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Abstract

This thesis describes the initial steps towards development of a modularized all-electric toolbox, to use during ROV intervention. Based on a vision of future subsea systems, which will rely on electrification and standardization. Inspired by standardized interfaces and interchangeability in toolkits used on land, the objective has been to research the possibility of implementing such concepts into the offshore industry.

The primary objective of this thesis was to create an understanding of ROV systems and their capabilities. The secondary objective of this thesis was to expand our understanding of relevant markets, and the services involved in these. What kind of tools are necessary to complete the given tasks? What characteristics are mandatory of an ROV to operate relevant tools in a safe and efficient manner? These questions determine what market segments are favorable and should be focused on, and thereby which tools are relevant. The third objective was to analyze the chosen tools to determine preferable properties towards electrification and modularization. The fourth objective is to determine what tools are best suited to proceed into concept and design evaluations. The properties of the selected tools are then reviewed, where necessities related to power input and outputs are established. Electric actuator solutions are then analyzed to find viable candidates within the suggested electric motor types. Several motors containing viable qualities where found. The qualities and restrictions that one must comply with during design and operation where adhered to, following these guidelines the best tooling solutions where sought out.

These objectives culminate into a goal of making it possible to enter the ROV market with limited experience, by learning the basics of the ROV business and thereby gaining insight into this trade. Based on the knowledge gained in every step of the process, datasheets containing recommended properties for four electric actuators are presented. These are capable of performing the criterions set for tooling actuators. Development processes might now proceed with the suggested candidates as the basis for further research.

Preface

This thesis concludes a master's degree in Offshore Technology at the University of Stavanger. The work was carried out in the period between February the 3rd and the 30th of June 2014.

The research performed throughout this period resulting in this report is the outcome of a market analysis with interviews and meetings with several companies working in the relevant fields. A study of relevant research literature, information gathered from companies working in relevant fields of expertise and the ones adjacent that act as a support structure to the ROV field.

Many companies have been extremely reluctant to share information that has been critical to performing the research in this thesis. This hesitancy is grounded in several factors amongst others are the fear that rival companies might benefit from non-patented or protected information and designs. Analyzing a tool is nearly impossible with just a name and function. A wider array of specifications and other information is necessary to be able to analyze the tools in use in the ROV trade. This has been a major problem throughout this process. To deal with such problems the solutions have been to either look for trends or do qualified guesswork backed up by calculations and expert opinions or leave the equipment out of the thesis.

My motivation for writing this thesis is my interest technological and scientifically progress. To be able to work with challenges the industry face and analyze their solutions is both interesting and inspiring. There is a lot to learn, since ROV systems encompass a vast array of actuators and sensors from highly distinct fields and coordinate them towards accomplishing common tasks.

I realized early that the task was very ambitious. The work needed to achieve a finished product is tremendous. On such a scale, that several engineers could work on it over a period much longer than the time one has available to write a master's thesis. The initial work that must be conducted to start the development of the products considered in this paper, is extensive and difficult to document. In addition, it is probably not the ultimate way to show off one's skills as an engineer, but the work has been very educational. I have for instance learned much that I was not taught throughout my education.

Topics include: Hydraulic systems, electrical actuating principles and design, market analysis, probing the industry to build relations and obtain information, find and acquire material through journals and research papers in databases and on the web, and in addition to that I have learned tremendously about everything related to the design and operation of ROV systems.

The immense scale of components within ROV systems and the accompanying tool pools means that unfortunately they cannot all be analyzed in this thesis. The scope of this thesis is not wide enough to include a great part of the equipment reviewed throughout this process. Some of it is not relevant enough to be included, the reasons for this can be that is placed too far outside of any one limit (power, size, effect etc.) or it might be too similar to a tool already reviewed. The ones that have been chosen is picked because they are better suited for the criteria set in this paper, they belong to a company/ brand/ tool type that is unique, a market leader, a promising newcomer or just because I found them interesting.

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Nomenclature

Symbols

A	Ampere, measurement of electric current
bar	Bar, measurement of pressure (1 bar = 105 pa)
Hp	Horsepower
I	Current, measured in Amperes
I_0	Fault current
I_b	Safe body current
J	Joule, measurement of energy (J = Nm)
kg	Kilo gram (1000 gram)
m	Meter
ms	Milliseconds
N	Newton, measurement of force (N= kg*m/s^2)
N/mm^2	Tensile strength
Pa	Pascal, measurement of pressure (pa = N/m^2)
R	Resistance, measured in Ohm
S_s	Safe distance, the range at which a current is un-harmful
s	second (unit of time)
Ton	All mentions are in metric tons (1000kg)
V	Voltage, measured in volts
W	Watt, measurement of power (W = Nm/s)
˚C	Degrees Celsius, measurement of temperature
Ω	Ohm
Φ	Phase (electric)

Abbreviations

AC	Alternating Current
API	American Petroleum Institute
AUV	Autonomous Underwater Vehicle
CURV	Cable-controlled Underwater Research Vehicle
DC	Direct Current
DNV	Det Norske Veritas (now DNV GL)
GUI	Graphical User Interface
IKU	Institutt for Kontinentalsokkel Undersøkelser (now SINTEF Petroleum)
IMCA	The International Marine Contractors Association
IMR	Inspection, Maintenance and Repair
ISO	International Standardization Organization
LARS	Launch And Recovery System
LIM	Line Insulation Monitor
MBE	Multi Beam Echosounder
MCM	Mine CounterMeasures
MSROV	Mid-Sized Remotely Operated Vehicle
MSW	Meters of Sea Water
NCS	Norwegian Continental Shelf
NDT	Non-Destructive Testing
NEK	Norsk Elektronisk Komite
NEMA	National Electrical Manufacturers Association
NORSOK	NORsk SOkkels Konkurranseposisjon
OCROV	Observation Class Remotely Operated Vehicle
OPEX	Operational Expenditure
O&G	Oil and Gas
RF	Radio Frequency
ROT	Remotely Operated Tool
ROV	Remotely Operated Vehicle
SBP	Sub-Bottom Profiler
SSS	Side-Scan Sonar
TDU	Tool Deployment Unit
TMS	Tether Management System
TT	Torque Tool
VAC	Volt in Alternating Current
VDC	Volt in Direct Current
WCROV	Work Class Remotely Operated Vehicle

1 INTRODUCTION

1.1 Background

The offshore industry in Norway is maturing, and the most accessible fields started producing long ago. The reservoirs firstly chosen for production are the largest, closest to land and at shallower depths. This leads to a situation where the challenges of producing from the remaining fields are ever increasing. Moreover, as new developments are being placed further away from existing infrastructure and at more environmentally challenging locations, a golden age of subsea installations have evolved.

The offshore fields in northern Europe contain the highest number of subsea wells in the world. In 2010, the production from subsea wells exceeded the hydrocarbon production from fixed platform wells on the Norwegian Continental Shelf (NCS). The subsea wells produced about 131.3 million standard cubic meters oil equivalents, which amounted to over 51% of the total production. [1]

With all these installations placed on the seabed, the whole support structure and operations related to them also need to operate underwater. Saturation diving is only possible down to about 300 meters, since manual labor is strenuous and time consuming at these depths. The already highly prevalent solution is to use remotely operated vehicles (ROV) to carry out a majority of the work underwater.

The necessities and practicalities that accompany the use of these vehicles has accelerated their development. Today there exist systems and tools to conduct just about any operation necessary. In order to carry out their tasks a diverse tool package with tremendous variations in form and function has emerged. Some tools have become standardized and are part of every tool pool however; the majority of the tools created are highly specialized and developed for specific situations.

For some years now, there has been a problem in the Norwegian oil and gas (O&G) industry, the issue has been brought up in every major O&G conference, the issue is cost efficiency. Apparently, the market is stagnating, with current oil prices, expensive field developments and budget overruns. Solutions to keep the industry to a certain level of sustainability are discussed

repeatedly. Two of the major solutions reached is standardization and electrification to lower manufacturing and operation expenses. This mindset is to be applied to numerous sectors within the industry for greater effect. [2]

In 2011, Statoil presented their subsea technology challenges where they detailed several of the problems just mentioned. Solutions for all electric subsea structures including control systems, valve actuation, pumps, trees and coalescers/ separators. Additionally, high voltage wet mate connectors, electric ROVs, -manipulators and -torque tools were requested. [3]

The industry continues to strive towards higher cost efficiency, and one way of doing this is standardizing interfaces. Another way of doing it is to develop a set of default tools to be able to perform the majority of tasks, which leads to these tools being mass-produced. Mass production and widespread use leads to lower prices. A byproduct of this is the collectively shared user experiences, which drives the design towards perfection.

How about taking it one step further; by modularizing tools, one can build several different tools by using the same basic components. The best way of doing this is by the use of electro-mechanical actuation.

Creating several different tools from a basic set of components is the formula that gives benefits to the producer, seller and the end user. The producer, gains by mass-producing a small repertoire of components. The retailer gains by selling high volumes of one kit. The end user gains by the low prices and small amount of spare parts needed. The operation acquires higher efficiency because of a lower total weight of tools and more effective tool replacement, eliminating the need to resurface to change tools. Additionally, replacement parts will be easier to find, swift to acquire and it all comes cheap.

A need for increased precision and control in addition to stricter environmental emissions creates a demand for fully electric intervention tools. These arguments have already planted the seeds of an all-electric offshore revolution.

1.2 Objective

The goal of this thesis is to develop the design criteria for electrical ROV-tools by looking at their components, with a special focus on the actuators.

The parts making up the tools should be interchangeable and modular, in such a way that a handful of basic parts can be combined to make up a whole toolbox.

The thesis will also conduct the research needed to lay the foundation for the development and production of such tools. This includes tools that are used when performing intervention tasks. This definition is not a very specific and a vast array of components is placed under the label. This thesis will look at tools comprising of one or more moving parts, or actuators, that is now powered by hydraulics, and how they can be converted into being powered by electricity.

To reach the primary objective several secondary objectives have to be reached:
- Map the market to get an overview of what kind of tools that gets used and the demand for each tool type
- Analyze their contents and index common components
- Ascertain whether the contents can be substituted by electric actuation
- Explore the boundaries of power and effect
- System engineering
- Possible design solution

1.3 Method

The methods used throughout this thesis to answer the research questions and reach the primary goal are listed below:

To find the most relevant tools for this thesis, it was necessary to conduct a survey on the ROV projects performed by various companies. The goal of this survey is to find trends in tasks completed by companies in the relevant market and the tools needed to complete them.

Mapping the existing ROV fleet with a focus on adaptation and the possibility of a transition to using electric intervention tools.

Assessment of relevant and applicable design standards for electrical subsea intervention equipment.

Create design specifications for the components necessary to the construction of electric intervention tools (power, force, torque, voltage, effect, control, communications, electrical interfaces, mechanical interfaces, instrumentation, sensors and requirements for testing/qualification).

Identify and review existing available standard components that can be included in these tools.

1.4 Limitations

This thesis is limited to tools that incorporate means of motion; by containing for example one or more actuators for rotary and/or linear movement.

- The focus will be on ROVs, more specifically Mid-sized or Work Class ROVs because these do the majority of utility work.
- Tools, which is most commonly used and/or have multipurpose will be prioritized.
- Autonomous Underwater Vehicles will only get a limited mention throughout this paper.
- The faculty and the university provided the criteria set for the thesis and its research.
- All units are in SI units, unless stated otherwise.
- The general laws of physics, level of technology and commonly known ways of calculations.
- This thesis has a bias towards the North Sea and European Oil and Gas industry, nevertheless a variety of other markets where ROVs are employed have been examined.

The research in this thesis is limited to the time available from the date the subject was received until the given deadline. In addition, it will be limited by my knowledge within the field, the availability of information, access to competent personnel within the field and the level of confidentiality and amount of information companies are willing to share.

1.5 Outline of the thesis

The second chapter paints a basic picture of remotely operated vehicles. First, the technological development of ROVs throughout history is described, going from the first forerunner until the advanced vehicles used at present day. Then the types of ROVs used today are described in further detail, what solutions and techniques do they offer to be able to perform their tasks? Then the basic formulas and principles that will be encountered and discussed throughout the paper is presented. Following is the basic principles of hydraulic and electric and the difference properties in the systems is analyzed. At last, a brief introduction of what kinds of legislative organizations that restricts the design and operation of the equipment used, and through what

mediums they apply this is. This encompasses the standards, forced- and recommended practices, which is required or recommended by the state's law or internally in the company. Then the dangers of electrical fault currents are analyzed in depth.

The third chapter focuses on the market aspects of the ROV trade. First the contract types and how they fit together with the chosen job and system. Then a description of typical work and the tasks related to them. Lastly, a look at the actual operations conducted in different projects by different companies, to see what ROVs and tools are deployed and the frequency of their use.

The fourth chapter dives into the tool pool used by modern ROVs. Looks at what tools are available and where are they used. Then a comparison of the technical specifications used or needed in the different tools. A look at common properties the different tools portray, and what can substitute or replace the functions they do.

The fifth chapter sets the preferable and the critical values needed in the operational functions the tool is conducting, to set design goals for the manufacturers. This is the functional design specifications. Afterwards, suggested rough design concepts are presented, before suggested datasheets for relevant actuators are introduced.

The sixth chapter conducts a discussion of the experiences gained in this study, the reasonable deductions and how they can be used or should be applied.

The seventh chapter draws the conclusion from the work performed in this paper. The validity of the work done, interesting findings and the conclusions drawn from the various chapters.

The eight chapter proposed the directions for continuing the development of the tooling solutions suggested. Additionally, some technologies and inventions of the near future is presented.

2 BACKGROUND INFORMATION

2.1 ROV History

Like most technological inventions, the first ROVs suffered from many hardships during their first years. Problems like hydraulic failures, leakage, they were hard to control, noisy, unreliable, needed constant maintenance, and even sunlight could cause them damage! [4]

Dimitri Rebikoff is the visionary credited by many as the creator of the first ROV in 1953. He called the vehicle "POODLE", and its main job was to conduct archeological research. The US Navy made significant advances in the development of operational and more reliable systems. Lost ordnance was a big problem for The Navy, they needed safe and efficient ways to find and retrieve them. They created the Cable-controlled Underwater Research Vehicle (CURV), originally created for torpedo retrieval; these models acquired fame among other by rescuing submarine crew and retrieving a nuclear warhead.

Driven by this success, they started building more varied and advanced vehicles. Such as; the Pontoon Implacement Vehicle (PIV) created to help the recovery of sunken submarines. A Navy funding program resulted in the "TORTUGA", a system that focused on deployment from submarines. The portable vehicle "SNOOPY", known as the first small-sized observation ROV. Originally hydraulic, but the following version was electrically powered, which increased its reach. [5]

In Norway, collaboration between IKU (Institutt for Kontinentalsokkel Undersøkelser) and DNV (Det Norske Veritas) resulted in the creation of the SNURRE system. It had its first seawater test in 1973, and despite several teething problems, by 1979 many claimed that it was one of the worlds most advanced underwater vehicle. Gripper arms, a camera with the ability to record in black and white and take colored stills were some of its impressive features. [6]

By 1974, 20 ROV systems were completed, and 17 of these were government funded. However in the period 1974 to 1982, 336 of the 350 ROVs constructed were privately funded, the ROV technology finally got its breakthrough. [5]

During this period, Myrens Verksted a Norwegian mechanical workshop developed a non-buoyant ROV, Spider. This 3.5 ton heavy workhorse had three thrusters positioned 120∘ apart that controlled all movement in the horizontal plane. The Spider is suspended in a wire from a crane on the vessel controlling its vertical movement. This made it into a controllable winch with eyes, with possibilities to lift extremely heavy loads. [7]

The ROV industry had a great growth spurt from 1982 to 1989. With a bloom industry, a new type of ROV emerged, the observation class. These vehicles are characterized by being a lot smaller and cheaper than their ancestors are. These qualities also gave them entry into completely new markets, civil organizations and academic institutions, which did not have the same amount of money as the oil industry. Chris Nicholson developed MiniRover, the original low-cost observation ROV, Benthos later picked up the concept. Deep Ocean Engineering followed by developing the Phantom vehicles. [5]

Finally, in the 1990s it seemed like the industry had matured enough to handle any challenge thrown at it. Boundries were crossed and records broken, it did not take long before the deepest point in the world was reached. Kaiko (seen in Figure 2.1) an ROV developed by the Japanese company JAMSTEC, reached the deepest point in the Mariana Trench, 10 911 meters below sea level. Throughout this decade subsea developments where placed at depths exceeding 3000 meters, far beyond the reach of divers. The offshore industry had to team up with ROV suppliers to design compliant systems to be installed, operated and maintained by ROVs. [5]

Figure 2.1: JAMSTECs Kaiko

2.2 State of the art

In this chapter, the general properties of each type, present technological level of ROV systems and some of the systems currently on the market will be covered.

Unmanned underwater vehicles are divided into two main categories, AUV's and ROV's. This thesis focuses on ROVs, but the future possibilities of adding tools to AUVs is discussed at a later point in this thesis.

Today ROV's are utilized for a variety of tasks, reaching from diver support to heavy subsea constructions. The ROV market is segmented into four broad classes defined by vehicle size and capability as seen in
Figure 2.2.
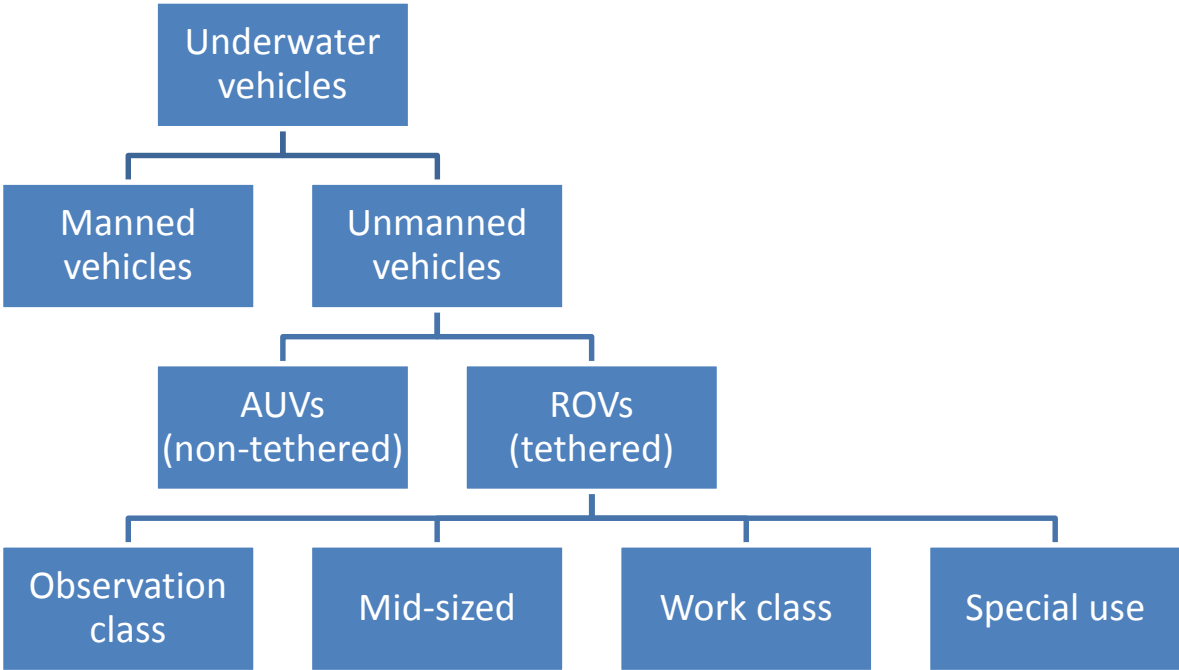
Figure 2.2: Classification of underwater vehicles

2.2.1 Autonomous Underwater Vehicles

Autonomous Underwater Vehicles is untethered underwater vehicles. Batteries power it, and this restricts the vehicles operation time and tooling. It moves without requiring direct input from operator and whose operation can be either fully autonomous (preprogrammed or logic driven course) or under minimal supervisory control. The AUV can be linked (figuratively) to a control console for direct contact through an acoustic modem or via radio transmitter as well with an optical link.

The AUVs most common job is to do site surveys. These job types does not have a need of direct input and feedback, the vehicle travels great distances along a preplanned course, and the gathered data is recovered together with the vehicle when finished. The vehicle benefits from a streamlined shape to minimize drag and needed propulsive energy during its long trek, illustrated in Figure 2.3.

Figure 2.3: Kongsberg Maritime's Hugin AUV

2.2.2 Remotely Operated Vehicles

Remotely Operated Vehicles are tethered underwater vehicles. A ROVs motion can be via either autonomous logic direction or remote operator control, depending on the operator's degree of input or vehicle's capability. They are highly maneuverable, and operated by a crew aboard a vessel. The vehicle is connected to the controlling vessel by either a neutrally buoyant tether or a load-carrying umbilical cable. An ROV's power can be situated both onboard (battery or engine powered) and off board (power supplied through conductors within the tether) or in a hybrid configuration (onboard battery which is recharged by power transmitted remotely through the tether).
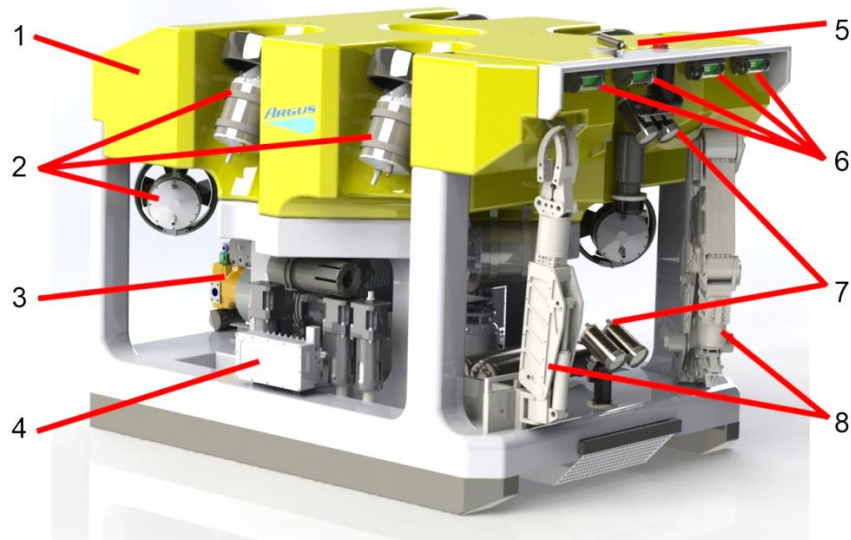
Figure 2.4: The anatomy of an Argus Worker ROV

The ROV is in all simplicity a mobile frame for sensor and tool deployment. The critical components of an electric work class ROV (WCROV) is highlighted in Figure 2.4, they are described in the following sections.

A buoyancy block (1) is mounted on top of the frame; thrusters (2) at various locations cover motion in all directions. Built into every ROV are also a power terminal (3) and the control module (4) that directs all the signals.

