delft University of Technology

Marketnews, Selger Siem Daya 1 For Usd 120m, Retrieved 23. April 2015: <http://marketnews.dk/artikel/19/16429/selger_siem_daya_1_for_usd_120m.html>

McLean G., Collins A., (2013) Contactless Power Transfer for Recharging Underwater, WFS, www.wfs-tech.com

Mendez A., Leo J. T., Herreros M. A. (2014) Fuel cell power systems for autonomous underwater vehicles- state of the art, Universidad Politécnica de Madrid, 1st Int. Electron. Conf. Energies, 14–31 march 2014; Sciforum electronic conference series, vol. 1, 2014

Midtun (2011) Evaluation of hydro acoustic condition monitoring of subsea processing equipment, M.Sc. Thesis, University of Stavanger

Miller T. F., Walter J. L., Kiely D. H. (2002) A Next-Generation AUV Energy System Based on Aluminum-Seawater Combution, The Pennsylvania State University, Retrieved 23. March 2015: <http://www.tfd.chalmers.se/~valeri/Ajax/aluminum_combustion.pdf>

Miller T. (2015) Find, fix, identify, engage: how today's AUV technology can compress the mine warfare kill chain, Center for International Maritime Security, 3 June, 2015, Retrieved 3 June, 2015: <http://cimsec.org/find-fix-identify-engage-todays-auv-technology-can-compress-mine-warfare-kill-chain/16729>

Mills S. (2010), Understanding Maintenance Key Performance Indicators, AV

Technology, Retrieved 2. May 2015:
<http://www.avtechnology.co.uk/technical_files/tech_article_109.pdf>

Nabla Ltd. (2007) Retrieved 23. February 2015:
<http://www.foamcfd.org/Nabla/guides/UserGuidese11.html>

NAXYS, Leak detection and Condition Monitoring, Retrieved 23. January 2015:
<http://www.naxys.no/page/281/Condition_Monitoring>

NGI, Warning system for seabed gas leakage, Retrieved 26. January 2015:
<http://www.ngi.no/en/Contentboxes-and-structures/Main-page/Feature-articles-/Warning-system-for-seabed-gas-leakage/>

Oceaneering (2012) Underwater Services Rate Schedule, Retrieved 2. May 2015:
<http://www.oceaneering.com/oceandocuments/rates/2012_rov_oas.pdf>

Oceaneering, Retrieved 6. May 2015: <Oceaneering.com>

OceanWorks International, Retrieved 6. April 2015: <www.oceanworks.com>

Okray S., Cost Estimating Methods, Munro & Associates, Lean design, Retrieved 2. April 2015: <http://www.leandesign.com/pdf/Cost_Estimating_Methods.pdf>

OXIS Energy, Retrieved 8. March 2015:
<http://www.oxisenergy.com/technology>

Parodi B. B. (2014) A Deep Dive into the Subsea Environment, Retrieved 12. January 2015: <http://www.geglobalresearch.com/blog/deep-dive-subsea-environment>

Phillips A. B (2010) Simulations of a self propelled autonomous underwater vehicle, University of Southampton, School of Engineering Sciences, Doctoral Thesis

Phillips A. B., Turnock S. R., Furlong M. (2009) The use of computational fluid dynamics to aid cost-effective hydrodynamic design of autonomous underwater vehicles, Published by SAGE: *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment* November 1, 2010 vol. 224 no. 4 239-254

Qi Wireless Power Consortium, A Qi wireless charger: Resonant as well as Inductive, Retrieved 22. March 2015:
<http://www.wirelesspowerconsortium.com/technology/qi-wireless-charger-resonant-as-well-as-inductive.html>

QinetiQ, Advanced Batteries and Power Solutions, Retrieved 2. April 2015:
<http://www.qinetiq.com/services-products/maritime/research-systems/pages/power-sources.aspx>

Rhodes M. (2006) Underwater Electromagnetic Propagation: Re-evaluating Wireless Capabilities, Wireless Fibre Systems Ltd, Published by Hydro

INTERNATIONAL, 2006

Siemens, SINAVY PEM Fuel Cell for submarines, Retrieved 12. March 2015: <http://www.industry.siemens.com/verticals/global/de/marine/marineschiffe/energieverteilung/Documents/sinavy-pem-fuel-cell-en.pdf>

Snøfugl (2013) Undervannsfarkost fant «svært spennende» anomalier på havbunnen utenfor Trondheim, Teknisk Ukeblad, 19 December 2013

Soares C. G. (2010) Safety and Reliability of Industrial Products, Systems and Structures, CRC Press, 2010

Stern Fred (2013) 57:020 Mechanics of Fluids and Transport Processes, College of Engineering, The University of Iowa, Retrieved 22. February 2015: <http://www.engineering.uiowa.edu/~fluids/>

Stinger Technology AS, Retrieved 22. January 2015: Stinger.no

Størkersen N. and Hasvold Ø. (2004) Power Sources for AUVs, Norwegian Defence Research Establishment (FFI), Retrieved 9. April 2015: <http://www.ffi.no/no/Publikasjoner/Documents/Power%20Sources%20for%20AUVs.pdf>

Tecnadyne, Thruster performance curve, Retrieved 8. May 2015: <http://www.tecnadyne.com/cms/index.php/products/products-overview/thruster>

University of Tokyo, URA Laborator, II, R-One Robot, Retrieved 18. February 2015: <http://underwater.iis.u-tokyo.ac.jp/robot/R1-T/R1-T2.html>

