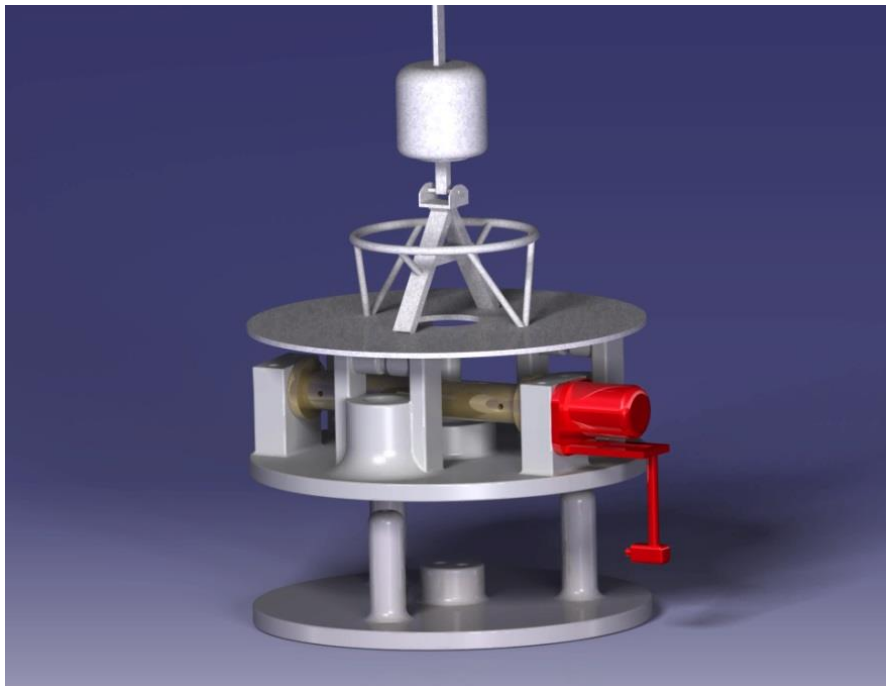


CHALMERS



Development of the installation process for the tidal power plant Deep Green at Minesto AB

A concept development

Bachelor's degree in Mechanical Engineering at Chalmers University of Technology

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ABSTRACT

The energy consumption on earth increases while the reserves of fossil fuels are running out and it is only a matter of time before we are dependent on renewable energy sources. Motion of water is an energy source containing a large amount of energy and to extract that energy out of tidal currents is one way to use it.

There are power plants using the energy in the tidal currents today, but only close to land due to the shallow water and the high velocities. Minesto is a company that sees the potential in the currents with low velocities further from land where the space is not a problem. This is where they see the future for their concept Deep Green.

Deep Green shortly consists of a kite equipped with a turbine that moves through the water in a shape of an eight to optimize the energy extraction at the low velocities. The electricity and signals are transferred from the kite through the tether and a bottom joint into a cable on the seafloor.

A prototype in small scale is being tested at the coast of Ireland and currently there is no good solution for servicing the bottom joint. A bottom joint containing a universal joint, a swivel with slip rings transferring power, electricity and signals to the seafloor cable is needed.

Therefore, a solution for the bottom joint's design and attachment on the base has been investigated. The purpose is to lower, fit and elevate the bottom joint to enable service for 20 years with a maintenance interval of about 5 years for the first 10-20 produced power plants.

This has been accomplished by doing research about the conditions at the seafloor, various offshore industries, equipment and techniques. Through these investigations in subsea engineering together with different methods for concept development, a final concept has been developed and visualized.

In this final concept the bottom joint will be lowered from a vessel by the tether and be winched to the base through a motorized cable mounted on the bottom joint. The bottom joint will use a camera to ensure its position and to supervise the fitting. Three pins on the base will be fitted in conical holes on the bottom joint along with a stab plate to transfer electricity and signals. The bottom joint will be elevated by the tether for service every fifth year. A 3D-model of the concept has also been printed to verify the fitting

No strength calculations are performed and the dimensions are only estimated since the concept is not developed for production.

PREFACE

This thesis is a part of the requirements for the bachelor's degree in Mechanical Engineering at Chalmers University of Technology, Gothenburg, and has been carried out at the Division of Marine Design, Department of Shipping and Marine Technology, Chalmers University of Technology between January and June of 2013.

We would like to acknowledge and thank our supervisor, Adjunct Professor Erland Johnson at SP Technical Research Institute of Sweden and at the Department of Shipping and Marine Technology at Chalmers, for his guidance and valuable input to our work. We would also like to thank our examiner, Professor Jonas Ringsberg, for giving us the opportunity to write this thesis at the Department of Shipping and Marine Technology Chalmers.

Finally, we would like to thank Minesto, especially our supervisors Olof Marzelius, Robert Perneborn and Mattias Andersson for their input to our work, their knowledge in subsea engineering and their guidance in the concept evaluation process. Without their help it would have been impossible to successfully develop the concept.

Gothenburg, June 2013

Adam Johannesson and Christian Andersson

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1. INTRODUCTION

1.1 Background

The energy consumption on earth increases while the reserves of fossil fuels are running out and it is only a matter of time before we are dependent on renewable energy sources. The renewable energy sources such as wind and water power are used today but in a small scale due to the lack of space and the limited amount of waterfalls and reservoirs. Therefore the industry is moving off shore where the lack of space is not a problem.

Wind energy is used to a greater extent compared to water because of its simplicity and already developed technology, although it is getting more common to use the water through waves and currents to generate electricity. The advantage of using waves and currents is the large amount of energy together with the predictability of the energy that it can offer. Water has 800 times higher density than air and can therefore generate 800 times more energy at the same velocity and volume of the fluid.

To generate electricity out of ocean currents is far more efficient than out of waves but the turbines used today has to be located on the bottom close to land since they require a high velocity on the water which is the case close to land. This limits the market because of the few and small areas that can be used.

The tidal and ocean currents further away from land have a lower velocity but if the energy from these currents can be captured, they have the advantage that the available space is vast and that the power plants have no visual impact on the environment. Minesto is a company that sees the potential in this and they are developing a concept called Deep Green to generate electricity from the low velocities of the tidal and ocean currents.

At the moment Minesto is testing a prototype in small scale closer to shore at the coast of Ireland and power plants in full scale will be set up at appropriate locations around the world in the future. The power plant converts the energy through a turbine hooked underneath a kite. The kite optimizes the low velocities of the currents through different motion patterns, for example along a shape of an eight, shown in Fig. 1.1.

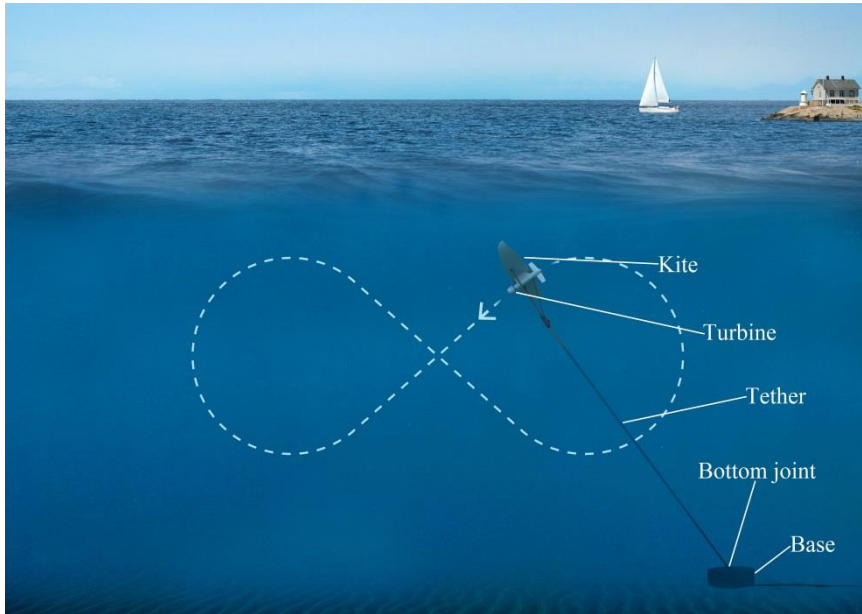


Figure 1.1. Deep Green in motion.

The power plant can be divided into four main parts: The kite with the turbine, the tether, the bottom joint and the base on the seafloor, see Fig. 1.1. The electricity and signals are transferred from the kite through the tether and the bottom joint into a cable on the seafloor. The bottom joint on the whole consists of a universal joint, a swivel with slip rings transferring power, electricity and signals. It is mounted on the base and is connected to a cable on the seafloor. The base can be designed either as a big concrete plate using gravity to stay on place or as a steel construction attached to the seafloor. Minesto is not sure of which one of these will be used yet.

Minesto is expecting the life of the power plants to be 20 years but all parts except for the base will need maintenance. The prototype that is currently being tested lies at a depth of about 20 meters and can therefore be handled by divers. The power plants in full scale will have the base at a depth of approximately 100 meters and can therefore not be handled by divers.

External conditions control the handling of the power plants to a large extent. The currents have different velocities depending on the type of tide and in what phase of the tide it is. Big waves can also cause problem during the installation. For further information about external conditions see the theoretical framework below.

The development is moving fast and Minesto specifically needs help to find and attach the bottom joint to the base. This work contributes to this and has been performed at Chalmers Lindholmen and at Minesto's office when the supervisors were needed.

1.2 Objectives

The objectives are to develop new techniques to use renewable energy sources such as tidal currents to be used in the future together with Minesto. As a part of their concept Deep Green,

a solution for the bottom joint's design and attachment on the base will be investigated. The purpose is to lower, fit and elevate, to enable service for 20 years with an interval of about 5 years. Right now there is no working solution for the full scale. The concept being developed will be used in the first 10-20 power plants. The concept should preferably be operated from the surface and at most using an ROV, an underwater robot. The final concept is to be visualized and prepared to be tested in small scale through 3D-printing.

1.3 Limitations

The tidal power plant extracts energy from both tidal and ocean currents but since the ocean currents are different depending on the geography and do not have as much effect on the power plant as the tidal currents, they are not investigated further.

Since the concept is not developed for production, the requirements of strength calculations, dimensions, drawings and preparing for manufacturing aren't significant in this phase. Therefore no strength calculations are performed and the dimensions are only estimated. Estimation of detailed costs is also not critical in the concept evaluation process. Furthermore, no drawings have been made, only simple sketches for the different solutions and 3D-models for the final concept. The focus has been on the idea generation and combining solutions to develop a strong concept.

1.4 Clarification of objectives

The objectives are to investigate and develop a concept for:

- How the bottom joint will be lowered to the base and steered in to the right position
- How the bottom joint's position will be ensured
- How the bottom joint will be fitted, connected electrically and locked
- How the bottom joint will be detached and elevated

The assignment also includes verifying and visualization of the final concept.

2. THEORETICAL FRAMEWORK

In this chapter existing studies and research about offshore engineering are presented to give a basic understanding of tidal and ocean currents, subsea engineering and equipment used for offshore installation.

2.1 Tidal current fundamentals

The fundamentals of tidal currents are described to clarify the presumptions for off shore installations.

Tidal currents are caused by the gravitation force of the moon. The sun also contributes but only with half the force, (Butikov, 2002). The drag force of the moon forces the ocean on earth to bulge outwards at opposite sides of the earth, see Figs. 2.2 and 2.3. The ocean water level rises at the earth's sides aligned with the moon and decreases at the sides perpendicular to the moon. These changes of water levels cause horizontal movement called tidal currents (Horton, 2013). There are several expressions for the different phases in tidal currents shown in Fig. 2.1. The most important ones are:

- **Flood current-** Sea level rises and a flood current occurs
- **High tide-** The Sea has reached the highest level
- **Ebb current-** Sea level falls and an ebb current occurs
- **Low tide-** The Sea has reached the lowest level
- **Slack water-** Just between and after the tide turns, slack water occurs which means that there is no movement at all in the tidal current. In this project, slack water periods can be used to the work at the bottom of the sea since there are no currents that can make the equipment drift away.

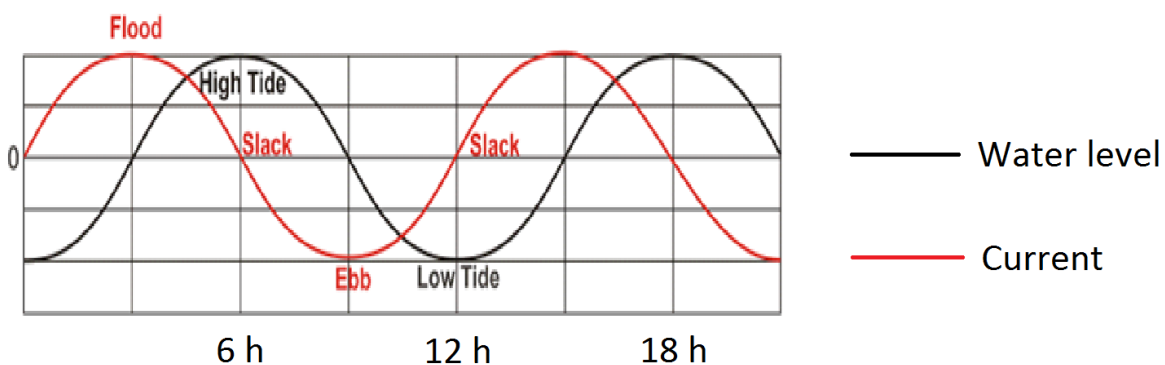


Figure 2.1. Water level in relation to the current velocity and common tidal expressions.

2.1.1 Spring- and Neap tide

The intensity of the tidal currents varies over time. When the moon stands either on the same or opposite side of the earth compared to the sun, as shown in Fig 2.2, spring tide occurs. Midway between spring tides, the moon stands perpendicular to the sun, see Fig 2.3, and the gravity force of the sun now creates lower high tides and higher low tides. This phenomenon is called neap tide.

The moon moves around the earth one lap every month which makes neap and spring tide occur twice each per month. When spring tide occurs there is a greater difference between high and low tide than during neap tide. This results in an increased flow during spring tide and a decreased flow during neap tide. The difference between spring and neap tide is dependent on where on earth you are but a rule of thumb is that the spring tidal ranges are twice the range of a neap tide. A higher tide results in more moving water, hence the current velocity doubles from neap to spring tide. Another important thing to know about tidal currents is that the shift between high- and low tide occurs four or two times every day depending on the geography, (Hagerman & Polagye, 2006).



Figure 2.2. Spring tide occurs when the moon and the sun are aligned.

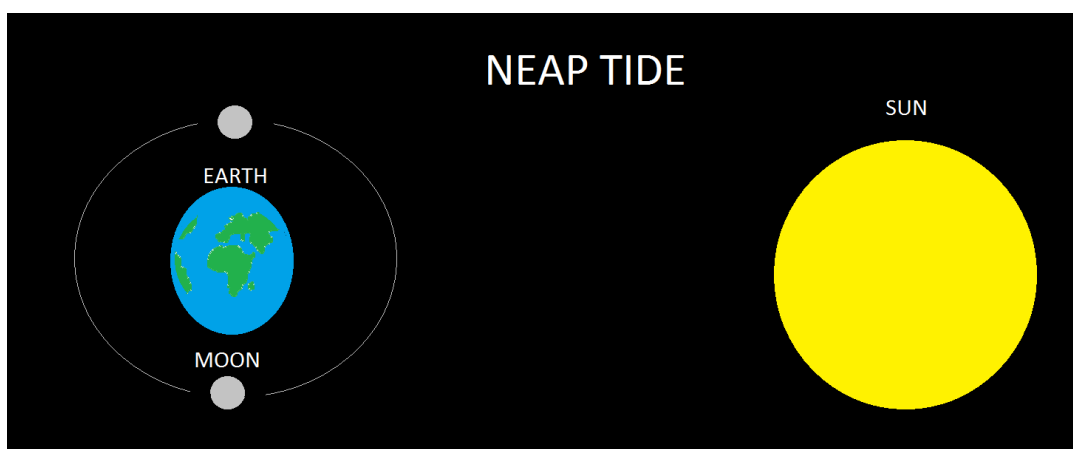


Figure 2.3. Neap tide occurs when the moon and the sun are perpendicularly positioned.