Altitude and positioning equipment (5) such as Sonar, altimeters, depth sensor and compass often have a forward placement at an upper position on the vehicle. Several light sources (6) negate distortion so the high definition video cameras (7) get the best possible picture. WCROVs are fitted with two manipulators (8), usually with five and seven functions.

One of the most important issues when choosing a type of ROV is the payload capacity, the additional weight a ROV can carry and still be operable. This is the limiting factor for what other sensors and tooling the vehicle can acquire. Some of the criteria that decide the payload capacity of an ROV are mentioned below.

Factors limiting ROV payload capacity:

Power

Does the vehicle have enough power to maneuver and operate the payload in a safe and correct way?

Structural integrity

Is the frame sturdy enough to take on all the loads it will be subjected to during operation?

Sea state and current condition

How to enlarge the operational window set on deployment and recovery by sea state. Is the design optimized to negate current induced drag in tether and vehicle?

Buoyancy

How much extra is it possible to add to negate the additional payload?

Manipulator load and torque capacity

Is it sufficient to operate in a safe and efficient manner?

[8]
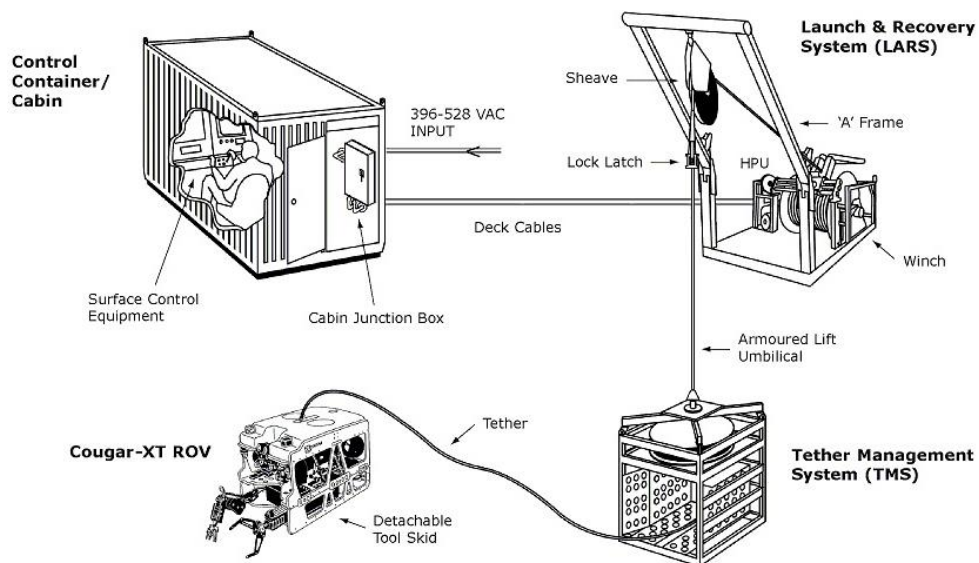
Figure 2.5: Saab Seaeye ROV system spread

When working in rough weather conditions or deep water, it is beneficial to handle the tether with a tether management system (TMS). The purpose of the TMS is to lengthen and shorten the ROV's tether to minimize the effect of cable drag caused by underwater currents. Another purpose is to limit the effects of weather and vessel motion on the tether to prolong its service life. The TMS is connected to the end of the lifting umbilical and hangs directly under the support vessel during operation. There are two kinds of TMS, the "top hat" and the "garage" type.

The Launch And Recovery System (LARS) is used to deploy the TMS along with its Work Class ROV. The main components is an A-frame, a winch for the steel reinforced lifting umbilical, a slip ring, a hydraulic power supply and an electrical power supply. The A-frame is used to lift the ROV and TMS over the side of the vessel. An ROV spread containing a LARS and a TMS is shown in Figure 2.5.

There is little consensus on the classification of ROVs. IMCA and NORSOK each created their own classification of the vehicles several years ago, but their system is vague and technology has already grown past it. The use of the standard's classification is not widely applied; on the contrary, sellers each have their own definitions, leading to arguments on the subject. Some operators link the capabilities of ROVs to horsepower and classify them hence; the related problems this brings will be discussed in "2.2.2.5 Comment". Defined within "The ROV Manual" is a much more robust classification system, this paper follows their classification. [3]

The following sections review each class in detail, most ROVs examined in this research fit within these. The characteristics that defines each class by size, payload- and task capabilities, is assessed to find tooling compatibility. There is a short summary of these in Table 2.1.

Table 2.1: A summary of general characteristics of the various ROV classes

Size Category	Input power	Vehicle Power	Telemetry Type	Depth Rating	Launch Method	TMS	Thruster/ Tooling	Tooling Fluid Flow
OCROV	110/220 VAC 1Φ	Low-voltage DC	Copper only	+/- 300m	Hand deploy	No	Electric/ electric	Electric only
MSROV	440/480 VAC 3Φ	Medium-voltage DC or AC	Copper or fiber	>1000 m	Crane or A-frame	Optional	Electric/ hydraulic	15lpm
WCROV	440/480 VAC 3Φ	High-voltage AC	Fiber only	>3000 m	A-frame	Yes	Hydraulic/ hydraulic	70lpm

2.2.2.1 Observation class ROV's

The observation class ROV's (OCROV) range from the smallest micro- vehicles to submersibles weighing up to 91kg. Generally, they are smaller; DC- powered, low-cost electrical ROV's which are used by divers or as a diver replacement for general shallow water inspection tasks. The vehicles within this class are mostly limited to depth of less than 300 meters of sea level. Vehicles in this classification are commonly deployed by hand and flow free from the surface with hand tending of the tether. Standard equipment load out is camera(s), lights and sonar, with the ability of adding basic NDT or manipulative tooling.

OCROV subcategories based upon vehicle weight:

- *Micro* (small) OCROV's- vehicles weighting from under 3 to 4.5 kg (e.g. AC-ROV, GNOM and VideoRay)
- *Mini* (medium) OCROV's with weight from 4.5 kg and 32 kg (e.g. JW Fisher SeaLion/SeaOtter, Outland1000, SeaBotix's LBV, vLBV or SARbot and Seamor Marine's Seamor vehicles)
- *Large* OCROV's – vehicles with weight from 32 kg to 90 kg (e.g. Benthos StingRay, SeaEye Falcon, Seatronics Predator, Sperre SUB-fighter 3k or DeepBot and Sub-Atlantic Mojave)

Figure 2.6: Seabotix SARbot, mini OCROV

2.2.2.2 Mid-sized ROV's

Mid-sized remotely operated vehicles (MSROV) weigh from 91kg to up to 1000kg. They are deeper-rated version of the OCROV's, capable of operating at deeper depths. Vehicles in this class are generally electrically powered with a limited hydraulic system for operating manipulators and small tooling tasks. Because of their weight category, these vehicles can be used either with a LARS and/or a TMS. The MSROVs electrical power supply can be both DC and AC.

MSROV subcategories based upon vehicle depth capability and performance:

- *Shallow* MSROV's – lower power vehicles with copper telemetry and <1000m depth capability (e.g. Benthos SeaRover, DOE S5N, SeaEye Falcon DR and Sub-Atlantic Mohawk).

- *Deepwater* MSROV's - vehicles which can run single or dual light manipulators as well as high- voltage power, light-duty electric and hydraulic manipulators, and fiber-optic telemetry (e.g. Argus Rover, Oceaneering Minimum, Sea Maxx or Spectrum, SeaEye Cougar, Lynx or Tiger, Sperre SUB-fighter 4,5k or SUB-fighter 7,5k and Sub-Atlantic Super Mohawk or Mohican).

- *Heavy* MSROV's – vehicles with electric thrusters, (by hydraulic powered unit or abundant electrical power) dual medium-duty manipulators, and capability of operating medium-duty tooling. (e.g. Argus Mariner, Seaeye Jaguar, Sperre SUB-fighter 15k or SUB-fighter 30k and Sub-Atlantic Comanche).
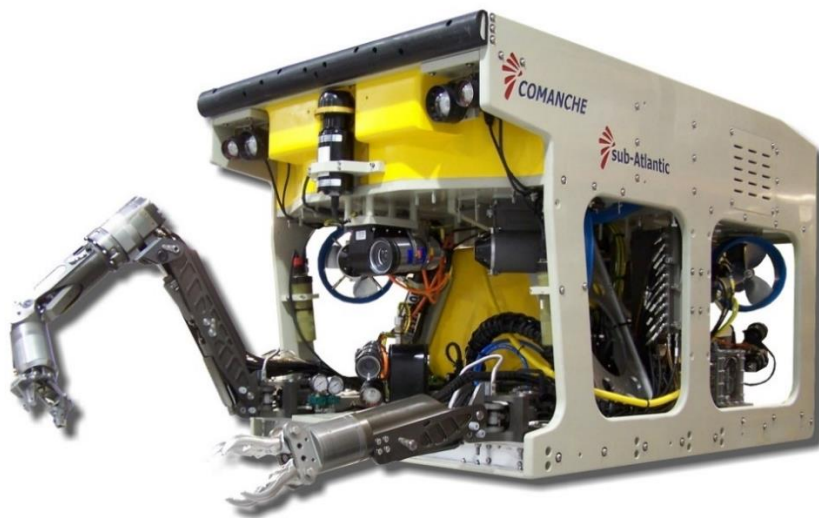
Figure 2.7: Sub-Atlantic Comanche

2.2.2.3 Work class ROV's

Vehicles within this class weigh in excess of 1000kg and use high-voltage (>3000 V) AC. Limits on diving depths are neglected in relation to these vehicles, as they are assumed able enough to reach any operation depth. The power which these vehicles are supplied with from surface sources is immediately transformed into hydro-mechanic energy for locomotion, manipulating tasks and as well as tooling capabilities. Work class ROVs (WCROV) are divided into two subcategories based on the horsepower supplied by the vehicles *primary* motor. The power and payload capabilities of these vehicles enables them carry and operate the majority sensors and tooling available.

WCROV subcategories based upon vehicle horsepower of the primary motor:

- *Standard work class* WCROV's – vehicles in the 100-200 hp range that are deployed in drill support and light construction (e.g. Argus Bathysaurus XL, Worker and Worker XL, Deep Ocean HIROV, Elsub 150, Kystdesign Supporter, Installer or Constructor, Modus CS125 or CS150, Oceaneering Magnum, Schilling HD and SMD Atom or Quasar.)
- *Heavy work class* WCROV's – large and heavy vehicles of >200 hp, which are used in heavy construction work (e.g. Elsub 200, IKM Merlin WR200, Modus MR1, Oceaneering Millennium Plus or Maxximum, Perry XLX 200, Schilling UHD and SMD Quantum).

Figure 2.8: FMC Schilling UHD II ROV

2.2.2.4 Special-use vehicles

This ROV class includes all of the other conceivable designs not classified under the other categories. Examples of vehicles that are placed in this category are prototypes or development vehicles, non-swimming vehicles such as towed vehicles, crawling vehicles or structurally compliant vehicles (i.e. non-free-swimming).

- The towed vehicles have none to limited propulsive power and are pulled by a vessel or winch at the surface. Typically deployed for survey tasks.
- Crawling vehicles maneuver the ocean floor by treads or wheels, some have the ability to hover short distances. The vehicles are normally of considerable bulk and weight, and are especially designed for heavy seabed related tasks, for example excavation and laying of cable and pipeline.
- Structurally compliant vehicles are fitted to any construction in need of regular inspection or sections that is extra critical.

Figure 2.9: SMD Ultra Trencher - 1, worlds largest

2.2.2.5 Comment

Technological development progress and the capabilities of every ROV increase. As the vehicles get rated for deeper waters, power increases, weight decreases, tools improve and the entire adherent repertoire of components shrink in size, the lines that separate each class continually grows more and more blurry. In the near future, the lines will eventually disappear and seize to exist. Presently there are already problems in the O&G industry related to defining size, power and capabilities for the purposes of setting minimum vehicular requirements in tenders related to intervention tasks. Some of the vehicles reviewed during the work on this thesis do already inherit such traits that put them within the definition of more than one class, as defined in The ROV manual. Especially the electric ROVs suffer under these labels. Take for example the Argus Bathysaurus they define it as a "Medium Work Class". It weighs 1600 kg while the weight criterion for being within the Mid-size category is less than 1000kg. It can also be rated for depths of up to 7000 msw, well beyond any class limit. However the minimum primary motor limit for being a WCROV is 100hp, and the Bathysaurus only has 60hp leaving it in between the two classes. The horsepower issue must arise from the fact that the electric ROV powers all functions by electricity, except for the manipulators driven by hydraulics. While the typical hydraulic ROV powers other auxiliary functions, such as thrusters, and is in need of more fluid power than just the amount for the manipulators. The vehicle is suitable with the Orion range of Schilling manipulators, which they categorize for "Medium work", and is a likely origin of Argus own labeling of the vehicle.

The authors of the ROV manual mentions an example in their discussion about the problems of vehicle classification. The setting is; a client of ROV services have limited knowledge of vehicle performance, while operators define the vehicle capabilities by horsepower, and a tender is created with a minimum limit in horsepower. The problem arises when the lucid definition of the horsepower measure do not describe the vehicles capabilities properly. Where and for what the power is used is not specified, and consequently a more efficient system in need of less power might be rejected.

In the example, a drill support contract had a limit for a minimum rating of 150hp; however, a 100hp electric vehicle was more than capable to perform all the tasks listed in the tender. The ingenious ROV operator solved the problem by mounting a 50hp pump on the TMS, together with the vehicle this amassed to 150hp, and they won the contract. [3]

2.3 Basics

This subchapter explains the basic principles and formulas behind key principles discussed throughout this paper.

2.3.1 Actuation

"Actuate" – To put into action or mechanical motion. An actuator is a mechanism that translates mechanical force into motion. Their motion can either be limited or continuous. Hydraulics transfers fluid motion into mechanical linear or rotary motion. Electric actuators perform the same transition of converting electricity to motion through an electric motor.

2.3.1.1 Rotary motion

The most common usage of a motor, by far, is the creation of rotary motion. The force that rotates an object is called torque. Torque (τ) is measured in the center of rotation, by the cross product of a force (F) applied, and the lever arm (r), the distance from center to the point at which the force is applied. If the force is not applied perpendicular to the arm, the angle of deviation ($\sin\theta$) is also applied:

$$\tau = \|r\| * \|F\| * \sin\theta$$

The output power (P_{ro}) of a rotational motor expressed in Watts can be found by multiplying shaft speed (ω) and torque (τ), expressed by radians per second and newton-meters. Henceforth called the rotational power formula.

$$P_{ro} = \omega * \tau$$

2.3.1.2 Linear motion

The power output (P_{lm}), in Watts, for a linear motor is found by multiplying the force F and velocity v, expressed in Newton and meters per second respectively. Henceforth called the linear power formula.

$$P_{lm} = F * v$$

The formula for calculating the force output when translating rotary to linear motion is:

$$F_{out} = \frac{\tau * 2\pi}{l}$$

Where l is the screw lead.

2.3.2 Electrical power

Electrical power is found by using the formula:

$$P_{el} = I * V$$

Where P_{el} is the instantaneous power, measured in watts, V is the potential difference across the component, measured in volts and I is the current through it, measured in amperes. Henceforth called the electrical power formula.

For ac-powered motors, the formula is alternated:
A constant needs to be added to the formula, dependent on the number of phases. It is the square root of the phase number, in a three phase ac motor; $\sqrt{3}$. The formula will also be multiplied by an additional input, the power factor. The power factor (PF) = $|\cos \varphi|$, is dependent on the impedance phase angle between the phases. Henceforth called the electrical AC power formula.

$$P_{AC} = \sqrt{3} * PF * I * V$$

2.3.3 Fluid power

Power calculation through fluid properties is done by multiplying the volumetric fluid flow rate (Q) with pressure (p). The SI units related to them are p is Pascal measured in N/m^2, while Q is written by m^3/s. Henceforth called the fluid power formula.

$$P_{fl} = p * Q$$

2.3.4 Efficiency

Regarding hydraulic tools, most manufacturers state the minimum or maximum properties needed to operate the tool in question. The problem here is the fact that it gives no indication of the efficiency of the tool; it is not possible to "use" all of the flow and pressure/ the energy that is associated with it. Only a certain amount of the energy contained within that effect is extracted, but this cannot be assessed if not both input and output is stated.

As motors, hydraulic or electrical, have varied efficiency, it is preferential to be aware of the needed output. The value can be multiplied by an efficiency accounting for losses in friction and gears etc. to find the needed input, which is easily converted to effect needed by an actuator.

If the actuator has a poor efficiency, a larger power input is needed to achieve the wanted input. Efficiency (η) is equal to output power (P_{out}) divided by input power (P_{in}):

$$\eta = \frac{P_{out}}{P_{in}}$$

Torque is usually associated with output power. One finds the efficiency in a hydraulic system by dividing the rotational power (P_{ro}) (output) by the fluid power (P_{fl}) (input). An efficiency value is achieved similarly in electric systems.

2.3.5 Electric System

The working principle of electromechanical motors is the interaction between an electromagnetic field and a conductor. When electricity passes through the conductor, they move in reference to each other, thus converting electrical energy into mechanical energy.

Basic considerations in motor construction:

Stator

    This is the static part of the motor. As it is commonly built into the frame, it sets the boundaries for the rotors motion. Depending on motor type, it holds either the windings or the magnets.

Rotor

    This is the moving part of a motor, which creates the mechanical power by turning the shaft. Depending on motor type, it holds either the windings or the magnets.

Air gap

    The gap between the stator and rotor, decides how powerful their interaction is, it should be as miniscule as possible.

Windings

    Decides the output capabilities of the actuator, the amount of electricity that is generated per revolution.

Commutator

    The mechanism that switches the direction the electrical current is traveling. It is essential to have the current traveling in an optimal manner. This ensures that the rotor motion is continual from one pole to the next.

Two types of electricity, direct current (DC) and alternating current (AC) can drive a motor. Direct current is a constant unidirectional flow of current, while alternating current periodically changes direction following a sinusoidal curve. Motors are then divided into their method of propulsion, by one or both these kinds of energy as seen in Figure 2.10.
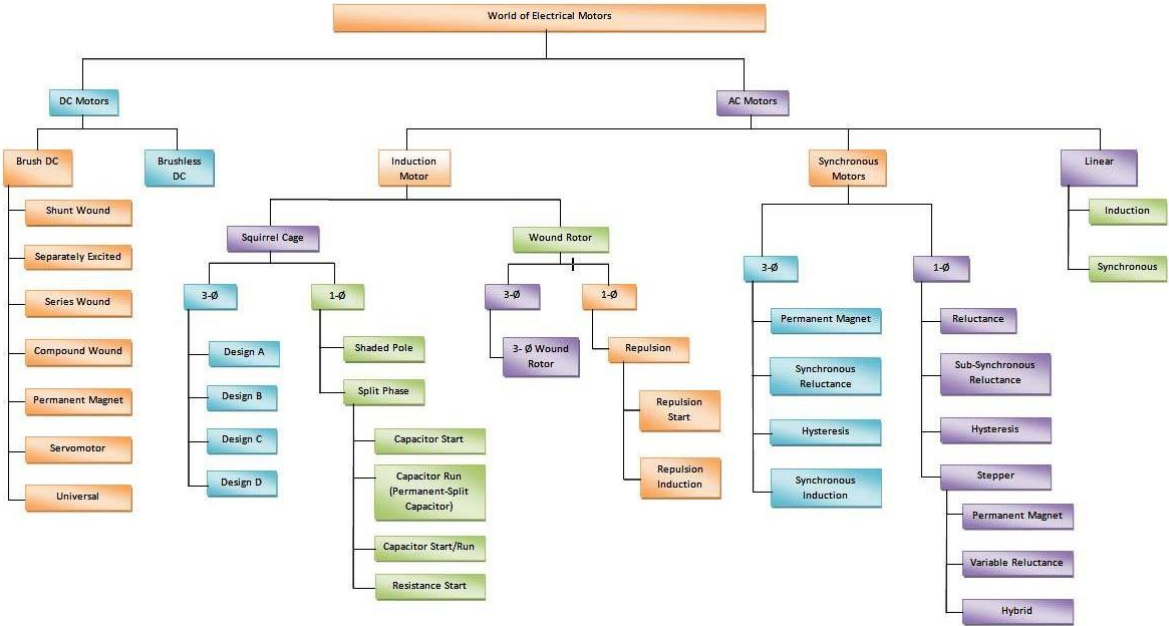
Figure 2.10: The family three of electric motors

Through the years, large variations and creative design solutions for electric motors have been invented. Depending on criteria of operation, suitability can be measured by the different characteristics each type portrays. Technological progress, operating environment, cost of components and mass production abilities have created rise and falls in popularity for each model. They will not all be reviewed in detail within this paper, but a summary of the elimination process is described in "5.1 Choice of motor".

2.3.6 Hydraulic System

Hydraulic power is the science of utilizing moving pressurized fluids to perform mechanical work. The hydraulic technology and fluid mechanic actuating is an old science. Nowadays many people would go as far as to say that it is also an outdated one. Modern hydraulic technique is rigorously tested and proven. There are centuries of experiences ensuring that the systems are kept as efficient and reliable as possible. The knowledge contained within the field accelerates troubleshooting and the solutions to any problems found is usually known. Other advantages linked to hydraulic systems are; the ability to multiply forces by increasing actuator area or working pressure, and because actuator torque and force is limited by pressure, high power to weight or volume ratios are attainable. Additionally, the circulating fluid act as lubricant and coolant.

The common solution is for an electric motor to drive the pump in hydraulic systems, hence the name electro-hydraulic power. Vehicles smaller than work class mostly use low volume pumps, based types that are readily available, like thrusters. While the powerful WCROVs requires a high-volume pump, able to satisfy the consumption of a large number of components.

"Schilling Robotics", a ROV company bought by FMC, utilizes a great practice of using two pumps, driven by a single potent motor. This results in two separate hydraulic systems, a main system for all the permanent components and one auxiliary system dedicated to tooling. This prohibits contamination of the sterile system by introducing polluted oil from an interchangeable tool. Competitors use other solutions for this, which often involves extra steps of filtering. Keeping a clean system is paramount for efficiency, reliability, durability and safety. Clogging can lead to unexpected and unwanted behavior of components. [9]

2.3.7 A comparison of system components

We look at two linear actuating systems to uncover some of the differences between electro-mechanical and hydro mechanical actuation.