Uyiomendo E. E., Markeset T. (2010) Subsea Maintenance Service Delivery: Mapping Factors Influencing Scheduled Service Duration, University of Stavanger, Stavanger, International Journal of Automation and Computing, DOI: 10.1007/s11633-010-0167-7, May 2010

Valtchev S. S., Baikova E. N., Jorge L. R. (2012) Electromagnetic Field As The Wireless Transporter Of Energy, UNINOVA, Retrieved 4. April 2015: <http://www.doiserbia.nb.rs/img/doi/0353-3670/2012/0353-36701203171V.pdf>

Versteeg H.K., Malalasekera W. (2007) An introduction to computational fluid dynamics: The Finite Volume Method (2nd Edition), Published by Paperback, February 26, 2007

VideoRay (2015) VideoRay Pro 4 ROV Successfully Completes 19-Month Permanent Deployment in North Sea, Retrieved 23. May 2015: <http://www.videoray.com/news/press-releases/114-2015/763-stinger-seaquito-permanent-deployment.html#3097-web_StingerROV>

Voelcker J. (2015) Electric-Car Battery Costs Fell 8 Percent A Year For Market Leaders: Study, Green Car Reports, Retrieved 28. April 2015:

<http://www.greencarreports.com/news/109 7792_electric-car-battery-costs-fell-8-percent-a-year-for-market-leaders-study>

Watson P. (2013) UUV garages for in permanent infield monitoring/inspection of assets, Ocean Power Technologies Ltd, Retrieved 20. February 2015: <http://www.oceanologyinternational.com/__novadocuments/46791?v=635290239765330000>

Zoksimovski A., Sexton D., Stojanovic M., Rappaport C. (2012) Underwater Electromagnetic Communications Using Conduction–Channel Characterization, Published in: Proceeding WUWNet '12 Proceedings of the Seventh ACM International Conference on Underwater Networks and Systems Article No. 20, ACM New York, 2012

Appendix A

This theory are derived from H.K. Versteeg and W. Malalasekera, 2007.

1 The three main CFD code elements

CFD codes are structured around numerical algorithms and contain three main elements:

1. **Pre-processor**, where input information of the flow problem is establish. It involves defining the geometry of the computational domain, selecting grid sizes, mesh generation of cells, selecting the physical and chemical phenomena, describing fluid properties and specification of boundary conditions.
2. **Solver**, which utilizes a numerical solution technique such as the finite difference method. It involves integration of the governing equations, discretization (converting the integral equations into a system of algebraic equations) and solving these algebraic equations using iterative method.
3. **Post-processor** that present data graphically. It can include data visualization tools such as domain geometry and grid display, vector plots, line and shaded contour plots, surface plots, particle tracking, animation for dynamic result display, etc.

2 The governing equations

The continuity, momentum and energy equations are used to analyse the physical behaviour of fluids. They are based on the three fundamental physical principles:

- Conservation of mass
- Conservation of momentum (Newton´s second law)
- Conservation of energy (First law of thermodynamics)

By using these principles and considering the changes of fluid in an infinitesimal element, the Navier-Stokes equations can be derived as a system of partial differential equations. Together these equations can describe the motion of a fluid in three dimensions and include the eight unknown dependent variables:

- ρ – Density
- p – Pressure
- u ,v, w – Velocity components in x, y and z direction
- T – Temperature
- μ – Viscosity
- k – Heat conductivity

Thus, eight equations are needed to find a solution.

In special cases, there are assumptions that can simplify these equations, such as steady-state and incompressible flow. The flow of interest can be studied as time-invariant, thus a steady-state solution of the Navier-Stokes equations are derived. For Mach numbers less than 0.3, the fluid flow can be considered as incompressible. (Stern 2013)

$$Ma = \frac{v}{c} \tag{17}$$

Where v is the local flow velocity and c is the speed of sound.

For an incompressible flow, the density of mass per unit volume is constant in time, thus:

$$\frac{d\rho}{dt} = 0 \tag{18}$$

2.1 Conservation of mass in three dimensions

The unsteady and compressible continuity equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=\frac{\partial \rho}{\partial t}+div(\rho \boldsymbol{u})=0 \qquad (19)$$

Where **u** is the flow velocity written in a Cartesian co-ordinate system, with x-component u, y- component v and z component w.

With the assumption of steady-state and incompressible flow, the eq. 19 is reduced to:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=div\,\boldsymbol{u}=0 \qquad (20)$$

2.2 Momentum equation in three dimensions

Newton´s second law is used to describe that the sum of forces acting on an infinitesimal fluid element, are equal to the rate of increase of momentum of the fluid element. This gives the momentum equation.

The *x*-component of the momentum equation:

$$\rho\frac{Du}{Dt}=\frac{\partial(-p+\tau_{xx})}{\partial x}+\frac{\partial \tau_{yx}}{\partial y}+\frac{\partial \tau_{zx}}{\partial z}+s_{Mx} \qquad (21)$$

The *y*-component of the momentum equation:

$$\rho\frac{Dv}{Dt}=\frac{\partial(-p+\tau_{yy})}{\partial y}+\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{zy}}{\partial z}+s_{My} \qquad (22)$$

The z-component of the momentum equation:

$$\rho \frac{Dw}{Dt} = \frac{\partial(-p + \tau_{zz})}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + s_{Mz} \tag{23}$$

Where u, v and w are the velocity vectors, τ is the viscous stress vector, and S_M is the source term that includes body forces like the earth gravitation force.