2.2 Subsea engineering

Different methods, techniques and equipment are used for installation and other subsea operations. Some of the most important ones will be described in this section. Conditions on the seafloor and suitable materials for these conditions are also investigated.

2.2.1 Conditions at the seafloor

When a subsea object is placed on the seafloor for a long time, sludge and fouling starts to gather. When constructing a product for long term use, which periodically will be elevated, lowered and attached again, parts with high precision must be designed to withstand these surrounding factors.

Another condition that is different on the seafloor compared to water closer to the surface is the velocity of the currents. Fig. 2.4 is visualizing the relation between depth and current velocity. In this figure you can see that the velocity on the seafloor is significantly lower than closer to the surface. The velocity increases rapidly and an increase of the current depth from 0 to 2% results in an increased velocity of up to 70 % of the surface velocity. For example if the depth is 100 meters and the current velocity is 4 m/s at the surface, the current velocity is approximately 3 m/s 2 meters from the seafloor and decreases rapidly coming closer to the bottom. The extremely low velocity close to the seafloor prevents sludge from coming loose from the bottom, (Marzelius, 2013).

2.2.2 Materials suitable for subsea use

Saltwater is tough for many materials, it is therefore important to use materials which do not corrode. There are a few suitable materials for use in saltwater, for example Bronze, aluminum, aluminum bronze, plastics and stainless steel under certain conditions.

It is also necessary to use good seals and gaskets that can withstand the saltwater and the pressure at the seafloor. The parts of the bottom joint will be made from materials which are not strongly affected by the pressure difference such as metal and other solid materials that do not compress that easily, (Houston, 2012).

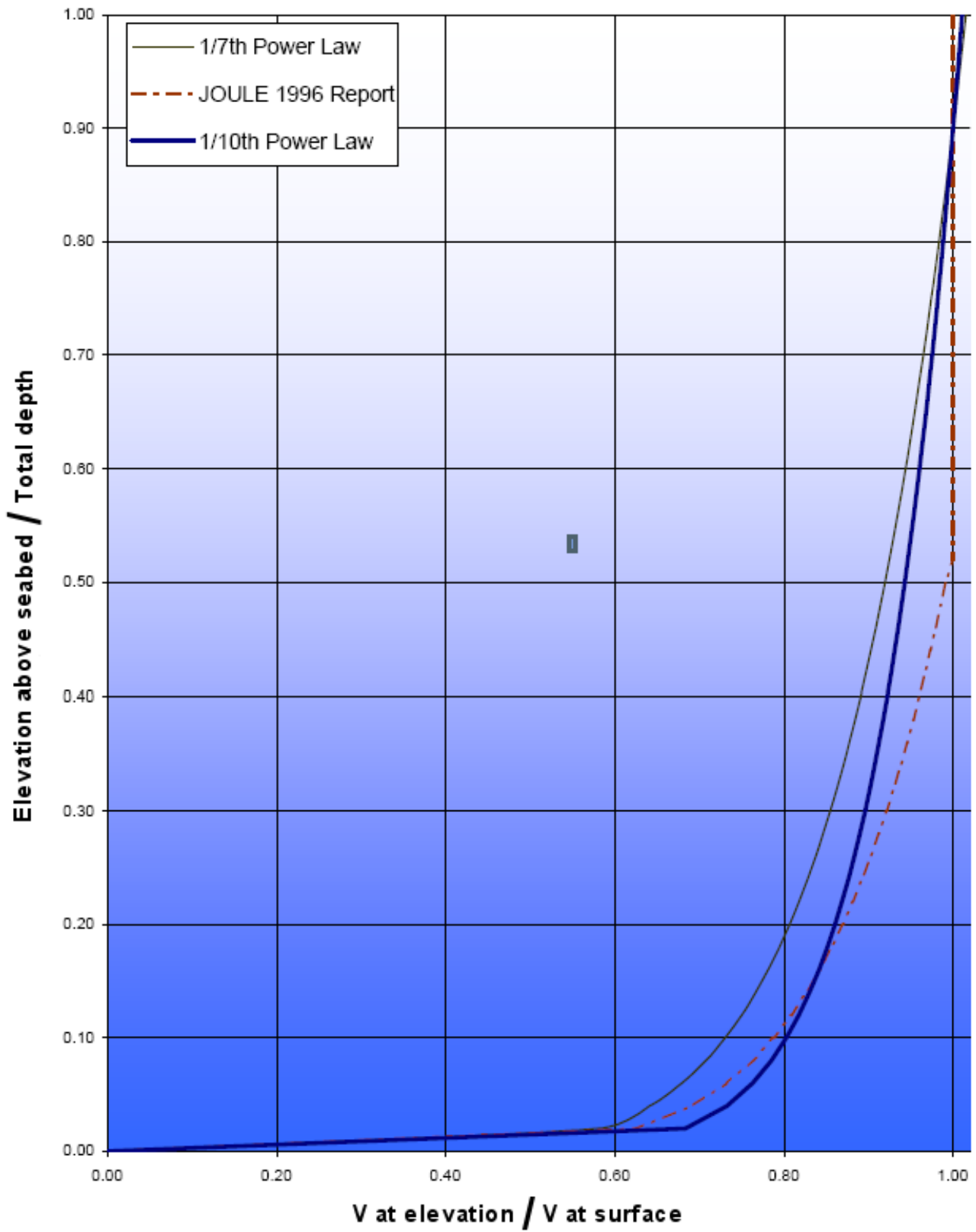


Figure 2.4. Current velocity relative to depth, (Hagerman & Polagye, 2006).

2.2.3 Subsea installation

When a subsea object is to be installed several factors must be considered. In Fig 2.5 interacting forces are illustrated and the vertical arrows pointing towards the surface illustrates the buoyant force of the subsea object. The horizontal arrows show the current's influence on the installation process. Heaves and waves also obstruct the installation and methods to prevent these are described in chapter 2.2.4.

Two methods are traditionally used for subsea installations, guideline method (GL) and guideline-less method (GLL).

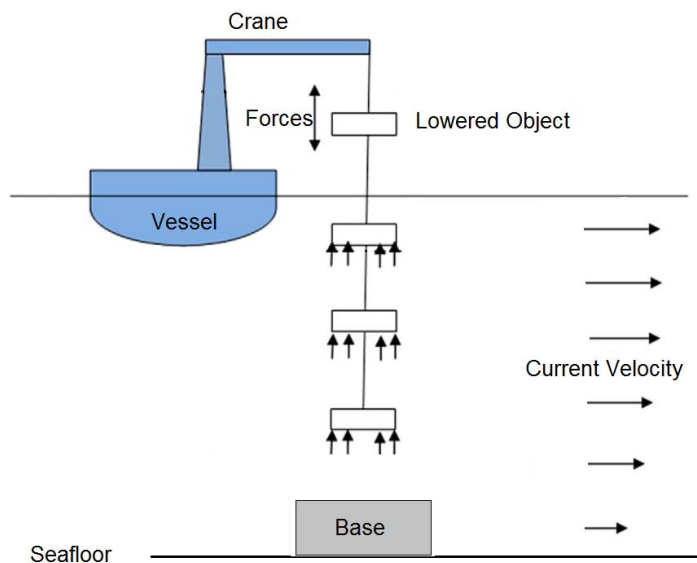


Figure 2.5. Forces acting on the equipment during an installation process.

Guideline method (GL)

The guideline method uses guidelines, often four tensioned wires, to lower and guide a subsea object to the right position on the seafloor. The subsea positioning has been simplified with the guidelines since instead of using free immersion the subsea object is physically guided all the way down to the base, (BOP landing, 2009).

Guideline-less method (GLL)

The guideline-less method performs the lowering of a subsea object without guidelines and it therefore requires a complex subsea positioning system to manage the precision requirements during installation in horizontal position, (Bai, 2012).

2.2.4 Motion compensating

Offshore work is often complicated due to the waves and heaves which the equipment is exposed to. For precision work, a so-called heave compensator is used to compensate these heaves created by the waves. There are several kinds of heave compensators and they can be divided into two groups, passive and active. There are also combinations called semi-active heave compensators. Another group of heave compensators is the polyester ropes that use its elasticity and its damping effect for motion compensation, (Hatleskog & Dunnigan, 2007).

The passive heave compensator (PHC) consists of a hydraulic cylinder and a gas accumulator. The gas is compressed by a piston when a vertical heave occurs. This gives the system a spring damper effect. A PHC has a damping effect up to 80 %, (Jakobsen, 2008).

An active heave compensator (AHC) holds static weight of load and compensates for vertical motion in one single hydraulic system, the compensation can be performed by a cylinder or by a winch. Electrical winches can also be used in an active heave compensating system. The damping effect of an active system has higher precision compared to a passive one but the active heave compensating system is also much more complicated.

2.2.5 Positioning

Installation of subsea objects requires the vessel to maintain its position in order to enable the positioning of the object with the required accuracy. The navigation includes both surface positioning and subsea positioning. Surface positioning refers to the positioning of the vessel, to keep the vessel at the same place during the whole installation process. Subsea positioning includes the positioning of the object relative the vessel, the installation equipment e.g. an ROV and also the seafloor or the base that the object is supposed to land on.

Surface positioning

A surface positioning system includes several components but it generally includes a power supply, a position reference system, normally DGPS (see section 2.2.6), a hydro acoustic measuring system and a system to maintain the position, either by anchoring or thrusters for dynamic positioning, (Bai, 2012).

Subsea positioning

When the surface positioning is managed and the vessel is in the right position, an object will be lowered through the water towards the target placed on the seafloor. During the lowering process the object will be tracked by a hydro acoustic unit to ensure the position. A gyrocompass and possibly an ROV will detect the inclination of the object if that is necessary, (Bai, 2012).

2.2.6 Installation Equipment

When a subsea installation is performed, several devices and different equipment is needed, some of the most relevant are described in this section.

Remotely Controlled Underwater Vehicle (ROV)

The ROV is remote, which means that it can be operated in every angle any time with the only limitation that it is attached to the vessel on the surface with an umbilical. There are many different models of ROVs that can be chosen depending on the specific purpose. Some can be operated in deeper water, some can handle stronger currents and some have greater possibilities in using different and more advanced tools etc., (Society, 2013). Depending on the size of the robot, the length of the tether connecting it to the surface and the velocity of the currents, different amount of power is needed to operate the robot, (MacArtney, 2012).

Another but similar vehicle is the AUV which stands for Autonomous Underwater Vehicle. The difference from the ROV is that the AUV is programmed and does not have an umbilical. It is used more frequently for research on the seafloor, (Oceanographic, 2013).

Wet mate

A Wet Mate connector makes it possible to connect cables transferring electricity and signals under water. There are many different manufacturers who make these connectors but with varying specifications. Depending on the amount of power that is needed to transfer, the size and price varies. Many or probably even all of the Wet mate- connectors on the market require an ROV for the connection but since Minesto wants to make the connection fully automatic, a solution with a connector that mates through gravity is to be investigated, (MacArtney, 2012).

There are three types of wet mates, optical that transfers signals, electrical that transfers electric power and finally hybrids that can transfer both of these through one connector, (Weiss, 2010).

Stab plate

To transfer electricity and signals, the connectors could be mounted on a stab plate. A stab plate basically consists of two parts, one fixed on the subsea base and the other on the object which is supposed to be attached on the base. Guiding pins are placed on the plates to help the mating. Wet mate connecting with stab plates needs great forces to mate successfully. As shown in Fig 2.6 some models of existing stab plates are ball jointed to manage misalignments better.

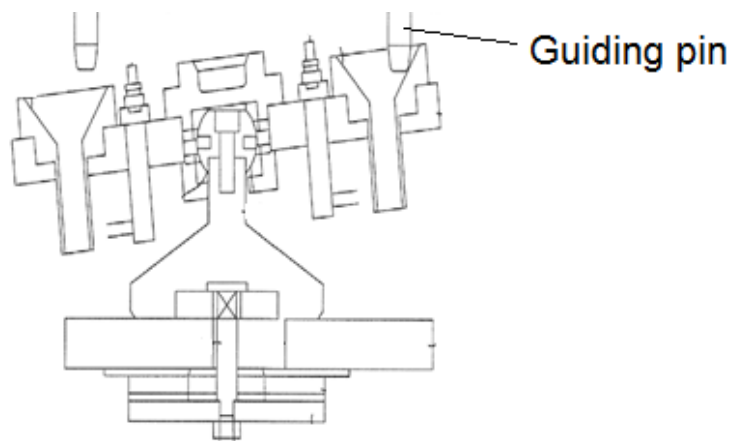


Figure 2.6. Stab plate with guiding pins and alignment.

DP-vessel

Dynamic positioning (DP) is a computer-controlled system used to automatically maintain a vessels position and direction. The system uses the vessels' own propellers and thrusters to keep it steady at sea. These vessels come in different sizes and shapes and are quite expensive to rent or to buy.

Differential Global Positioning System (DGPS)

Precise and reliable positioning system is needed for the DP-vessel to maintain position.

DGPS is a more precise positioning system than regular GPS and the margin of error is 0,5 to 5 meters. The DGPS requires that a GPS receiver is set up on a precisely known location. This GPS receiver is the base or reference station. The base station receiver calculates its position based on satellite signals and compares this location to the known location. The difference is applied to the GPS data recorded by the second GPS receiver, which is known as the roving receiver. The corrected information can be applied to data from the roving receiver in real time in the field using radio signals or through post processing after data capture using special processing software. (Pratt, 2013)

Lifting bags

Lifting bags are often used to elevate an object from the seafloor to the surface or to move an object vertically. The bag is made of a plastic material and is filled with gas to produce lifting force. The pressure in the bag can be varied to control the lifting force. A problem with this kind of lifting bag is the risk with increased pressure when lowering it. When the pressure increases, the lifting force decreases because of the compression of the bag. There is also an alternative using incompressible tanks made of steel whose lifting force can be varied by variable compression from an air-filled cylinder with a piston, (Torok, 2013).

3. METHOD

The concept development has been performed as a product development for new construction. Since the project does not aim to develop complete construction drawings or prepare the product for manufacturing, focus will be on the prestudy and the concept development which are the early phases of the product development process., Fig. 3.1 (Ulrich, 2008).

Apart from the theoretical framework, the prestudy is divided into two chapters: A function analysis which is done together with Minesto to describe the problem that the concept will solve and to identify and structure main and sub functions. Along with this analysis, the specifications of requirements are listed to identify the customer needs.

The concept development is divided into three chapters: The idea generation which is started to come up with solutions for the different functions based on the conditions found in the prestudy through both rational and creative methods together with the supervisors at Minesto. The solutions are investigated, evaluated and then also reduced together with Minesto to come up with the final concept to develop further. These concepts will also be visualized and be prepared to be verified with a 3D-printed model.

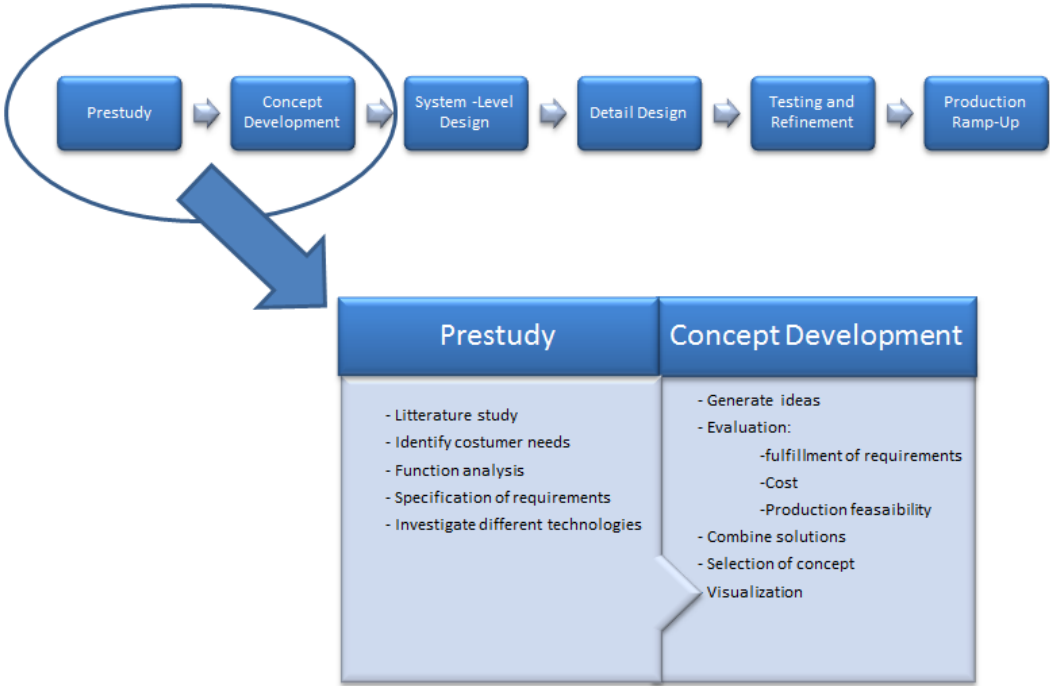


Figure 3.1. The product development process and its different phases. The focus will be on the two early phases.