A single acting, uni-directional hydraulic cylinder system is one of the simplest system solutions. It can perform in only one direction; a bi-directional system has a higher complexity. Components are listed below:

1. Hydraulic cylinder
2. Electric pump motor
3. Hydraulic pump
4. Hydraulic oil reservoir
5. Check valve
6. Operator push button box
7. Relay cabinet
8. Unloading valve
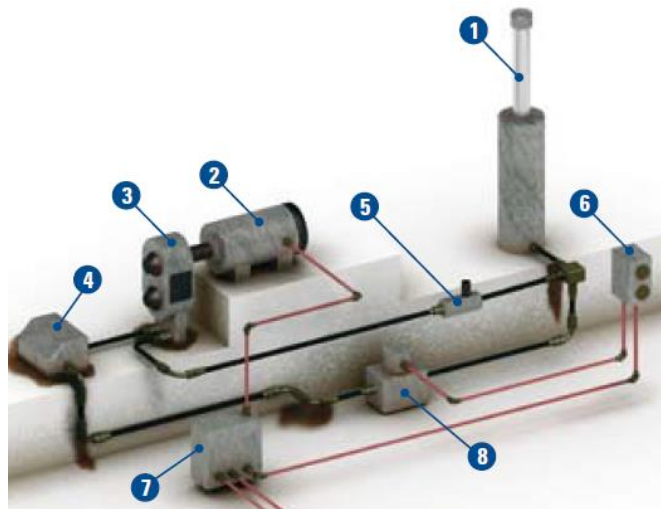
Figure 2.11: Singel acting, uni-directional hydraulic cylinder system

An Electric linear actuator system, with consistent operation in both directions has fewer building blocks. The components are listed below:

1. Linear actuator
2. Actuator control
3. Hand held pendant

Figure 2.12: Electric linear actuator system

2.3.8 Achieving linear motion

Hydraulic cylinders work in a very efficient manner, governed by Pascal's principle. It states that in a fluid at rest in a closed container, a pressure change in one part is transmitted without loss to every portion of the fluid and to the walls of the container. In essence this tells us that the amount of force the piston enact is a product of the input pressure times the area of the cylinders piston. The force output is multiplied by the size ratio of two piston areas. Enabling the hydraulic pistons to perform tough operations that require high force output.

Regarding electrical solutions there are many. Linear motors are essentially «unrolled» rotating motors, producing force along a straight line instead of torque. Induction- and stepper motors are the most commonly used for creating this linear motion, as known from rollercoasters and maglev trains. These motors can have enormous accelerations, high precision, speed, low force and very expensive. The problem with linear motors is that they have no means of breaking, if mounted vertically a power outage can have grave consequences. These properties makes the linear motor unsuited for our application. [10]

For displacement over limited distances, rotating actuators are geared to translate rotation into linear motion. There are four major options, their characteristics are:
Acme screw (a): High friction leads to low efficiency, speed, and acceleration in addition to high maintenance. One of the great benefits of this design is a self-locking ability.
Ball screw (b): Low friction gives high efficiency, moderate speed, acceleration and maintenance.
Roller screw (c): Low friction gives high efficiency, very high speed and acceleration.
Belt drives: High efficiency and maintenance, low repeatability and accuracy but are cheap and have a good stroke length. The screw options are illustrated in Figure 2.13.

(a) Acme screw   (b) Ball screw   (c) Roller screw
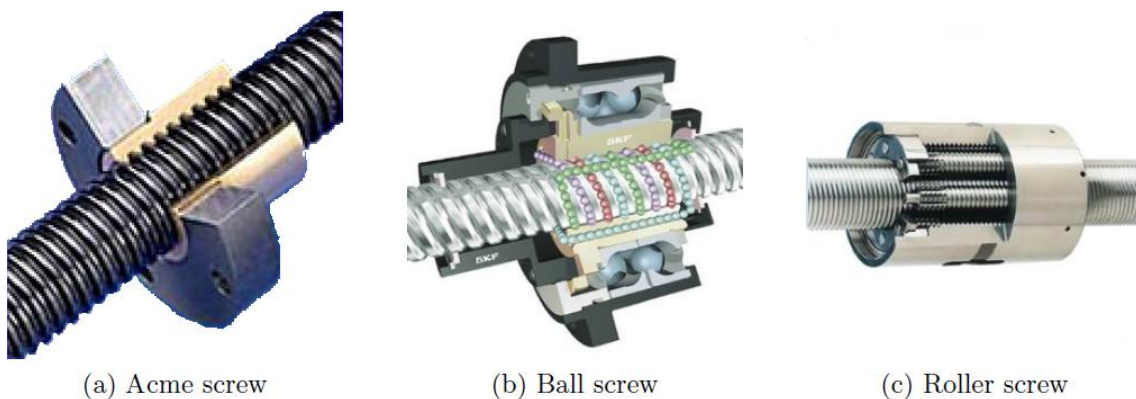
Figure 2.13: Linear motion screw options

2.4 Hydraulic versus Electric actuation

Hydraulics can use accumulators for energy storage; this can lead to a reduction in pump size and energy use. However, over the long run hydraulic systems generally use more energy by running pumps over longer periods to sustain system pressure. In contrast, electric systems only run actuators at the exact point when actuation is needed.

The industry will always have a drive to become more efficient and reliable. As technology progress, sensors and actuators improve continually. Today there are still many issues and challenges that can be solved for a better future. In the following sections, some of the challenges related to the objective of this thesis will be assessed. Some of these are obstacles standing in the way of realizing the goal of the thesis. While others are related to the systems used today, which the solutions posed in this paper will hope to solve. Table 2.2 gives an overview of the problems and shows which system has the best solutions; each problem is explained further in the sections following.

Table 2.2: Comparison of Electric and Hydraulic properties

Problem	Electric	Hydraulic
Leakage	✔	✘
Safety	✘	✘
Noise	✔	✘
Maintenance	✔	✘
OPEX	✔	✘
Thermal Issues	✔	✘
Controls and feedback	✔	✘
Spare parts	✘	✔
System complexity	✔	✘
Strength to weight ratio	✘	✔
Energy efficiency	✔	✘
Total	8	2

Leakage

Leakage is a major problem in today's industry. Commonly used hydraulic fluids is not especially environmental friendly. Mineral oils are used for their properties such as; lubrication, viscosity, thermal capacity, conductivity, fire resistance or erosion resistance. They can contain a wide range of chemical compounds such as ester, glycol, hydrocarbons or silicone, and these are just a small part of a complex mixture.

These compounds harm the environment because they are toxic, contaminate water and have a long decomposition time. The emissions lead to long lasting damages and destroy ecosystems. Hydraulic fluid leakage occurs when there is a sealing problem and the pressure is great enough to leak to the exterior.

The system is under constant pressure, which can cause a great deal of wear and tear. One of Deep Ocean's ROV technicians uttered that most of the oil leakages in their experience where due to wrong use of either fittings or inadequate operation of the system in question. The causes can be fittings of wrong size or rating, system overuse or it is put under loads a great deal over its rated capability. The new trend is to use biodegradable fluid, this concept great in theory, but the market is divided on the degree of "environmental friendliness" these fluids actually provide. [11]

Safety

Safety is crossed out for both systems, because the major safety hazard is electrical fault currents. Both systems use the same maximum voltage; as such, they both have the same degree of safety issues. This topic is elaborated in 2.5.2.1 Safety and .

Noise

Hydraulic systems cause far greater noise pollution, because not only do their motors make more noise, but they also run more frequently. This can cause interference on sensors and disturb marine wildlife.

Maintenance

To prevent any damages in hydraulic systems, a tight maintenance schedule is to be followed. Constant high pressures and strains to all parts of the system, and if anything goes wrong, the whole system can go down. Contained fluid brings unwanted particles and material on a roundtrip, causing unwanted operation or even total system collapse. In electric systems, wiring or motors can short circuit, resulting in control loss and burnout.

OPEX

Hydraulic systems need more upkeep and frequent maintenance, among other as a consequence of hydraulic oil leakage. Money is spent on replenishing oil and other services, known as operational expenditure (OPEX).

Thermal issues

Hydraulic systems might suffer from several problems relating to fluctuations in temperature, because of the corresponding changes in properties. The result can be changes in viscosity and volume, which furthermore affects the flow and pressure characteristics. These characteristics are paramount for determining the performance of the system.

Inaccurate controls and feedback

Hydraulic components are normally controlled by regulation of flow and/or pressure. The effects of these adjustments are pretested so the outcome of these adjustments is known.

For example: The objective is to create motion in a straight line, by a linear actuator, in the case of hydraulics this can be a hydraulic piston. The goal is to displace the piston cylinder to the position that is the halfway point between the minimum and maximum points of displacement. If no other sensors are used to measure state or monitor position of the given equipment, operators have to rely on the details acquired from the pretest. They proceed to set flow parameters to so and so, relaying fluid to the correct inlet in the piston that should result in the predetermined placement.

The problem is that the position cannot be verified, and an accurate positioning guaranteed. This can be the underlying cause of inaccurate controls and feedback. The effect is also immensely inflated if occurrences like previously mentioned, alterations in fluid property because of thermal fluctuations, affects the operation.

Spare parts

As hydraulic systems have been a favorite for decades, it is extremely easy to get ahold of spare parts. Additionally, they are very cheap and delivery times are miniscule. In opposition to electric motors that can take weeks acquire.

System complexity

As illustrated in 2.3.7 A comparison of system , the electric system has fewer components by far. Hydraulic systems have the ability to compete with electric systems if there are many functions needed, where electric systems will need an actuator at every section.

Strength to weight ratio

As described in 4.3.1 Manipulators and 2.3.1.2 Linear motion, Hydraulics have superior force density together with an ability to generate great peak forces by relative low power usage. By the use of accumulators and Pascal's law.

Energy efficiency

Hydraulic systems lose power due to fluid friction in pumps, valves, and piping. Hydraulic actuators are commonly known for their imperfections regarding efficiency or energy utilization. During the energy conversions from mechanical, to fluid and back to mechanical the remaining effect might be 60% of the initial rating.

2.5 Regulations

American Petroleum Institute (API) and the International Organization for Standardization (ISO), where two of the primary organizations spearheading the creation of standards for oilfield exploration and production equipment. Created to ease manufacturing of subsea equipment with common interfaces built within a given framework. As the transition from human divers to include ROV interface was made, the standards adapted to reflect this. API RP (Recommended Practice) 17H and ISO 13628 covers both design and operation of subsea production systems, wellheads and tree equipment. ISO 13628:2002 is divided into nine parts, beginning with general requirements, moving onto recommended practices of manufacturing equipment to the common interfaces for remote intervention and remotely operated tooling. Standards are also generated by various other organizations, including: DNV, NORSOK

(NORsk SOkkels Konkurranseposisjon), and IMCA (International Marine Contractors Association) as well as company-specific guidelines.

ROV operators are mainly concern by ISO 13628 Part 8 and API 17H (which are identical standards) for "ROV Interfaces on Subsea Production Systems". ISO 13628 will not be detailed in this thesis; however, important aspects from many of the nine parts of are used.

Fully electric tools, as new inventions, have no specific guidelines on how to proceed in development. This is usual practice in the industry, the equipment and technologies comes first, and then regulations are created after widespread use and testing. With the exception of a few tools, including TT, there are no detailed guidelines for tool designs. Understandable with the large variation of equipment, with no special interface or interactional needs.

In truth there is not enough standards or standardizations within ROV tooling. This might be because there market is so diverse and there are built so many one-use tools for highly specialized tasks. Nevertheless, is it preferential to standardize and put restrictions on tools? Does this kill creativity by limiting the design engineer's options? The standards regarding ROV design, operation and interfaces, does state several quotes to cover the practice of common sense and gives special attention to risk mitigation. However, any specific approach to operation and design is blurred by unclear and non-specific requirements. As such, there is little to no specific restrictions on the tool designs researched within this paper, except for the general guidelines listed below.

Generally, it is stated in every standard there are some guidelines that should apply to all tools under given situations.
- All tools shall be designed to operate in a safe and efficient manner, with considerations taken to keep them as simple and understandable as possible, to ease use and repair.
- All tools that fasten the ROV or ROT in any way or form to a structure shall have a failsafe mechanism which auto-releases if power or control is lost.
- Qualified electricians should handle electric equipment, and special training is required to handle high voltage systems.
- Common sense and safety considerations should always be exercised and equipment is to be operated according to manufacturer's recommendations or tested limits.

2.5.1 Design criteria

ISO 13628-8:   "ROV Interfaces on Subsea Production Systems", provides guidance on design and operational requirements for maximising the potential of standard equipment and design principles. Enabling the user to select the correct interface for a specific application.

API 17H   "Remotely Operated Tools and Interfaces on Subsea Production Systems", almost totally identical to ISO 13628-8 and -9.

NEK (Norsk Elektronisk Komite) and NEMA (National Electrical Manufacturers Association) create standards for design and operation of electric equipment. Specific standards must be collected in relation to the equipment in question.

2.5.2 Operational criteria

NORSOK U-102:   "Remotely operated vehicle services", defines basic requirements for personnel, equipment and systems for ROV operation related to the petroleum industry.

IMCA R 004:   "Safe and Efficient Operation of ROV", as the name suggests it describes the relationship between operations and equipment. Then guidelines for optimization in safety and efficiency is given.

IMCA R 009:   "ROV Mobilisation", provides guidance for best possible preparation of ROV and crew when mobilizing onto a vessel.

IMCA R 015:   "The Safe Use of Electricity Under Water", describes safe operation and handling of electric equipment, before, under and after unwanted release of electric currents to a divers working environment and the potential unwanted effects following.

The listed standards is a selection of the ones found to be of highest relevance in relations to the research performed in this paper.

2.5.2.1 Safety and electric fault currents

IMCA R 015 "The Safe Use of Electricity Under Water" portrays the effects on the human body submerged in water as an electric charge is released into the medium. Precautions to be implemented to avoid the hazards and how to minimize the outcome. The cause of such a release originates from the degradation of electric insulation, and result in the creation of an electric field around the source. This field retains a spherical shape where the full source intensity is experienced at the center, and is deteriorating as moving outwards. Furthermore, they explain the three degrees of exposure or hazards during a dive, listed by harmfulness:

- *Awareness/Feeling*

  As a diver enters the field, he becomes aware of the sensation surrounding him. Ranging from barely noticeable, to a weak tingling it will progressively become more uncomfortable, but it never results in any harm or long-lasting effects.

- *Muscle contraction*

  Sufficient electric power can result in involuntarily muscle contraction. A result of this can be a diver's inability to let go of something held in his hands, which by itself is normally of no further consequences. There is danger of contracting the muscles of respiratory organs, rendering the diver incapable of breathing.

- *Fibrillation*

  External electric sources can disrupt the natural electric pulses within the body that creates heartbeats. This so-called ventricular fibrillation disrupts the heart rhythm, which leads to a failure in the blood supply. This is the highly critical situation; acute medical attention might change the outlook, although it is unlikely help can be applied quickly enough in a diving situation.

There are three ways to avoid experiencing the unwanted effects of an electric fault charge.

1. Work with a voltage rated under the maximum safety limit.
2. Keep outside of the minimum safety distance from a harmful voltage source.
3. Isolate or disconnect the power source.

The first task will be to calculate the safe voltage limit:

The primary part used when calculating the voltage a human can be exposed to, is the safe body current. Safe body current is the maximum current that can flow within a diver's body without causing unwanted harm or unsafe effects. This factor depends on the current being AC or DC and if the supply employs a trip device to cut power upon detecting a fault.

The second part used is the diver's body resistance, which is the naturally occurring mean resistance of the human body parts. In the case where a diver is fully submerged in seawater resistance is commonly set to 500ohm (voltage > 50), and for 750ohm (voltage < 50).
In addition, some factors affect the current and resistance:

- Water salinity, a higher concentration raise conductivity of the water, which naturally denies the current from traveling through the diver.
- Sex of the diver, female body types have less resistance and thus react different from males.
- Temperature, as it increases conductivity also increase.
- Pressure, changes in this parameter do no significant effect on the human body's reaction to electricity.

In an example where a diver is working in the close vicinity of an ROV. There can be an electricity fault originating from a component in the ROV.

Considerations:
- Diver fully submerged in sea water of normal salinity
- Surrounding water temperature within range of $0°C$ to $30°C$
- The pressure in the vicinity is dependent on the depth

Assume the power supplied from vessel is 3Φ 440V, stepped up to 1100V through an isolating transformer to provide 1000V via the umbilical to the hydraulic pump motor mounted on the vehicle. A Line Insulation Monitor (LIM) connected to an alarm monitors this supply. Lights and controls are also fed in a similar manner and monitored by a second LIM.

Safe voltage is calculated by using Ohm's Law, expressed by the equation:

$$V = R * I$$

Where R, is the resistance in a conductor, measured in Ohm (Ω).

In the case of AC electricity and a trip device set for 20ms or less, safe body current is set at 500mA. These parameters are conservative and based on decades of research on electricity.

Table 2.3: Safe voltage evaluation for an electric fault originating from ROV

	Safe Body Current mA	Body Route Resistance Ω (Ohms)	Safe voltage	
			Maximum V	Nominal V
	(I) x	(R) =	(V)	(V)
AC with trip device	500	500	250	220
A supply fed from an AC isolating transformer with non-earthed secondary. Using a LIM with circuit breaker	N/A	N/A	In this case a single fault does not present a hazard and thus no maximum voltage needs to be stipulated provided the protective devices are able to prevent the occurrence of a second fault constituting a hazard	
A supply fed from an AC isolating transformer with the secondary earthed through an impedance to limit fault current to 1A and trip device	N/A	N/A	No voltage limit is stated as the diver is protected by the fault current limit and the associated trip device	

Based on Table 2.3 and the content of the resent articles, ways of assuring diver safety can be listed as below:

1. If operating voltage of the ROV is under the maximum safe voltage level of 250V ac and a trip device is fitted with a reaction time of less than 20ms.
2. Feeding the ROV main electrical supply from an isolating transformer set up in one of the ways detailed above.
3. If the diver can be physically restricted such that he can be assured to remain at least the minimum safe distance away from the ROV at all times.
    Note: As both diver and ROV will be changing position during the dive, this method should only be used if there is an absolute guarantee that the safe distance can be maintained in all foreseeable circumstances.

4. If the ROV malfunctions such that normal control is lost by the ROV pilot (control problems; partial or total power loss; physical damage; entanglement of vehicle etc.), and a diver is asked to intervene. Then it will normally be necessary to isolate the ROV electrically before the diver approaches it, unless there are other ways in which diver safety can be guaranteed. Any isolations need to be carried out very thoroughly and carefully.

When the limit of safe voltage is acquired, the next step is then to calculate the safety distance. The formula given by IMCA to calculate approximate safety distance in normal salinity seawater (3,5%) is:

$$S_s = \sqrt{1 + \left\{ \frac{\left((I_0 * 10^{-4}) \right)}{I_b} \right\}} - 1$$

The safe body current (I_b) will be the same as seen in Table 2.3 (500mA), since the current is alternating and the system has a trip device. We can also look at an instance where there is no tripping device; the safe body current will then be 10mA.

Next the steady state fault current (I_0) is needed:
The fault current is found simply by using Ohm's law.

$$I_0 = \frac{V}{R}$$

Voltage (V) is known at the fault source to be 1000V, to find the current we need to first find the resistance in the tether leading to this point.

Table 2.4: American Wire Gauge, Standard copper wire, resistance over nominal lengths

Wire gauge (approximation)	Ω /km
20	33,3
18	21
16	13,2
14	8,3
12	5,2

Table 2.4 gives us an approximation of realistic values to work with. In reality, the cable resistance is affected by factors such as temperature, but this is not considered here. The resistance is defined, as being cumulative and linear, i.e. 2km of wire gauge 18, equals 42 Ohm. The wire with the largest dimension is chosen (wire gauge 20 results in 33,3 Ω/km), this is after all a high voltage umbilical.

The resistance values accompanying the relevant lengths of cable can be seen in Table 2.5. The length of the tethers considered is chosen arbitrarily, but should be representative to the lengths used for an ROV working at the same depths as divers.

Table 2.5: Copper wire resistance in assorted lengths of tether

Resistance corresponding to various lengths	
1000 m	33,3 Ω
500 m	16,7 Ω
250 m	8,3 Ω
125 m	4,2 Ω
50 m	1,7 Ω

With the resistances found, the fault current and following safety distances is calculated:

Table 2.6: Safety distance dictated by tether length and the use of trip device

Safe body current:	Length of tether [m]:	Fault current [A]:	Safe distance [m]:
AC with trip device = 0,5A	1000	30,5	0,003
	500	61	0,006
	250	122	0,012
	125	244	0,024
	50	610	0,059
AC without trip device = 0,01A	1000	30,5	0,142
	500	61	0,268
	250	122	0,489
	125	244	0,854
	50	610	1,663

As seen in Table 2.6, the safety distances are small in the case of a system with a trip device (set for <20ms). The largest distance is set to less than 6cm, a distance that should be easy to keep outside, unless the diver is tasked with working on the error source itself.

When the safe body current is adjusted to a situation without a trip device, the safety distance values achieved seems to be more of a challenge. This situation is analyzed even though such a case without trip device is highly unlikely, since this is an industrywide custom. Depending on the job at hand, a safety evaluation on the probability of proceeding with conducting work in a satisfying manner should be taken.

Consideration can be given to the validity of the values achieved in Table 2.6:

Firstly, the thickness of the cables used and their qualities regarding resistance values are subject to great variation and dependent on the choices of the operator, based on factors such as price, conductivity, availability, durability and the assignment.

Secondly, the values achieved are linear and neat, how realistic it is for them to occur in this manner is a subject of discussion. Since the effect of resistance over given distances can behave adversely according to temperature or at especially high or low voltages.

Given the situation of a fault current at the source of 610A and the safety distance of 1,66m. Does the current strength decrease linearly over this distance?

Assuming the current of 0,01A at the safety distance 1,66m. The current have been decreasing by 609,99A over a distance of 1,663 meters.

The decrease of current per. cm is then:

$$\frac{609,99A}{166,3cm} = 3,668 \sim 3,7A/cm$$

If this is true, does the voltage behave in the same linear way? Can a safe voltage distance also be found in the same manner? Well that is a subject for another thesis.

This subchapter is about safety in electricity; however, the problem will not be exclusive to fully electric ROVs. As shown in this example about the end terminal going to a hydraulic pump, this is the point at which the highest voltage is measured. Similarly, the electric ROV will have a point at which the highest voltage is concentrated, but both types of ROVs usually

have the same maximum voltage. As such, this problem is of similar importance and risk character, for both systems of actuation.

Some of the electric vehicles divide the tether into several separately isolated conductors that deliver power to separate components, raising redundancy and integrity of the system. This can be done because there is no single part in need of a higher voltage, unlike the hydraulic pump that can demand considerable amounts. Under such a pretext, the all-electric system is actually safer by having a lower measurement of the maximum voltage value.

On the issues regarding tooling, there is no special reduction in safety in relation to using electromechanical over electrohydraulic. The reason is that the main issues in risk have a direct correlation to maximum voltage and current, and any tool must have a lower consumption than what is available at the power terminal. The exception is if the tool has an external power source, as in the case of ROTs, and in such a case, an ROV might not even be involved in the process. A point to be made though is the elevation in complexity the addition of electric tools produce in the electric system, adding components equals more components that can fail. Simple statistics and Murphy's Law dictate this, and the chance of a breach in insulation is raised, however so slightly.

