The implementation of an underwater navigation system, applied to Ortega's submersibles

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Preface

The cause that lead to writing this report, is Erik Terhorst, who I've met randomly in life. He told me about the existance of Ortega Submersibles, and from that moment I knew it would be an awesome bachelor thesis project. Such a small start-up company would probably give me more participation and besides, submersibles are just awesome.

Thanks to Daan and Filip, co-founders of Ortega, for the oppertunity to participate in Ortega. And a special thanks to Winnie Dankers, my supervisor, for al her optimism and patience.

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SUMMARY

The objective of this research, is to design a navigation system that can be integrated into Ortega's submersibles. The insights gathered in the research phase resulted in a combination of an Inertial Navigation System (INS) and Doppler Velocity Log (DVL) to be the most suitable system. In contradiction to other available methods, this combination could handle almost all environments and activities.

The Spatial FOG INS and the Syrinx DVL have high accuracy characteristics, and enable for custom made casings, which can be designed such that installation takes minimum time and effort.

In the final design, which is chosen out of three concept designs, the Spatial FOG is placed in a waterproof casing, together with a Global Navigation Satelite System (GNSS) antenna. The casing is placed in the upper middle of the submersible, behind the second seat. The GNNS had to be placed at altitude, and the INS performs best when placed near the centre of gravity of the submersible.

The DVL's transducer heads must be in direct contact with water, and aligned facing the seafloor. In the submersible, is placed more to the front, away from thrusters and motors. To protect the transducer heads, it is placed in a hull, such that is nicely concealed with the submersible's shell.

Sensor implementation and attachment is performed including the installation steps. Solidworks models and parts lists are included.

SAMENVATTING

Het doel van het onderzoek is het ontwerpen van een navigatiesysteem, dat geintegreerd kan worden met Ortaga's duikboten. Verkregen inzichten uit de onderzoeksfase resulteerden in een combinatie van een intertie-gebaseerd navigatie systeem (INS) en een Doppler sensor (DVL) als geschikt systeem. In tegenstelling tot andere methodes, kon dit systeem opereren in alle omstandigheden en activiteiten.

De Spatial FOG and Syrinx DVL hebben een hoge nauwkeurigheid, en opent de mogelijkheid tot het ontwerpen van een eigen casing, wat tot minimum tijd en moeite kan leiden bij het installeren.

In het eindontwerp, wat gekozen is uit drie concepten, is de Spatial FOG geplaatst in een waterdicht omhulsel, samen met de bijgeleverde Globale Navigatie Satteliet Systeem (GNSS) ontvanger. Het omhulsel is geplaatst bovenin het midden van de duikboot, achter de tweede stoel. De GNNS moest hoog geplaatst worden, en de INS zo dicht mogelijk bij het massazwaartepunt.

De sensorkoppen van de DVL moeten in het water geplaatst worden, uitgelijnd zodat de kop naar de bodem wijst en ver van propellors en motoren. Om de kop te beschermen, is hij in een omhulsul geplaatst dat mooi uitgelijnd is met de romp van de duikboot.

De implementatie en bevestiging van de sensoren is uitgevoerd met installatiestappen, en een solidworks model is en onderdelenlijst is bijgevoegd.

2

Introduction

A BRIEF HISTORY OF DIVING

Underwater exploration is something people have been trying to do for decades. Snorkelling began with the use of bamboo sticks to breathe through, and people used sheep or goat bellows as an air sack to breathe in. The first step to underwater exploration was the diving bell, invented by Aristoteles approximately 330 years before Christ. This is a bucket upside down filled with air, which could be drowned a couple of metres and tied to the bottom. Divers could swim around in the water, and when they had to breathe they could swim to the diving bell and take a breath. It would not take long, however, for the air in the diving bell to be unusable because of the increase of carbon dioxide (SSI, n.d.).

Diving

In the 18th century pumps were developed that could deliver pressurised air from the surface. Diving equipment was invented in the form of a suit and a helmet filled with air (SSI, n.d.). In the beginning, this suit was so heavy that divers would sink to the bottom and walk around on the sea floor, but later on people got knowledge on how to retain buoyancy.

In 1943, Jacques Cousteau developed a demand-driven regulator, which enabled divers to dive with compressed oxygen flasks. This regulator can transform pressurized air to the correct inhaling pressure, which is depth-dependent. No longer were divers limited to air cables or heavy and inconvenient equipment, but could move freely through the water (SSI, n.d.).