3.1 Function analysis

The function analysis is done in the initial phase of a product development to describe the different functions for the concept. The different functions were formulated together with Minesto to visualize a clear and common goal. The different functions are illustrated in a function means tree, Fig.3.2. The function means tree divides the complex main function into different member and sub functions. The purpose with the function analysis is to simplify the problem solving by making it more comprehensible. Since the main problem is divided into a number of sub problems, different solutions can be generated to each sub problem and be combined into total solutions in the concept development phase (Summers, 2010) .

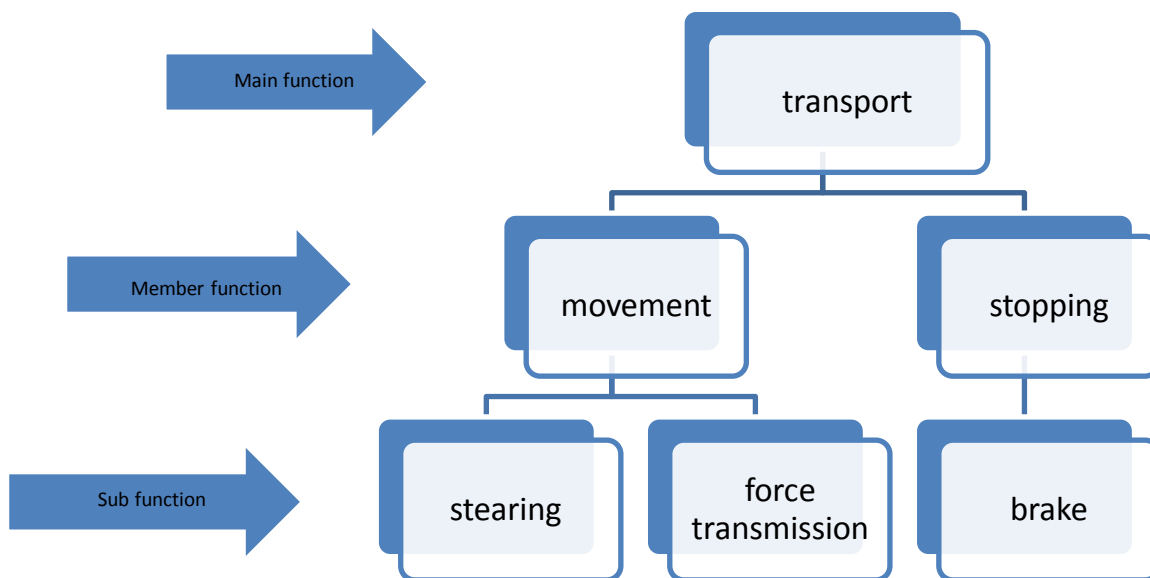


Figure 3.2. A function means tree visualizing the main function, the member functions and the sub functions.

3.2 Specification of requirements

Before starting with the concept development, critical requirements and objectives have to be identified. To make a detailed specification of requirements has several benefits. For example it will describe the goal of the project so that anyone can verify if the concept development is heading in the right direction. Usually it is the customer's needs which are translated into concrete measurable product specifications but in this case, the specification of requirements has been developed together with Minesto. It is an assurance that the customers and the developers of a new product agree about the products properties and design before the development has started. When several concepts are developed, the specification of requirements is used to pick out the concept which matches the customer's desire the most.

The experienced supervisors at Minesto are trustworthy and qualified to decide which requirements and requests to be added in the specification of requirements. Further, the specification of requirements will be used to decide which solutions to keep and investigate further.

3.3 Idea generation

To find solutions to the identified sub functions in the function analysis, an idea generation has been done. The technique investigated in the idea generation is supposed to be wide and include as many areas as possible. There are two well-known methods for this that has been used; rational and creative methods.

Rational methods

The rational methods include a series of steps that uses already existing information. The rational methods that have been used are:

- To look for solutions in literature and patent
- To investigate analysis of competitors and similar products and industries
- To have interviews with experts and lead users

The Interviews have been done with experienced employees at Minesto and with the supervisor of the project to give a greater understanding in the different areas investigated.

This method can often be combined with the brainstorming since the brainstorming results in new solutions that might be optimized if they are combined with technique that is available and approved, (Johannesson H, 2005).

Creative methods

A typical creative method for generating ideas is brainstorming. In the brainstorming, a small group of people get together and generates ideas. The purpose with a brainstorming session is to generate as many ideas as possible, the quantity is more important than the quality of the generated ideas. A few rules are implemented to get the best result. First of all, no criticism is allowed regardless if it is negative or positive. Quantity is sought since the chance to find a good idea increases with the number of ideas in the selection phase. "Thinking outside the box" is encouraged, an idea seems crazy in the beginning but with some modification it may be a success. By using this method, many different solutions using different techniques are found.

A student in mechanical engineering assisted the group member with his thoughts and ideas for the different sub functions. The group consisting of three mechanical engineering students wrote down different solutions on notes and put them into a chart.

The solutions were presented for the supervisor Olof Marzelius, engineer at Minesto. When these solutions were discussed some new ideas were brought up. These ideas together with the knowledge from the investigations in the rational methods were then put into a chart explaining what problem they solve.

Along with the chart from the brainstorming, there is a section explaining the different solutions. Along with the explanation, pros and cons for the solution will be presented.

3.4 Reduction and evaluation

After investigating the different solutions, the chart from the brainstorming will be reduced from solutions that do not qualify according to the specification of requirements. The reason for reducing a solution depends on its ability to fulfill the specification of requirements.

The solutions in the reduced chart were then investigated further, evaluated and compared within the development group to lay the foundation for the decision of the final concept.

3.5 Final concept

After the evaluation and comparison among the remaining solutions, the best of the alternatives are combined to create concepts. The winning combinations are described more carefully and modeled in Catia. The final concept is described with both pictures and words. To illustrate the installation process, a model for 3D-printing is designed for Minesto to use in the future.

4. PRESTUDY

Based on the research in the theoretical framework, presumptions and demands for the product are identified. This is accomplished with a function analysis and a specification of requirements.

4.1 Function analysis

A function analysis was performed to divide the main function into less complex sub functions, see Fig. 4.1. The sub functions were used in the brainstorming phase, where solutions to all sub functions were found. The main function is to connect the bottom joint to the base. Identified member functions are service, withstand surrounding, transfer force and transfer electricity. The member functions were divided into sub functions to simplify the idea generation. The critical sub functions to use in the brain storming session were:

- Vertical positioning
- Horizontal positioning
- Fitting
- Ensure position
- Angle alignment
- Locking
- Electrical connection

The remaining functions were chosen not to be taken into the idea generation phase and are not fully investigated due to the limitations. The function analysis is visualized in a function means tree, see Fig 4.1.

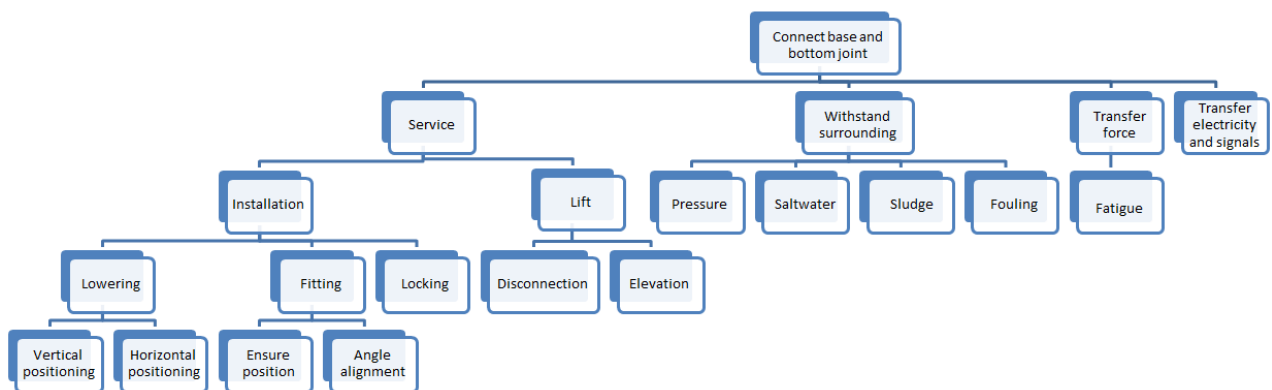


Figure 4.1. Function analysis is visualized in a function means tree. The main function is divided into sub functions.

4.2 Specification of requirements

The pre-study and function analysis resulted in a specification of requirements where Minesto's demands and requests were translated into measurable or concrete requirements. These requirements are further used in the reduction and evaluation processes and are presented in table 4.1. The requirements are based on the fact that Minesto wants to use well known technique for the first 10-20 power plants to prevent failure.

Table 4.1. Requirements identified in the prestudy.

Requirements	Comments
Functional	
Vertical positioning	Heaves, weight, lowering, elevating
Horizontal positioning	Manage the velocity of the currents
Ensure position	Visual contact, indication when fitted
Fitting	180°
Angle alignment	If it is necessary to straighten up the joint
Locking	remote-controlled
Transfer Electricity and signals	500 kW, 690 V
Withstand surrounding environment	
Pressure	10 bar
Corrosion	20 years
Sludge	Minimal
Fouling	Design to avoid impact of fouling
Life length for equipment on seafloor	20 years
Life length for equipment on bottom joint	5 years
Requests	
Comments	
Installation	
Avoid ROV	Only used if failure occurs
Avoid Wet mate	Only if necessary
Increase available installation time	Regarding currents
Use technique proven to work	Used for similar tasks
Automatic electric connection	Through gravity or remote controlled
Reduce installation time	Whole process duration
Design	
Permit maintenance on vital equipment	Place permanent equipment on bottom joint
Physical contact between base and bottom joint	E.g. wire
Physical contact between boat and bottom joint	E.g. wire
Robust without failure	No fragile equipment on base
Fit both types of bases	Concrete and steel construction base

5. IDEA GENERATION

Through brainstorming and different rational methods, a chart with solutions for functions has been generated, see Appendix 1.

The functions from the function analysis are:

- Vertical positioning
- Horizontal positioning
- Fitting
- Ensuring position
- Angle alignment
- Locking
- Connecting

The most interesting solutions are investigated, described and if needed visualized in this chapter. Both new and well known technology is used for the solutions in this chapter.

5.1 Vertical positioning

When descending the bottom joint, a force opposite to the gravity is needed to prevent the bottom joint to sink without control of the speed, see Fig. 5.1. This force can be created in various ways and appropriate ways that came out of the idea generation are listed below and described in this section.

The bottom joint will be brought up from the base through coiling the tether. The reason for this is that the only thing connecting the bottom joint to the surface when the power plant is operated is the tether and to use another device to bring up the bottom joint would be unnecessary.

- Lifting bags
- Wire from vessel
- Tether from vessel

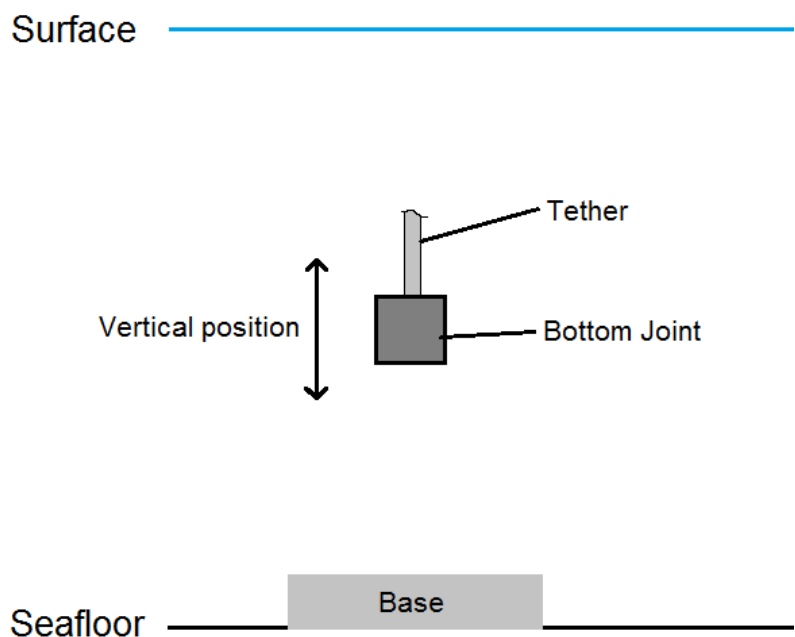


Figure 5.1. The vertical positioning in the lowering process.

Lifting bags

The lifting bag is a bag filled with a gas and then attached to the bottom joint to provide lifting force, see Fig. 5.2. A big advantage is that it is simple to adjust the lifting force, it is easy to store and it is not expensive to purchase. Two disadvantages are that the “shell” is compressible and will therefore have less volume and lifting force with higher pressure which occurs at greater depth and that the big volume of the lifting bags can cause them to be caught by the currents. Since the lifting bags are not affected by the movement of the vessel it might be very profitable to use lifting bags if a heave compensator is hard to use.

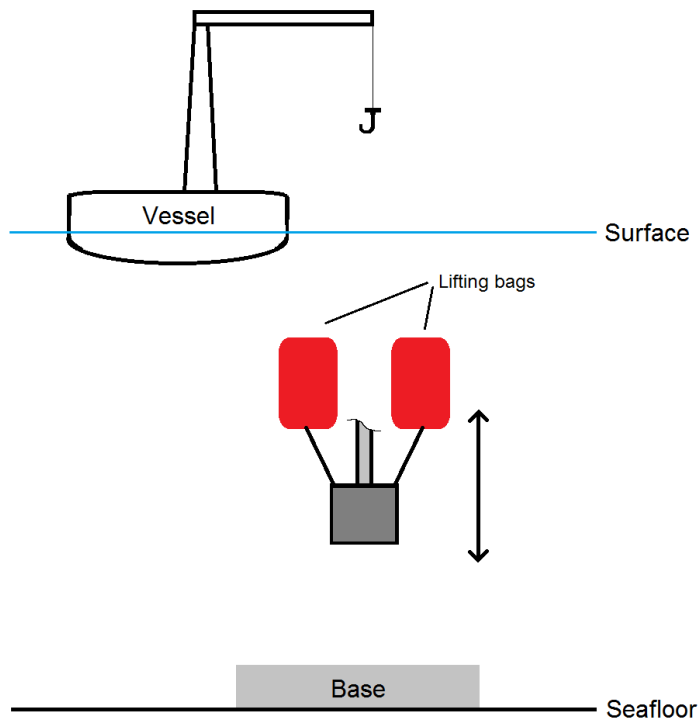


Figure 5.2. Lifting bags used to provide lifting force.

Wire from vessel

To give the bottom joint lifting force, another possibility is to lift it with a wire from a vessel, see Fig. 5.3. The solution is very simple and robust since the increased pressure caused by changing depth will not have any effect on the wire. The speed is very easy to control since the load has the same speed as you move the wire with. A disadvantage is that since this solution uses the force of the vessel which moves up and down with the waves, a heave compensator will be needed to control the depth of the bottom joint. Without a heave compensator an undesirable impact can occur between the bottom joint and the base.

An alternative method is to use two or more wires. Using more than one wire helps both the fitting and the angle alignment. Two wires prevent the bottom joint from twisting and to lift it in more than one wire makes it more stable and prevents the bottom joint from tilting. The disadvantages with this method are that you now have several wires to keep track of and to heave compensate.