2.3 Energy equation in three dimensions

The first law of thermodynamics is used to describe that the rate of increase of energy of an infinitesimal fluid element, is equal to the rate of heat addition to the fluid element and the rate of work done on the fluid element. This gives the energy equation, which can be written for compressible flow as:

$$\begin{aligned}\frac{\partial(\rho h_0)}{\partial t} + div(p h_0 \boldsymbol{u}) \ = \ div(k\ grad\ T) + \frac{\partial p}{\partial t} \\ + \left[\frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{yx})}{\partial y} + \frac{\partial(u\tau_{zx})}{\partial z} + \frac{\partial(v\tau_{xy})}{\partial x} + \frac{\partial(v\tau_{yy})}{\partial y}\right. \\ \left. + \frac{\partial(v\tau_{zy})}{\partial z} + \frac{\partial(w\tau_{xz})}{\partial x} + \frac{\partial(w\tau_{yz})}{\partial y} + \frac{\partial(w\tau_{zz})}{\partial z}\right] + S_h\end{aligned} \tag{24}$$

In the above equation, h_0 is the specific total enthalpy:

$$h_0 = i + \frac{p}{\rho} + \frac{1}{2}(u^2 + v^2 + w^2) \tag{25}$$

In the above equation, “i” is the specific internal energy.

The heat conductivity constant k, can be expressed with Fourier´s law of heat conductions and written in vector form as:

$$q = -k\ grad\ T \tag{26}$$

2.4 Equation of state

The relationship between the four thermodynamic variables (ρ, p, i and T) can be described with the assumption of thermodynamic equilibrium. The equation of state is then described by two state variables, such as ρ and T:

$$p = p(\rho, T) \quad and \quad i = i(\rho, T) \tag{27}$$

The state equations of ideal gas can then be useful:

$$p = \rho RT \quad and \quad i = C_v T \tag{28}$$

2.5 Navier-Stokes equations

For a Newtonian fluid, the viscous stresses are proportional to the rates of deformation, thus the momentum equations reduces to the Navier-Stokes equations. Together with the assumption of incompressible fluid flow, the x-component of the Navier-Stokes equations can be written:

$$\rho \frac{Du}{Dt} = -\nabla \mathrm{p} + \mu \nabla^2 u + s_{Mx} \tag{29}$$

y-component:

$$\rho \frac{Dv}{Dt} = -\nabla \mathrm{p} + \mu \nabla^2 v + s_{My} \tag{30}$$

z- component:

$$\rho \frac{Dw}{Dt} = -\nabla \mathrm{p} + \mu \nabla^2 w + s_{Mz} \tag{31}$$

3 Turbulence modelling

Developments of turbulent flows are present in most engineering situations and are usually included in CFD analysis with a large amount of attention. Turbulence is highly unsteady flow with instantaneous field fluctuations in three-dimensional motions. It generates interaction of fluid parcels with differing conserved properties in a process called turbulent diffusion.

Due to the action of viscosity, a reduction of velocity gradients occurs as fluids with conflicting momentum meet. A lost of kinetic energy is then transformed to internal energy. Depending on the application, turbulence can improve a design´s performance or opposite. For a chemical process engineer, turbulent flow can increase the mixing of chemicals and improve efficiency.
Whereas for a hydrodynamic design, an increase of turbulent flow means more mixing of momentum causing higher frictional forces, thus more power is required to move an underwater vehicle through the fluid (Ferziger & Peric 2002).

3.1 Reynolds-averaged Navier-Stokes (RANS) equations

In order to capture the effects of turbulent flows in a CFD analysis, terms and consequences of velocity fluctuations have been introduced to the Navier-Stokes equations. These effects can be reasonably analysed with Reynolds-averaged Navier-Stokes (RANS) equations, obtained by averaging the equations of motion over time, with focus on the mean flow (Ferziger & Peric 2002). For most engineering applications, the information provided by the time-averaged properties of the flow is sufficient.
RANS equations include additional stresses on the fluid due to the turbulence, adding six unknown variables called the Reynolds stresses. Extra terms are also added from the time-average scalar transport equation. In order to model these additional terms and close the equations, it is necessary to introduce a turbulence model (Versteeg & Malalasekera 2007).

3.2 Shear Stress Transport k -ω Model (SST k -ω Model)

The SST k -ω model is used in this project. It merges the two-equation turbulence models, k-ε model and the standard k -ω model, which are some of the most known turbulence models used by engineers today. The models are characterized by their two extra transport equations that describe the properties of the turbulent flow. This information enables them to account for history effects, such as convection and diffusion of turbulent energy (Versteeg & Malalasekera 2007).

The “k” represents the transport variable, turbulent kinetic energy and the transport equation for k is as follows:

$$\underset{(A)}{\frac{\partial(\rho k)}{\partial t}} + \underset{(B)}{div(\rho k\boldsymbol{U})} = \underset{(C)}{div\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right) grad\ (k)\right]} + \underset{(D)}{P_k} - \underset{(E)}{\beta^* \rho k \delta_{ij}} \quad (32)$$

“ω” represents the specific dissipation of turbulence and the related transport equation is:

$$\underset{(A)}{\frac{\partial(\rho\omega)}{\partial t}} + \underset{(B)}{div(\rho\omega\boldsymbol{U})} = \underset{(C)}{div\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right) grad\ (\omega)\right]} + \underset{(D)}{\gamma_2\left(2\rho S_{ij}\cdot S_{ij} - \frac{2}{3}\rho\omega\frac{\partial U_i}{\partial x_j}\delta_{ij}\right)} \quad (33)$$

$$\underset{(E)}{-\beta_2\rho\omega^2} + \underset{(F)}{2\frac{\rho}{\sigma_{\omega,2}\omega}\frac{\partial k}{\partial x_k}\frac{\partial \omega}{\partial x_k}}$$