Submarines

The first known mention of submarine came from William Bourne in 1580. He wrote about the principle that by displacing water the ship in and out, the ship would alter its altitude. The first workable submarine was invented by a Dutchman: Cornelius Drebble and was based on the diving bell principle: a decked-over rowboat, propelled by twelve men with peddles. However, there were no documents found, and the only proof of existance were eyewitnesses. An explanation of the working principle, is that the boat had a downward sloping foredeck that creates a downward movement while speed is retained. When the rowers stopped rowing, the boat would slowly rise to the surface (Harris, 2015).

The military recognised that the depths of the sea is the most efficient space to effectively hide militairy power. Even in this early stage, stories and paintings tell us that comparable primitive submarines were already used to spy on enemy territory and explore unknown territory for the presence of enemies (Wikipedia, 2016). In the 1800s, many variations of the submarine were built for several military purposes, but most of them did not survive long. It took until the first Wold War for the submersible to become an effective weapon of war. At this time, using submersibles in warfare was seen as an unethical tactic. After Germany used submarines to sink merchant ships, the face of war had changed completely (Chandler, 2016).

In the second World War, submarines were used in increased numbers to cut supply lines, destroy enemy ships, or explore enemy territory. The use of submersibles during WWII and the technological improvements in diving equipment lead to the

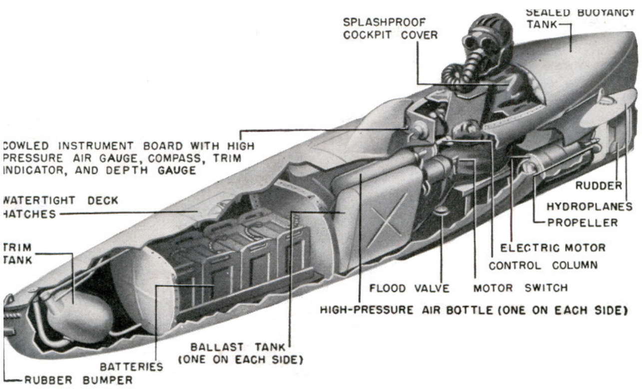


Figure 1 - *The Sleaping Beauty*

invention of the Sleaping Beauty: a motorised canoe-shaped submersible, as illustrated in Figure 1. During the second world war, this invention got implemented broadly to explore enemy territory without being noticed. The submersible was small and undetectable, just like a diver, but could travel much more distance. Although The Sleeping Beauty was a Britisch invention, the submersible has also been used by Asia against Japan. After her successful introduction during the WWII, the design got forgotten because there were still some drawbacks present in the design (Jurgens, 2015).

ORTEGA SUBMERSIBLES

Ortega is a company that tries to revive the idea of the Sleaping Beauty. The idea was initiated by Filip Jonker, who was always fascinated by submarines. During a wreck dive he noticed it would be nice to have some kind of motorised vessel, to cover longer distances and to bring some equipment. He found the documents of the Sleeping Beauty, together with a report of required adjustments to make the design reliable.

Filip got a team together of enthusiastic people, including his co-founder Daan. They are now working on three different submersible types. The