When using wires to descend the bottom joint, the tether has to be handled. There are two possibilities for this. Either the tether is coiled and follows the bottom joint down to the base and the upper end of the tether is brought up with the wire used for the descending or it is uncoiled and is lying free in the water with one end attached to the bottom joint and the other attached to a float on the surface.

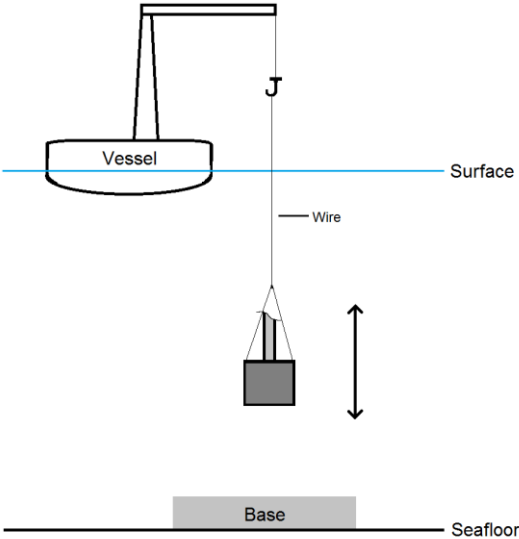


Figure 5.3. A wire used to provide lifting force.

Tether from vessel

Instead of using a separate wire from the vessel, the tether can be used to control the vertical position by unwinding the tether from a cable reel on the vessel, see Fig. 5.4. An advantage is that separate wires are not needed. This reduces the amount of wires in the water and therefore reduces the risk of getting them entangled. A heave compensator mounted on the cable reel is also needed for this solution. The tether will also be used to bring up the bottom joint. It is important to make sure that the tether is not damaged when it is used to provide force.

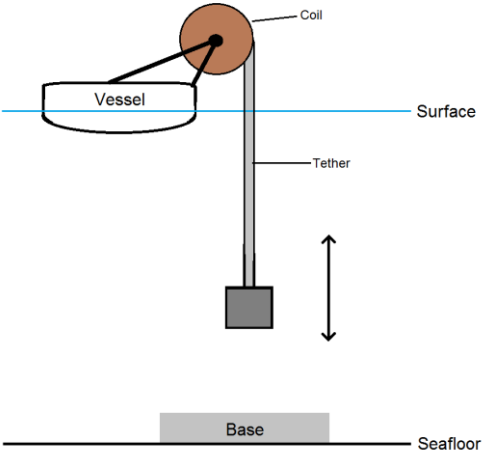


Figure 5.4. The tether is used to provide lifting force

5.2 Horizontal positioning

Steering the bottom joint into the right position requires some kind of force in horizontal direction, see Fig. 5.5. This force can be developed through different solutions described in the section below. The cable reels can be powered by different power sources described at the end of this section. The different solutions are:

- Thrusters
- Air jets
- Water jets
- ROV
- Cable reel on base
- Cable reel on bottom joint

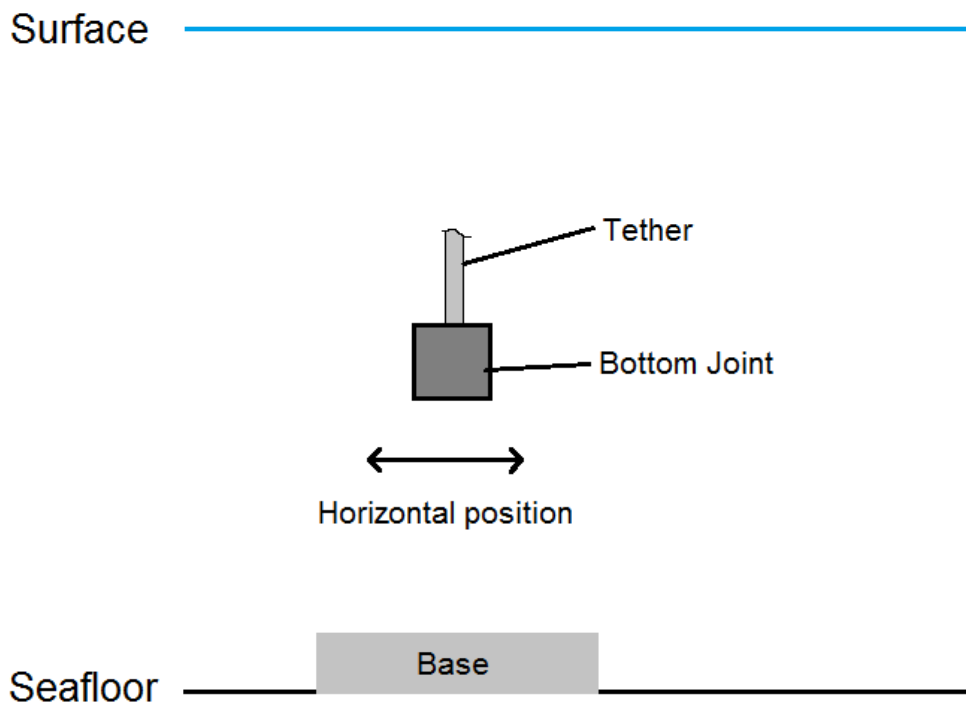


Figure 5.5. The horizontal positioning in the lowering process.

Thrusters

Using thrusters is one way to steer the bottom joint into the right position, see Fig. 5.6. By using thrusters connected to the bottom joint, navigation in any direction is possible. The basic idea is to have at least four thrusters mounted on a module and to dimension the thrusters depending on the estimated velocity of the currents. It is an expensive solution to develop and produce but if it is a good solution with a one time fee it might be cheaper than other solutions anyway. A big advantage with this solution is that the bottom joint can be kept free from wires and cables underneath.

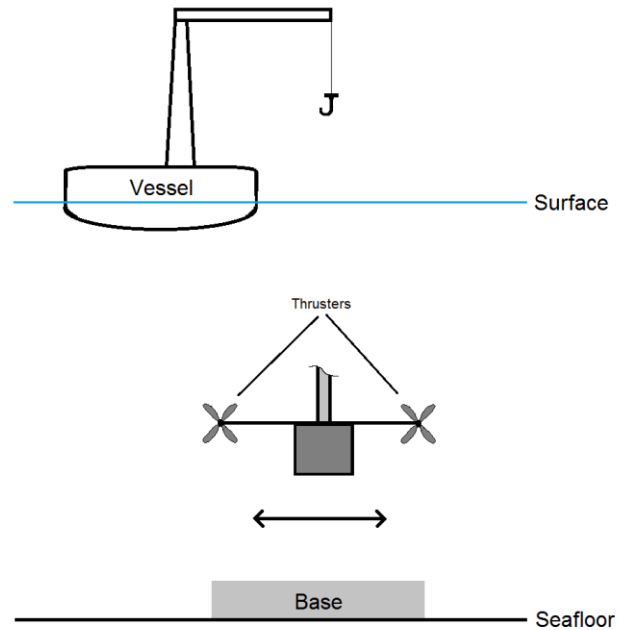


Figure 5.6. Using thrusters for horizontal positioning.

Air jets

The air jets will be used in the same way as the thrusters, see Fig. 5.7. These jets have an advantage compared to the thrusters through their simplicity. The power source is a compressor that pumps air into different tubes connected to nozzles located at the bottom joint. Since the engine supplies the power from the surface through a thick hose you only need valves that distribute the air into the different nozzles. A disadvantage, which also might be a reason for why these jets will not work, is that the pressure at 100 meters will be approximately 10 bar. This means that the pressure in the tubes must be quite high to keep their shape. Another disadvantage is that the air coming from the nozzles creates bubbles that reduce the visibility.

Water jets

The use of water jets is the same as the air jets but instead of compressing air, water is pumped through hoses down to similar nozzles as the air jets, see Fig. 5.7. This solution has the same advantages as the air jets considering simplicity and reliability. A big advantage with using water is that the pressure needed to move the bottom joint is not so high thanks to the density of the water.

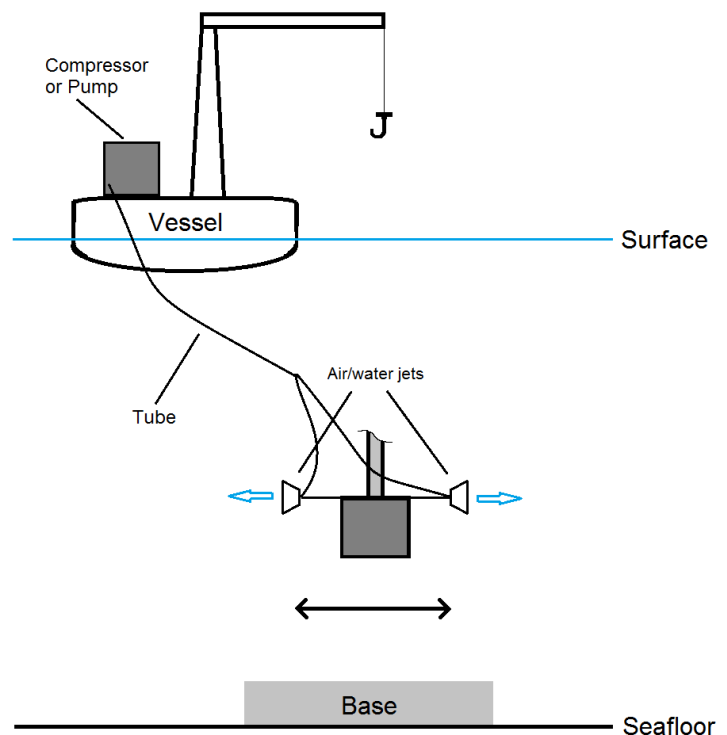


Figure 5.7. Using air/water jets for horizontal positioning.

ROV

An ROV can be used to follow the bottom joint down to the base. The thrusters of the ROV will be used to move the bottom joint horizontally and keep it in the right position all the way until it is fitted on the base, see Fig. 5.8. An advantage with this solution is that it is simple and that the technique is available and has been used before. The disadvantages are that it might need quite powerful thrusters depending on the velocities of the currents and that it might be expensive to use including the operators.

Cable reel on base

To descend the bottom joint, a cable reel can be used to pull the bottom joint from the surface down to the seafloor. The cable reel can be mounted on the base and pull down the bottom joint from there, see Fig. 5.9. The solution has an advantage in its simplicity since the cable reel can be attached to the base on the bottom. This results in a lighter bottom joint that is easier to handle since it is lighter and smaller. A disadvantage with this solution is that if the cable reel breaks or jams it has to be fixed with an ROV or a diver. Since the reel has to lie on the bottom from the time when the base is submerged until the power plant is taken out of service, it has to have a durability of more than 20 years. This might be hard to predict considering the hostile environment.

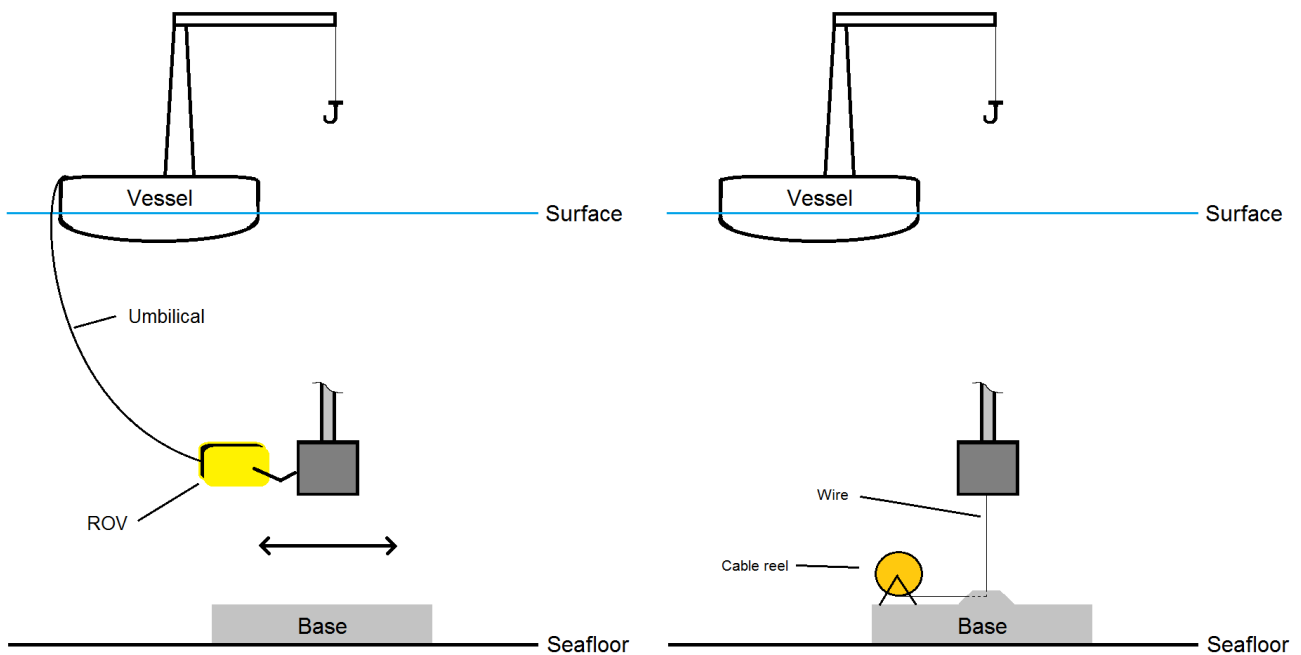


Figure 5.8. Using an ROV to follow the bottom joint down to the base

Figure 5.9. Using a cable reel on the base for horizontal positioning.

Cable reel on bottom joint

The cable reel can also be mounted on the bottom joint and the horizontal position will be determined by the guiding line between the base and the cable reel on the bottom joint see Fig. 5.10. This technique resembles the guiding line method (GL), described in the Theoretical framework.

Before the bottom joint is installed, the base has to be positioned on the seafloor. When descending the base to the seafloor, the wire which will be used in the cable reel of the bottom joint is held on the surface attached to a float while the other end of the wire is attached to the base, see Fig. 5.11. This float stays on the surface until it is time to connect the bottom joint to the cable reel.

A disadvantage is that this cable reel has to lie on the bottom until the next service. Therefore the life length of a cable reel in saltwater has to be at least five years. It would be a big problem if the reel gets jammed when it is time to bring the joint up to the surface.

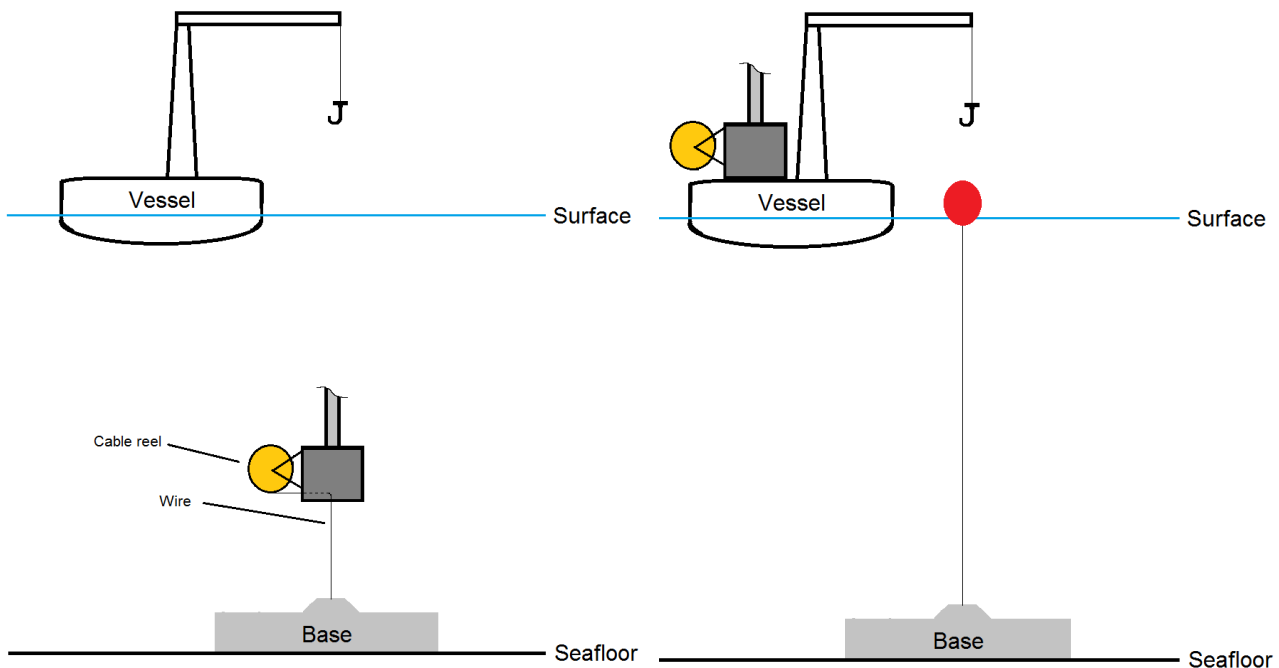


Figure 5.10. Using a cable reel on the bottom joint for horizontal positioning.