In the above equations, (A) is the rate of change of k or ω, (B) is the transport of k or ω by convection, (C) is the transport of k or ω by turbulent diffusion, (D) rate of production of k or ω and (E) is the rate of dissipation of k or ω.
The extra source term (F) in the transportation equation for ω is a cross-diffusion term, which arise from the ε=kω transformation of the ε –equation in the k-ε model. Menter presented this hybrid model in 1992, which takes use of the advantages of the k- ω model in near-wall region, where the k-ε model fails to predict the flow without extra wall-damping functions for low Reynolds numbers. The k-ε model is utilized in the fully turbulent region far from the wall. Reynolds stresses are expressed with Boussinesq´s assumption, which describe the stresses as proportional to the mean rates of deformation. With these modifications has proven the SST k-ε as the most general turbulence model for external aerodynamics. In addition, the boundary treatment allows for coarser mesh, which is more economical for the CFD analysis.

Appendix B

Simulation of Operation and maintenance

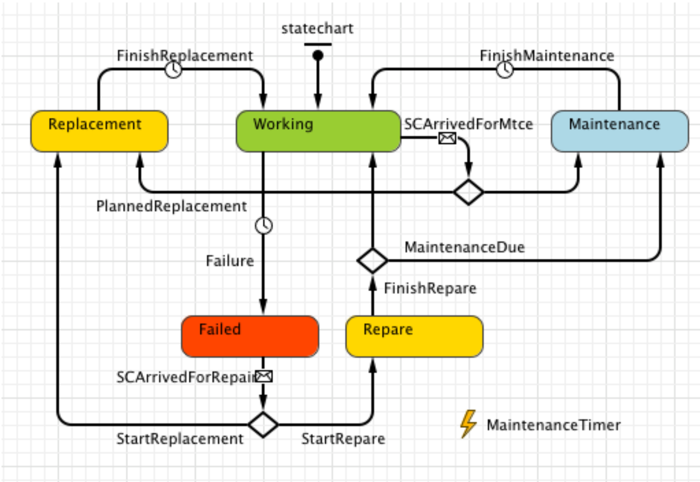
Soares C. G. wrote in Safety and Reliability of Industrial Products, Systems and Structures (2010) that, "Various so-called periodic or scheduled maintenance optimization models have been introduced for modelling scheduled maintenance in which both costs and benefits of periodic maintenance are quantified and an optimum compromise between the two is sought. Well-known models are, for example, the so-called age and block replacement models.

Certainly, the increasing need for realism in the model of the degradation, ageing and repair processes (imperfect repairs, limited number of repair teams, spare parts logistics and so on) entail a continuous increase of the use of simulation for the quantification of the models. The resulting simulation models can then be embedded in efficient maximization tools for optimization of the inspection and maintenance time schedule. Here the concern is that of computing time since the simulation model must be run for every proposed maintenance schedule examined by the optimization algorithm during its search for the optimum. In this regard, the combination of evolutionary optimization techniques, such as the genetic algorithms, with Monte Carlo simulation has proven rather efficient in several example problems and need to be further tested in the practical field.

From the practical point of view, preventive maintenance is strongly advocated as a means to reduce failures, for safety reasons, and unplanned downtime, for economic reasons. In many companies, large time-based preventive maintenance programs have been set up."

In light of this simulation software such as Anylogic can be used as part of the development and optimization process of maintenance and inspection programs. Endrerud in cooperation with Statoil, used the software in 2014 to simulate operation and maintenance activates of an offshore wind turbine farm. The simulation provided Statoil with valuable strategic information by observing how different operation and maintenance schemes affected revenues.
The program is capable of simulating time dependent events based on information about subsea assets such as equipment MTBF, MTTR and other limiting factors such as weather conditions, recharge time, operational range, speed and likelihood of detection. By simulating inspection and maintenance activities throughout the lifetime of a subsea field, it is possible to find an optimal solution of an inspection and monitoring system, maintenance approach, vessel selection, number of inspection by ROV, etc. by observing the change of equipment availability, costs, revenue, service crew and vessel utilization. Simulations may also give indications of how often inspections should be performed and what logistic strategies should be used to achieve minimum LCC. The following maintenance algorithms used in operation and maintenance simulations by AnyLogic, is briefly explained with emphasis on how different maintenance policies are integrated. It includes implementation of failure probability distribution models and scheduled maintenance to execute time dependent scenarios. The algorithms that manage failure and maintenance of equipment are described with a failure example of a subsea oilfield.
The proposed further work is based on this program, where the following algorithms can be used to test the feasibility of different monitoring and inspection solutions, and maintenance strategies to achieve maximum profits.

The following algorithms presented are obtained from Anylogic7 Examples. It is only used to illustrate some of the basic algorithms that may be use to further analyse maintenance strategies and inspection approaches of subsea production systems. Failure rates and maintenance intervals should be further modified better to suit the nature of a subsea Oil and Gas field study.



State chart (AnyLogic7, 2014)

The state-chart shows the model, which organizes what actions that the ROV need to perform. Actions are created from the behaviour of the subsea assets. Firstly, a calculated countdown time, based on the failure rate of components, which defines when a failure occurs. The timeout interval until failure is randomly computed from a calculated exponential distribution model. This distribution model is based on predetermined probabilities and age factors.