Figure 2 - *Ortega's three submersible types*

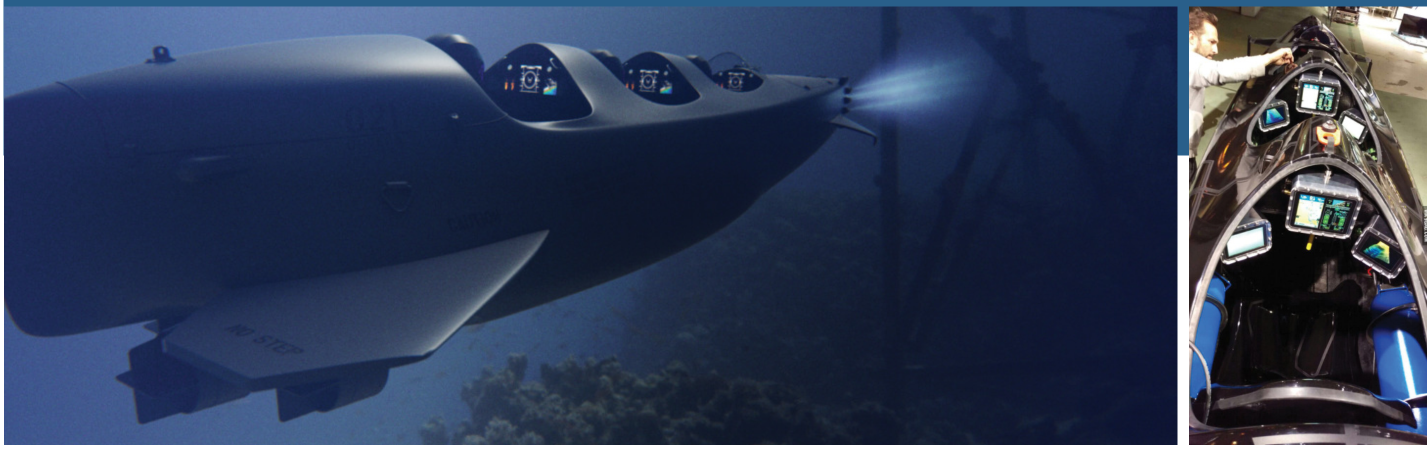


Figure 3 - *The MK1C*

MK1A, a single seated submersible which is specifically designed for surveys and offshore industries; The MK1B, a double seated version where underwater research and harbour protection are more of interest; and the MK1C, a three-person submersible which is developed primarily for defence objectives. The three types are presented in Figure 2.

All types are still in its prototyping phase. The one-seater is Ortega's first proof of concept, and the team has shown great performances with this prototype. The submersible can travel both above surface and underwater and reaches a velocity of approximately 12 km/h, and has a range of 100 km (Jurgens, 2015). As more and more companies were interested in a three-seater, Ortega decided to upgrade their model. The MK1C has been updated with new batteries, based on an open source project of Tesla. With this technique, the submersibles speed can go up to 25 km/h and having a range of 200 km. Although the three-seater is not completely finished yet, some models have already been sold. The company is currently getting more and more recognition and attention from companies that really see an added value in the design. Figure 3 shows the three-seater more extensively, because in this report, the design will be applied on this submersible.

Market research

Currently, underwater activities are very broad: from harbor protection to building underwater infrastructure, seafloor mapping, marine applications, scientific surveys and wreck diving: There is much to do. Although many submersibles are already operational, none are comparable to the designs of Ortega. They are either expensive submarines controlled by robotic arms, or very simple units with a screw and some handles, which can pull the diver trough the water. Besides, their maximum speed and range does not even get close to the MK1C.

Driver Propultion Devices (DPD)

Figure 4 - *The STIDD DPD (American Special Ops, n.d.)*

The Driver Propulsion Device manufactured by STIDD Systems Inc. is the vehicle that is currently used by the U.S. military. Figure 4 shows the submersible, that consists out of a single thruster, powered by an Lithium-Ion battery, and can carry two men and some equipment. It can operate up to 35 m below surface with a speed of 2,5 km/h. The DPD has a range of 12 km (American Special Ops, n.d.).

Small submarines

Small submarines are often used for exploration and scientific purposes, but the military uses them as well. They are often used when much equipment is required for the operation, because it can be upgraded with all kind of sensors and robotic arms to achieve many tasks underwater. The C-Explorer 3, manufactured by U-boat Worx and shown in Figure 5, have a dive time up to 16 hours and is operational at 300 metres (U-Boat Worx, n.d.). Most small submarines however, can go much deeper and are often used for deep-sea exploration.

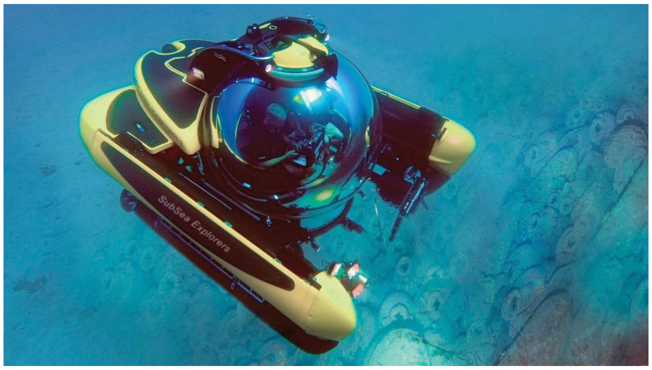


Figure 5 - *C-Explorer 3*

Remotely Operated Vehicles (ROV's)

Recent technological improvements in underwater communication and navigation systems have enabled underwater vehicles to be controlled from a distance. ROV's are often used in deep-water surveys, but are more and more employed for other scientific purposes and maintenance work. The ROV in Figure 6, the Cougar XT, is operational for many subsea tasks like general survey, light work duties, subsea installation, recoveries, salvage and measurement equipment deployment.