Figure 5.11. Using a float on the surface for the wire connecting the bottom joint to the base.

Alternatives for powering the cable reel

Regardless of the placing of the cable reel it somehow has to be powered. Three alternatives have been identified:

- **Electric motor-** The reel will be run by an electric motor. The motor can either be fixed on the cable reel, on the base or be designed to be attachable and removable from the bottom joint. If the motor is fixed on the base, it must survive for at least 20 years. If the motor is placed on the bottom joint it could be powered through the tether. If the motor is designed to be removable, the electricity can be supplied via a separate cable that only has to last while bringing the bottom joint down to the base. When the bottom joint is in its place, the motor is released and brought up to the surface. With this method, the motor does not have to last longer than the time it takes to lower the bottom joint. The solution also has one component less on the bottom that can cause trouble.
- **Spring loaded-** With the spring loaded cable reel, the force will be supplied by a coiled spring in the reel similar to a blind for a window. This allows the descending to be automatic without using any type of engine. A big advantage with this solution is that it will run by itself and you just need to supervise and lower the speed when the joint approaches the base. A disadvantage is that the mechanism in the reel has to be under water for the same time as the cable reel which can be 5 or 20 years depending on the placement of the cable reel.
- **ROV-** Another option is that an ROV equipped with an engine will be used to power the reel. This solution is more expensive than the spring loaded or motorized cable reel but it is a good solution if the other solutions do not work. If the reel is mounted on the base, the ROV reels down the bottom joint. If the cable reel is mounted on the bottom joint, the ROV will follow the bottom joint down driving the reel in the same way as on the base. This is a simple solution since the technology already exists.

Pulling the bottom joint from underneath or holding it from above

A disadvantage with holding the bottom joint from above is that the bottom joint is hinged and therefore not very stable while descended. There is a big risk that it will start to swing and therefore land on the base in the wrong angle, even if using angle alignment, see Fig. 5.12. If the bottom joint is pulled down, the attachment of the wire is on the lower part of the joint, which is the part that will have to be fitted in. By pulling it and using the angle alignment you can be sure that it is fitted in the right angle and on the right place, see Fig. 5.13.

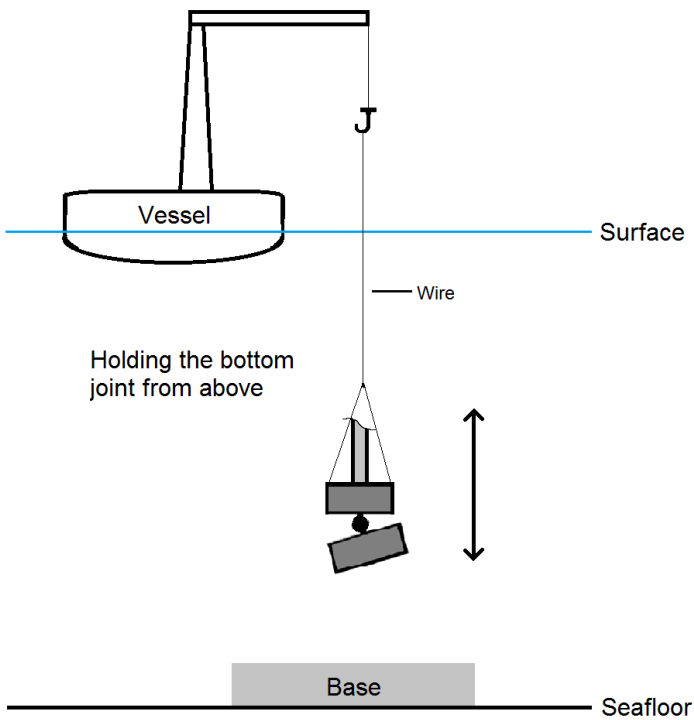


Figure 5.12. Holding the bottom joint from above

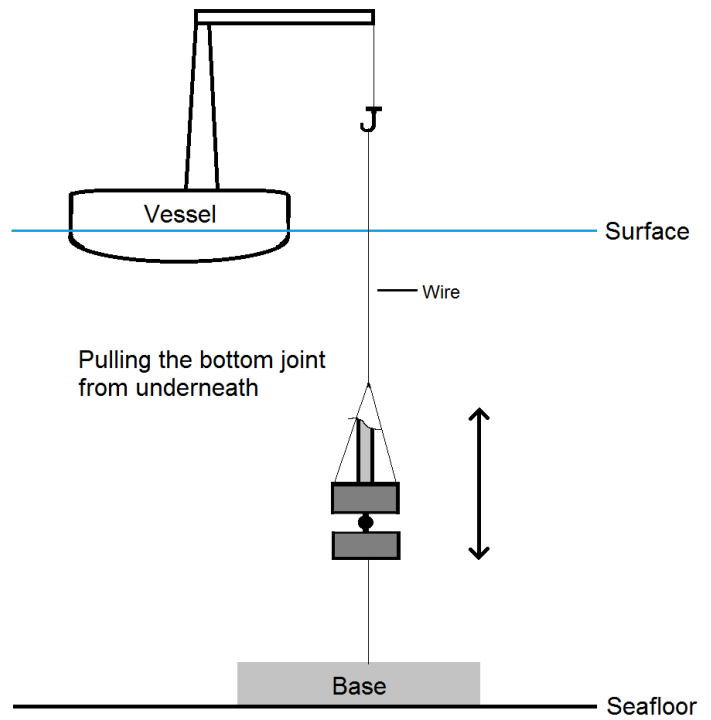


Figure 5.13. Pulling the bottom joint from underneath

5.3 Fitting

When the bottom joint reaches the base during the lowering process it has to be fitted in some way. The fitting is dependent on different kinds of interfaces that can be used to mate the bottom joint and the base mechanically. An interface consists of two matching components that are designed to be mated with each other at a simple and robust way. When the bottom joint is lowered it might not be lowered in the exact right position because of the error margin in the horizontal positioning. Therefore the fitting has to be able to compensate for that error margin.

When designing the fitting, the rotation angle has to be considered. Due to the universal joint and the design of the stab plate, the bottom joint can only be fitted in two directions separated with 180° as in Figs. 5.14 and 5.15. Minesto hopes that the angle will not matter for the bottom joint in the future but in the near future these two fitting angles are still required.

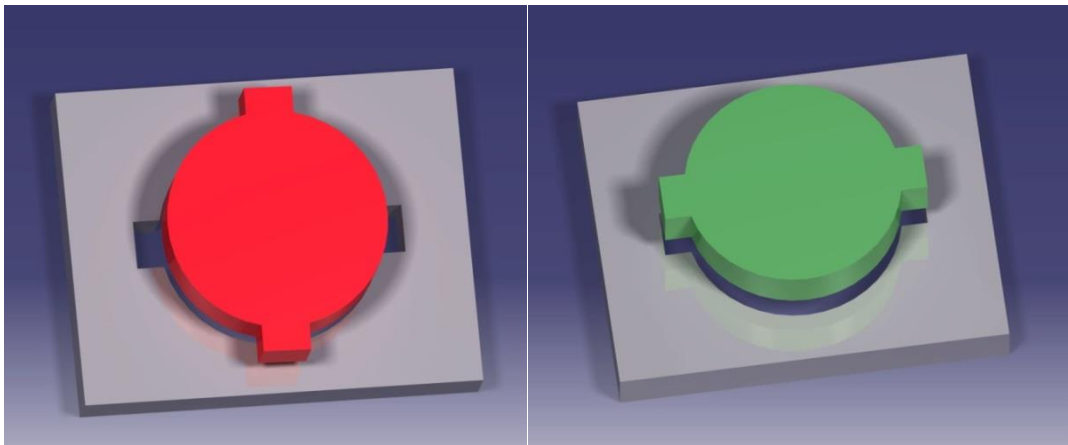


Figure 5.14. Fitting is not possible

Figure 5.15. Fitting is possible

The following fitting solutions are investigated:

- Track similar to a thread
- Oval interface
- Conical interface
- Slide in horizontally

Tracks similar to a thread

A hole on the base is designed with tracks similar to thread in a screw-nut. The bottom joint has a horizontal guiding pin with a matching thread that makes it turn into the right position when the guiding pin hits the hole. Growth and sludge could prevent the function of the slip zones on the threads which causes a total error in the installing process.

Oval interface

A pair of spherically shaped oval components creates an interface where one of them is placed on the bottom joint and one of them on the base, see Fig. 5.16. The oval shape is supposed to help the rotation of the bottom joint into the right position. If the two suiting shapes would meet each other at wrong angle, the oval shape helps the bottom joint to be positioned after the base.

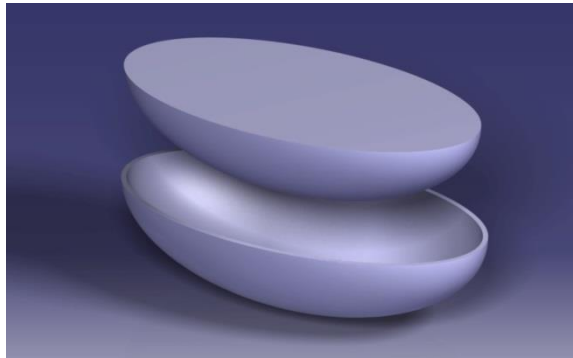


Figure 5.16. Oval interface for fitting

Conical interface

The interface consists of one or many guiding pins that are fitted into conical holes, see Fig 5.17. The conical shape helps to guide the pins into the right place. This solution has the same advantages as the oval interface except that this interface does not help to rotate the bottom joint into the right angle. The conical interface therefore only works if the rotation angle on the bottom joint towards the tidal current does not matter, if at least two wires are used to pull the bottom joint to the base or if thrusters or similar solutions are used to rotate the bottom joint. The solution gives some slack for the horizontal positioning since the pins have good margin when they are fitted into the conical holes.

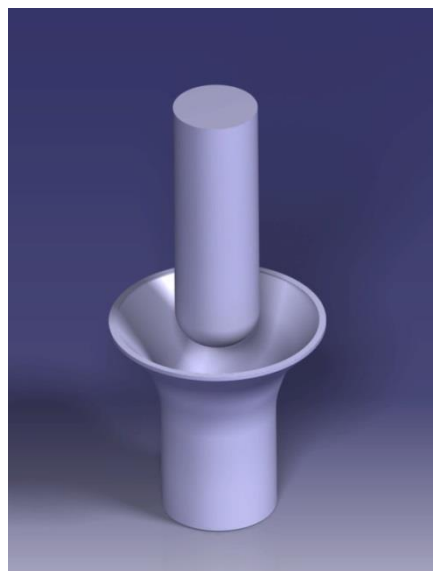


Figure 5.17. Conical interface for fitting

Slide in horizontally

To slide in horizontally is a solution that lets the bottom joint be free from the base in the lowering phase, see Fig 5.18. The solution requires that the base is made of concrete, has a big area and is tilted. The bottom joint is descended and landed on the tilting plane and slides against the corner of the base where a matching interface of the bottom joints interface is casted. This solution sets fewer demands on the precision of the horizontal positioning and does not need anything that steers it from underneath. A disadvantage is that it only works with the base made of concrete and not with the steel constructed base since it has to have a big surface to land on and that the concrete permits that.

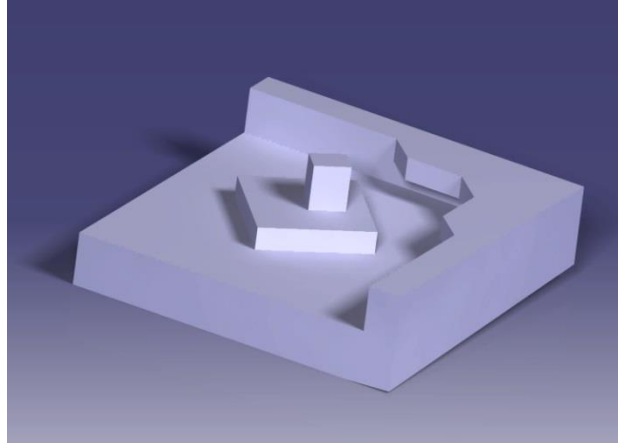


Figure 5.18. The bottom joint slides in horizontally

5.4 Ensuring position

During the whole lowering process operators need to ensure the position of both the bottom joint and the base. When the bottom joint is lowered, knowledge of the position relative the base is critical to make the fitting possible. Depending on which method is used for the fitting different kinds of measuring instruments with different accuracy are used. These instruments should manage to find and position the base at the seafloor and then ensure the position of the bottom joint when it approaches and make sure that the fitting proceeds as expected. Probably different navigation systems must be combined, one for the long range navigation and one for the near base navigation, including the fitting process. The following solutions have been found and been investigated:

- Camera
- ROV/AUV
- Sonar
- Pressure sensor
- Inductive sensor
- Compass
- Gyroscope

Camera

An underwater video camera is placed on the bottom joint and connected to the surface with an umbilical to send live video to operators on the vessel, see Fig. 5.19. The operators can through this visual contact receive information and steer the bottom joint into the right position. An advantage with a camera is the insurance that the equipment works and the security with visual contact. No separate vehicle is needed and therefore it is a relative simple and cheap solution that has been used before.

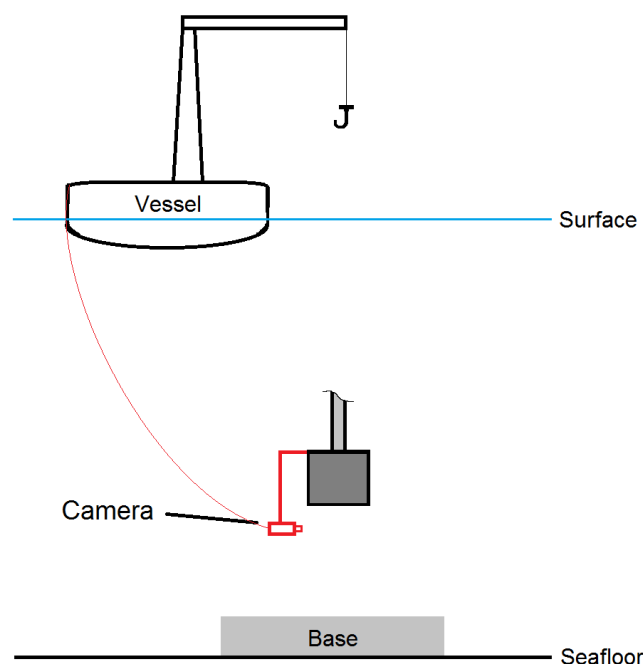


Figure 5.19. Camera connected to the bottom joint

ROV/AUV

An underwater vehicle with a camera sends a live video to the operators on the surface, see Fig. 5.20. If an unpredictable problem occurs the ROV or AUV can change position and film and possibly fix the problem which is a big advantage compared to a fixed camera on the bottom joint. A disadvantage is that it is quite expensive to use an ROV just for filming.

Sonar

Sonar uses sound waves to identify and determine position and distance relative an object. Sonar could be placed on the bottom joint and send the information to the surface. Sonar is a well-used system for subsea navigation which is an advantage for this solution.