The whole issue about safety is entirely related to cooperative working along with divers, but this is a situation in strong decline, as divers are less and less used in the Petroleum industry. The effects of fault currents on other electromechanical systems has no mention, but it is safe to say that as components are isolated against "leaking" to the environment, is also isolated against receiving such effects from the environment. Sensors of various kinds might receive noise or distortions by the electric fault currents or adhering electromagnetic fields. [12]

3 MARKET

3.1 ROV services

Their extreme versatility has given the ROVs job in a variety of fields. Known for the adaptability and capability to carry an almost infinite repertoire of tools and sensors. This has enabled them to not only catch up to the abilities of man, but also far surpass him. With just minor modifications, the vehicles can be prepared for executing about any job available.

3.1.1   Call out versus contract work

Mainly dependent on the duration of the project, ROV services are divided into two major categories:

Call-out work:

Is usually defined as a job with a duration of less than 6 months. The positive side of this type of jobs is that they are very profitable. The negative side of this type is that the workloads are highly unpredictable. The origin of these tasks are often unplanned and unexpected, such as breakdown of critical equipment or production "downtime". In this business, there are not many competitors, because many companies collapse due to the unsustainable level of jobs.

Contract work:

These long-term assignments last for longer than 6 months. Allocating such a large part of the economy and resources to carry out such a workload over a greater period, integrating the system into the work platform can be justified. A rig can have its own section specified for carrying the ROV spread, or a dedicated ROV vessel with the system integrated and specialized for ROV tasks. Such a specialized vessel boasts large day rates both in operation and on stand-by, and therefore should have a continuing workload for mobilization over a lengthy period.

3.1.2 The vehicles role and system footprint

In addition, other considerations will have to be taken into account when choosing:
[13]

The vehicles role

If the ROVs only role is support, it might just be available as a backup solution for the divers, delivering tools, monitoring the divers or their tools. Then the assets available for the vehicle and its support system might be severely limited.

However if the vehicle itself is performing the primary role, doing diver-less operations subsea, the ROV system will have assets designated towards redundancy, reliability and a high "uptime". Pipeline survey, remote intervention and structural inspection at deep water might be some of its tasks.

System footprint

As the ROV system grows in size and complexity, their safety, support and supply requirements also expand. All of these separate components forming the footprint of the ROV system also known as "spread".

While many OCROV can be deployed by hand, and a standard 220 VAC single-phase electrical household outlet fulfills its power need. The situation might be very different for MSROVs and WCROVs. These vehicles demand their own high voltage power source, a LARS, a TMS and a container housing the control room. Mobilizing such a spread can amount to substantial expenses. The system can weigh more than 50 tons, along with the size, might even eliminate transport over land as a viable option.

Equipping a new vessel with a WCROV spread will take several days of integration and configuration. This makes it a poor investment regarding call-out tasks. The better option would then be to hire a dedicated ROV vessel, but as mentioned earlier, they are expensive to keep at hand while staying idle at dock.

The best solution might be to hire a dedicated vessel that is in between jobs, if such an option is available. In comparison, the whole OCROV spread might fit in a suitcase to be carried by hand onto the vessel of opportunity.

3.1.3 ROV Work

To summarize the services completed by ROV systems, it is advantageous to first look at the industries that the vehicles contribute, and what operations they perform. Following is a description of prevalent industries and corresponding tasks performed. Table 3.1 illustrates the jobs performed by ROV within each industry.

3.1.3.1 *Industries*

Oil and gas

This industry has been the catalyst developing ROV technology into its modern state; by their dependency for efficient and reliable systems accompanied by their large investment abilities. The offshore O&G industry worldwide has come to rely on ROVs for most subsea intervention tasks, to enable deep water exploration and development projects. Their tasks range from simple survey and seabed intervention to complicated drilling support, inspection, repair, maintenance tasks, subsea construction and decommissioning services. Unmanned vehicles from every classification are used within this industry. The need of exact type of ROV is usually depending upon the operating environment (surface conditions, currents, depth etc.) and the type of deployment.

Underwater mining

Underwater mining is a new industry, which gained popularity throughout the past decade. Valuable raw metals, such as gold, copper, cobalt, silver etc. can be found in high concentrations at seabed. The underwater mining industry base itself on existing equipment used in the O&G sector, with some influence from subsea dredging and offshore diamond mining methods. ROVs are used to both survey and inspect the seabed as well as to cut and lift sections (seabed intervention) of the seafloor or vacuum and pump up sediment and gravel through a flexible pipeline to a vessel at the surface. ROVs within this industry are working at depths of 1,500m or more. Missions are typically in the realm of WCROVs. As technology is evolving to work in underwater environments, a number of mining companies are beginning to explore the possibilities and benefits of this new wave of marine "gold rush".

Renewable Energy

As in the petroleum industry, there are many similar tasks to do within the offshore renewable energy sector. Deep Ocean is one of the companies that provides a range of solutions related to wind- or hydropower. Its five core services are: Survey and Seabed-mapping, Subsea Installation, Seabed Intervention, IMR and Decommissioning. Recently there have been a rise in construction contracts awarded to ROV operators, and more renewable projects are in their planning phases. The renewable energy industry is blooming in Europe, and numerous countries, companies and organizations are gearing up their efforts towards the climate goals set by EU for 2020. [14]

Aquaculture

As the world's population constantly increases and oceans remains over-exploited, fish farming industry has become more perceptible in the world's food production. The various usages of ROV technologies are becoming widespread for both fish farms and production support. The most common tasks of ROVs within this sector is inspection of fish cages, nets (for holes), IMR- removal of (dead fish) from cages for health/sanitation occasions as well as assurance of integrity for the farm. The intervention need is minimal and the operation is at shallow waters, making the OCROV the preferred vehicle.

Science

This job type is performed by industrial, governmental and university research organizations. Common requirements are gathering of sensor data, taking physical samples to understand operational environment (study the ocean), as well as discovering underwater animals and plants in their natural inhabitance. Depending on the research that is being conducted, a science ROV will be equipped with various sampling devices and sensors to provide various surveys, inspection and seabed intervention tasks. The science industry also deploy technology that has been developed for the commercial ROV sector, such as hydraulic manipulators and highly accurate subsea navigation systems. OCROV and MSROV dominate within this industry.

Public Concerns

The homeland security and public safety industry is generally the concern of police and fire department. This envelops periodic inspection of various vulnerable locations for structural integrity, presence of public safety threats, deploying research and rescue tasks in addition to responding to public needs. ROVs are used for periodic ship hull and pier security survey and inspection. They also assist in search, gathering and recovery of evidence at crime scenes. OCROVs with minimal tooling and sensor capabilities are needed for these types of missions.

Military

Today vehicles have four main functions within the military industry, mine countermeasures (MCM), explosive ordinance disposal, inspectional/security tasks and object recovery service. For the MCM function, survey is done at a location to identify targets using mine-hunting sonar or laser line scanner. After the target is localized, neutralization is requirement before final disposition. Mines are neutralized by detonating a charge in close proximity; this explosion should trigger a mine detonation. Cheap "suicide" OCROV can be mounted with such a charge, or MSROVs can place a remotely detonated charge before evacuating. Retrieval functions require WCROV to rig heavy-lifting gear for retrieval to the surface.

Table 3.1: Selected job types performed by ROVs according to industry

Job Types / Industry	Survey	Seabed intervetion	Drilling support	Operaction assistance	Installation assistance	Inspection	Maintenance and Repair	Decommissioning
O&G	X	X	X	X	X	X	X	X
Underwater Mining	X	X		X		X	X	X
Renewable Energy	X	X			X	X	X	X
Aguaculture	X				X	X	X	
Science	X	X						
Public Concerns	X					X	X	
Military	X					X	X	

3.1.3.2 *Job types*

The term subsea intervention refers to all activities that are implemented subsea. The tasks reviewed are biased towards offshore O&G, because they originate from that industry and it's the only one that incorporates them all. Table 3.2 summarizes the tools and the job types that include them. Detailed in the following sections are parts of the work that ROVs perform:

Survey

A survey needs to be completed before various oil- and non-oilfield related activities. The usage of surveys depend on industry and the required tasks. The subsea survey for positioning and soil investigation is one of the main activities for subsea field development. Other variations include: seabed mapping, pipeline route, site survey, pre-lay survey and cable lay surveys. Nevertheless, there is wide range of other surveys also performed within aquaculture, science, commercial- and archeology sector, military, security/public safety, underwater mining as well as renewable energy industry. This job type does not use any heavy tooling and can be accomplished with the smaller and cheaper ROV systems, such as Observation class or light MSROVs. [8]

Seabed intervention

Seabed intervention is all operations involving intervention and alteration of seafloor features. Although the O&G industry does the majority of such tasks, other markets (Table 3.1) also apply the same techniques of seabed preparation. To place a subsea structure on the seafloor securely, the seabed must be as regular and flat as possible, if not the structure will suffer the risk of spanning and overstressing. Subsea structures are often exposed to high external pressures and low temperatures which are affected by tidal movements, currents and scour unless trenched or buried in the seafloor. Preparation of the seabed is therefore of crucial importance. Tasks include: Debris removal, cleaning and high pressure water jetting, trenching and mechanical cutting, ploughing, pre-cut trenching and cable burial, leveling of installation site as well as core sampling and other kinds of digging/filling of material. These tasks are normally in realm of MSROV, WCROVs or the specialized trenching vehicles. [15]

Drilling Support

It has now become an industry standard to have a ROV systems overseeing and supporting all drilling operations. Drilling tasks for production drilling and completion usually include:

- Implementation of acoustic units such as transponders or beacons by an ROV for surface or underwater positioning
- Bottom surveys by using visual observation from a ROV with supplemental equipment such as cameras and video
- Structure setting of permanent- and temporary guide base
- Debris removal

Vehicles participating in this work is OCROV, light MSROV or ROTs. Intervention and interface is performed during structure placement and testing.

Operation Assistance

During the operation phase, ROVs are normally not required except for noncritical valve actuation and possibly intermittent status checks, taking samples, etc. Tasks include flow control by chokes and valves operated externally by ROV or ROT intervention;

- Monitoring of flow temperature and pressure by relevant measurement meters
- Chemical and inhibitor injection for corrosion, waxing, and hydrate formation resistance
- Hatch operations on subsea structures and valve stations
- Flow separation of liquids, gases, and solids (filtering)
- Flow boosting by pumping
- Flow heating or cooling.

Vehicles working within this category are heavy MSROV and WCROV, able to handle adequate manipulator and torque tooling.

Installation Assistance

Subsea equipment and structures are transported to site and installed by specially designed vessels. Subsea equipment includes trees, manifolds, flowlines, pipeline, and umbilicals. The installation of a subsea production system can be divided into two separate operations, performed by different vessel types. A conventional floating drilling rig can do installation of subsea equipment such as trees and templates, whereas an installation barge using S-lay, J-lay or reel lay, installs subsea pipelines and risers.

The installation methods for subsea equipment are divided into categories by weight.

1. Large subsea hardware (weights > 300 metric tons) is commonly installed by a heavy lift vessel. An alternative is to install it by using the drill tower on a rig; their lifting capacity might be up to 600 tons.

2. Smaller subsea hardware (maximum 250 ton), a standard vessel may be used, as long as it is equipped with a crane rated for over boarding the hardware.

Installation in an offshore environment is a dangerous activity, and heavy lifting is avoided as much as possible. ROVs are used for observation and position verification throughout the complete process, but also for engagement and release of guide wires and hooks. The capacities of the heavy duty WCROVs with cutting and grinding tools, manipulators, jetting and dredging tools, are needed during this type of job.

Inspection

To make sure that no external damage or hazards are present that can affect the system's integrity, periodic inspection is required. Structures are expected to deteriorate due to flowline vibration, internal-/ external corrosion and erosion, etc. This job type is normally carried out by an OCROV or light MSROV.

For floating systems such as the Tension Leg Platform, an inspection would examine the tendons as well as the hull and production riser. Inspections of other systems can be investigating the mooring system components as well as production components (trees if subsea, pipelines, risers, umbilical, manifold, etc.). Digital video and still photography documentation of every step is always done in all ROV tasks, but especially under inspection were this might be the whole purpose of the job. [13]

Inspection tasks include:

- General visual inspection, including cathodic measurements and marine growth measurements
- Electrical faultfinding and hydraulic leak detection
- Detailed inspection including close visual inspection, crack detection, wall thickness measurements, and flooded member detection by use of non-destructive testing (NDT)
- Routine pipeline inspection, including tracking and measurement of cover depth for buried pipelines, which is also applicable to control umbilicals and power cables
- Physical cleaning is required before performing a majority of these tasks.
- Cleaning may be performed by an ROV with brushing tools or high-pressure wet jets with grit entrainment. Crack detection may be performed by an ROV with magnetic particle inspection, eddy current or alternating current field measurement methods

Maintenance and Repair

Maintenance and repair are the actions performed following an inspection, with associated defects located. The ability to efficiently keep production wells one stream is one of the most important factors determining field economic performance. A strategy on how to manage the intervention, maintenance and repair (IMR) activities is therefore of outmost importance. Maintenance activities include repair or replacement of modules, usually performed by retrieving the module to the surface and subsequently replacing it with a new or a substitute module. Most components within subsea equipment are modular, with built-in redundancy to expedite retrievals in the event of a failure. Mobilization of a drilling rig or specialized intervention vessel is required for intervention into most subsea systems. Pipeline operations, can either cut and retrieve sections of pipe, or mend a set area of a pipe. However, maintenance and repair activities are performed in a myriad of ways in various industries, not just O&G. This job type is normally carried out by an MSROV or WCROV. [16]

Decommissioning

As the oil and gas fields impoverish and wells are plugged and abandoned, structural decommissioning tasks become a necessity. Concrete gravity based platforms may be left upon closure of production, however normally steel and parts subsea structure in excess of one meter from the concrete must be removed. It needs to be ensured that the recovered steel, risers, flexibles, umbilicals, or concrete are disposed onshore in an environmentally safe approach. All parts must be brought ashore for considerate disposal. Further a contract with a disposal facility must be established, and their environmental standards will be evaluated in cooperation with the decommissioning customer. The typically decommissioning missions include pre and post survey, cleaning and high pressure water jetting, cutting and recovery, pipeline and subsea structure removal, towing and transport, as well as disposal of offshore structure back to land. The capacities of the heavy duty WCROVs with large cutting, grinding tools are deployed under this type of job. [8]

Table 3.2: A Selection of tools and complementing job types

Job Types / Tools	Survey	Seabed intervention	Drilling support	Operation assistance	Installation assistance	Inspection	Maintenance and Repair	Decommissioning
Manipulators		X	X	X	X	X	X	X
Torque Tools			X	X	X	X	X	
Cutting Tools		X	X	X	X		X	X
Grinding Tools			X	X	X		X	
Cleaning Tools		X		X		X	X	
Jetting/Dredging Tools		X	X	X	X	X	X	X
Multibeam Echosounder	X	X	X	X	X	X	X	X
Side Scan Sonar	X	X	X	X	X	X	X	X
Altimeters	X	X	X	X	X	X	X	X
Sub-Bottom Profiler	X	X	X	X	X	X	X	X
Core Sample Tools		X		X		X		
Drill		X			X		X	X

3.2 Market Statistics

For this chapter an extensive market research have been performed, with the goal of getting some hints to how the ROV business is going. A selection of ROV operators have been reviewed, where all their projects have been analyzed to build an understanding of queries such as:

- o What kind of work is performed
- o What ROV system are used
- o What tools are needed throughout the tasks
- o How often are the various tools used

Five companies were examined through available data, gathered over the internet or through company representatives. The companies in question are Argus Remote Systems, Deep Ocean, IKM Subsea, Oceaneering and Subsea7. Focusing only on projects performed within Europe, during the period 2004- 2014. A summary of the gathered information is represented in the following graphs. This information might not represent the actual workload performed by operators, as the survey might not be extensive enough. The number of jobs completed are calculated by the amount of ROVs performing them. If a job is completed by a construction vessel over 3 years, using three WCROVs, three WCROVs are registered under installation assistance, for each of those 3 years.
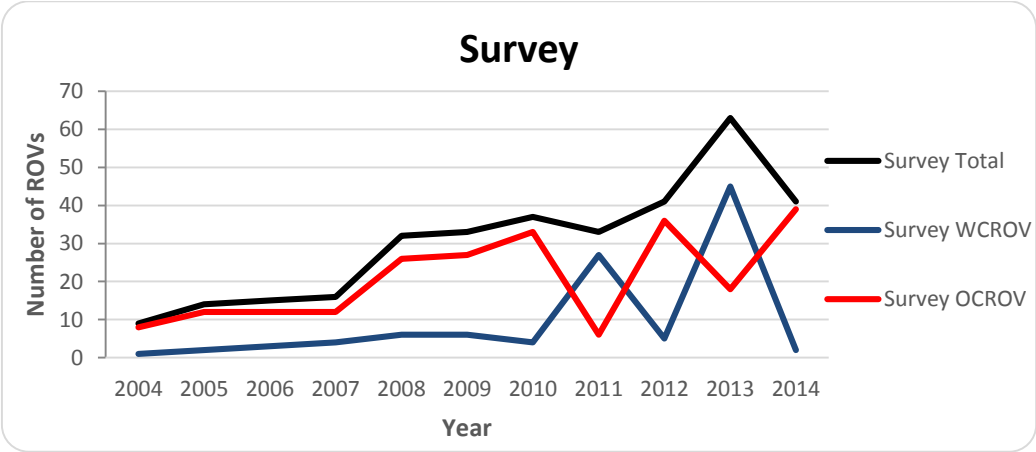
Figure 3.1: Survey tasks overview

Survey tasks that are illustrated in Figure 3.1, which shows a steady increase of total surveys during the period from 2004-2013. Peaking in 2013 before decreasing in 2014. A high number of WCROVs overtake the workload in 2011 and 2013. After a 3-year growth, OCROV's rate of usage fell significantly in 2011. Following a biannual power fluctuation between OCROVs

and WCROVs. In 2013, WCROVs reached their highest peak. In the following year, it shows a dramatic downward trend when the rate hit the lowest point of usage, by two vehicles of the totaling 41 completed survey missions.
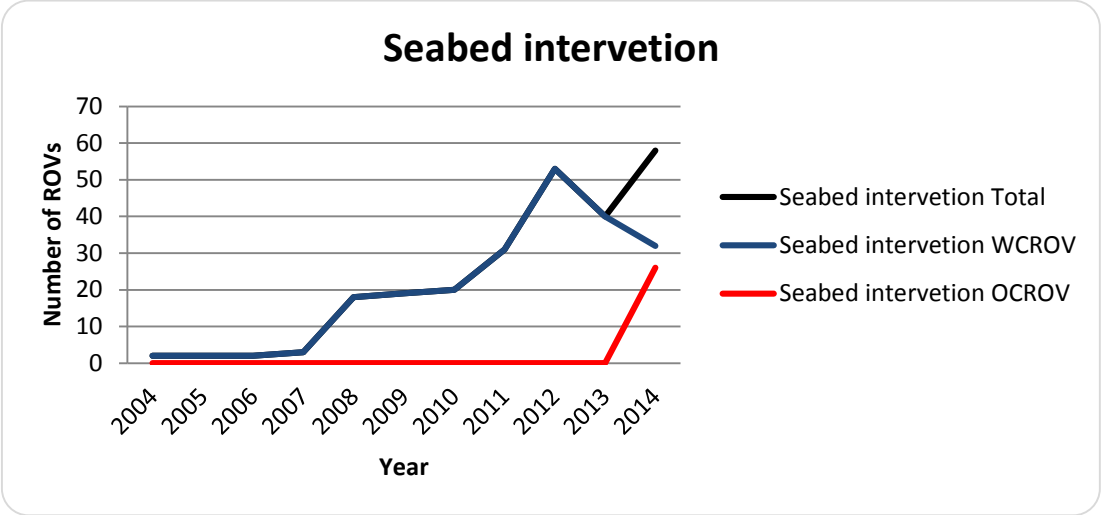
Figure 3.2: Seabed intervention tasks overview
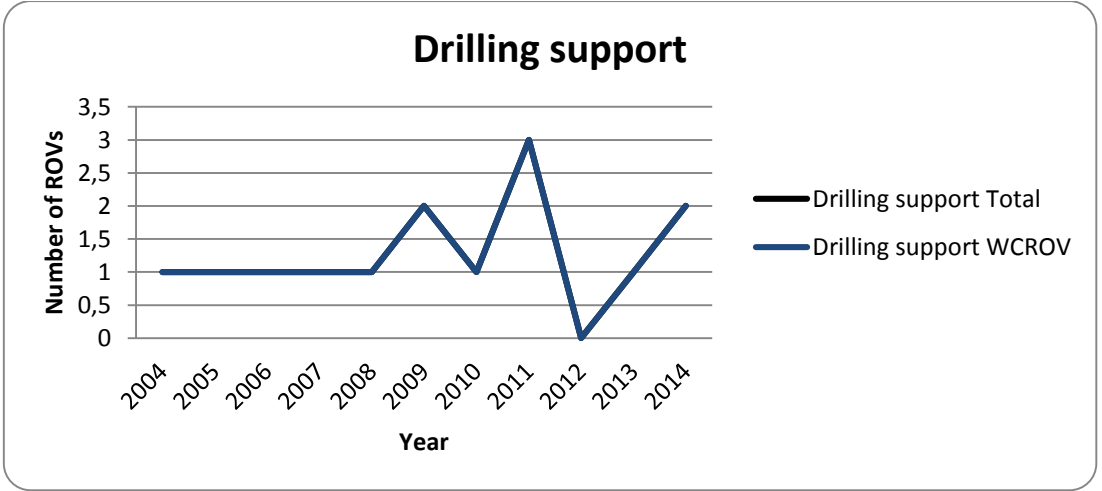
Figure 3.3: Drilling support tasks overview

The total amount of performed tasks throughout all graphs illustrate a rising trend. The trend is sustained until 2011/2012, before sudden fluctuations occur. The fluctuations can be seen in Figure 3.2, Figure 3.3 and Figure 3.4.
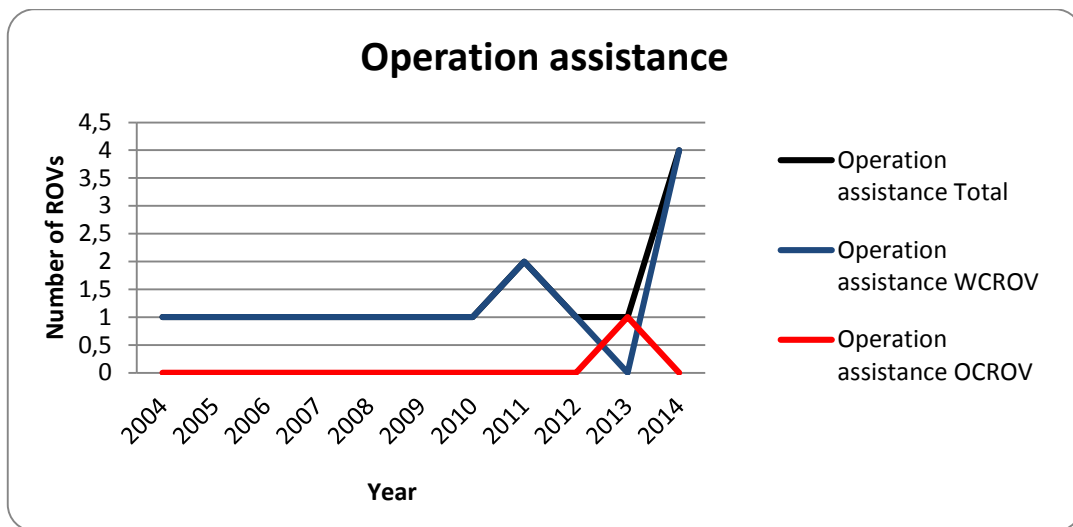
Figure 3.4: Operation assistance tasks overview
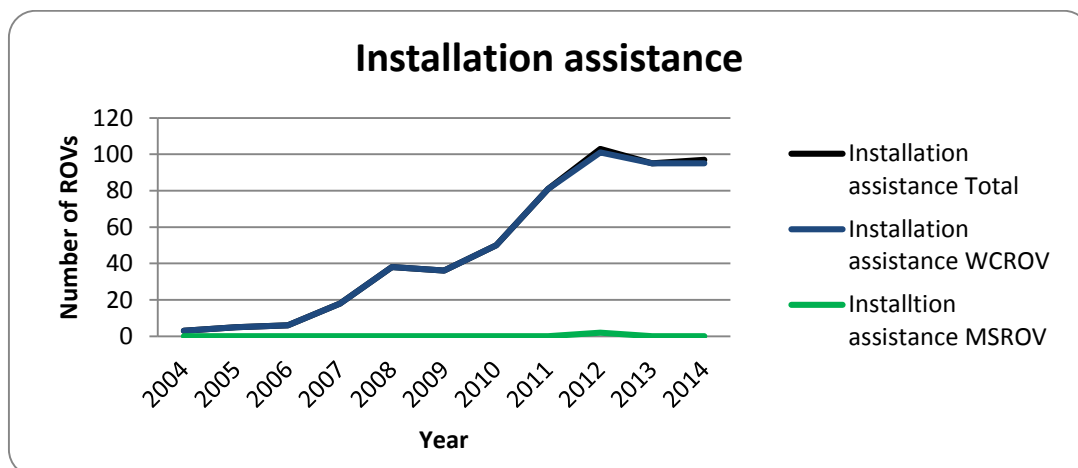
Figure 3.5: Installation assistance tasks overview

Installation assistance is the task type with the most sustainable growth until 2012. The graph in Figure 3.5 also shows a stabilization of workload in the last years. This job type is also the only one with registered MSROV usage, which comply with the mission's vehicle requirement

The inspection tasks illustrated in Figure 3.6 show an alarmingly low usage of OCROVs. Only showing a rise in 2013, before shrinking the next year. However, this decrease is occurring to all vehicle types used for inspection jobs, and the amount of OCROVs is actually larger than the number of WCROVs in 2014.