Figure 6 - *Cougar XT*

Future plans

Ortega wants to outsource most of their production tasks, so the team itself can keep focussing on innovation and upgrading the submersible. Their goal is to make operating the submersible as easy as possible. With the use of various sensors, many actions that a navigator has to execute, can be partially or completely taken care of by the submersible. With a clear interface, showing the most important information, a lot of brain processing and training can be reduced, enabling the driver to focus completely on the task it has to execute. The integration of a navigation system is the next step in this direction. By enabling the user to know its exact location underwater, many navigating tasks can be neglected. This can save a lot of time, but also the amount of trainings can be reduced to do underwater operations.

After this, plans are present to upgrade the system with virtual reality. Underwater, in many cases, you should be lucky to see more than a couple of metres ahead. With the use of a virtual reality goggle, it is possible to not only create a brighter picture of the environment, but also to implement important data like speed, pith, roll, current location and remaining air right in front of you. Operating the submersible becomes even more intuively, reducing more time and costs.

3

Assignment description and outline

THE ASSIGNMENT

In the previous chapter was stated, that the implementation of a navigation system will be Ortega's next step. They had however, not yet really deepened into the subject. This is how the assignment came into existence. The first thing a navigation system would require to be operational, is to require information about the submersible's exact location. This is not as easy as it seems, because the most commonly used positioning method, satellite navigation, uses signals that cannot penetrate water. Various other methods for obtaining position information are established and broadly used. In this report, available methods will be elaborated, and a suitable system will be chosen and implemented into the submersible.

The most elegant option is to convert any input signal into global position coordinates. Only here you can get an absolute position, which you can locate on a global map. The objective is to design or construct a measuring and processing device, which can obtain global position coordinates by converting sensor information into coordinates. The goal is to find a solution within acceptable error margin and range.

The measuring and processing device has to be implemented in the submersible. Sensors and possible casings have to be placed such that they have maximum accuracy, are easy to implement, and correspond with the design of the submersible. The interface design of the navigation system is beyond the scope of this project.

OUTLINE

In the research phase, information is acquired about the company concerning their design wishes and competition, and a research into current underwater navigation systems is conducted. With the insights gathered in the research phase, the most suitable navigation method could be chosen.

In the second phase, more information about both the INS and DVL is collected. This information concerned market availability and shows the performances of various sensors. After choosing a specific sensor, its requirements are obtained concerning sensor placement and implementation.

Then, three concepts are elaborated that include solutions proposed in the second phase. Based on the requirements of the INS and DVL, and the requirements set by Ortega, the most suitable concept is chosen.

At last, a detailed engineering solution is given, that takes into account how the sensor is attached into the submersible, and what installation steps are. Solidworks models and parts lists are included.

4

Requirements

After some discussion with Ortega, the conclusion was that no concrete requirements could be set for the design of the system. Accuracy and price is a trade-off where the company expected me to use common sense, and find a suitable and not too expensive solution that fits within the future vision of the company.

With the use of common sense, the following requirements were found.

To have a range of 200 km
The submersible can travel 200 km underwater without running out of battery. Therefore, this is the working range of the submersible. There are however, only a few underwater activities that require such ranges. A common range during underwater operations is approximately 30 km.

To have an acceptable accuracy
There is no tangible number given, because for most underwater navigation systems accuracy there is a trade-off against range and dive time or range and depth, and also the costs of the system are correlated to accuracy, as high accuracy sensors are more expensive. A consideration has to be made by the company what price to pay for a certain accuracy. This is strongly dependent on the type of activity that has to be performed by the submersible.

To have a depth range between 0 m en 100 m
Because the submersible is open, depth limitations are the same as with divers. While breathing air in high pressure surroundings there is an increased risk in nitrogen narcosis or oxygen toxicity. The limits for recreational diving are therefore 40 m, where technical divers can go up to 100 m. There are possibilities to dive even deeper, but then, atmospheric suits are a necessity. These suits are big and not (yet) suitable for most underwater activities because it is very hard to make hand movements. They are therefore neglected as target group.

To be water-resistant at 11 bar
This is the surrounding pressure at 100 m of depth.

Output signals should be global coordinates

5

Underwater positioning systems

Challenges are present for obtaining location information underwater, since the signals from the widely known Global Navigation Satellite System (GNSS), which includes the commercially used Global Positioning System (GPS), cannot penetrate the water. Any vessel that is submerged merely 20 cm underneath surface will lose signal. Nevertheless, various methods for underwater positioning do exist and are widely implemented. These positioning systems can be divided into four groups: Acoustic positioning systems, inertial navigation systems, geophysical identification and cabled connection with a floater.