***double** timesincemtce = time() - TimeLastMaintenance;*

The “time since last maintenance” is 95 days. Thus initially, “The time when the failure occurred” – “The time when last maintenance was done” = 95 days.

***double** mtceoverduefactor = max(1, timesincemtce / MaintenancePeriod);*

The maintenance period can be set every 90th day.

The “maintenance over due factor” is then equal to the highest value between 1 and 95/90=1,056.

```
double agefactor = max( 1, age() / ( 3 * MaintenancePeriod ) );
```

The "age factor" is the highest value between 1 and (The age of the component since last replacement) / (3* Maintenance period). If the component was replaced 1 year ago, the age is 365 days and the maintenance period is 90 days. The second value becomes 365/270 = 1,35. Thus, the age factor is 1,35.

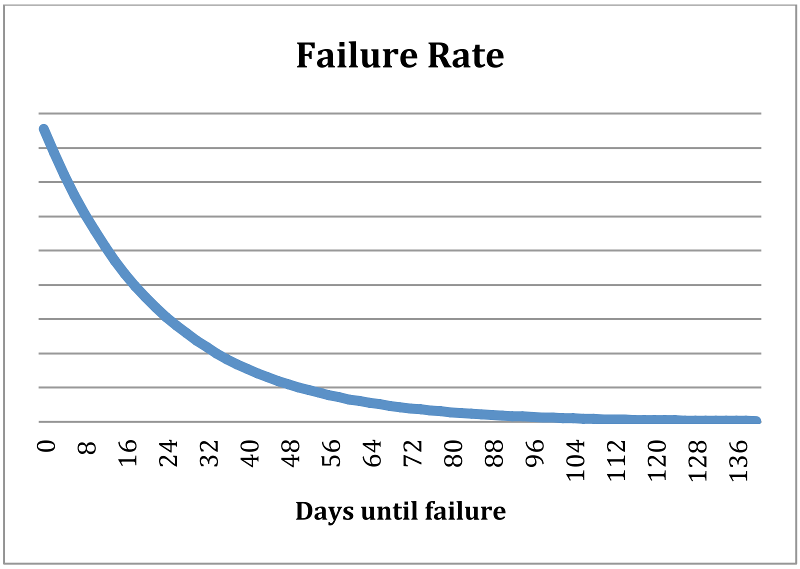
```
return exponential( NormalFailureRate * mtceoverduefactor * agefactor );
```

The "exponential (λ)" is an AnyLogic function that generates a sample of an exponential probability distribution, $\lambda e^{-\lambda x}$ from x=0 -> ∞, where λ=1/β.

With a normal failure rate of 3% per day, the λ is:

λ= Normal Failure Rate * Maintenance Over-Due Factor * Age Factor
= 0,03*1,056*1,35 = 0,042768

AnyLogic then compute a sample of the exponential distribution model with λ= 0,042768.



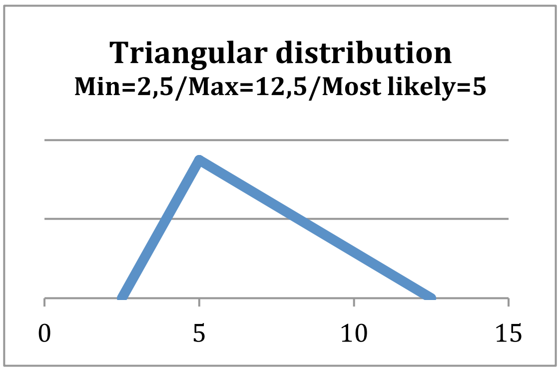
The expected time until failure is then 1/ λ = 1/0,042768 = 23,4 days. However, the computed timeout time is a random chosen value from this distribution sample.

If we compare the previously result, with other circumstances, e.g. at start, no maintenance/replacement has been performed and the component is new. Thus, λ = Normal failure rate = 0,03. The expected time until failure is then 1/ λ = 1/0,03 = 33,3 days. The formula clearly demonstration how the age of the component and time since repaired influence the expected time until failure.

```
get_Main().ReplaceOldEquipment && age() > get_Main().MtcePeriodsToReplace *
MaintenancePeriod || randomTrue( ProbabilityReplacementNeeded )
```

When the subsea asset has failed, the algorithm checks if there is a replacement policy activated. If that is true and the component has reached the age limit (>270days), it is replaced. There is also 10% chance that replacement is the only option. If none of those conditions above are true, the component is repaired.

```
triangular( RepairTypicalTime * 0.5, RepairTypicalTime, RepairTypicalTime * 2.5 )
```



The repair time is variable, depending on the failed equipment, knowledge available, weather conditions, etc. It may take more time to repair a valve leakage, than a sand system and wind can delay the lift of important components up to the nacelle. Thus, a triangular distribution model is build by Anylogic7 and a random value is computed from this sample. This model of often used when we have little or no data available. The most likely repair time is set to 5 hours, the minimum repair time is 2,5 hours and the maximum repair time is 12,5 hours, an example can be viewed in the figure above.

When a ROV has performed a repair, they check if the subsea asset is due for scheduled maintenance on any of its other components.

```
! MaintenanceTimer.isActive()
```

If the maintenance timer is not active (<90days), they carry out further maintenance in the same trip.