Figure 3.6: Inspection tasks overview
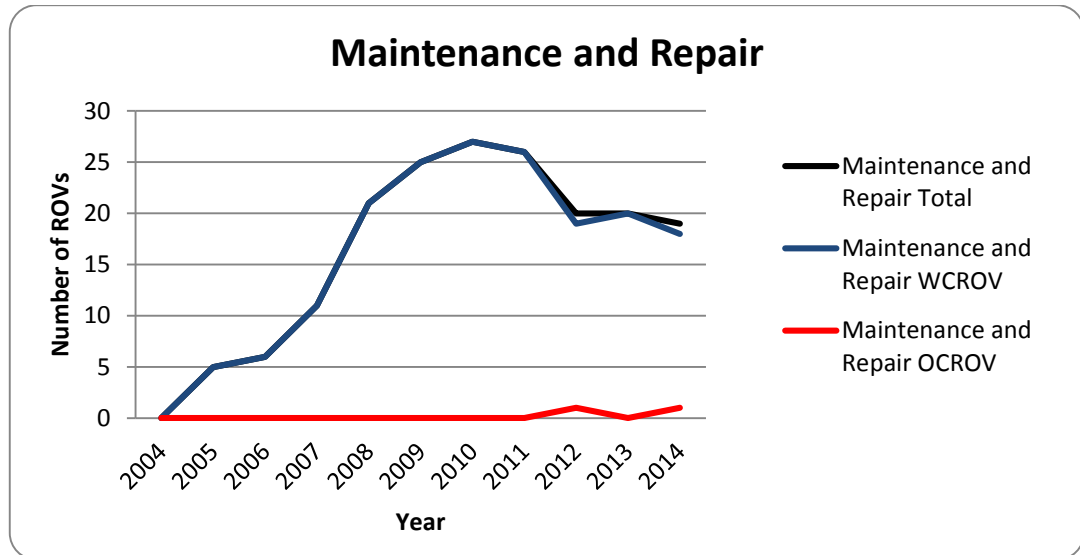
Figure 3.7: Maintenance and repair tasks overview
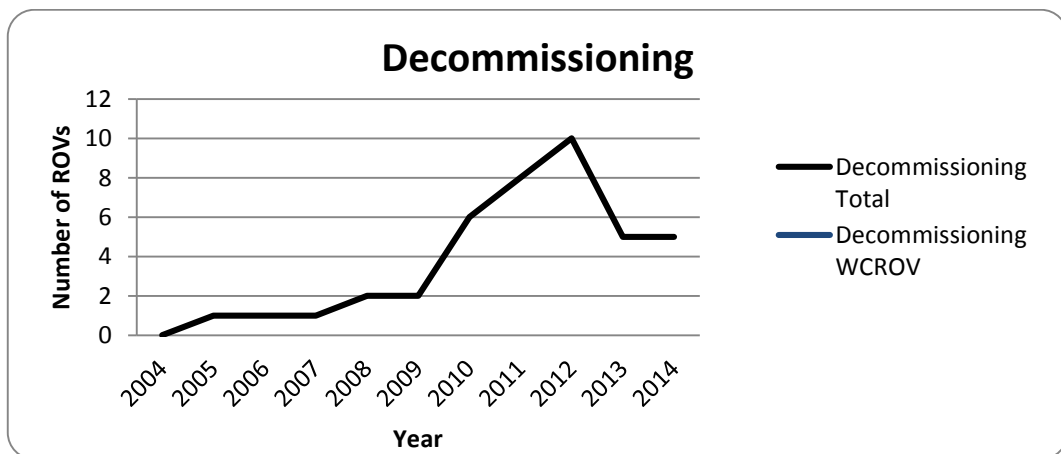
Figure 3.8: Decommissioning tasks overview

Figure 3.7 and Figure 3.8 show the same tendency as the installation assistance task, with a steady growth and decline before stabilized during 2013-2014. The last two graphs highlight the fact that WCROVs perform the majority of decommissioning, maintenance and repair tasks.

The golden rule for choosing equipment is said to be; choose the smallest and cheapest ROV system possible, as long as it is able to perform the task set for it. However, it seems like whatever work is to be executed, the trend is to use WCROVs.

Why are companies doing this? Are they uncertain of limitations and performances applying to vehicles in separate classes? Are they afraid of speculating with vehicles along the border of the performance needed, and they chose to stay safely far above the limits? Is it because vessels seldom stay at the docks preparing for new assignments, as such there is no time to change ROV spread to tailor it to the workload? Might the reason be that a vessel is constructed to conduct several jobs like pipelay, construction and IMR, and the heaviest workloads are in need of WCROVs, as such they continue using it in every situation? Could they have a special deal with a preferred retailer for discount prices? Alternatively, maybe the retailer prefers to sell the costlier systems of which his earnings are largest.

The reasons can one or several of these, or maybe something completely different. Every company labels vehicles according to their own leisure, and there is no uniform ROV labeling spanning the various suppliers. It is difficult to mark ROVs according to our classification system, when the brand and model is not specified. MSROVs are labeled as WCROVs and OCROVs. WCROVs are even labeled as OCROVs, but as long as the only information available is their classification, all we can do is follow. Even as a couple of instances was uncovered during the process, the majority of projects did not specify ROV models. Although if every model was specified, there would still be a majority of overqualified ROVs performing simpler tasks than they are capable of. The trend is still puzzling.

4 TOOLS

4.1 Tool deployment concepts

API RP 17H describes two major techniques for deploying intervention tools. These two solutions for accessing the interfaces on subsea production systems are through Remotely Operated Tools (ROT) and Remotely Operated Vehicles. When designing the tool, the deployment concept needs to be discussed. Should it be reliant on one configuration or have the ability to be deployed in several ways?

4.1.1 ROV Configurations

The standard further describes six typical ways of configuring an ROV for performing intervention tasks. Illustrations of the various configurations can be seen in Figure 4.1.

a) With manipulators for direct operation of the interface panel

b) In addition to the manipulator option, the operation may be supported by an external underslung basket, to hold manipulator deployed tooling.

c) With a manipulator-held tool

d) With a Tool Deployment Unit (TDU) with a single point docking.

e) With a dual docking point Tool Deployment Unit (TDU)

f) With tool skids mounted on the external surface of the ROV. The most commonly used mounting option is underslung, but rear, front and side mounting is also done.
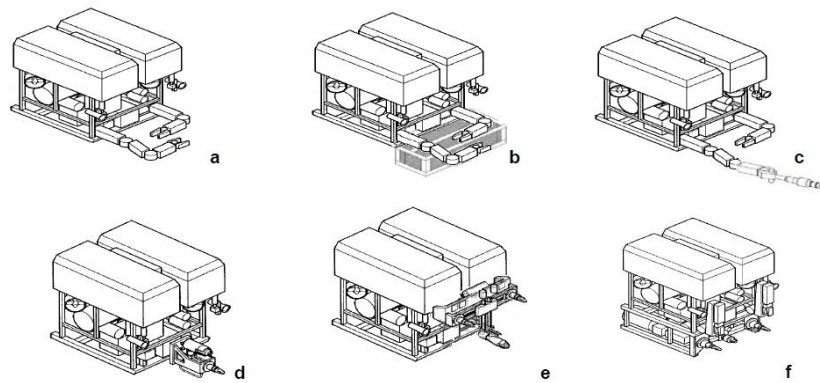
4.1.2 ROT Configurations

Installation and retrieval of subsea components and modules may be performed by use of ROVs or ROTs or a combination of these. We use the ROT system for installation and IMR tasks that require lift and/or handling capacity beyond that of free-swimming ROV. A lift line or drill string designed to support the weight and dynamic loads of the tool and the component, handle the replacement of subsea components and modules. Lateral guidance may be via guidelines, dedicated thrusters or ROV assisted.

The ROT can have its own control system (Option: A), or via an ROV (Option: B).

The second option (B) further has two alternatives. Alternative one is control through the ROVs control system for managing electricity and hydraulics. The second alternative is control done mechanically by its manipulators or through an ROV tool; these are regarded as similar options. Illustrations of the different options for control are shown in Figure 4.2.

OPTION: A

LIFTWIRE
(CRANE / WINCH)

ROT CONTROL
SYSTEM

ROT W/ SELFCONTAINED
CONTROL SYSTEM

ROT

OPTION: B

LIFTWIRE
(CRANE / WINCH)

CONTROL OPTION:

ALT.1:
CONTROL THROUGH
EL/HYDR. SUPPLY
FROM ROV

ALT.2:
MECANICAL
ACTUATION
BY ROV

ROT CONTROL
SYSTEM

TMS

ROT OPERATED BY/
THROUGH ROV

ROV

ROT
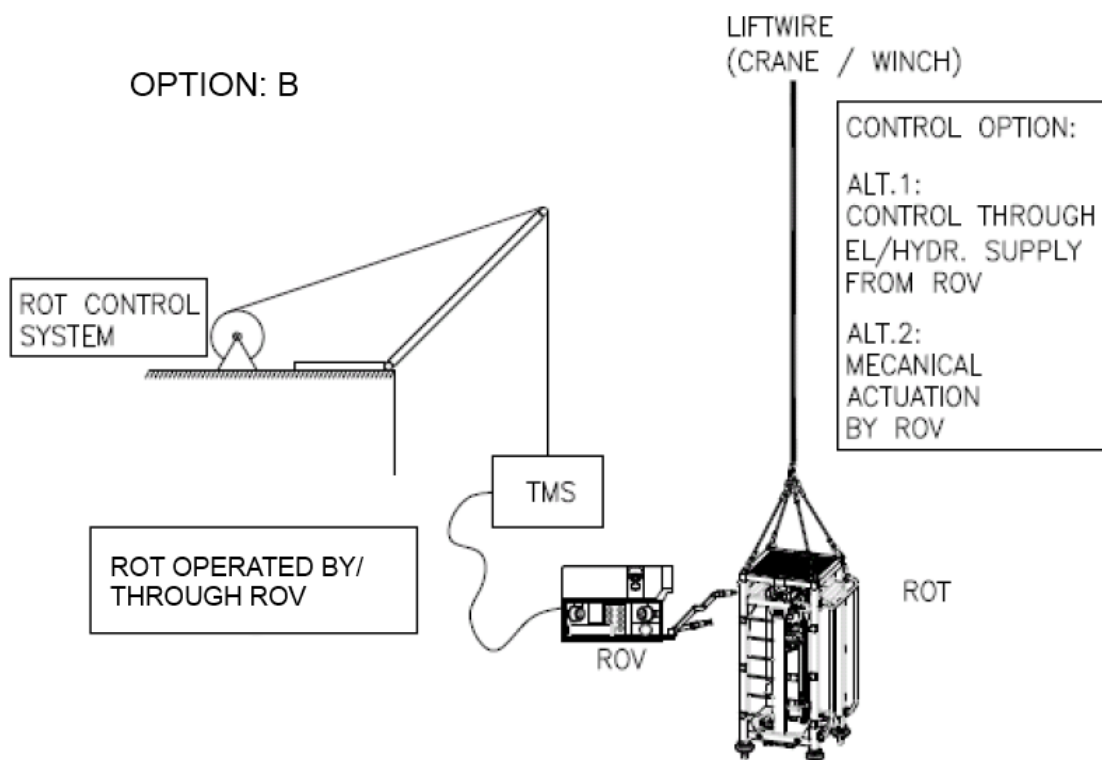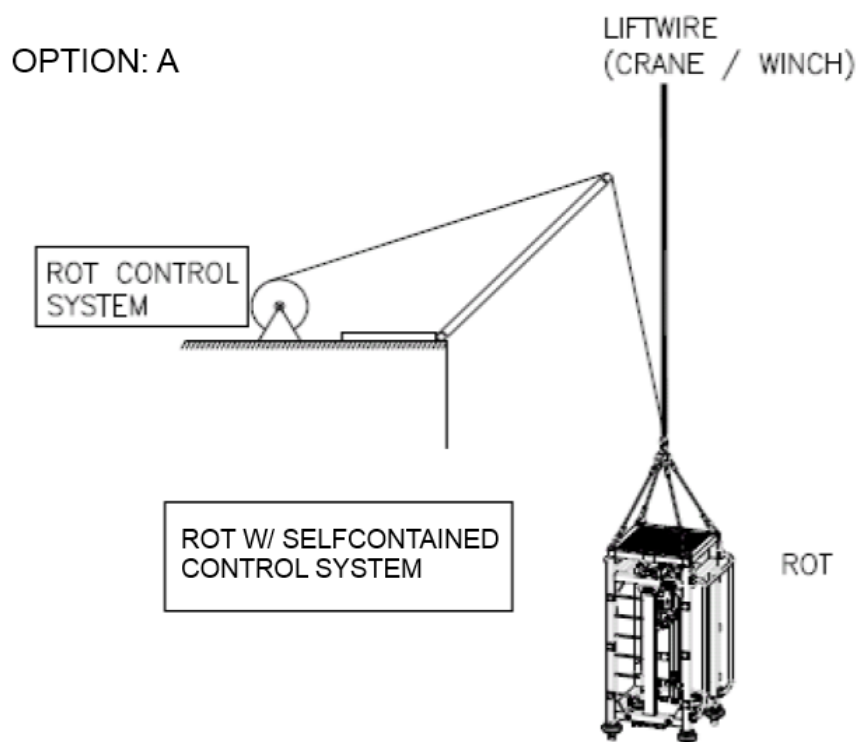
Figure 4.2: ROT control system options

4.2 Relevant tools

There is a humongous variety of different tools used in offshore and subsea ROV operations. Many are just the same concepts of onshore tools modified to operate under water; some are tailor made for an interface with subsea O&G structures and modules, while others are custom made for a highly specific event.

In this chapter, the most used tools, containing minimum one mean of actuation, will be reviewed. The tools in question are listed under, and will be described further in each own section following:

4.2.1 Manipulators

The manipulator is the main tool used by the ROV to interact physically with its surroundings. Often addressed as the ROVs arm, its task is similar to that of a human arm.

Manipulator systems vary considerably in size, load rating, reach, functionality, and Controllability. They may be simple solenoid-controlled units or servo valve-controlled position feedback units.

The manipulator is classified primarily by how nimble it is, which is specified by its degrees of freedom, also known as functions. There are several individual components that together make up a manipulator, see Figure 4.3.
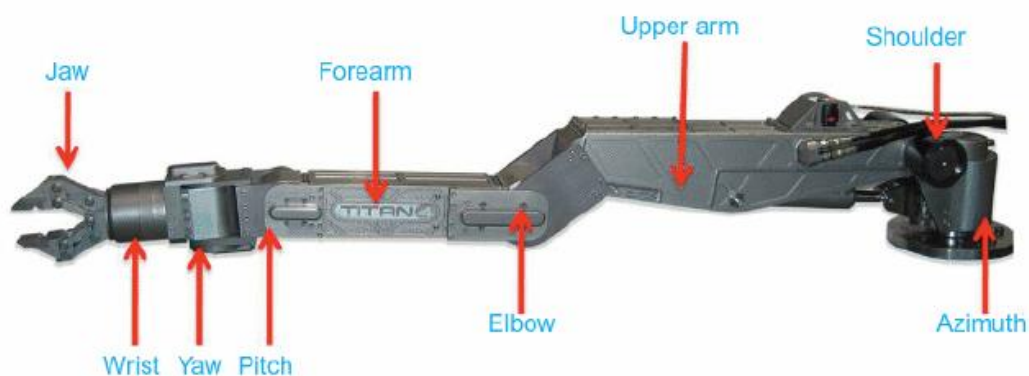
Figure 4.3: Schilling Robotics Titan 4 with named links, joints and end effector

The base is the point that joins the manipulator to the vehicle. This have to be sturdy and braced in several directions to manage forces like torsion stress sustained by the manipulator.

The links are the load bearing portions that connects the base, joints and eventually the end effector, represented by the upper- and forearm in Figure 4.3.

The joints are the connection points that induce motion between the components. Each joint contains an actuator, which translates motion between the base, links or end effector. They are divided into two categories depending on the type of motion they translate. This can be either revolute or prismatic, which translates rotary and linear motion respectively. The first six functions are represented by; 1st the azimuth (Left/Right), 2nd shoulder (Up/Down), 3rd elbow (Up/Down), 4th pitch (Up/Down), 5th yaw (Left/Right) and 6th the wrist (Rotation Left/Right). The last function derives from the jaws open and close action.

The objective of all the components is to position the end effector at a desired point so it can fulfill its purpose. This is dependent on the kind of end effector is mounted on the manipulator, of which there is a vast array. Created for operating equipment, grabbing tools, and structures or it can be a tool in itself. The simplest ones used for attaching to structures are suction foots, electromagnets or basic jaws. Ranging from the elementary grippers to elaborately designed hands the most popular by far is the intermeshing jaw.

A selection of end effectors can be seen in Figure 4.4; a) Parallel jaw, b) 4- fingered Intermeshing Jaw, c) Scissor jaw, d) 3- Fingered Heavy Duty Floating Jaw, e) 2- Fingered Floating Jaw and f) Suction Foot

a)   b)   c)

d)   e)   f)
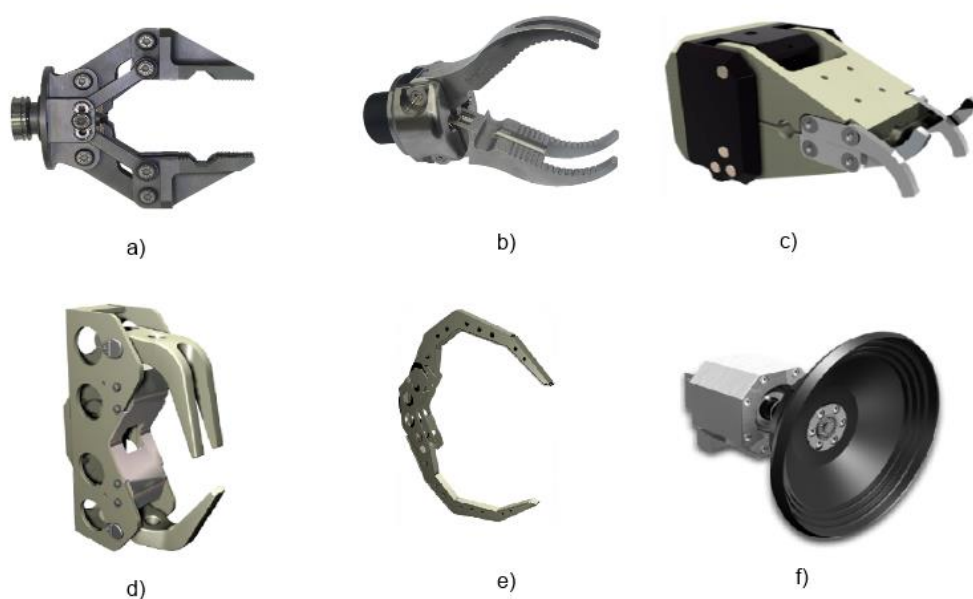
Figure 4.4: A Selection of end effectors (Courtesy of Schilling, Imenco and Perry)

Manipulators are divided into two main categories based on complexity:

Dexterous arms commonly have at least six degrees of freedom; they have the dexterity and control to execute any complex feat of manipulation. Usually they are designed in a manner to reach any spot that can be required of them, while maintaining full visual overview of the tasks executed under the operation. Some even have the ability to mount cameras on the wrist for a detailed look. As complexity increase, so does weight and the probability of failure, and this is problematic.

Grabbers have fewer degrees of freedom and are the simplest manipulators. As the name suggests their main or only purpose is to grab on to stuff, either to hold the vehicle in position or to retrieve objects from sea bottom. Because of their limited dexterity, they rely more on the vessel to position it to reach the destination point. The most basic one function grabber is just an end effector mounted directly on the frame of an ROV. A grabber might have up to five functions, limited manipulative tasks can be completed at this complexity.

Because of their simplicity, grabbers are easier to create, and most manufacturers have their own version. Consequently, a myriad of designs exists, leading to many smart solutions.