ACOUSTIC SYSTEMS

Regarding various forms of radiation, sound can travel best through water. Therefore, acoustic positioning systems are commonly used for underwater positioning (Tomczak, 2011). These systems rely on baseline stations, which must be installed carefully prior to installations. By measuring travel time, distances between the target and baseline station can be measured to calculate the target position (Acedemy of Positioning Marine and Bathymetry, n.d.).

Although sound can travel well through water, reaching high accuracy in larger range operations is still a major challenge. Higher frequency signals attenuate rapidly and the underwater environments are unstructured (Paull, Saeedi, & al., 2014). Acoustic receivers will not measure direct signals, but also signals that reflect against the water surface and sea floor. Especially in shallow waters, this so-called multipath interference increases the time required between pulses. Furthermore, sound velocity varies with temperature, salinity and pressure. Unless these factors are measured and countered for, this

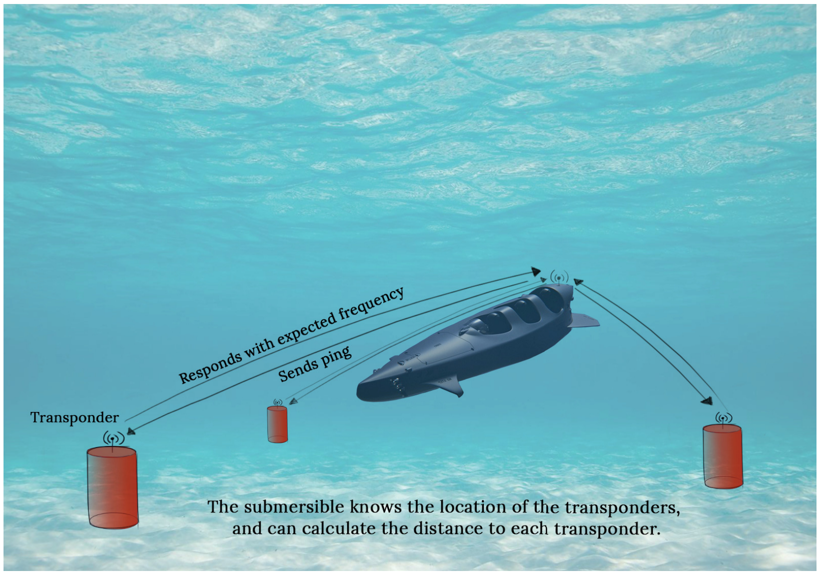


Figure 7 - *Long Baseline (LBL)*

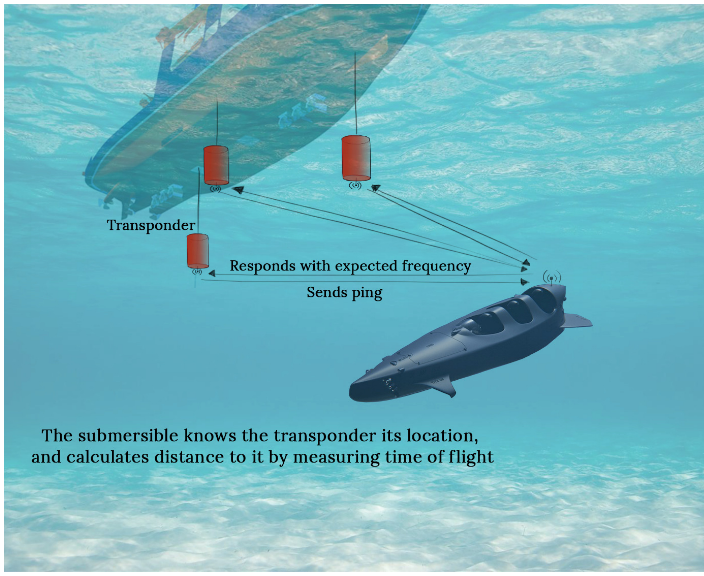


Figure 8 - *Short Baseline (LBL)*

will also reduce the measurement accuracy (Kuch, Butazzo, & al., 2012).

Long Baseline (LBL)

Long Baseline. as demonstrated in Figure 7 is a high accuracy and long range method where three or more fixed beacons are installed on the seafloor. These transponders have to be GPS-referenced or calibrated in order to know their location. A transceiver is mounted onto the submersible, and will calculate its distance to each of the beacons by pinging them and calculating the time required for the signal to travel back and forth. With the use of trilateration, the location relative to the beacons can be determined. Because the beacons are GPS-referenced, it is possible to obtain the absolute location of the submersible (Khan, Taher, & Hover, 2010) (Tomczak, 2011).