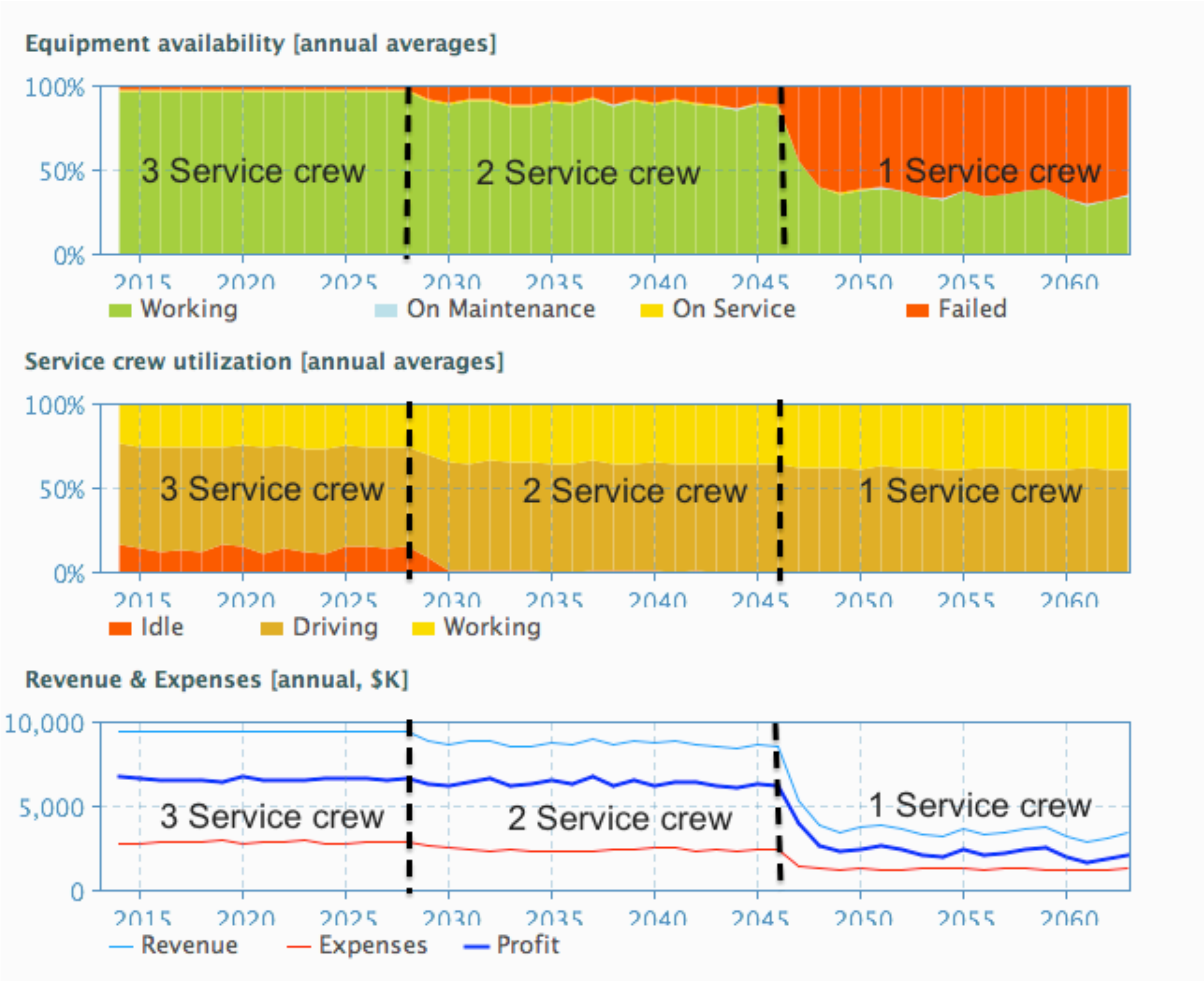
```
triangular(MaintenanceMeanTime * 0.5, MaintenanceMeanTime, MaintenanceMeanTime * 1.5)
```

The duration of maintenance also change from time to time. A similar triangular distribution model is computed from predetermined parameters. The most likely maintenance time is set to 3 hours, the minimum maintenance time is 1,5 hours and the maximum maintenance time is 4,5 hours.

Such a simulation combined with different vessels and landers can be assigned different missions according to inspection type, weather conditions and maintenance type.

```
if (weibull(1.5, 2.5) < 1.5)
  sendRequest(LightVessel);
else
  sendRequest(HeavyVessel);
```

This simple statement, assigns the maintenance mission to a ROV vessel if the significant wave height is below 1,5 m. A Weibull distribution model provide the probability of this happening with parameters a=1,5 and b=2,5.



Derived from an Anylogic7 Example, (AnyLogic7, 2014)

The figure above illustrates a simulation where different number of service/maintenance crew is evaluated.

- The first part of the simulation is with three service "crews", which could be ROVs or AUVs. It clearly shows that they can maintain a high production (equipment availability). The service "crew" utilization can provide a reason why. Only around 90% are working, the 10% is waiting for orders. In this case, profits are stable and expenses are stable.

- In the second part of the simulation only two service "crews" are available. The result then is lower production, thus less revenue and profits. Both service crews are working all the time. Profits are still stable and high with good utilization of personnel.

- In the last part of the simulation, only one service crew are available, the result then is under 50% equipment availability, less profits and low revenue. The expenses are rather constant, because the same amount of spare parts are needed, but there is a slightly difference that represent increased labour costs.