The British company AC-CESS, have created the world's smallest dual function grabber for their ACCROV, seen in Figure 4.5.
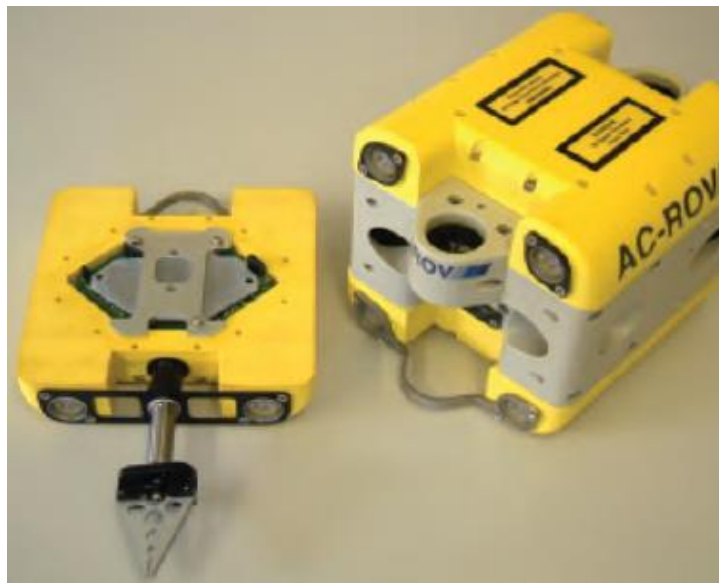
Figure 4.5: AC-ROV with dual-function grabber upgrade

It is most common to design single function grabbers around a linear actuator. Designs created by the companies; a) Articulating arm by Teledyne Benthos, b) Seabotix grabber with end-effector options and c) Nuclear grab by ROVTECH Systems Ltd can be seen in Figure 4.6.

a)   b)   c)
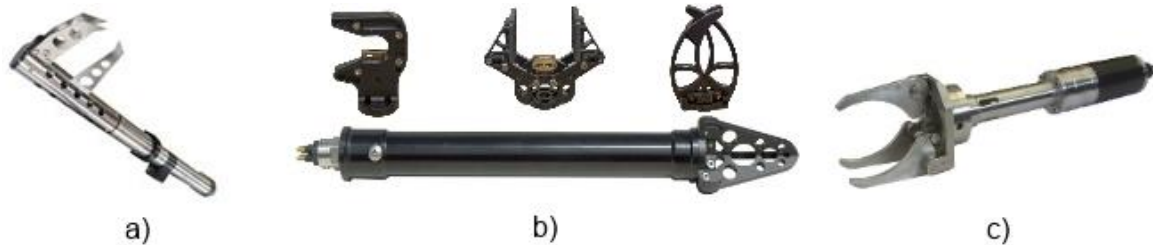
Figure 4.6: A selection of single-function grabbers

A Norwegian electric ROV company Sperre have designed a single-function grabber (Figure 4.7) in a clever manner, which incorporates a cutting ability. A floating jaw (1) and a clipper (2) is opened and closed alternatively as the actuator is operated.
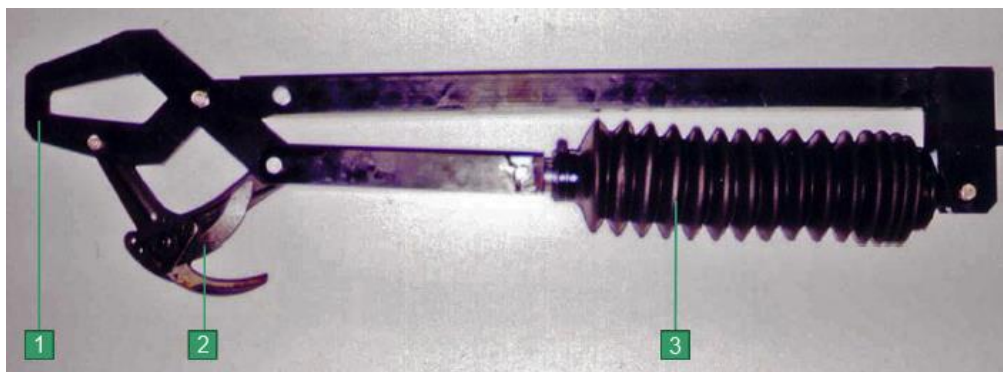
Figure 4.7: Single-function grabber by Sperre

Grabbers are also designed on the rotating actuator principle; an example of this can be seen in Figure 4.8. A hobby ROV enthusiast created this invention, based on a cheap 2,4Nm torque drill.
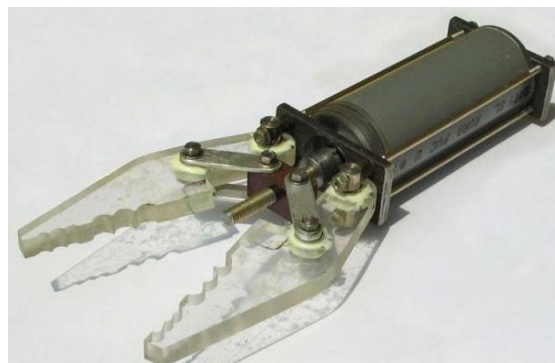
Figure 4.8: Hobby grabber (courtesy http://aquaticus.info/manipulator)

As electric ROV technology expands, complex electric manipulators have been requested [3]. French company, HYTEC Robotics seems to be the pioneer within this niche, as the only company on the market offering a relevant option. Powered by oil-filled brushless DC actuators the ARM 7E is illustrated in Figure 4.9. The jaw of the end-effector displays characteristics like a rotational speed of 42 RPM, torque of 25Nm and a closing force of 80kg.

Figure 4.9: HYTECs ARM 7E Electric manipulator

4.2.2 Torque Tools

Torque tools (TT) are the most used tool within the offshore oil and gas industry, not counting manipulators. It consist of an actuator placed inside a housing, which provides standardized interface, used to translate rotary motion to subsea structures for various purposes. In addition to the actuator, there are gears that increases the torque output, counter to monitor the operation, latches to lock the tool together with the receptacle and any circuit boards for electric control and logging.

The ISO 13628-8 standard separates the tools into various classes based upon their capacity, see Table 4.1. Tools are normally created to deliver torque from the most commonly needed first throughout fourth class. The actuator usually provides less than the torque needed for even the first class. It uses gears to reach the torque levels of the classes needed. There are special large and powerful tools created specifically to reach class five to seven, but there are also build adapters for conversion of the class 1-4 torque tools.

Class	Max. design Torque Nm
1	67
2	271
3	1355
4	2711
5	6779
6	13558
7	33895

The different classes also have corresponding receptacle classes in varying shapes and sizes. The standardized torque tool receptacle is designed to keep the tool in position and prevent transmitting rotary reaction to the vehicle. The vehicle camera can typically see the tool turning and can thus count the number of revolutions of the tool. Several manufacturers have created electric revolution counter, which can be a separate module or integrated (Smart Torque Tool) for both mechanical and digital counting. Such a modified torque tool, with the electric revolution counter (square blue box) integrated into the right end of the tool is seen in Figure 4.10.

Figure 4.10: OceanWorks Tornado TRO Smart Torque Tool (courtesy of OceanWorks)

At the time companies like Forum Energy Technologies, Oceaneering and Blue logic are all in various stages of development of electrical torque tools. This new solution has been requested by the market for some time now. [3] A benefit of going electric is a GUI that can limit torques, control speed, and direction as well as log values. Live feedback under operation and logging of earlier history connected to the valve in question can be immensely valuable for operators. By the use of servomotors, an electric tool has the potential to provide a much better accuracy, reliability and usability. [11]

Through conferring with ROV operators present disadvantages of hydraulic tool operation were discussed, some of their issues were:

- All hydraulic torque tools need frequent calibration of output torque, since the operating environment change the properties of the fluid. Many of the companies calibrate the tools in a test jig onboard the vessel before lowering it to seabed. However, as the vehicle descends changes in pressure and temperature will alter the tools output, resulting in problematic operation. Others perform calibration at seabed, but the act of lowering the calibration jig and operating it there still cause hassle.
- At smaller torque values, the precision of hydraulic tools are lowered. [11] + [17]

4.2.3 Cutters

There exists a large variety of different cutting tools, the large variation in design and function might be because there is no specific standard guiding and restricting them. Cutters are mainly operated in the subsea construction, repair and decommissioning applications. Some of the main categories, utilization and the distributors will be assessed in the following sections:

4.2.3.1 Piston based cutters

The most popular term used to describe this design, by the industry, is guillotine cutters. These tools contain a blade mounted on a hydraulic piston, when activated the piston moves the blade linearly against an anvil, and the item selected for cutting is positioned in between the two. The majority employ a hydraulic intensifier that converts the 200 bar input into 700 bar of hydraulic pressure. When the selected material is pressed against the blade and anvil by the piston and meets resistance, pressure is accumulated until the force is large enough to cut the object. These cutter types are sometimes called rams, due to the similarities to BOP shear rams.

Variators Webtool is a very successful company on these kinds of tools, and almost retains a monopoly in this subsea market. By having a good grip on the American markets, and a good standing in the European. Created to cut rope, wire, cables, chains, umbilicals and risers, they divide their Webtools into three subcategories see table 4.2:

	Soft Line Cutters	Cable Cutters	Wire Rope Cutters
Cutting dimension	55 - 135mm	100 – 270mm	38 – 190mm
Material type	Soft lines and fiber ropes	Cables, hydraulic lines, riser and umbilicals	Wire rope, cables and umbilicals
Material grade	N/A	N/A	1770 – 1960 N/mm^2
Max hydraulic pressure input	210 – 690 bar	690 bar	690 bar
Tool weight	10 – 34 kg	28 – 352 kg	18 – 296 kg

These varied cutters are distributed between two types of designs. The open-faced cutting tools, with its frame shaped like a hook it has an opening on one side to insert cable. This design is chosen for performing light to medium duty tasks.

In the gate-face variant, the frame is shaped like an upside down "U", with the opening at the bottom, and the anvil acts as a gate closing the opening after insertion of material. The gate-face design is commonly used for heavy-duty operations.

Even the smallest of the cable cutters is able to cleave chain, steel sections, and other hard materials, up to a limited diameter, with only 200 bar hydraulic pressure. However, the larger variants of the cutting tools rapidly get too big and heavy for manipulator deployment or vehicle integration. Weighing close to 300kg, which surpasses the payload capabilities of most ROVs, deployment of these are best left for the ROT configurations.

Other suppliers of guillotine cutters is the British company JAG industries, known for their powerful yellow cutters. The various cutter designs can be seen in Figure 4.11, a) JAG Guillotine Cutter, b) Webtool open-faced and c) gate-faced cutters.
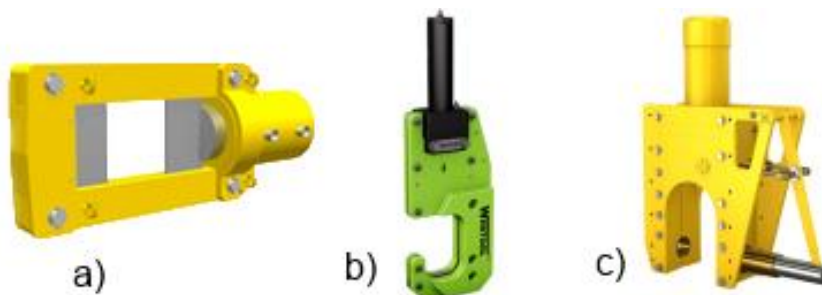
Figure 4.11: Classic piston cutter designs (Courtesy JAG Industries and Webtool)

4.2.3.2   Jaw cutter

Depending on the supplier, jaw cutters can also referred to as claw- and shear cutters. Common for them all is that they resemble and act like scissors, with two parts joining together with the material to be cut in between pressing against the object until enough force is generated to shear it. These cutters are also driven by the power supplied through a strong hydraulic piston. Some versions are true behemoths resembling lobster claws able to dismember the widest and toughest of obstacles; their size restricts them to ROT use. IKM has a version of a Holmatro hydraulic jaw cutter modified for subsea ROV use seen in Figure 4.12. Holmatro cutters were originally created for dismembering automobiles at crash sites, and the quality of their cutters gave them a pass into the subsea industry.

Figure 4.12: Holmatro jaw cutter

4.2.3.3   Rotary cutter

Rotary cutters come in various sizes and types. Commonly consisting of a powerful motor that rotates a circular blade, with a handle that is held by a manipulator or mounted on a frame, constructed to be fitted on the object to be cut. Depending on the necessity to create a clean and accurate cut, the deployment method is chosen. During decommissioning, the purpose is to remove and scrap the cut material, the operation does not have to be made in a controlled manner. While under repair or maintenance operations one might want to replace the piece removed, a frame is used to make the cut so that the replacement component is easily refitted in a manner that sustains integrity.

The blade can be a steel-toothed saw blade, an abrasive disc or a diamond wheel, the blades are chosen depending on the material of the object to be cut. A tungsten carbide tipped steel blade allows cutting of abrasive coatings and steel. The Abrasive disc is used to cut steel or concrete. Diamond wheels are applied in reinforced concrete cutting operations.

The frames are designed in several ways:

- Chop saws are fastened on one side and (directed) forced directly against the object to cut straight through it. This severely limits the object that can be cut, because the outer diameter of the cut object has to be less than the radian of the blade diameter. A variant of the chop saw is designed with two opposing blades mounted on a rigid U-shaped frame where the material is positioned between them, increasing speed of the cutting operation. Such a design can be seen in Figure 4.13.

- Circumferential saws tracks around objects like pipelines enabling a limited diameter blade to cut a pipe of far greater diameter. The saw however depends on a unobstructed path around the object, limiting its operation if the pipeline is resting on the seafloor. The cut depth can also be adjusted to just remove certain layers of coating etc.

- Linear track saw frames are constructed to create incisions along the length of the chosen object. Benefitted with a small footprint.

Figure 4.13: Oceanerring's ROV Deployed Chop Saw

4.2.3.4 *Diamond wire saw*

The diamond wire saw has one of the highest anticipated power needs among the IMR and light-intervention task tools. The saw requires both high pressure and a high flow rate to its hydraulic motor, to create the needed speed and torque. The motor is mounted on a large frame containing several guiding wheels, which moves the wire into cutting position and back again in a continuous loop (seen in Figure 4.14). The wire is diamond coated, adding the hardness to the abrasive cutting method, opening the possibility to cut through almost any material. Additionally, the saws are normally fitted with a clamping mechanism to fasten the work piece, and a function that directs the wire into it.
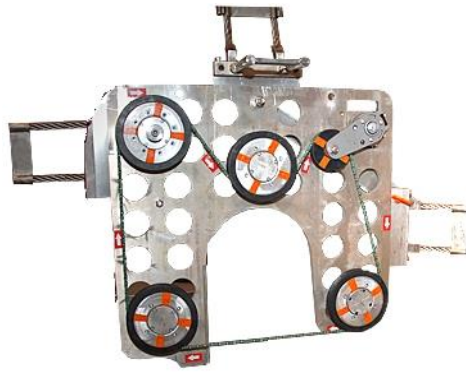
4.2.4 Grinders

ROV grinders are very similar to the angle grinder handheld power tools used for cutting, grinding and polishing in workshops on land. They function similarly to a rotary cutter but the grinders seems tinier and manageable. Similarly, they have a range of options in blades and abrasive discs, but grinders often have even more options. Shaped to be held by hand or manipulator, it also has a screen that covers most of the rotating part.

Figure 4.15: Stanley GR29 Grinder

The Stanley GR29 Grinder (seen in Figure 4.15) is an extremely popular choice for this type of tool, which should be a testament to its capability. By internalizing the working components inside the hydraulic tool, Stanley has created a compact and durable frame.

Seanic Ocean Systems offers a self-contained hydraulic ROV cutter (seen in Figure 4.16). Rated for 3300m depth, and with an ability to cut up to 152 mm of the majority of materials. The clever solution used in the design is to base it on a familiar and readily available actuator, the Sub-Atlantic SA420 thruster.

4.2.5 Multipurpose Cleaning tool

The multipurpose cleaning tools (seen in Figure 4.17) consist of a motor, placed in a frame with a handle. A rounded bristled head is mounted on the front, the motor rotates the head. The head is usually interchangeable and comes with nylon or steel brushes; this allows for cleaning, removal of marine growth, residual corrosion or hydrocarbon deposits on sealing surfaces. Many variants come integrated with a fluid ejecting ability to boost the operation. Relatively small, the head has a diameter of 30cm and the complete tool weights around 10kg.
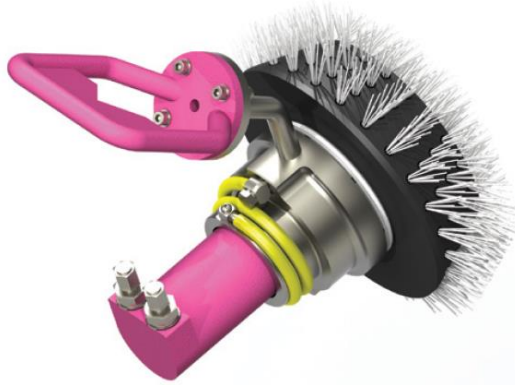
Figure 4.17: Velocious Multipurpose Cleaning Tool

4.2.6 Water dredging and jetting tool

It is a water pumping system driven by hydraulics. A dredging tool acts like a vacuum cleaner, collecting debris or sediments during excavation activities. The material is sucked through a long tube to be collected or disposed of at the opposite end. The jetting unit does the opposite, by compressing water into great pressures and releasing it through nozzles at increased speeds. This stream of water have several uses like cleaning or cutting.

4.2.7 Special tools

Tools created on demand after a critical situation arises are specialized to perform one task and have no particular application beyond that, and as an extension limited market value. Equipment like this is very hard to get a hold of any specifications or even their existence at all. The creation of emergency equipment as a rush job comes with an immense price tag, but the operator usually has no other option.

Most of these tools cannot be coined as exclusive ROV tools, since many of them only need to be guided to their position of operation or are ROTs. Not flown around for regular use, but may be structurally compliant.

Specialized tools like these can include mooring line cleaning tools or pipeline inspection tools (visual, X-ray and other). These tools can be fairly advanced, with many parts in need of coordination to operate synchronous to each other, demanding a good control system. An example of such a pipeline inspection tool can be seen in Figure 4.18.

A factor of uncertainty is associated to the special tools, because of their varied design. Their randomness is a cause of production irregularities, regarding the different characteristics and properties they necessitate. It would be prudent to offer a small repertoire of actuators and components with the combined ability to meet all requirements set for such tools. Although none of these tools gets a detail review in in this thesis, the choice of actuators should reflect such utilization. [18]
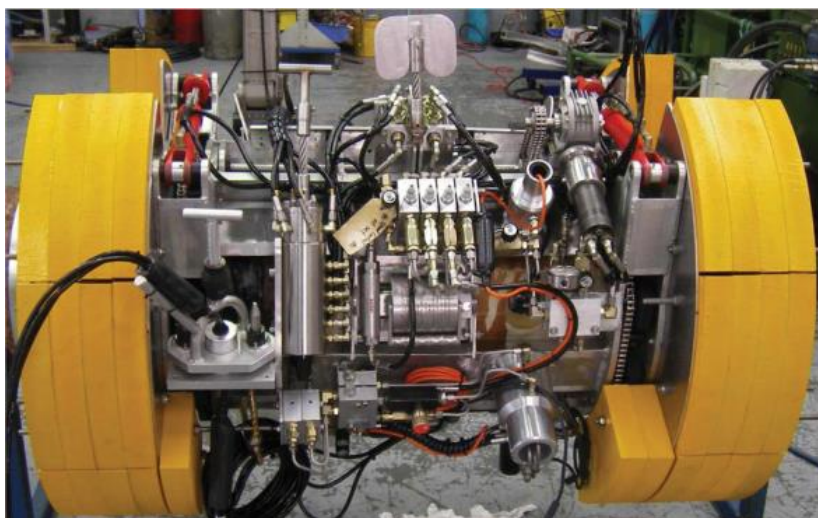
4.3 Comparison

Within this section is a comparison of the properties and characteristics of various tools. Following is a series of graphs and tables describing the properties of the tool types analyzed throughout the research period. Many of these are summaries that portray the whole range of values acquired, and not what traits the majority of the given tool variant.

4.3.1 Manipulators

Historically manipulators have been operated by hydraulics, because the vehicles large hydraulic power supply, and the fact that hydraulic arms have a good strength to weight ratio. However, as all-electric vehicles keeps growing in size and capabilities, so does the demand for electric tooling. There are many good single function electric grabbers on the market today, but the more complex manipulators seems to remain elusive, until now.

The heavy hydraulic ones are the real leviathans among manipulators. Starting with them and decreasing in power, a selection of seven-function manipulators are listed in Table 4.3. These dexterous arms are commented in the following sections.

Table 4.3: Selected seven function manipulators with characteristics

Manufacturer	Name	Reach [cm]	Weight (Air) [kg]	Depth rating [m]	Operating pressure [bar]	Flow Rate [LPM]	Lift capability (Full extent) [kg]
Schilling	Titan 4	192	100	4k (7k)	206	5,7 - 19	454 (122)
Schilling	Atlas 7R	166	73	6,5k	206	5,7 - 19	500 (250)
ISE	MAGNUM 7	152	71	6k (11k)	69	19	454 (295)
Hydro-Lek	HLK-40500R	150	59	N/A	160 - 210	N/A	210 (150)
Seamor	7F-H-ARM	107	32	0,3k	35	4,5	N/A (5)
ECA HYTEC	Arm 7E	179	69	6k	N/A	N/A	N/A (40)

FMC's Schilling Robotics have kept their niche under strict control, for a long period. As they have been the manufacturer of choice for heavy duty work manipulators. Characterized by their heavy weight, lift capability, but also a large power consumption. The equipment consumption is calculated to 2– 6,5 kW.

A competitor was found that have the possibility to give Schilling a run for their money. Canadian company ISEs Magnum 7, with approximate properties as deducted from the table. The advantage is a lower consumption of 2,19kW, while being able to lift equally or more! The edge derives from their ability to run at low pressures.

One class under, specializing on MSROVs light work applications, Hydro-Lek have an upper hand in the market. Although they do not specify the hydraulic flow requirements for their manipulators, they claim to have a "low" power consumption stated as less than 1,5kW. By using a maximum pressure of 210bar and reversing the formula for fluid power, they use a flow of maximum 4,3 LPM. Which is even lower than what Seamor supplies their manipulator.

Seamor have designed their own seven-function manipulator to be mounted on their mini-OCROVs. The 7F-H-ARM is believed to be the smallest hydraulic seven-function manipulator on the market. The miniscule weight of 32kg and hydraulic power requirement of only 262,5W, testifies that the tool is an impressing feature indeed. However, as the larger vehicles might have a dedicated hydraulic pump, Seamor need a tool skid integrated with its own HPU. It has an electrical input of 500W, and the hydraulic output of 262,5W, giving it an efficiency of 52,5%. Showing the downside of the miniature system, a power loss of almost 50% in the energy conversion between electric to hydraulic power.

ECA HYTEC is a company that has developed the first all-electric seven-function manipulator. It shows some promising characteristics like a long reach, good depth rating and low power consumption. While it falls in between categories, as the typical strength to weight ratio of electro-mechanical demands it to be mounted on a powerful ROV, but lacking the lift capability that is complimentary. Power consumption of this manipulator is calculated by use of the formula for electric power. It has a voltage of $24 - 36$ VDC and the amperage is listed as max. 4 A per function ($4A * 7 = 28A$). The maximum power consumption is then found to be $36A * 28V = 1008W$. This an amount that most ROVs can supply, the limiting factor will be the payload capability.