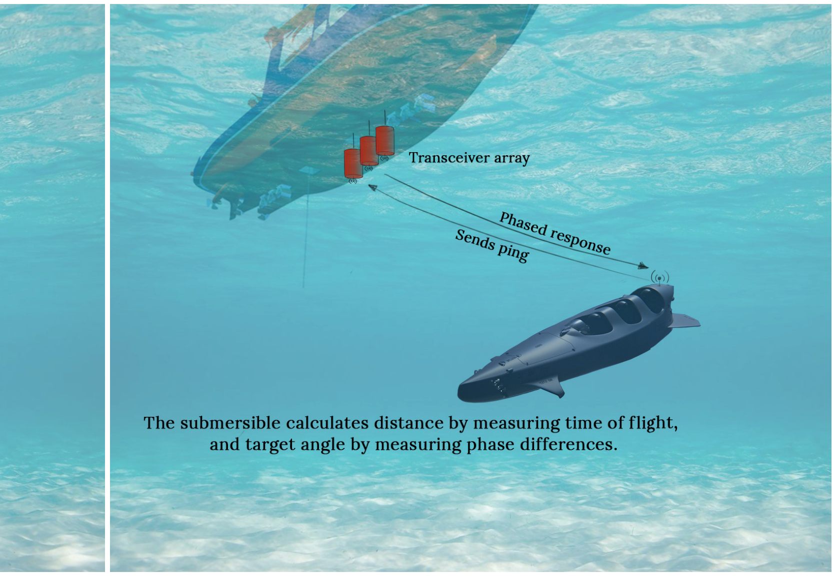


Figure 9 - *Ultra-Short Baseline (USBL)*

Short Baseline (SBL)

The Short Baseline method uses a similar trilateration technique to LBL, but here a baseline is used consisting of three or more transducers that are wire connected. As can be seen in Figure 8, these systems are typically mounted on ships and have a shorter range than LBL systems, but when working from a fixed platform and transducers can be placed in greater distances from each other, measurements accuracy and range can be similar.

Ultra-Short Baseline (USBL)

Ultra-Short Baseline uses a transceiver array that is mounted vertically on a ship, and a transponder placed onto the submersible. The set-up is demonstrated in Figure 9. Unlike LBL and SBL, USBL measures time of flight to calculate distance, and phase differences to derive target angle (Khan, Taher, & Hover, 2010). When a transceiver on the submersible pings, this signal is received by the transponder array and each transponder replies with its own acoustic signal. This signal is then received by the submersible and distance and target angle relative to the surface vessel can be derived. (Acedemy of Positioning Marine and Bathymetry, n.d.). In contrast to LBL, USBL is a short-range system and generates the most accurate measurements in shallow waters (Tomczak, 2011).

Acoustic modem

In the last couple of years, technical improvements have been made in the field of underwater communications. Within transmitted acoustic pulses, some kilobytes of information can be transferred to the receiver. Figure 10 shows that floating beacons can automatically geo-reference themselves using a GPS receiver, and can transmit its GPS-coordinates with the use of acoustic pulses. The transceiver on the submersible can measure both the distance to the beacon by measuring time of flight, and the beacon location since this information is stored in the signal. Using acoustic modems does not require calibration of the beacons, which is a time-consuming process. Additionally, it allows the beacons to move during operations, which might increase long-range accuracy (Paull, Saeedi, & al., 2014). Although frequent information loss is still a challenge in underwater communications, the submersible can indicate a possible position range from previous measurements, and can neglect or restore messages with information loss.

One way Time-Of-Flight (TOF)

All of the methods stated above calculate distances by measuring TOF. For most applications, a two-way TOF is measured, where the submersible sends a ping, and the transponder mounted onto a beacon responds directly to the ping. With the use of synchronised clocks in both devices, it is possible to apply one-way TOF, enabling stealth mode. This applies for all acoustic methods that use TOF.

INERTIAL NAVIGATION SYSTEM (INS) BASED SOLUTIONS

Underwater location can be calculated with the use of on board sensors calculating relative displace-ment. With the use of three-axial gyroscopes, accelerometers, and magnetometers, the position and heading of the submersible can be calculated. Displacements are measured in all six possible degrees of freedom, as shown in Figure 12. Before submerging, the system is georeferenced by either a GPS-receiver or by calibrating. From there, the current location is then estimated by calculating its location relative to the previous measured location, also called dead-reckoning (Kuch, Butazzo, & al., 2012).