The simulation requires reliable data to produce accurate results. These data may often be difficult to attain before the field has been in operation over a long period, thus data from similar subsea assets and solutions are used. However, each subsea asset is often custom design for the specific O&G field, with unique environment and chemistry. As the industry become more standardized, even for subsea installations, such simulation has the potential of reducing O&M costs. In the future it will become more important to collect and analysis relevant data, such as failure statistics, failure modes and other measurements that may assist the model of producing accurate data. It seems favourable to further develop simulation methods to improve O&M strategy. The need and importance of advanced condition monitoring methods to allow cost effective oil and gas production in deep waters is evident. The bottlenecks regarding weather conditions, inspection coverage and detection may not be totally overcome, but can certainly be further improved. Improved technologies and concept selection processes will continue to increase asset integrity and cost of operation and maintenance activities.

Appendix C

controlDict:

```
/*--------------------------------*- C++ -*----------------------------------*\
|      o        |                                   |
|    o    o     | HELYX-OS                                   |
|   o   O   o   | Version: v2.1.1                            |
|    o    o     | Web:     http://www.engys.com              |
|      o        |                                   |
\*---------------------------------------------------------------------------*/
FoamFile
{
    version 2.0;
    format ascii;
    class dictionary;
    location system;
    object controlDict;
}

    startFrom startTime;
    startTime 0;
    stopAt endTime;
    endTime 1500.0;
    deltaT 1.0;
    writeControl timeStep;
    writeInterval 1000.0;
    purgeWrite 0;
    writeFormat ascii;
    writePrecision 10;
    writeCompression uncompressed;
    timeFormat general;
    timePrecision 6;
    graphFormat raw;
    runTimeModifiable true;
    functions
    (
    totalDrag
    {
        type forceCoeffs;
        functionObjectLibs ( "libforces.so");
        patches ( AUVcop300mhydro);
        rhoName rhoInf;
```

```
    pName p;
    UName U;
    rhoInf 1027.3;
    CofR ( 0 0 0);
    liftDir ( 0 1 0);
    dragDir ( 0 0 1);
    pitchAxis ( 1 0 0);
    magUInf 1.5;
    lRef 1.26;
    Aref 0.11;
    log true;
    outputControl timeStep;
    outputInterval 1;
}

);
```

fvSchemes:

```
/*--------------------------------*- C++ -*----------------------------------*\
|       o         |                                                |
|    o     o      | HELYX-OS                                       |
|   o   O   o     | Version: v2.1.1                                |
|    o     o      | Web:     http://www.engys.com                  |
|       o         |                                                |
\*---------------------------------------------------------------------------*/
FoamFile
{
    version 2.0;
    format ascii;
    class dictionary;
    location system;
    object fvSchemes;
}

    ddtSchemes
    {
        default steadyState;
    }

    gradSchemes
    {
        default Gauss linear;
        grad(nuTilda) cellLimited Gauss linear 1;
        grad(k) cellLimited Gauss linear 1;
        grad(kl) cellLimited Gauss linear 1;
        grad(omega) cellLimited Gauss linear 1;
        grad(epsilon) cellLimited Gauss linear 1;
        grad(q) cellLimited Gauss linear 1;
        grad(zeta) cellLimited Gauss linear 1;
        grad(v2) cellLimited Gauss linear 1;
        grad(f) cellLimited Gauss linear 1;
        grad(sqrt(kt)) cellLimited Gauss linear 1;
        grad(kt) cellLimited Gauss linear 1;
        grad(sqrt(kl)) cellLimited Gauss linear 1;
    }

    divSchemes
    {
        default Gauss linear;
        div(phi,U) Gauss upwind;
        div(phi,k) Gauss upwind;
        div(phi,epsilon) bounded Gauss linearUpwind grad(epsilon);
        div(phi,zeta) bounded Gauss linearUpwind grad(zeta);
```

```
    div(phi,q) bounded Gauss linearUpwind grad(q);
    div(phi,omega) Gauss upwind;
    div(phi,nuTilda) bounded Gauss linearUpwind grad(nuTilda);
    div(phi,T) bounded Gauss limitedLinear 1;
    div(phi,kl) Gauss limitedLinear 1;
    div(phi,kt) Gauss limitedLinear 1;
    div(phi,R) Gauss upwind;
    div(R) Gauss linear;
    div((nuEff*dev(grad(U).T()))) Gauss linear;
    div(phi,v2) bounded Gauss linearUpwind grad(v2);
    div(phi,f) bounded Gauss linearUpwind grad(f);
}

interpolationSchemes
{
    default linear;
    interpolate(HbyA) linear;
}

laplacianSchemes
{
    default Gauss linear limited 0.333;
}

snGradSchemes
{
    default limited 0.333;
}

fluxRequired
{
    default no;
    p ;
}
```