Pressure sensor

The pressure sensor is placed on the bottom joint to indicate pressure and in this way the current vertical position is identified. A disadvantage is that the vertical angle of the joint cannot be identified without other sensors or systems. If a wire or cable is attached between the bottom joint and the base, a pressure sensor is unnecessary since the depth could be measured by the amount of wire or cable released.

Inductive sensor

An inductive sensor works similar to a metal detector; the sensor indicates when a conductive material is approaching. This could be used to identify and find the right position before the fitting begins.

Compass

A compass are placed on the bottom joint to make sure that the bottom joint and the base are aligned before the fitting begins. To receive information from the compass, a camera could be fixed above it. This is a simple solution used for the rotation angle on the bottom joint relative the base.

Gyroscope

To ensure orientation of the bottom joint, a gyroscope is placed on it to register movement and tilt relative to the base. The advantage with a gyroscope is the received information about how the object leans in every direction.

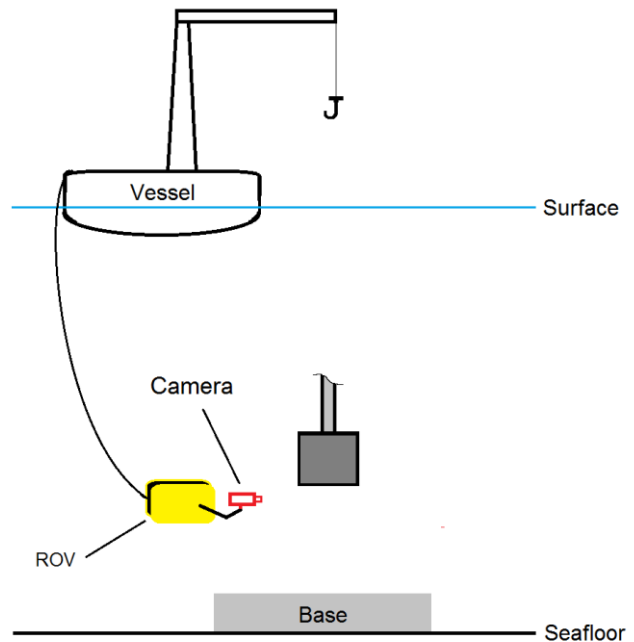


Figure 5.20. ROV filming

5.5 Angle alignment

When the bottom joint approaches the base it is likely that the bottom joint leans due to the currents pushing the tether sideways, see the angle of the bottom joint in Fig. 5.21. How the angle on the bottom joint varies depends on which method is used to position the bottom joint. It can be positioned either with a wire between the bottom joint and the base or with the bottom joint hanging free without any wires between the bottom joint and the base. If the bottom joint is hanging free as in Fig.5.3, no effort has to be done to straighten it up. If a wire is connected to pull the joint towards the right position as in Figs. 5.9 and 5.10 it is more likely that angle alignment is necessary. A solution to straighten the bottom joint up is described below.

Leverage

When the bottom joint approaches the base it is straightened up by a lever before the final fitting is done. The lever could consist of a metal plate with a larger diameter than the current interface of the bottom joint and the base, see Fig 5.21.

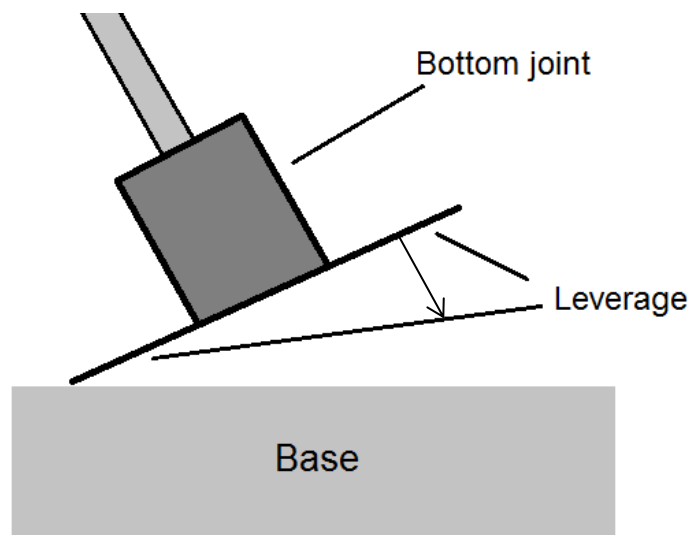


Fig. 5.21. The bottom joint is straightened up by leverage

5.6 Locking

When the kite is dragged by the stream to generate electricity, a major force is transferred via the tether to the base through the bottom joint. The bottom joint has to be connected and designed so that it withstands this force during millions of cycles. The bottom joint will be elevated for service periodically. Therefore the bottom joint must somehow be locked and unlocked from the base. This can be achieved through the following solutions:

- Bolt/screw
- Slide under base
- Ball lock
- Sprint
- Spring loaded clamp

Bolt and screw

One way to lock the bottom joint to the base is to use a hole-pattern in both the bottom joint and the base and with the difference that the holes in the base are threaded. An ROV will then be used to screw in the bolts.

Slide under base

The base could be designed so that the bottom part of the bottom joint is able to slide under a part of the cast base, see Fig. 5.22. In this way, the robust design of the base will take up the drag force. The construction still needs a solution for locking but the locking only has to hold it on place and ensure there is no clearance between the base and the bottom joint. An advantage with this solution is the simple and robust design. A disadvantage is the fitting which does not work together with many other solutions since it is fitted horizontally.

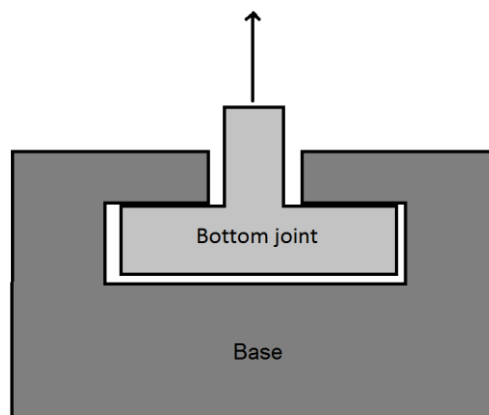


Figure 5.22. The bottom joint is locked by sliding under the base

Ball lock

A set of steel balls are placed on a piston which is pushed down in a cylinder on the base. The steel balls are pushed into tracks by a release pin on the inside of the piston and thereby transfers the vertical drag force from the bottom joint to the base, see Fig. 5.23. When the bottom joint is to be elevated, the release pin is pushed back and the steel balls slide back from the track. The release pin could be driven by an electro magnet, an electric or hydraulic motor, or a manually driven lever.

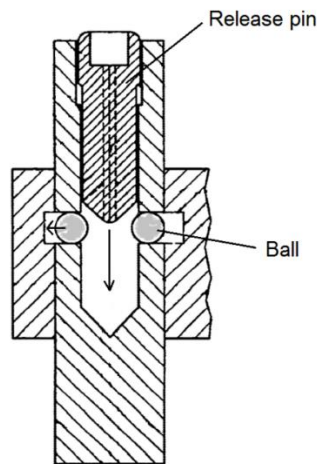


Figure 5.23. The bottom joint is locked by a ball lock

Sprint

When the bottom joint is in place, locking sprints are pushed into holes on the base, see Fig. 5.24. The sprints are pushed in and out by an electro magnet, a hydraulic or an electric motor. For example if hydraulics are used, a hose from the surface could be used to build up pressure at the bottom. An advantage with the solution is that it can be used regardless of the choice of solution for fitting.

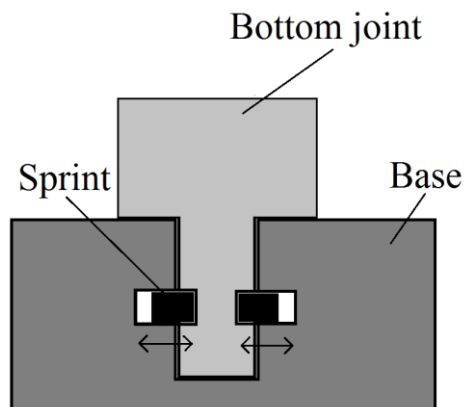


Figure 5.24. The bottom is locked with sprints

Spring loaded clamp

The spring loaded clamp uses the clamps to lock the bottom joint to the base using a force in the direction of the red arrow in Fig. 5.25. The blue arrow represents the force of a spring being tensioned when the clamps lock the bottom joint to the base. The tension of the spring will be released when the bottom joint is to be brought up to the surface. When the tension is released, the clamps release the bottom joint from the base. An advantage with this solution is that the force used to press the bottom joint and the base together can also be used for mating a possible stab plate.

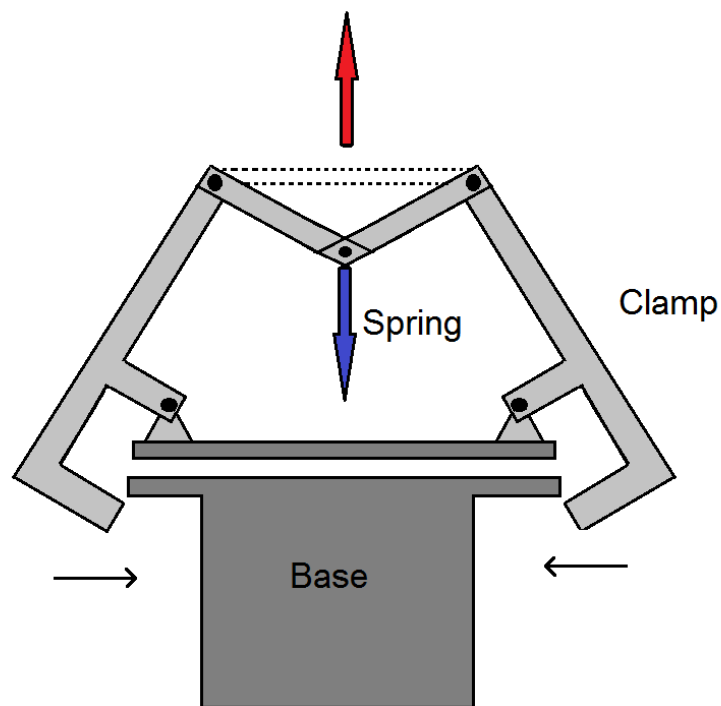


Figure 5.25. The bottom joint is locked by a spring loaded clamp

5.7 Connecting

The power plant generates electric power by the generator placed below the kite. Power from the generator must be transferred to a cable on the seafloor via the tether along with signals to and from the kite. Sustainability is in focus when finding a method for the connecting between the tether and the seafloor cable.

- Wet mate
- Cable reel (one time)
- Stab plate

Wet mate

A wet mate connector is an underwater connection for electricity and signals. If such a device is to be used, an ROV is needed to perform the mating between the cable on the bottom joint and the one on the base, see Fig 5.26. A benefit gained compared to using a stab plate is that the connectors are free and not fitted on the bottom joint and the base. A disadvantage is the need of an ROV. More about wet mate connectors can be found in the theoretical framework.

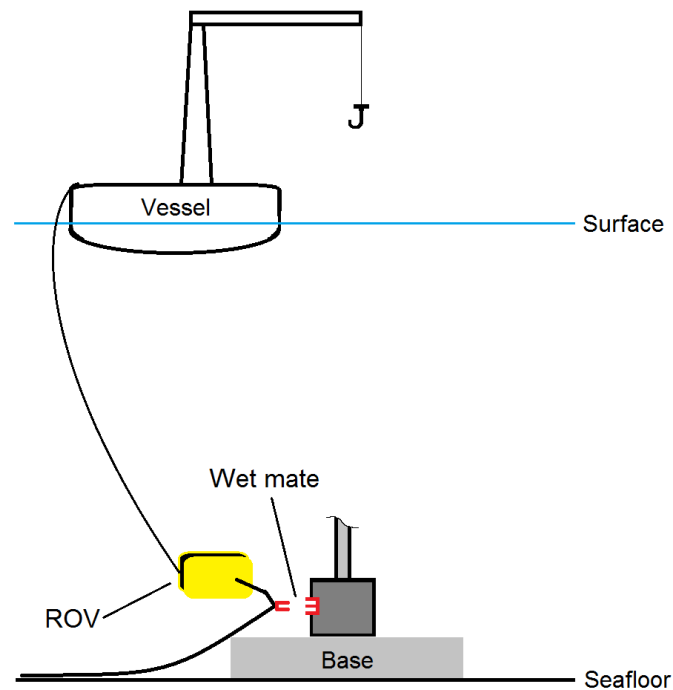


Figure 5.26. ROV connecting a wet mate connector

Cable reel

If the cable reel for transferring electricity is placed on the bottom joint, it only has to be connected to the seafloor cable one time. To permit service, the cable reel releases the cable keeping the bottom joint connected to the base. The cable reel can then be disconnected from the cable at the surface and be replaced with a float until the service is performed. A benefit with this solution is the lack of electrical mating under water.

Stab plate

A stab plate is a device consisting of two separate parts which connect electrical devices (Fig. 2.6). The mating force can be provided by the weight of the object, see Fig. 5.27. The idea in this case is to place a stab plate under the bottom joint which is mated through gravity with the matching plate on the base. The stab plate can also be mated with an ROV or other technical solutions that creates force.

Advantages with using a stab plate are that the connection can be permitted without help from an ROV. The mating will be done in the same step as the fitting of the bottom joint into the base which combines the electrical and mechanical connecting into one step. A disadvantage is that if a problem with the fitting would occur, there is a risk for the connectors on the stab plate to be damaged and result in expensive repairs.

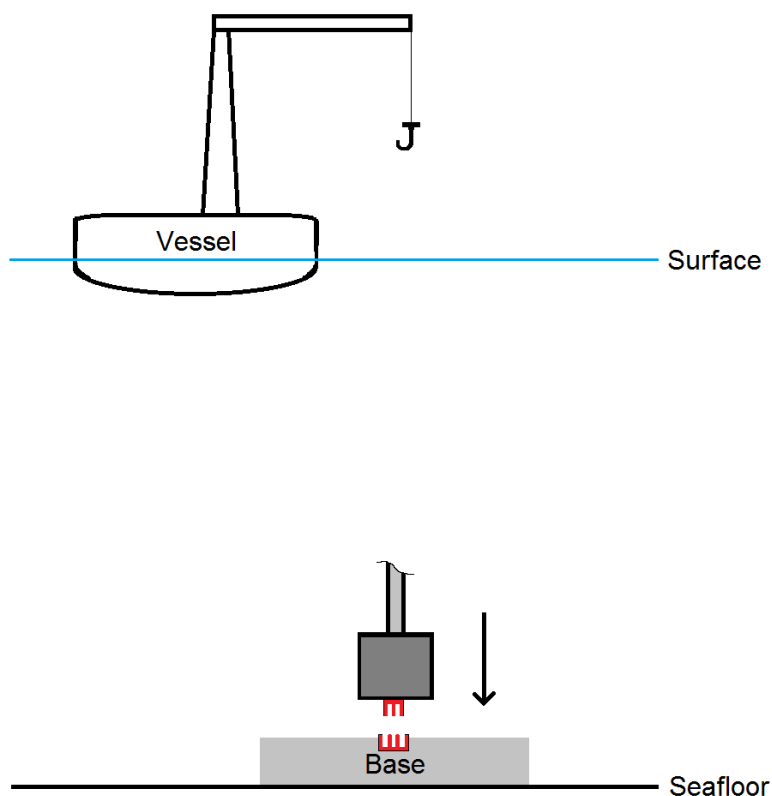


Figure 5.27. Stab plate is connected between bottom joint and base

6. REDUCTION AND EVALUATION

A reduction of the solutions in the chart from the brainstorming (Appendix 1) has been done according to the specification of requirements in Table 4.1 and considering that the final concept is to be used for the first 10-20 power plants. The reduction has resulted in a chart containing the solutions that fulfill those requirements, see Table 6.1. The solutions that do not fulfill the requirements are reduced and are not investigated further.

Table 6.1. The reduced chart containing the most interesting solutions.

Vertical positioning	Horizontal positioning	Fitting
Lifting bags	Water jets	Oval interface
Wire from vessel	Motorized cable reel on bottom joint	Conical interface
Tether from vessel		

Ensuring position	Angle alignment	Connecting
Camera	Leverage	Wet mate
Sensor	No leverage	Stab plate

The different solutions for each function in the reduced chart were further investigated, evaluated and compared to motivate which solutions to combine in the final concept.