The navigation system, however, is susceptible for accumulative errors, resulting in less accurate cal-culations over time. Even the most high-end INS systems have a drift of four metres after being sub-merged for only one minute under good conditions (Source: E-mail conversation with Pierre Inisan, a sales manager that sells INS systems). This is why INS systems are commonly used in combination with other systems or sensors, providing real-world aiding possibilities.

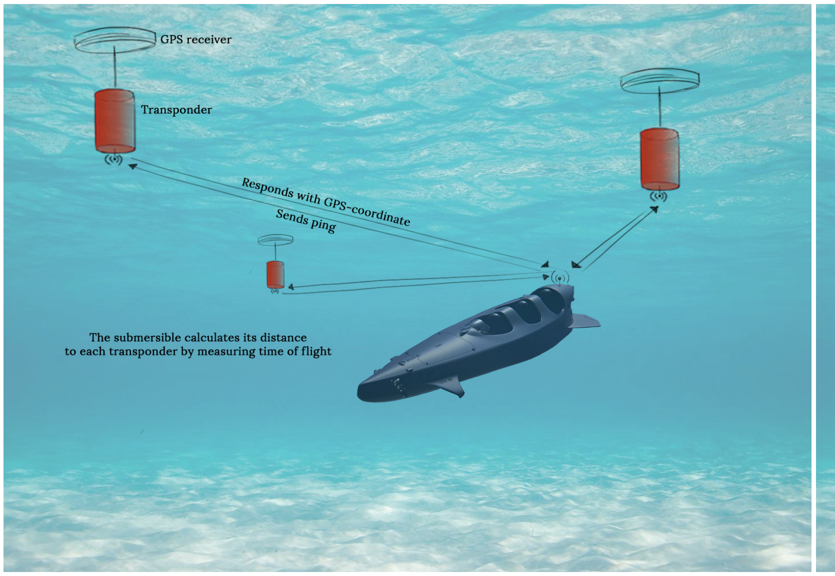


Figure 10 - *Acoustic modem*

Doppler Velocity Log (DVL)

INS systems can be upgraded with a DVL, a sensor consisting of four sonar beams, where each beam can measure its velocity relative to a reflection point. The Doppler effect states that signal frequencies change when the receiver is moving relative to the receiver. In the DVL, transceivers are mounted onto the submersible. While pointing downwards, as shown in Figure 11, an emitted ping will reflect upon the bottom (or in some cases a water layer) and be received again by the submersible. By measuring the change in frequency, velocity relative to the reflection point can be determined. By implementing four ping beams, the submersibles velocity can be measured as well as the direction it is headed in three dimensions (Oceanology International, 2013). Even though the DVL is a dead-reckoning sensor, it is able to increase accuracy tremendously in INS systems. Under good conditions and with the use of high-end sensors, it is possible to have a drift of 0,1% of the travelled distance.

INS combined with acoustic navigation methods

Acoustic navigation methods are often used in combination with INS, as it increases the accuracy of the LBL systems or acoustic modems with a factor of three or more (CDL Intertial Engineering, n.d.). It also opens up the possibility to use less beacons. As every beacon is a real-world reference point for the INS, dead-reckoning uncertainties decrease. There are examples of the acoustic modem method, where only one surface vessel is used that is able to send its current location underwater. In contradiction with LBL systems, the surface vessel can move along with the submersible, resulting in an infinite range.