fvSolution:

```
/*---------------------------------*- C++ -*-----------------------------------*\
|       o          |                                                 |
|    o     o       | HELYX-OS                                        |
|   o   O   o      | Version: v2.1.1                                 |
|    o     o       | Web:     http://www.engys.com                   |
|       o          |                                                 |
\*---------------------------------------------------------------------------*/
FoamFile
{
    version 2.0;
    format ascii;
    class dictionary;
    location system;
    object fvSolution;
}

    SIMPLE
    {
        nNonOrthogonalCorrectors 0;
        pressureImplicitPorousity false;
        pRefCell 0;
        pRefValue 0;
        residualControl
        {
            U 1.0E-5;
            k 1.0E-5;
            epsilon 1.0E-5;
            omega 1.0E-5;
            nuTilda 1e-5;
            T 1e-5;
            p_rgh 1e-5;
            p 1.0E-5;
        }

    }

    solvers
    {
        p
        {
            solver GAMG;
            agglomerator faceAreaPair;
            mergeLevels 1;
            cacheAgglomeration true;
            nCellsInCoarsestLevel 200;
            tolerance 1e-7;
```

```
    relTol 0.01;
    smoother GaussSeidel;
    nPreSweeps 0;
    nPostSweeps 2;
    nFinestSweeps 2;
    minIter 1;
}

p_rgh
{
    solver GAMG;
    agglomerator faceAreaPair;
    mergeLevels 1;
    cacheAgglomeration true;
    nCellsInCoarsestLevel 200;
    tolerance 1e-7;
    relTol 0.01;
    smoother GaussSeidel;
    nPreSweeps 0;
    nPostSweeps 2;
    nFinestSweeps 2;
    minIter 1;
}

f
{
    solver GAMG;
    agglomerator faceAreaPair;
    mergeLevels 1;
    cacheAgglomeration true;
    nCellsInCoarsestLevel 200;
    tolerance 1e-7;
    relTol 0.01;
    smoother GaussSeidel;
    nPreSweeps 0;
    nPostSweeps 2;
    nFinestSweeps 2;
    minIter 1;
}

U
{
    solver smoothSolver;
    smoother GaussSeidel;
    tolerance 1e-6;
    relTol 0.1;
    minIter 1;
}
```

```
k
{
   solver smoothSolver;
   smoother GaussSeidel;
   tolerance 1e-6;
   relTol 0.1;
   minIter 1;
}

kl
{
   solver smoothSolver;
   smoother GaussSeidel;
   tolerance 1e-6;
   relTol 0.1;
   minIter 1;
}

kt
{
   solver smoothSolver;
   smoother GaussSeidel;
   tolerance 1e-6;
   relTol 0.1;
   minIter 1;
}

q
{
   solver smoothSolver;
   smoother GaussSeidel;
   tolerance 1e-6;
   relTol 0.1;
   minIter 1;
}

zeta
{
   solver smoothSolver;
   smoother GaussSeidel;
   tolerance 1e-6;
   relTol 0.1;
   minIter 1;
}

epsilon
{
   solver smoothSolver;
   smoother GaussSeidel;
```

```
    tolerance 1e-6;
    relTol 0.1;
    minIter 1;
}

R
{
    solver smoothSolver;
    smoother GaussSeidel;
    tolerance 1e-6;
    relTol 0.1;
    minIter 1;
}

nuTilda
{
    solver smoothSolver;
    smoother GaussSeidel;
    tolerance 1e-6;
    relTol 0.1;
    minIter 1;
}

omega
{
    solver smoothSolver;
    smoother GaussSeidel;
    tolerance 1e-6;
    relTol 0.1;
    minIter 1;
}

h
{
    solver smoothSolver;
    smoother GaussSeidel;
    tolerance 1e-6;
    relTol 0.1;
    minIter 1;
}

T
{
    solver smoothSolver;
    smoother GaussSeidel;
    tolerance 1e-6;
    relTol 0.1;
    minIter 1;
}
```

```
    v2
    {
        solver smoothSolver;
        smoother GaussSeidel;
        tolerance 1e-6;
        relTol 0.1;
        minIter 1;
    }

    rho
    {
        solver PCG;
        preconditioner DIC;
        tolerance 0;
        relTol 0;
        minIter 1;
    }

    rhoFinal
    {
        solver PCG;
        preconditioner DIC;
        tolerance 0;
        relTol 0;
        minIter 1;
    }

    e
    {
        solver PBiCG;
        preconditioner DILU;
        tolerance 1e-06;
        relTol 0.1;
        minIter 1;
    }

}

relaxationFactors
{
    fields
    {
        p_rgh 0.3;
        p 0.3;
        rho 0.05;
    }

    equations
```

```
    {
        U 0.7;
        h 0.5;
        k 0.7;
        kl 0.7;
        kt 0.7;
        q 0.7;
        zeta 0.7;
        epsilon 0.7;
        R 0.7;
        nuTilda 0.7;
        omega 0.7;
        T 0.7;
        v2 0.7;
        f 0.7;
    }

}
```

transportProperites:

```
/*--------------------------------*- C++ -*----------------------------------*\
|      o        |                                      |
|    o     o      | HELYX-OS                                      |
|   o   O   o     | Version: v2.1.1                               |
|    o     o      | Web:     http://www.engys.com                     |
|      o        |                                      |
\*---------------------------------------------------------------------------*/
FoamFile
{
    version 2.0;
    format ascii;
    class dictionary;
    location constant;
    object transportProperties;
}

    materialName water;
    transportModel Newtonian;
    NewtonianCoeffs
    {
    }

    rho rho [1 -3 0 0 0 0 0 ] 1027.3;
    mu mu [1 -1 -1 0 0 0 0 ] 0.0016514875;
    nu nu [0 2 -1 0 0 0 0 ] 1.6076000194685098E-6;
    Cp Cp [0 2 -2 -1 0 0 0 ] 3993.0;
    Cp0 3993.0;
    Prt Prt [0 0 0 0 0 0 0 ] 11.4375;
    Pr Pr [0 0 0 0 0 0 0 ] 11.4375;
    lambda lambda [1 1 -3 -1 0 0 0 ] 0.57814;
    pRef pRef [1 -1 -2 0 0 0 0 ] 101325.0;
    beta beta [0 0 0 -1 0 0 0 ] 0.0207;
    TRef TRef [0 0 0 1 0 0 0 ] 278.15;
```