It appears unwise to enter the dexterous arm market at first. Since the manipulators are complex tools with advanced control systems. Additionally, the strength to weight ratio demanded will not be easy to achieve. A solution might be to acquire small and powerful electric motors, which uses rare and strong magnets. Motor prices are kept reasonable to a certain point, but as actuator sizes shrink while trying to maintain performance, the cost rises exponentially to the size attained.

Looking at the HYTEC manipulator, having a weight approximate to Schillings equipment, while only able to lift 40kg at full extension. This leads to the fact that these electric manipulators need a strength increase of three to seven times the current ability, while maintaining the same weight! The price difference between the two manufacturers is unknown, but if a considerable gap is uncovered, buying improved electric motors can be a solution. However, technology can be the limiting factor, there might not exist electromechanical motors today with such properties, if so there really is no choice.

This issue of specialized and expensive actuators are some of the main arguments for why manipulator technology should not be considered in relation to the objective of this thesis. Because such motors directly contradicts the goal of generalizing components for widespread application.

With less functions the grabbers are easier to create, and most manufacturers have their own version. Consequently, a myriad of designs exists, leading to many smart solutions. Unfortunately, the creators reviewed throughout this thesis do not specify any information about the actuators used. Consequently, they cannot be analyzed like the rest of the tools in this chapter.

4.3.2 Torque Tools

Since torque tools are created after the regulations set by ISO and have torque classes to adhere to, it is possible to calculate many of their properties. Patterns relating to the various combinations of input pressure and -flow, and efficiency can be calculated to find good combinations. As seen in Table 4.4, which show the large range of values acquired from the many variations in design and properties.

Table 4.4: A summary of torque tool characteristics by classes

Type	Weight, Air [kg]	Weight, Water [kg]	Work pressure [bar]	MAX. Hydraulic Pressure	Hydraulic Flow [L/min]	Torque [Nm]	Angular velocity [RPM]	Calculated power (by Fluid) [Kw]	Calculated power (by Torque) [Kw]
Hy. TT Class 1- 2	25 - 36	18- 25	100- 140	200	4- 10	20- 400	10- 20	0,93- 3,4	0,03- 0,84
Hy. TT Class 3- 4	42	30	85	85	24	270- 2710	8	3,4	2,27
Hy. TT Class 1- 4	30- 45	26- 35	85- 169	207	2,5- 25	20- 2710	8- 20	0,7- 3,9	0,02- 2,8 (5,6)
Hy. TT Class 5	54- 84	41- 61,5	100	140- 210	10- 24	502- 6780	4- 10	3,4- 5,6	1,4- 2,8 (7,1)
Hy. TT Class 6-7	74	55	N/A	210	5- 20	17000	2	1,7- 6,9	3,56

Note: *Some of the extreme values gained when calculating possible min. and max. values for power consumption are in reality highly unlikely to be encountered.*

Let us take a closer look at one of the torque tools analyzed, a specimen covering the average characteristics of the general torque tool, Subsea7/ i-Tech7s "B4 Class 1-4 Torque Tool". The properties of the tool is given in Table 4.5.

The benefit with this tool is that the RPM corresponding to a set hydraulic flow is stated. The resulting perquisite is a more accurate calculation. The information obtained from companies are usually maximum values for each parameter, but a scenario where they simultaneously reach a maximum cap is impossible. By example, a tool geared for maximum torque cannot attain high speeds, and high flow is commonly occurring in combination with high speeds. Similarly, peak pressure is attained when large torque resistances are met and rotation comes to a standstill.

Table 4.5: i-Tech7 B4 Class 1- 4 Torque Tool characteristics

Manufacturer	Name	Weight (air) [kg]	Hydraulic pressure [bar]	Flow [LPM] @ 8RPM	Angular Velocity [RPM]	Torque [Nm]	Power (calculated by fluid) [kW]	Power (calculated by torque) [kW]
i-Tech7	B4 Class 1- 4 TT	52	85	24	8	2710	3,4	2,3

Commenting on the tool

It has a weight just above the average torque tool. The power input of 3,4kW needed is standard for these tools, as the average lies at 3,5kW. The calculated powers based on fluid input and the torque output can be used to find the efficiency. This equipment has an efficiency of 67,6%, which is pretty decent for this kind of tool. The average efficiency calculated for all the torque tools reviewed during this research is approximately 60%. The efficiency of this specific tool might arise from the low pressure and high flow solution, normal pressure for TTs are closer to 200bar. If that is not the origin of its efficiency, it can be that the stated flow/angular velocity is not applicable in maximum torque situations.

Electric Torque tool

Blue Logic is one of the companies that have been able to create a functioning electric torque tool, it properties are listed in Table 4.6. The weight is average for a class 4 tool. The power consumption of 1,54kW, is less than half of the requirements for hydraulic tools. The efficiency is calculate to 84,4%, both of these findings are as expected from an electric tool.

Table 4.6: Blue Logic Class 2- 4 Electrical Torque Tool characteristics

Manufacturer	Name	Weight (air) [kg]	Angular Velocity [RPM]	Torque [Nm]	Power (calculated by torque) [kW]	Voltage (single Φ, AC) [V]	Current [A]	Phase Power factor	Power (calculated by electricity) [kW]
Blue Logic	Class 2- 4 Electrical TT	45	4,61	2710	1,3	110	20	0,7	1,54

Torque tools are highly specialized and design is governed by standards. Consequently, they might be challenging to integrate into the modular toolbox concept while maintaining their strict composition constrains.

Since electric torque tool technology is emerging from several specialized companies, it can be problematic for a modular tool to compete with their performances. Nonetheless, as long as a torque tool has the ability to deliver according the standards claims, exploits beyond this will be of less relevance.

Following this argumentation torque tools should not have a major precedence regarding critical elective processes during development. Even though the modular tool initially will not incorporate a torque tool option, selecting an actuator with attributes akin to what is demanded of a torque tool might be emphasized. If such criteria are taken into account then we are opening for the possibilities of using the actuator in a separate torque tool solution, at a later stage.

4.3.3 Piston based Cutters

Webtools were unwilling to share the power consumption of such tools, however in one of Velocious product brochures it was stated that the flow rate of these tools were up to 5 LPM. Together with the stated pressure of 210 and 690bar used in their equipment, the max. needed power can be found. It is calculated to be 1.75kW and 5,75kW for the smaller and larger cutters respectively. Although these power requirements might be inside of the limits for what is reasonable for an electric actuator, they are not the deciding factor. Since this is linear motion cutting, the factor limiting the motor is its output ability measured in tons.

Tecnadyne's most powerful linear actuator is rated to 1,5kW, it weights 23kg, and has a force output ability of 2,3ton. While cutting a 22mm average steel wire, forces amounting to over 400tons are needed to shear the wire rope. The gap between electric and hydraulic linear motion performances is simply too great. The reason is the combination of abilities gained in hydraulics by employing accumulators, intensifiers and the effects of Pascal's principle.

4.3.4 Diamond wire saw

Diamond wire saws are generally large and power consuming, because they need both speed and torque. A summary of diamond wire saws reviewed is illustrated in Table 4.7 below.

Table 4.7: Average Diamond Wire Saw characteristics

Name	Weight (air) [kg]	Hydraulic pressure [bar]	Flow [LPM]	Angular Velocity [RPM]	Power (calculated by fluid) [kW]	Cutting Diameter
Diamond Wire Saw	43- 450	70- 210	50- 90	1200- 1500	5,8- 21,8	2"- 84"

These tools made for ROV use actually have a smaller power consumption then what is normal. As midsized cutters can easily have a power need exceeding 25kW. If such a tool is to be made electrically driven, it should be designed towards the lower part of the spectrum. It is preferable to design towards the lowest weight and power consumptions, as these will put constrains on electrification. [3]

4.3.5 Rotary cutters, Grinders and Cleaning tools

These tools contain many similarities, as manifested by the Stanley GR29. Even though individual designs contain various properties, a summary of these tools can be seen in Table 4.8.

Table 4.8: Average Rotary cutter, Grinder and Cleaning tool characteristics

Name	Weight (air) [kg]	Hydraulic pressure [bar]	Flow [LPM]	Angular Velocity [RPM]	Power (calculated by fluid) [kW]
Rotary cutter	14- 120	110- 225	6- 65	15- 4000	1,1- 22,5
Grinder	5- 54	70- 206	15- 75	2700- 4500	1,75- 26
Cleaning Tool	10- 20	125- 206	16- 34	625- 1950	3,7- 7,9

All of these tools show a range of values within each characteristic, but the positive side is everyone overlap at some point. The trick is to create a design containing traits from a point at where they all intersect. Cutters here have an average power input of 10kW, but it should be fully viable to create a weaker specimen. Based on the fact that the smallest consumption barely peaks 1kW. The average speed is also low, 250- 300RPM. The peak speed of 4k is a phenomena only occurring in a single tool. Grinders are found to have a mean hydraulic input of 4kW. The larger part of this value derives from the large flow rate, contributing to the ability of high speed output. Cleaning tools can be seen as the softer and less power hungry of these tools. Most likely a consequence of the tools function being of lesser criticality. They were well documented as torque values were found, as the only one of these three tools. It will be a deciding factor when gearing against speed.

4.3.6 Water jetting and dredging tool

The main part of these tools are the pump, which is the component analyzed in Table 4.9.

Table 4.9: Average characteristics of dredging and jetting pumps

Name	Weight (air) [kg]	Hydraulic pressure [bar]	Flow [LPM]	Power (calculated by fluid) [kW]	Jetting/ dredging
Dredge and jet pump	10- 40	140- 275	15- 110	4,5- 45	12- 500L/min @ 0,5- 500bar or 500- 4000L/min

Jetting applications moves smaller amounts of fluid at immense speeds, during dredging the opposite, large bodies of water is moved at reduced speeds. Anyhow, the pump needs to be driven by an excessive hydraulic flow rate. Such hydraulic configurations can have immense power draws, as seen in the table. Although the typical pump show characteristics like 180bar, 50L/min and 10kW, the aim for an electrical version might be set lower. The paramount outcome is the Jetting and dredging characteristics, which should be within a certain range of usefulness.

4.4 Common components

This section looks at the common components used in various tools, and the characteristics they portray. A look at the modularization or interchangeability of parts between the tools is done.

By removing the extremes and focusing on the more manageable tool sizes in both weight and power. Tooling power consumption is calculated by hydraulic fluid input. The relevant tool types can be summarized in the Table 4.10.

Table 4.10: Summary of relevant tooling characteristics

Name	Weight in air [kg]	Power [kW]	Rotational speed [rpm]	Torque [Nm]
Torque tool Class 1-4	40	2	8- 20	20- 2710
Cutter, Linear, Soft line	10- 20	1,15- 1,75	N/A	N/A
Cutter, Diamond wire	43- 95	5,8- 17,5	1200- 1500	N/A
Cutter, rotary	15- 35	2- 12	15- 300	N/A
Grinder	6,5	4,5	2700- 4000	N/A
Cleaning tool	10	4,5	625- 1950	10- 40
Dredging/ jetting pump	10- 30	5- 15	N/A	N/A

Commenting on the table:

By calculating input and output values for Class 1-4 torque tools it is inherent that the average input power value should be around 2,5kW. Blue Logic proves that it can be achieved at just over 1,5kW; it seems obvious that electric mechanical actuators have a far greater efficiency. Because of the lack of information about torque values and no precise test data available for the rest of the tool types, it cannot be confirmed if this trend applies to other tool types. However, if this applies, the power consumption values listed in the table can be downgraded to some extent regarding electrical actuation.

Regarding linear cutters, the only reasonable option is the small soft line cutters, since bigger cutters have excessive power consumption, bulk and force requirements.

Regarding diamond wire cutters there are separate levels of power, with steps like 6, 10, 15 and 20kW. The two lowest steps being the most viable options for an electromotor design choice. Research should be conducted into the limitations of splitting the power consumption between several motors, dividing the speed and torque requirements among them. Since these saws already use several guide wheels to lead the wire. Why not use three 2kW actuators to drive one wheel each, or five wheels of 2kW?

Regarding rotating cutters, they also have steps as the Diamond wire saw, but these are at 2, 6, 8, 10 and 12kW. However, this needs to come from a single motor, with speeds limited to 300RPM. Several different speeds where recorded in these tools, the mean was placed between 250 and 300 RPM. At such low speeds, the motors have larger torque values.

Grinders show many similar characteristics, although they do have fluctuations in designed consumptions, they are not uniformly distributed. Instead, they have a gap between the smaller and larger motors. Performances lay around 2, 4, 8 and 10kW before there is a jump straight to larger than 20kW. This should immediately discount the bigger ones.

Cleaners have a more evenly distributed average power draw for values around 4,5kW. However, as additional info enables calculation of the output power in one instance and rated electrical power is given in another, a realistic electrical value can be found. The input in the given instance is 4,2kW and an output of 2,6kW, giving it an efficiency of just over 60%. The other instance is a 3,7kW motor, with an output of 1,8kW. If driven electrically resulting efficiency is less than 50%!

The dredging and jetting pumps show widespread and evenly distributed characteristics. As such, it will be necessary to design towards the lower end of the spectrum, focusing on the 5, 6, 8, or 10kW range. Even though speeds are not stated, it can be indicated by the high hydraulic flow rate. As such a gearing solution towards high speeds will be needed in an electric version.

The results seem positive in the light of power consumption, as indications point towards a much lower power need than previously thought. Lesser electrical actuators might drive tools requiring actuator sizes that initially seemed hard to reach. The next step is then to find the available power supplied by various ROV classes. Table 4.11 shows power available to additional equipment like tooling, manipulator and sensors. The range of available payload capacity adhering to the vehicles reviewed in each class is also listed.

Table 4.11: ROV classes and their power and payload capabilities

Rov class	ROV Sub-class	Available power [kW]	Payload option [kg]
OCROV	Micro	N/A	N/A
	Mini	0,1	2,3
	Large	0,1-0,5	5-15
MSROV	Shallow	0,5-1,5	15-45
	Deep	1,5	30-45
	Heavy	15-30	50-250
WCROV	Standard	24-41	200-300
	Heavy	35-200	250-450

One can see that the WCROVs have capabilities of catering to most necessities. For large electric vehicles, this power might be reserved for a hydraulic tooling skid, but as long as the power-hungry hydraulic pump is dropped, there should be plenty of power available to run most tools.

The heavy MSROV also have great capabilities in both respects, while the smaller MSROVs are lacking in power supply. This might be a result of the retailer's inability to relay information. Not the fact that the vehicles cannot deliver over 1,5kW in auxiliary power, because they most likely exist.

5 FUNCTIONAL DESIGN SPECIFICATIONS

5.1 Choice of motor

5.1.1 Operational environment

The tool is operation submerged in seawater. The environment put several constrains on the tool, they have to be considered when choosing motor and housing.

- Corrosive environment, seawater is corrosive towards several metals.
- Low temperatures, temperatures decrease as descending.
- High pressures, ambient pressure increase as descending.

A housing shall be made of corrosion resistant materials, to limit or prohibit degradation of equipment. All materials shrink and compress to a varying degree when chilled, extra consideration should be given to elastomeric materials like O-rings. Great pressure result in a risk of leakage and water intake, the housing and electrical cabling must be designed to resist such failures. The housing can be oil filled to compensate for the pressures sustained by the environment. The oil needs a set of thermal properties assuring optimum viscosity at operating temperature and pressure. Considerations should be given towards application of failsafe mechanisms during control and power failures. [19]

5.1.2 Motor Type

In order to find the best-suited motor for our applications, a review of the different types and their properties have been conducted.

The most relevant types of motors for our application is found to be externally commutated synchronous motors. These types of machines are described in the following sections, along with the reasons to why they are suited for our usage.

5.1.2.1 Permanent magnet synchronous motors

Permanent magnet synchronous motors (PMSM) are the best choice regarding the applications for our motors. Permanent magnets create a constant flux in the air gap; this lends the properties of a synchronous motor to the asynchronous induction motor, providing them with the label permanent-magnet synchronous motor.

5.1.2.2 Advantages

The magnets give a strong flux; reducing the requirements of a small air gap, and produce a higher output in relation to motor size. Another major advantage of these motor types is the ability to run them filled with fluid, protecting against environmental pressures and adding superior benefits to cooling. A poly-phase power supply is preferential as this gives better control over speed adjustment and torque at lower speeds.

5.1.2.3 Disadvantages

Permanent magnet motors have an unwanted issue, cogging. This is a resistance to rotational motion, created by the attraction between the rotor's magnets and the stator. The solution to this is having many rotor poles. Another issue is that overheating might demagnetize the magnets, as magnetic fields are strongest at lower temperatures.

5.1.2.4 AC versus DC

Of all available types, we focus on brushless DC motors and AC synchronous. The difference between AC and brushless DC- motors, are the integrated inverter and rectifier, sensor and inverter control in the DC version.

Table 5.1: DC brushless and AC synchronous properties

DC brushless	AC Synchronous
High peak torque and acceleration	Capable of high torque or speed output over time
Efficiency drops with voltage increase	Simple design
High dynamic response	High power density
Excellent control accuracy and speed variation	High efficiency
High initial cost	Challenging control accuracy and speed variation
Power range up to 1MW	Power range up to 10MW
Cogging	Low cogging
Excels at low voltages	Excels at higher voltages

[20]

The original thought was to create multiple tools, based on the same actuator. It is advantageous if this actuator already has some degree of popularity, this reduce costs and increase availability. As the research was conducted several companies with the same aspirations where uncovered.

Hydraulic examples are previously mentioned, like the Stanley GR29 and Shark technologies grinder. However, a company with an electric version was found, Norwegian all-electric ROV Manufacturer "Sperre". Based on their thruster of choice, they have created drills, grinders and pumps.

The thruster is in the 2kW range, actual power consumption varies from 2,36- 2,44kW. Supplied with 3Φ 460 V, 3,6A and a power factor of 0,84, power is calculated to 2409W. With an efficiency of 85%, the power output will result in 2047W. Output speed is set to 1690rpm giving a torque of 11,6Nm. The performance of their tool is unknown. However, if he drill is able to pierce most relevant materials, the grinder is able to cut and grind relevant materials and the pump can deliver needed jetting and dredging capacity without the motors stalling and degrading, this is a testament to the possibilities of achieving the goal of this paper. [21]

The characteristics of relevant motors designed by "Parker" have been calculated, to get a feel of the qualities that can be expected of potential actuator candidates. Calculations have been made on their frameless PMSM; HKW: Frameless Electro Spindle Servo Motor kits and NK/ NW: Frameless Low Cogging Servo Motor kits (see Figure 5.1). Characteristic summaries and some of the relevant motors will be described in the following sections, the full list can be found in Appendix B.

Figure 5.1: Parker NW: Frameless Low Cogging Servo Motor

The first thing to deduct from Table 5.2 is the severe increase in motor capabilities when water-cooled. Torque and speed capabilities are effectively doubled, but power consumption is also raised more than threefold! This confirms the ability to push the limits of electric motors with proper cooling, while maintaining motor size and weight. These motors have the added ability low cogging brings, smooth and accurate control at low speeds.

Table 5.2: Parker frameless servo motor

Parker Frameless Low Cogging Servo Motor – NK/NW Series	
Frameless servomotors	
Low speed torque	0,4- 42 Nm
Max. Speed	8000 min^-1
Max. Constant power	0,25- 7,7 kW
Inertia	13- 9200 kgmm^2
Weight	0,42- 17,44kg
Frameless With water cooling	
Low speed torque	3,4- 72 Nm
Max. Speed	15000 min^-1
Max. Constant power	4,7- 30 kW
Inertia	79- 9200 kgmm^2
Weight	0,88- 17,44 kg
Size	Small: 62mm dia. * 75mm length. Large:143mm dia. * 240mm length

The speed and torque range together with the low weight seems promising; let us take a more detailed look at specific motors.

Table 5.3: Selected NK Series Parker motors

Power supply [VAC]	Rated Torque [Nm]	Max. Speed [min^-1]	Nominal Current [Arms]	Power input electric [W] three phase	Power calculated by Output [W]
2kW					
230	4,29	4000	5,28	1788	1797
230	7,42	2200	4,99	1690	1709
400	4,29	4000	3	1773	1779
400	4,1	4500	5,56	3274	1932
5kW					
230	13,24	3600	14,82	5018	4991
230	22,88	2200	15,70	5316	5271
400	12,94	3900	9,07	5341	5285
400	23,17	2100	8,47	4988	5095

For the low cogging type needed info for the water-cooled types where unattainable, however the air-cooled can be seen in Table 5.3. The characteristics of the motors seems well balanced and have the same efficiencies regardless of input. This is recognized when the speed is doubled, then torque is halved, if two motors of the same power is compared. The motors show characteristics that is within the range of our tooling needs. The motors with power consumption around 1,7kW can definitely be run at 2kW with water-cooling. The black sheep here is the fourth motor under the 2kW label. It must be stretching its capabilities for its size category, because it shows extremely bad efficiency (59%) compared with the others.

Table 5.4: Selected Parker HKW series water-cooled motors

Parker Frameless AC Brushless Motor - HKW Series, Permanent magnet synchronous motor								
Motor	S1/S6 Power [kW]	Low speed Torque [Nm]	Low speed S6 Torque [Nm]	Base speed	Max. Speed [min^-1]	Permanent current at Low Speed [Arms]	S6 current at Low Speed s8 [Arms]	Weight [kg]
HKW 85 66 BAU	2,3	4,9	7,3	4480	50000	6,8	13,50	3,9
HKW 85 99 BAQ	4,7	7,4	11,0	6070	50000	12,6	27,00	5,2
HKW 85 66 BAP	4,9	4,5	7,3	10400	50000	12,2	27,00	3,9
HKW 108 80 CAN	4,9	10,0	15,0	4680	30000	10,6	16,20	6,5
HKW 108 200 CAJ	9,0	30,0	45,0	2870	30000	23,1	35,60	14,0
HKW 85 99 BAL	10,0	7,3	11,0	13100	50000	24,7	50,20	5,2
HKW 155 120 CAR	10,0	48,0	75,0	1990	24000	21,8	36,30	12,0
HKW 155 160 CAR	10,0	68,0	100,0	1410	24000	23,2	36,30	16,0
HKW 195 180 CAT	10,0	120,0	180,0	798	16000	26,1	47,20	35,0
HKW 85 66 BAK	10,2	4,2	7,3	23200	50000	22,4	54,00	3,9
HKW 155 80 CAR	10,3	28,0	42,0	3510	18000	19,0	29,40	8,0
HKW 108 80 CAI	10,4	10,0	15,0	9930	30000	21,3	32,40	6,5

Selected water-cooled Parker HKW motors at the stages 2, 5 and 10 kW are seen in Table 5.4. The motors within this table built towards higher speeds than the NK series, they also show more similarities to the properties sought by the tools we want to build. These motors appear to perform just a bit better than the NK series, but this is at the expense of the low cogging ability that ensures control at lower speeds. However, for the tooling options we seek, this ability might be of less relevance. Thus, an advantage might be given to the HKW series. The weights listed for the models also look reassuring, weight for specific NK models is unattainable, but is likely to be similar. [22]

5.1.2.6 Cooling

The strength of a magnetic field is reduced when a magnet is heated, it is therefore necessary to keep it from overheating. Cooling will not be a major issue when the tool is fluid filled and submerged, heat will quickly dissipate into the surroundings. The fluid should have lubricating properties and be environmental friendly.