During a meeting with the supervisors Robert Perneborn and Mattias Andersson at Minesto it came clear that all the equipment needed for the installation will be mounted on some kind of module, see Fig. 6.1. The module will be fitted with various equipment and have different appearance depending on which solutions are to be used.

The principle with using a module is shown in the figure. The module will be mounted on the bottom joint before the lowering process has begun. The module is then supposed to follow the bottom joint down to the base and be disconnected when the installation is done and be brought up to the surface again.

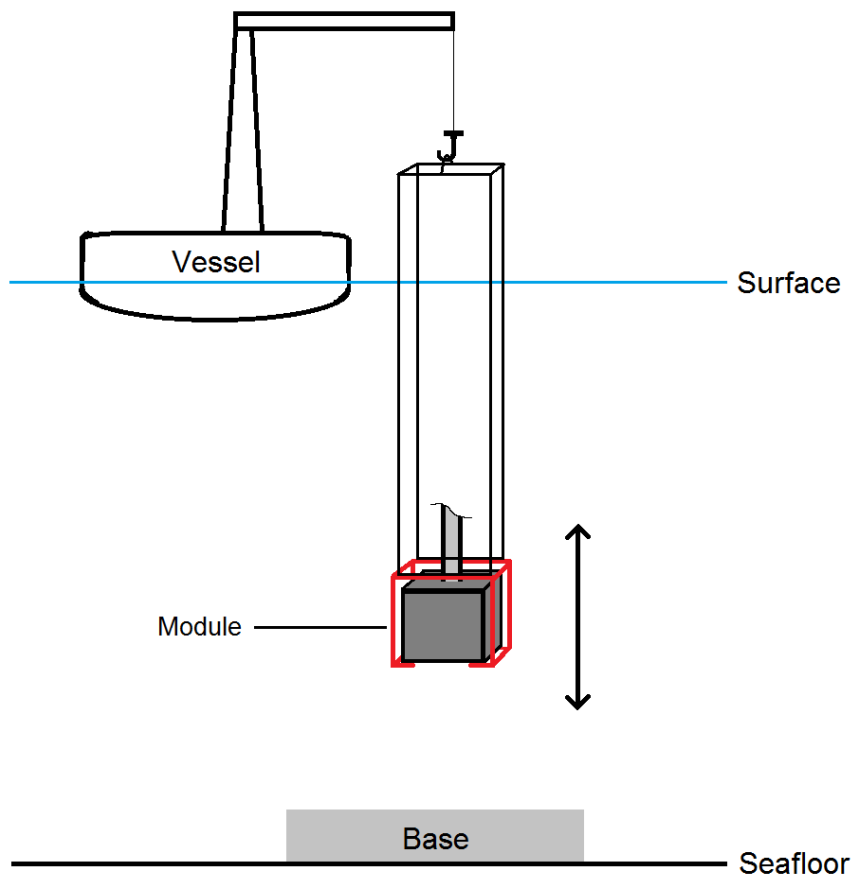


Figure 6.1. The module used to descend the bottom joint and to carry various equipment

6.1 Vertical positioning

Lifting bags (Fig.5.2) are a good help to provide lifting force but is not stable enough to be used without any type of direct contact with the surface. Therefore the bottom joint has to be descended by one or many wires or via the tether.

If the tether is used for the descending, it is coiled at the vessel connected to a heave compensator that reels down the bottom joint (Fig. 5.4). The tether can be coiled on the vessel and does not have to lie free in the ocean attached to a float and thereby be affected by currents and waves.

Another alternative is to use up to four wires connected to a heave compensator at the vessel for the descending. The tether can either be coiled on the vessel during the lowering or be attached to a float and lie free in the water.

Both the tether and the wires fulfill the request to maintain contact between the bottom joint and the vessel. Using the tether for the lowering saves both time and money since no wires are needed and does not have to be disconnected when the bottom joint is fitted.

6.2 Horizontal positioning

According to the specification of requirements, the best and safest way to steer the bottom joint into the right position is done by using direct contact between the bottom joint and the base. To use a cable reel permits good control and ensures that the bottom joint is heading in the right direction (Fig. 5.10).

The positioning of the cable reel on the bottom joint is chosen since it can be brought up to the surface if an error occurs. If the cable reel is placed on the bottom joint, it is brought up to the surface every fifth year and can therefore be maintained along with the other components on the bottom joint

There are a few solutions in the idea generation that meet this request and to use a motorized cable reel on the bottom joint was judged to be the best choice among them, see cable reel on bottom joint in Fig. 5.10. Using a motor to power the cable reel is better than using a loaded spring since the spring would take a lot of space and is not as reliable. Using an ROV to follow the bottom joint down is unnecessary since a motor can manage the same task cheaper and with less technology. The motor can also be mounted on the module and be brought up with the rest of the equipment. By doing this, the motor only has to be in the water during the lowering.

To turn the bottom joint and move it sideways when the velocity of the current increases, water jets can be mounted on the same module as the motor to provide a force to do this (Fig. 5.7). The jet nozzles will be attached on the module pointing in four directions along with one nozzle placed to create a torque to permit rotation.

The reason why the water jets are selected instead of the thrusters is that the power source can be placed on the vessel where the lack of space is not a problem. Since the engine supplies the power from the surface through a thick hose you only need valves that distribute the water into the different nozzles which is less complicated than having a separate engine for each thruster below the surface.

To use air jets is just a more complicated way to provide the same kind of force as with the water jets. A big advantage with the solution to use water is that the pressure needed to move the bottom joint is lower than with the air thanks to the density of the water. You do not need to use pressure to keep the hose from shrinking since the pressure on the outside of the tube is the same as on the inside. It is also easier to build up a high pressure with water than with air, since the water is incompressible.

6.3 Fitting

A concept where the risk of failure is insignificant is required, hence the interface must be designed so that it cannot jam in the fitting process. The oval interface (Fig. 5.16) and the conical interface (Fig. 5.17) are both robust and simple and therefore considered to be working solutions for the fitting.

An advantage with the oval interface is that it does not need more than one wire to ensure that the bottom joint is rotated in the right angle since it can be fitted in two directions separated 180°, see Figs. 5.14 and 5.15.

There are two alternatives for the design of the conical interface. One alternative is to use conical holes and guiding pins without modification as in Fig. 5.17. To use this concept means that two or more guiding pins with matching holes must be used.

The other alternative is to replace the pin with a pair of cones equipped with matching tracks, see Fig 6.2. This means that only one pair of cones is needed. This solution came up in the evaluation stage of the concept development. The solution requires water jets or a similar power source to rotate the cone in the approximately right angle.

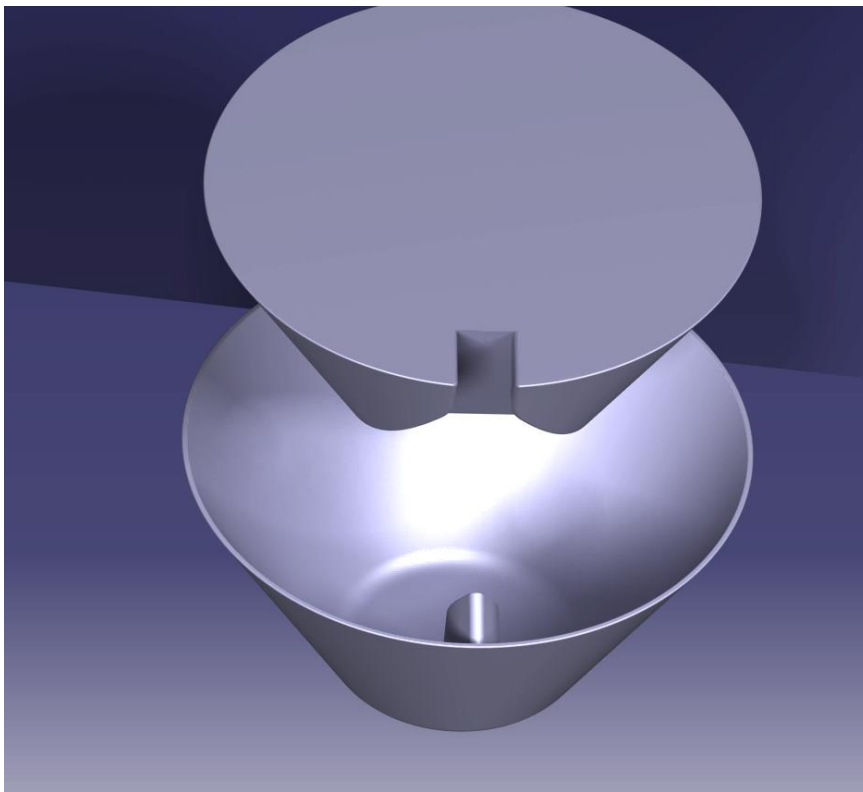


Figure 6.2. Solution for fitting with only one conical interface

To slide in horizontally was considered to be an uncertain solution according to the specification of requirements since the design of the base is not determined. Tracks similar to a thread and the oval interface with bearings were considered too complex and uncertain solutions to use since they have not been used in this context before.

6.4 Ensuring position

A visual contact and a secure way to see that the bottom joint is in the right position both before the fitting is started and to ensure that the fitting has been successful is a request. A video camera contributes with a live image of the process compared to the sensors which only indicate with sound or light. A camera for the main part of the navigation is therefore decided to be used (Fig. 5.19). The camera will be mounted on the module which is brought up when the installation is accomplished.

Other positioning systems can be used as a supplement to ensure the position. A sensor could indicate when the locking is performed correctly and a gyro could be placed on the bottom joint to identify the vertical angle. Since the concept should be as simple and robust as possible, many excessive solutions have been reduced. The sonar, PING, the pressure sensor and the gyro are all unnecessary if the camera works as expected. Using an ROV/AUV to monitor the fitting results is a more complicated operation and is therefore excluded for the final concept (Fig. 5.20). A compass is considered too sensitive and therefore rejected.

6.5 Angle alignment

To align the bottom joint with a lever close to the base is a good complement to the fitting (Fig. 5.21). Although, due to the requirement that the concept should be simple, the leverage should only be used if necessary. It is believed that an angle alignment is needed if only one or two wires are used to pull the bottom joint down toward the base. The angle alignment seems excessive if three or more wires are used in the fitting process since the angle alignment then already is done.

6.6 Locking

During the investigation it was found that it was complex to find, evaluate and visualize a functional solution for the locking mechanism. This was therefore judged to be out of the scope of the present work.

6.7 Connecting

There are several possibilities to transfer electricity from the bottom joint to the seafloor cable. The stab plate (Figs. 2.6 and 5.27) and the wet mate (Fig. 5.26) are both solutions that fulfill the specification of requirements. The stab plate is proven to work and is simple to connect since it is mated during the fitting of the bottom joint. The wet mate connector is safer to use since it is mated after the fitting of the bottom joint.

Both the stab plate and the wet mate has to be mated every time the bottom joint is lowered but the wet mate has to be connected separately with an ROV (Fig. 5.26) which takes time and could cause problems since it adds a step in the installation. A disadvantage with the stab plate is that the fitting has to work as expected to be sure that the stab plate will not brake.

A connection via a cable reel causes an investment in longer, more advanced and more expensive cables, an extra cable reel and an extra swivel which results in more moving parts compared to the stab plate and the wet mate.

The cable reel has never been used in reality and the risk of failure is significant. Therefore, the cable reel will not be included in this phase of the Deep Green project.

7. FINAL CONCEPT

The solutions that fits the specification of requirements best are now combined to create the final concept.

7.1 Describing the final concept

The concept is visualized using Catia v5, see Fig. 7.1. The model is neither made for production nor is it in the right scale. The part simulating the bottom joint is made as similar as possible to the current prototype.

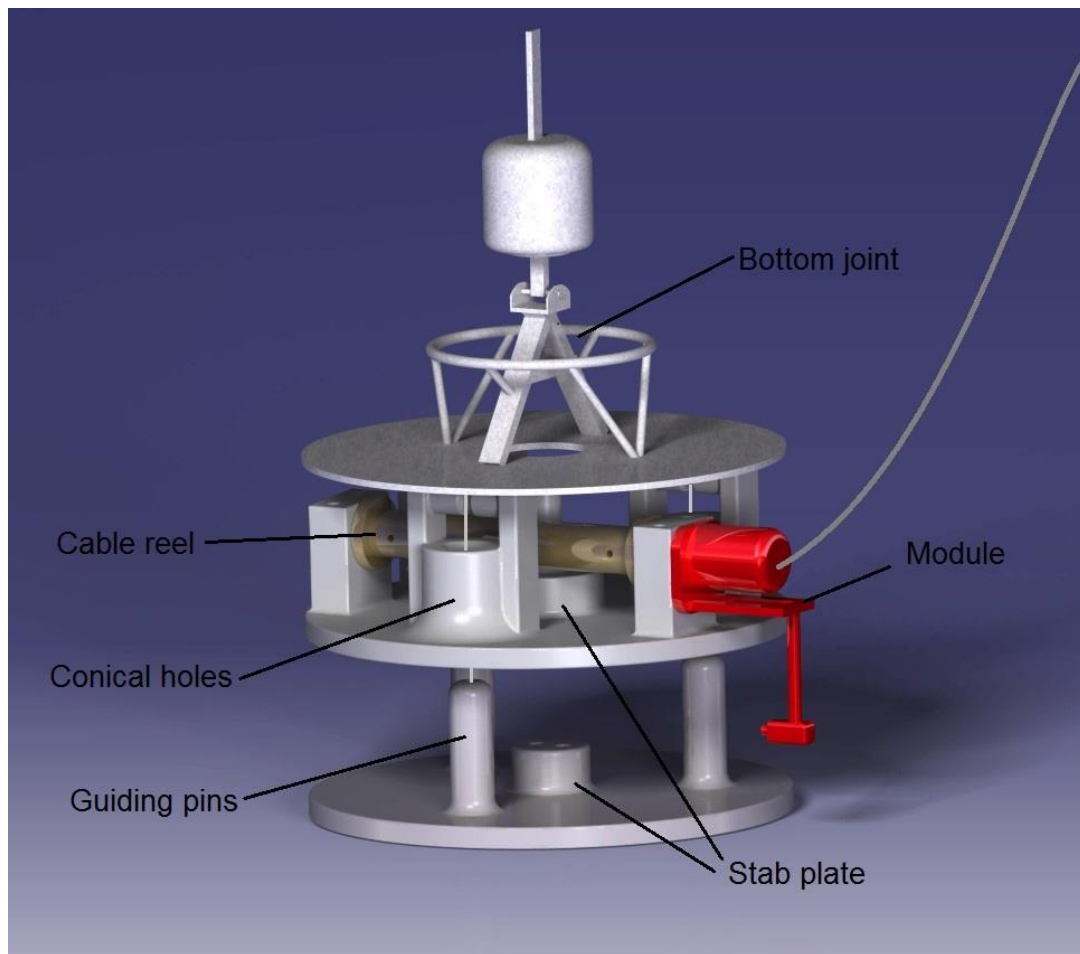


Figure. 7.1. The final concept using three pins

Vertical positioning – Tether from boat

The solution using the tether for the lowering is chosen because it is possible and very simple (Fig. 5.4). To use the tether for the descending means that no other equipment is needed to provide the force required to descend the bottom joint. This solution is therefore the simplest and cheapest. It also solves the problem that the tether needs to be managed during the lowering process.

Horizontal positioning – Motorized cable reel on bottom joint

The motorized cable reel fitted on the bottom joint is considered to be sufficient for the horizontal positioning, see Fig. 7.2. Water jets are considered excessive at this point in the Deep Green concept development since an ROV can be used for the same task if a problem with the horizontal positioning occurs when the first 10-20 power plants are installed. To use an ROV is not a problem even if this might take more time and be more expensive.

If the water jets are considered to be useful in the future, they can be installed at that point.