5.1.2.7 Duty cycle

The duty cycle of an operation is the total percentage a motor is on, during a specific time period for a complete on-off cycle. The length of this period can vary for magnet size and its heat properties. A magnet can be rated for a continuous or intermittent duty cycle, dependent on its ability to run throughout the period in room temperature without overheating. The chosen motor should have a long duty cycle.

5.1.2.8 Sizing

Based on previous conclusions a suggestion is put forth to narrow the choice of actuators down to four. To focus on these and build tooling systems around them. They can each be the main actuator or one of several in a multi-function tool.

Today a large part of the electric equipment is based on a typical power consumption of 2kW. It should be fully possible to create most of the tooling options examined, with an actuator of this size. However, performance might balance on the edge of what is demanded. Especially since the typical tools reviewed, prefer high-speed values and to a certain degree large torque. For a tool to stall, or be stuck during a subsea cutting operation is a highly unwanted situation. Table 5.5 show theoretical obtainable torque values related to motor sizes and speeds of 2000rpm.

Power [kW]	Speed [rpm]	Torque [Nm]
0,5	2k	2,38
2	2k	9,55
5	2k	23,87
10	2k	47,75

It would be beneficial for the motors to have the speed and torque characteristics preferred by the majority of tools, as their standard properties. This means that gears can be eliminated for the majority of operations. Gears is then created for the minority of tools that prefer different characteristics.

For the specialized tools, there might be several support applications and actuations need, with lesser requirements regarding output torque. For such applications the smaller 500w motor can be recommended, this is not based on any concrete requirements, as they would vary with each individual case. It will in any case be preferential to select a motor as a standard for such applications, to focus on stock availability and price reduction. As such, it will be beneficial to construct the functions of the specialized tool to accommodate this motor size, instead of being bothered with carrying a large stock with a range of motors. The applications for such a motor are most likely low voltage and high precision and speed control, the PMDC motor is recommended. Basic properties of such a motor might be as plotted in Table 5.5, because large torque operations will most likely not be its main purpose.

The rest of the motors might be set to a standard around 10Nm, as this might be the maximum torque they will encounter in most situations. The 2kW motor can just stay as it is listed in Table 5.5. The 5kW motor will get a speed increase to 4775rpm, and the new 10kW motor's speed is 9550rpm. [23]

In PMSM the speed is controlled by the input power frequency. Frequency is measured in hertz, output speed can be calculated by the formula:

$$RPM = \frac{Hz * 120}{Number\ of\ poles}$$

5.1.3 Gearing

From the last subchapter the three larger motors where set to a standard of 10Nm, by gearing them for high torque cutting operations the values found in Table 5.6 can be obtained. In this solution the motors where originally created for high speeds, and then geared for the opposite extreme of high torque. Individual gears are needed for each motor type, and if these two options together with frequency speed control are unable to cover the needed ranges, more gears must be created.

Table 5.6: Suggested motor basic speed properties geared for high torque

Power [kW]	Speed [rpm]	Torque [Nm]	Gear ratio	Speed [rpm]	Torque [Nm]
2	2000	9,55	1:4	500	38,2
5	4775	10	1:10	478	100
10	9550	10	1:20	478	200

A better solution might be to keep the standard motor load out properties to a mean, like the initially mentioned 2000rpm, and gear up and down with the same ratio, leading to the necessity of only designing two types of gears. If the motors initial standard properties are as stated in Table 5.5, a gearing solution could be as demonstrated in

Table 5.7. This solution leads to the ability to reach three useful speed and torque ranges, by only creating two gearboxes. This can be a major advantage, as long as these ranges are outside the capabilities of frequency speed control. If a frequency speed-control solution has the same efficiency, mechanical gearing is rendered obsolete.

Table 5.7: Suggested simplified gearing solution

Power [kW]	Gear ratio	Speed [rpm]	Torque [Nm]
2	1:3	666.7	28,7
5	1:3	666.7	71,6
10	1:3	666.7	143,3
2	3:1	6000	3,2
5	3:1	6000	8
10	3:1	6000	16

5.1.4 Deployment options

Tools can be deployed by solutions detailed in subchapter "4.1 Tool deployment concepts". For the tool design sought in this paper it might be preferable to deploy with a handle for manipulator use, since the cutting, cleaning and grinding tools might want to reach certain spots. However, designing or modifying for several deployment options is no difficult task. The following subchapter further details the handle solution.

5.1.4.1 Handles for use with manipulators

Handle bars are mounted on tools for lifting by ROV manipulators. There are three standard handle designs; the T-bar, D-ring and the X-bar (fishtail). They are designed to be compliant with the diverse types of manipulator grippers or jaws. Material strength is recommended to exceed 450 N/mm^2.

The designs have various properties but they share characteristics like:
- Low cost
- Fast and easy mounting and dismounting
- Cheap maintenance
- Standardized design

However, caution must be made when applying torque or force, they might not be able to handle excessive amounts. The T-bar has only one stem, and need to be handled with special care. Another danger of using this bar is the risk of snagging present, good thing that it is the cheapest alternative. [24]

5.2 Possible design concept

The following subchapter runs through several of the criteria and observations made throughout the thesis, and based on these; make a suggestion for rough design concepts that might be the basis for the solution to the objectives of this thesis.

The design should consist of a housing for a frameless actuator. Such a housing might look like Figure 5.2; the actuator is placed inside, producing torque in the shaft protruding from the front. A control unit like the electric of a servo might be placed at the far end inside the housing. The

housing should have some kind of simple locking mechanism (as seen in Figure 5.2) along its length, this can hold a ring that can mount a handle, like a D-ring, for manipulator deployment.
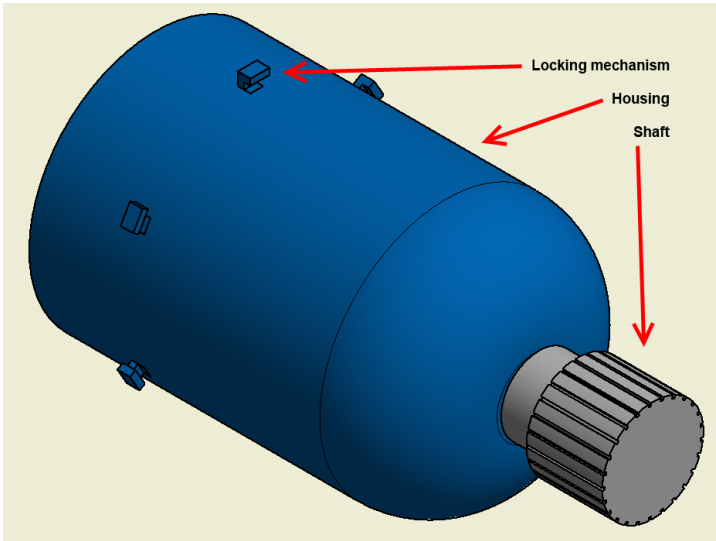

Figure 5.2: Suggested motor housing design

The housing shall be composed of corrosion resistant metallic material, popular choices are listed in Table 5.8.

Table 5.8: Properties of potential metals

Metallic material	Stainless steel	Titanium	Aluminum
Density	7,86g/cm^3	4,51g/cm^3	2,8g/cm^3
Specific strength	254kN*m/kg	288kN*m/kg	214kN*m/kg

The best-suited alternative is aluminum, with a specific strength (214kN*m/kg). Its best feature is a very low density (2,8g/cm^3). There is a high probability that the housing have no need for the durability provided by titanium, and steel lead to weight problems. Aluminum also has a cost benefit in comparison to the other materials. Aluminum is going to be anodized to further increase corrosive resistance. The effects of shrinking in the chosen aluminum housing design due to changes in temperature shall be researched.

All components should be water tight and able to handle pressure. For depths down to 300m, common housings might be filled with pressured air. For greater depths, the housing will need to be fluid compensated to counteract the ambient pressure. The size and requirements of oil compensation equipment in the suggested design must be researched.

Weight should be kept under 30kg, to cater to ROV payload limits, additionally Hytec's electric manipulators lifting capability limit of 40kg.

To ease modularity and interface for components that is to be mounted on the front of the motor housing, to interact with the shaft, a locking mechanism needs to be designed. As exemplified in Figure 5.3, where a gearbox is to be locked in place at the front of the housing. The motor shaft interacts with the receptacle in the back of the gearbox, and gears inside transforms the torque into wanted output from the gearbox shaft. The locking mechanism should be a simple "twist and click" design that binds the equipment together, but is still simple enough to be assembled/disassembled by a ROV manipulator.
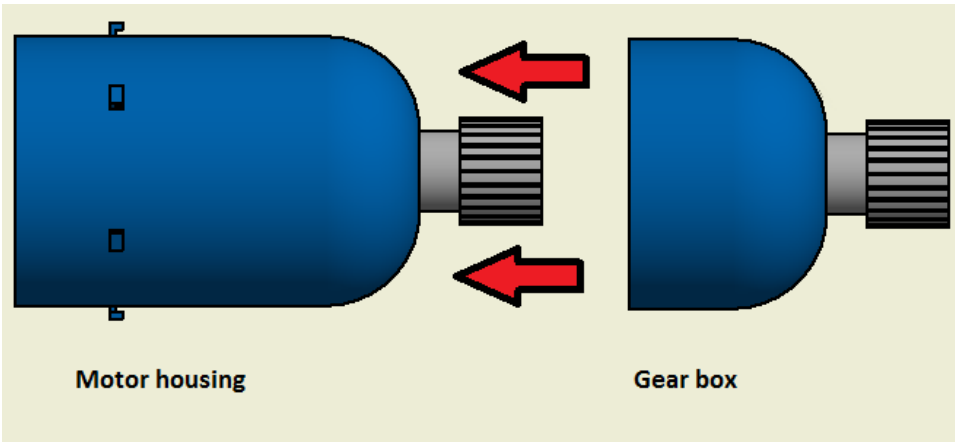

Figure 5.3: Suggested motor housing and gearbox solution

Figure 5.4: A selection of end effector options

Various options of attachable equipment as illustrated in Figure 5.4, should allow the actuator to perform cleaning, cutting, drilling and grinding operations.

Furthermore, the locking mechanism in front of the motor housing shall allow fastening into point (b), where the shaft might drive impellers (c) inside of a pump house (a), as illustrated in Figure 5.5. If this has hoses and other equipment necessary, it can perform dredging and jetting tasks. Detailed design of the housing and the remaining equipment is off course needed.
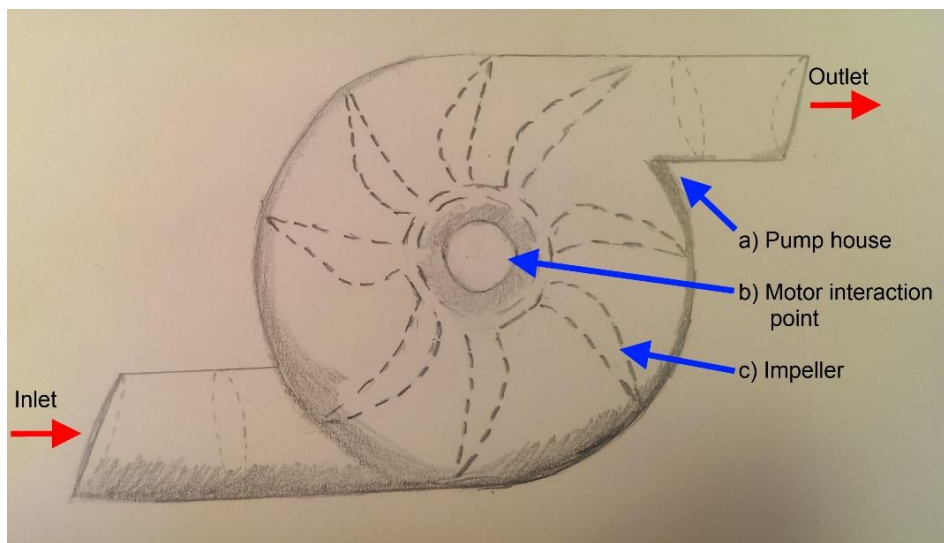

Figure 5.5: Suggested pump housing design

If the actuator is mounted on a linear screw gear solution, it can transform its torque into linear force. This linear actuator (a) can be locked inside an open-faced cutting tool housing (b), with pre-mounted blades (c), as seen in Figure 5.6. This tooling solution will be limited to soft line cutting, as the actuator is unable to generate the forces needed to cut wire and cable. As such, this solution might have limited value being so complex in comparison to preexisting solutions.

A diamond wire tool is also a possible tool solution, like the two previous tools, it will also be in need of a mounting frame, and this one is rather large and complex. It is of considerable size so it has the possibility of being mounted on a pipeline, or similarly large object. In addition, the diamond wire guide-wheels are needed, but also a locking mechanism to attach to the object to be cut. The 500W DC might power such locking mechanisms, and the largest 10kW motor should be the main drive motor for the wire. This configuration would need both AC and DC power, resulting in further tool complexity. This design is therefore not a solution to contemplate before a later stage.
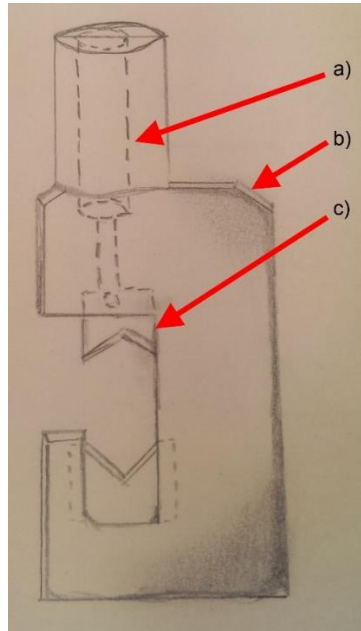
5.3 Possible datasheets

Within this sub-chapter, lies the tables that represent the suggestion of the preferred actuator design characteristics. The creation of these is one of the main goals of this thesis, and they each represent culmination of the research performed throughout this paper. The industry has been asking for standardization of electrical equipment, but also technological development to ease the operation of high voltages subsea. This is why the AC actuators reach voltages of 3k. [11] [17]

The first of the actuators is the 0,5k PMSM, it's datasheet is found in Table 5.9. This is a smaller motor with the purpose of performing tasks of higher accuracy, with a lesser need of force. This has the size and performance of many other motors on the market today. These motor types are popularly used as thrusters. Initially it does not have the same purpose as the rest of the actuator presented in the thesis, but is rather a step towards standardizing and electrification of the specialized tools. Many engineering firms repeatedly perform such projects of designing costly, unique and specially designed tools. By repeated use of a familiar actuator, the cost of performing such projects might decrease. All the actuators options proposed, might be used in conjunction to achieve advanced feats of engineering. The actuator might also be a thruster motor, if so an agreement can be made with a supplier for a good delivery deal. It is usually an advantage to utilize a popular model, because there generally is a lower delivery time and higher reliability, until demand exceeds the manufacturer's production capabilities of course.

Model	0,5k PMSM
Type	DC brushless
Housing material	Aluminum
Pole number	8
Phase voltage	110-440VDC
Rated current	1,1- 4,5A
Rated power	0,5kW
Torque	2,5Nm
Rated speed	2000rpm
Efficiency	85- 95%
Power factor	0,75- 0,85
Corrosion protection	Anodizing
Cooling	Liquid
Mass	5kg

The second datasheet (Table 5.10) is of the 2k PMSM, this is the smallest of the main drive motors in the suggested tool designs. The power consumption of only 2kW suggest a pass into must systems, as this is an amount most ROVs have available. The water-cooling suggests that in reality the motor can be rated for a lower consumption, giving it a pass into the even less capable systems. However, it might be problematic if it is used in tooling applications beyond its intended purpose, like cutting of an especially though material.

Table 5.10: Suggested characteristics for a 2kW motor

Model	2k PMSM
Type	AC synchronous
Housing material	Aluminum
Pole number	12
Phase voltage	110-3000VAC
Rated current	0,7- 18A
Rated power	2kW
Torque	9,6Nm
Rated speed	2000rpm
Efficiency	85- 95%
Power factor	0,75- 0,85
Corrosion protection	Anodizing
Cooling	Liquid
Mass	10kg

The third actuator solution suggested is the 5k PMSM (Table 5.11). This motor should be powerful enough to drive most tooling without problems.

Table 5.11: Suggested characteristics for a 5kW motor

Model	5k PMSM
Type	AC synchronous
Housing material	Aluminum
Pole number	12
Phase voltage	110-3000VAC
Rated current	1,7- 45A
Rated power	5kW
Torque	23,9Nm
Rated speed	2000rpm
Efficiency	85- 95%
Power factor	0,75- 0,85
Corrosion protection	Anodizing
Cooling	Liquid
Mass	15kg

The real heavy duty workhorse of the suggested actuators is the 10k PMSM (Table 5.12). This actuator can definitely power al the suggested tooling options, but finding available power gets increasingly harder as consumption rise. Today's ROVs might designate it for other purposes.

Table 5.12: Suggested characteristics for a 10kW motor

Model	10k PMSM
Type	AC synchronous
Housing material	Aluminum
Pole number	12
Phase voltage	110-3000VAC
Rated current	3,3- 90A
Rated power	10kW
Torque	47,8Nm
Rated speed	2000rpm
Efficiency	85- 95%
Power factor	0,75- 0,85
Corrosion protection	Anodizing
Cooling	Liquid
Mass	20kg

6 DISCUSSION

A manufacturer will always claim to have the best solution, whether it is a hydraulic or electric. Luckily, most major manufacturers deliver reliable equipment, and if they do not, they are quickly overrun in a competitive market. There might also be easier to get ahold of spare parts for a major manufacturers system. Fewer parts necessary for keeping a system operational and the faster one can obtain these, hence better it is. All-electric vehicle have fewer parts and simpler overall system. Hydraulically system has more components, leading to more faults. Leakage is major problem adding to OPEX. Loss of energy due to conversion efficiency, and continual losses in lines and valves due to pressure and flow upkeep. Power converted once, and then supplied to every component.

Electrics need actuators at every point; these are larger and heavier than the hydraulic counterparts are, and thus leads to bulkier system and tools. However, if there is an electric failure in the system it might not ruin several components.

The hydraulic system links all the components together, like the blood supply in our bodies, with the pump acting as a heart. If the system is worked hard and not maintained properly, it can generate a pump failure, which can have catastrophic effects. This can lead to fluid contamination which progress to damage the entire system. Even if environmental friendly hydraulic fluids are used, leakage is something to be avoided.

When the heavy tools needed in construction, repair and maintenance exceeds 75 horsepower, it can be preferable to save weight by only having one prime mover, the hydraulic pump. When the solution to the problem is to put hydraulic skids on an all-electric ROV to support tooling, a majority of the advantages are negated.

It is argued that hydraulic power is a necessity for operating the heaviest of tools. This is true in relation to manipulators, where the strength to weight ratio still cannot be matched. There is also advantages regarding maximum power output in linear actuators, achieved by the use of accumulators and Pascal's principle.

As the electric actuators decrease in size and increase in power, electric manipulators will eventually become comparable to the powerful hydraulic ones. As noted in relation to torque tools, where the electric versions presently stand ready to replace the hydraulic, with improved performance. Electric manipulators are still in their adolescent, and do not pose any direct threat to the well-established hydraulic solutions.

For the time being, it appears as the various ROV classes and their capabilities place them in separate niches, where they flourish individually. At least as long as the electric ROVs need auxiliary hydraulic power to run the most demanding equipment.

7 CONCLUSION

The objectives of the thesis have been executed, and knowledge within the relevant issues gained. The purpose of acquiring an overview of the relevant fields necessary to initiate a development phase with the best possible starting conditions.

The research performed during this period have gathered the information to build a foundation for making critical choices on how to proceed with development. The knowledge needed to determine the quality of the proposed solutions, whether a development program is to be initiated or not, and if so how to progress further shall be clear.

Firstly a background and foundation of the ROV business and the related content was established. Then the differences and challenges between electric and hydraulic systems, the conclusion was divided. The electric systems are able to surpass the hydraulic in several respects, but the hydraulic will always have advantages in some respects. Regulations and standards were of little restraining effect, to our design and operation.

Through market analysis, manipulators and torque tools were found to be heavily used, but they are not well suited for a modular tool concept. Trends of using heavier vehicles than necessary was found in the markets, this leads to the benefit of the large power available from WCROVs.

From analyzing tools, the properties sought after was narrowed down, eliminating tools and actuator types until there was a limited variety left. In chapter five, the advantages and disadvantages of various solutions was reviewed until left with the result.

Based on the knowledge gained in every step of the process the information got refined. The conclusion to be drawn from the research process is that the suggested design solutions summarized in the datasheets certainly has the possibility to progress further into a development process.

8 FUTURE WORK

I would advise to get a hold of the set of actuators chosen for further development and conduct testing on them, because no matter how much and accurate calculating is done, performance can always differ, and one cannot know this before it has been verified.

Continuing working on the project started by this thesis, following are suggested tasks to be performed:

- Elaborate on the limits related to gearing. Where are the limits of what is possible and what is practical regarding gearing solutions. The values set for the max. speed/low torque versus the combination of max. torque/ low speed.
- The ability of several smaller motors to replace one that is bigger and more powerful. The practicality and potential benefits of such a solution. One application for this might be diamond wire saws.
- Obtaining test data from several sources. Like for the electrical torque tool, the only source of data is Blue Logics solution, it would be prudent to also explore the properties of Oceaneering's tool.
- The demands and implications of oil compensation for components in the suggested design must be researched.
- Detail design of housings and the other components of the tooling concepts.
- Creation of a graphical user interface and coding for control and interpretation of actuators and sensors.
- Locate and make arrangements with suppliers of materials and equipment, or eventually find a manufacturer to produce the whole actuating solutions.

As requested by the industry a focus should be pointed towards developing safe and efficient high voltage systems. The step of removing all hydraulics must be taken; it is understandable that ROV operators show skepticism, as replacements for existing tools are limited. The paradox is: The power consuming hydraulic pumps must be removed to free enough power needed by heavy duty electric tools. Until this power is made available, there is limited research done on such tooling solutions. Anyhow, ROV suppliers are not willing to remove the hydraulics until an electric solution is present.

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APPENDIX

Appendix A

Excel sheet: Appendix A, Market Analysis

Appendix B

Excel sheet: Appendix B, Testdata Electric Torque Tool BlueLogic

Appendix C

Excel sheet: Appendix C, Parker Motors

Appendix D

Word doc: Appendix D, Company and equipment internet references
As there have been an enormous amount of information gathered from the internet, the links accessed are collected in a separate document.