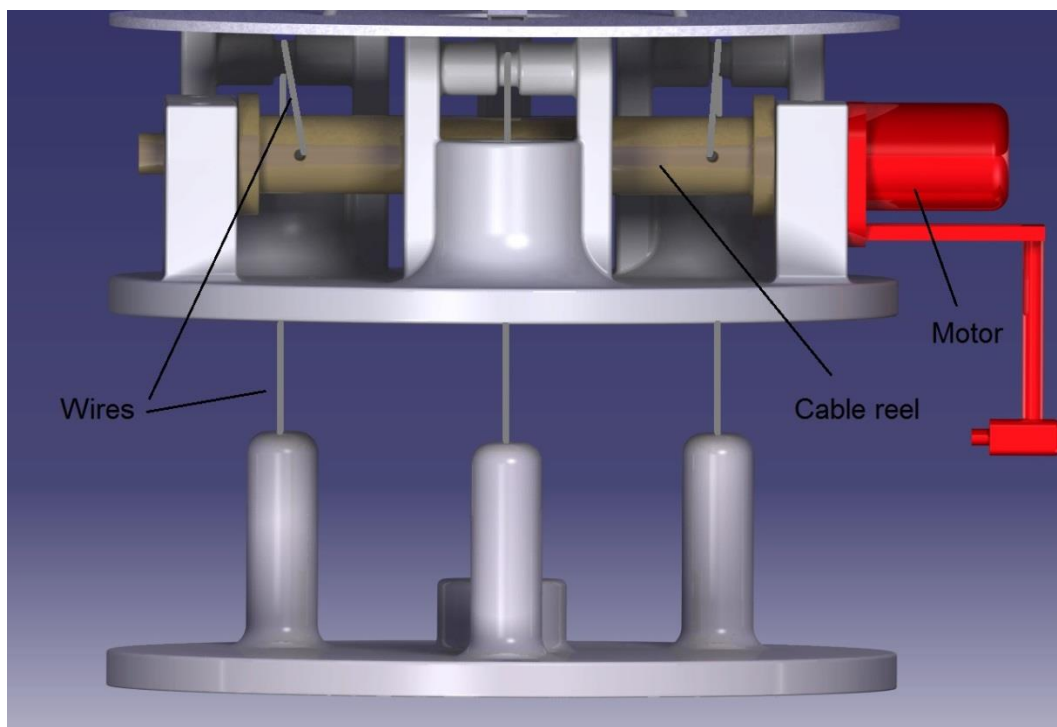


Figure 7.2. Horizontal positioning uses three wires driven by a motorized cable reel

Fitting – Conical interface

The original conical interface without modification (Fig. 5.17) is chosen since it is proven to work in contrast to the oval interface (Fig. 5.16) for which no field experience exists. Using the conical interface also results in that more than one pin and hole will be mated which results in a more robust fitting. The conical interface is also easier than the oval interface to manufacture which makes the tolerances better.

Apart from the final concept, a second solution for the fitting is presented. The reason for that is that two of the fitting solutions using a conical interface are considered to be suitable solutions. One of the concepts uses three guiding pins and the other one uses two. The concept using three guiding pins is chosen for the final concept since similar solutions have been used before and it is more likely to work. The concept will be using three wires mounted on the top of each pin and be connected to the cable reel on the bottom joint through the conical holes, see Fig. 7.3.

The second concept uses a fitting solution with two guiding pins connected to wires, see Fig. 7.4. In this concept, one of the holes for the pins is oblong to make the tolerance less affective. This solution has the advantage that it only has one connection with a tight fitting, making it less sensitive if misalignment would occur, although since there are only two supporting points, the risk of misalignment is greater.

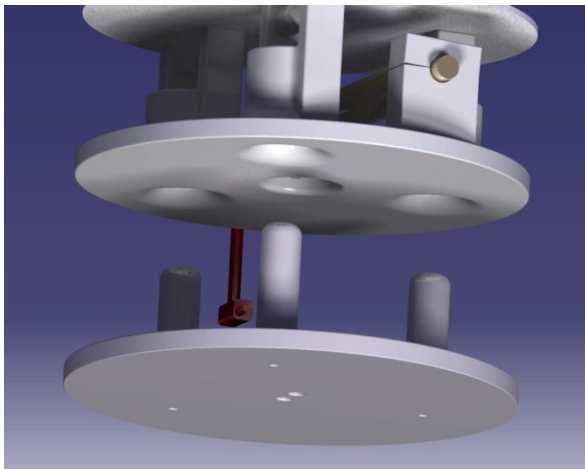


Figure 7.3. Fitting using three pins

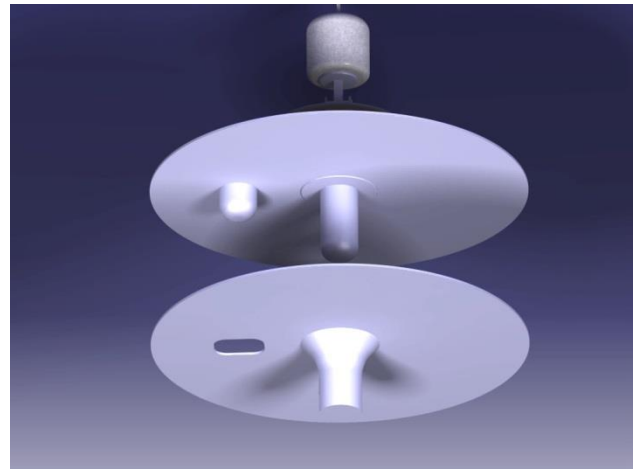


Figure 7.4. Fitting using two pins

Ensuring position – Camera and sensor

As mentioned before, a camera is to be used to ensure the position, see Fig. 7.5. To use a sensor is both a backup if the camera breaks or the visibility is bad and a verification that the bottom joint truly is in its right place. Therefore both a camera and a sensor will be used in the final concept. The sensor is not included in the figure.

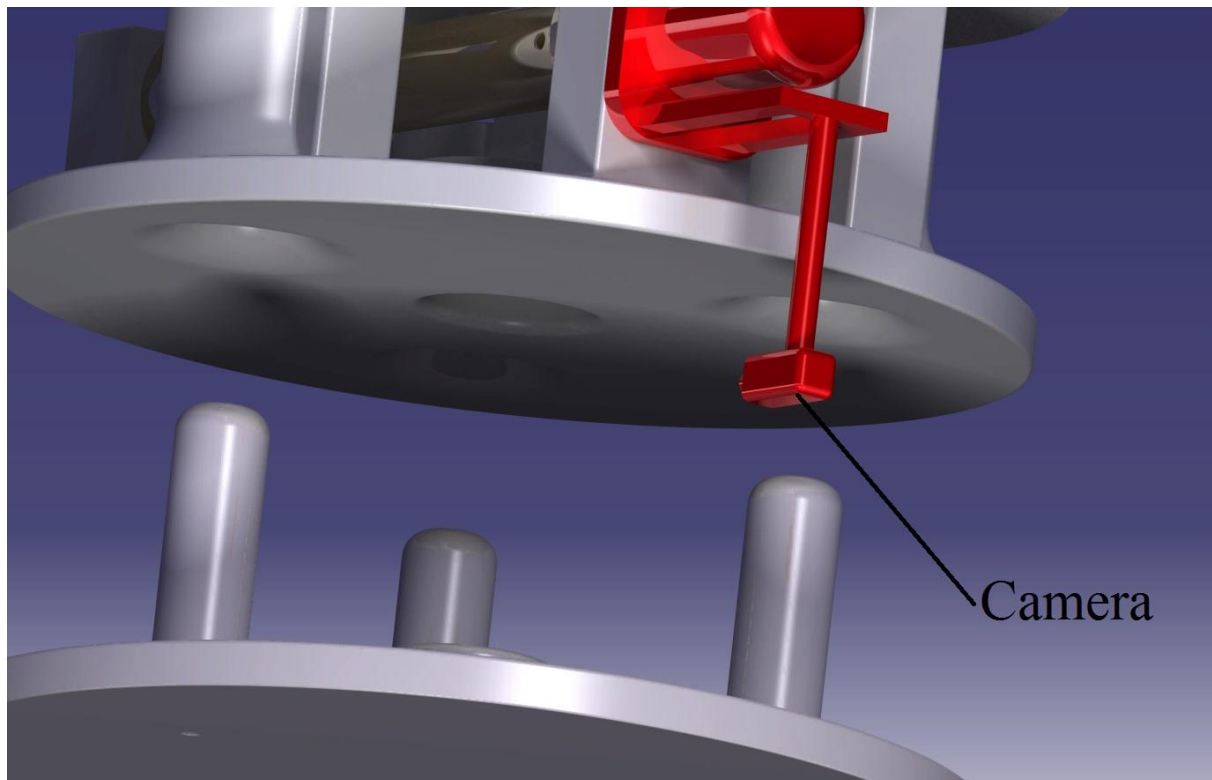


Figure 7.5. Ensuring position using a camera on the module

Angle alignment - No leverage

Since the angle alignment is accomplished with the final concept using three cones with pins (Fig. 7.3), no leverage will be needed at this stage of the developing process.

Connecting - Stab plate

The electrical connection will be managed with a stab plate (Figs 2.6 and Fig. 5.27), see another simplification in Fig. 7.6. The stab plate is chosen since the mating of the connector is done in the same step as the fitting of the bottom joint while the wet mate has to be connected separately which adds an extra step in the installation and therefore also a risk of failure.

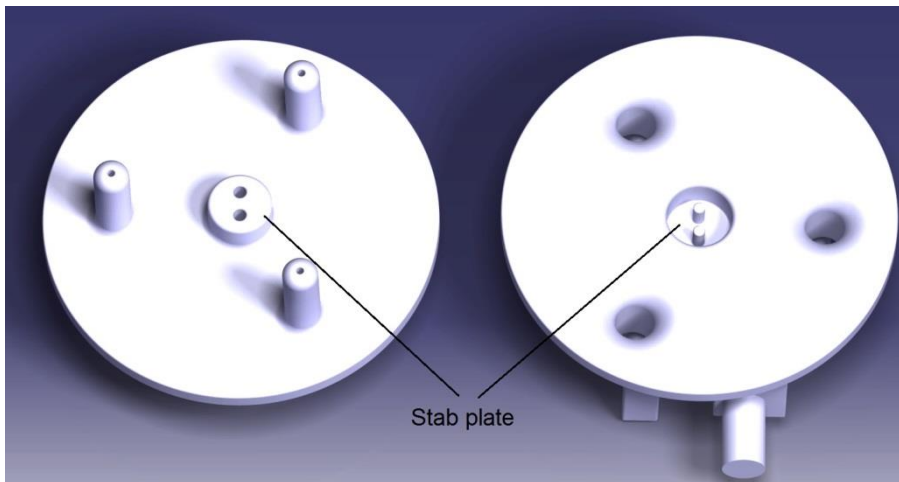


Figure 7.6. Using stab plate for the electric connection

7.2 Verification

To verify the fitting and the horizontal positioning, a model has been developed exclusively for verifying the function, see Fig. 7.7. The concept is printed in 3D and is supposed to simulate the lowering and fitting of the bottom joint in order to identify problems such as the misalignment. Since the bottom joint will be equipped with a motorized cable reel, a small electric motor will power the reel.

The model looks nothing like a product made for production and is only produced to verify the fitting and horizontal positioning. It is reinforced to manage the load from the cable reel, since it is in a small scale, about 10 cm in diameter when printed.

The reason why we chose to use the concept with three pins for the verification prototype is that it has been used for similar tasks and is therefore seen as the most likely solution to use.

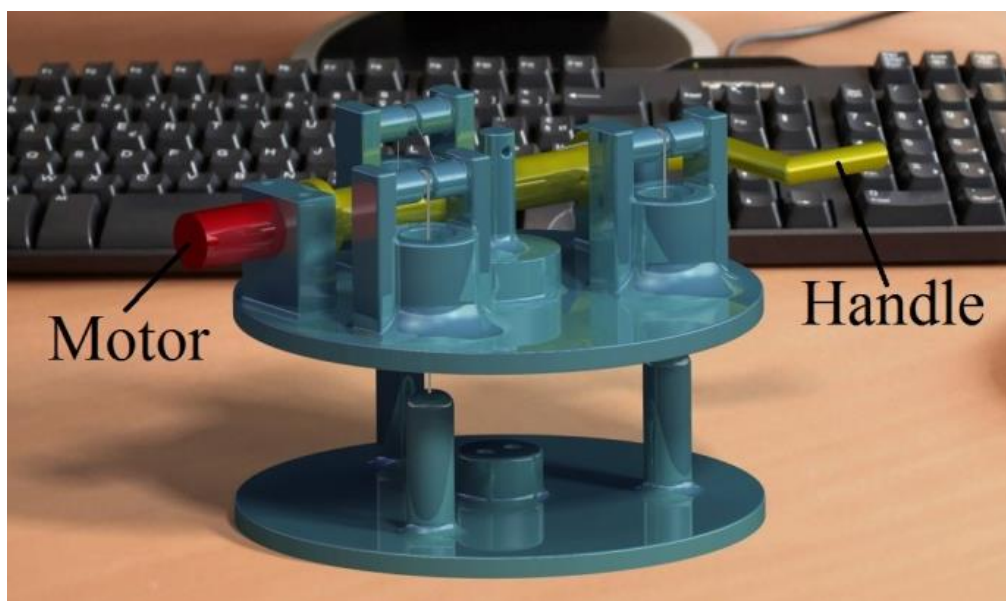


Figure 7.7. Model for verification through 3D-printing

8. CONCLUSIONS

A ground has been set to find a final concept for the lowering- and elevating process of the bottom joint. This has been accomplished by doing research about the conditions at the seafloor, various offshore industries, equipment and techniques. Through these investigations in subsea engineering together with different methods for concept development, a final concept has been developed.

- The bottom joint will be lowered to the base by the tether which is coiled on the vessel and connected to a heave compensator. To steer the bottom joint in the right direction it will also be winched down to the base in three wires by a cable reel, driven by a motor mounted on the bottom joint.
- To ensure the position of the bottom joint, a camera with lights will be used together with a sensor, ensuring that the bottom joint is in its right place. The motor that powers the cable reel, the camera and the lights will be mounted on a module attached to the bottom joint to keep as many parts as possible from the seafloor at a long time. The module will be separated from the bottom joint and brought up to the surface when the bottom joint is installed.
- The bottom joint will have conical holes which are fitted over matching pins on the base. When the pins are steered into the holes, a stab plate is connected to transfer electricity and signals. During the investigation of the locking in chapter 6, it was found that it was complex to find, evaluate and visualize a functional solution for the locking mechanism. This was therefore judged to be out of the scope of the work.
- To elevate the bottom joint, the locking mechanism is unlocked and the bottom joint is winched up in the tether. To repeat the procedure, the module with the motor, camera and lights are once again mounted to lower the bottom joint.

The two final concepts are modeled in Catia v5 for visualization and not for function. A prototype has been modeled and printed in a 3D-printer to verify the fitting.

Suggestions for further work

Since the project aim is not to develop complete construction drawings or prepare the product for manufacturing, focus has been on the prestudy and the concept development which are the early phases of the product development process. Therefore all of the solutions and concepts have to be further developed, tested and prepared for production.

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APPENDIX 1. Idea generation

Vertical positioning	Horizontal positioning	Fitting	Ensuring position
Lifting bags	Thrusters	Track similar to a thread	ROV/AUV
Wire from vessel	Airjets	Magnetism	Camera
Tether from vessel	Waterjets	Spikes in holes	Sensor
	ROV/AUV	Oval interface	Sonar
	Spring-loaded cable reel on bottom joint	Cone	PING
	Spring-loaded cable reel on base	Cones/wedges	Compass
	Motorized cable reel on bottom joint	Slide in horizontally	Pressure sensor
	Motorized cable reel on base	Oval interface with bearing	Inductive sensor
	Cable reel on bottom joint driven by anROV	Circular tracks	Gyro
	Cable reel on base driven by an ROV		Clear marking
Angle alignment	Locking	Connecting	
Leverage	Bolt/screw	Wet Mate	
No leverage	Magnetism	Cable reel (one time)	
	Slide into tracks	Stab plate	
	ROV locks		
	Electromagnet		
	Electric motor		
	Hydraulic sprint		
	Electromagnetic sprint		
	Slide "under" base		
	Electric ball lock		
	Hydraulic ball lock		
	Locking in cable reel		
	Oil pressure locking teeth		