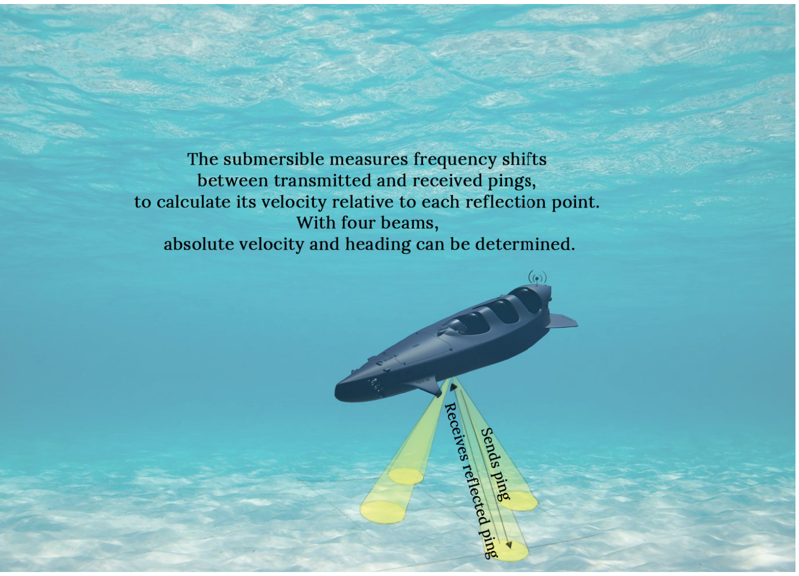


Figure 11 - *Doppler Velocity Log (DVL)*

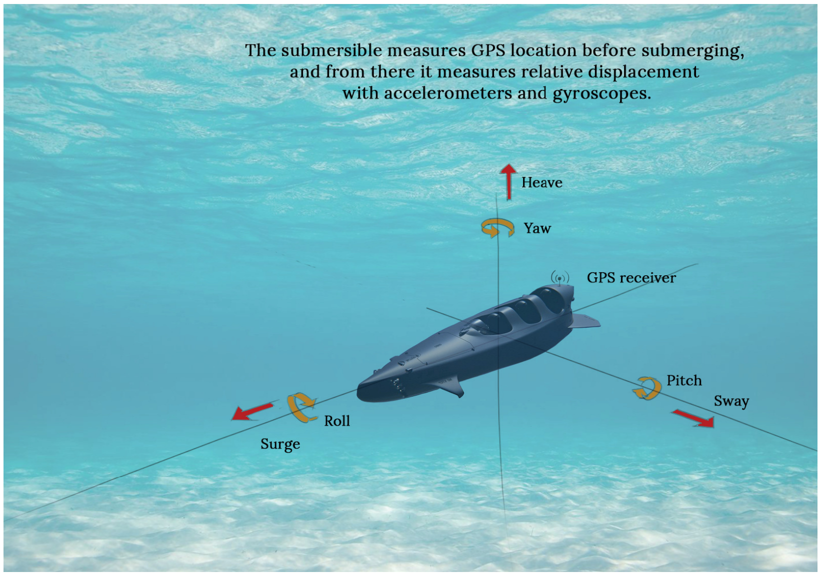


Figure 12 - *Inertial Navigation System (INS)*

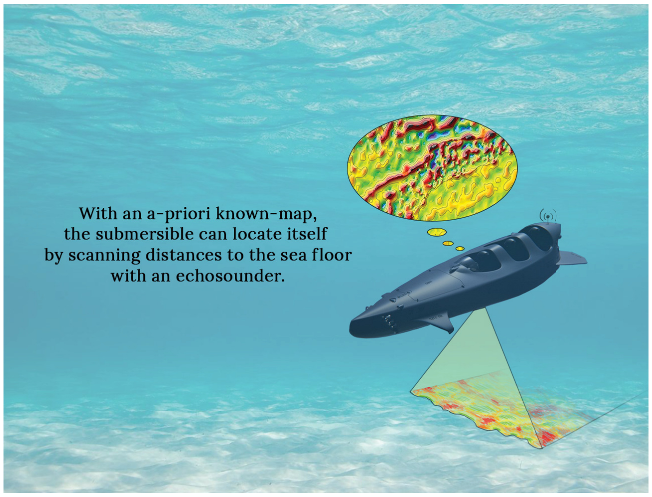


Figure 14 - *Terrain Aided Navigation*

Terrain Aided Navigation and INS

For most of the infrastructure that is implemented nowadays, exact locations are known and logged precisely in geographical information systems (GIS). Structures of the seafloor are also measured and mapped into an altitude map. As demonstrated in Figure 14, ranging sonars connected to the submersible can measure distances to certain infrastructure, and reference this information with an a-priori known map of the environment. Commercially available sonar ranges can go up to 100 m.

Simultaneous Localization and Mapping (SLAM)

Another method based on Terrain Aided Navigation is SLAM, where an echosounder is placed in front of the submersible, scanning the seafloor and making a map out of it. Then, at the end of the submersible a doppler sensor works together with an INS to measure distances to the seafloor. These distances are then compared to the just made map to locate itself in the map. This technique however, is yet in its infancy, and no products are available for commercial use yet.

CABLE CONNECTED, SURFACED GPS RECEIVER

This is not the most elegant and accurate solution, but by far the cheapest. Figure 15 shows how the submersible is cable connected with a floater, which is equipped with a GPS-receiver. To reach the most accurate measurements, the floater has to be located exactly above the submersible and therefore the cable has to be tensioned continuously. Although it sounds simple, surface winds, wave motions and the motion of the submersible itself create a drift.

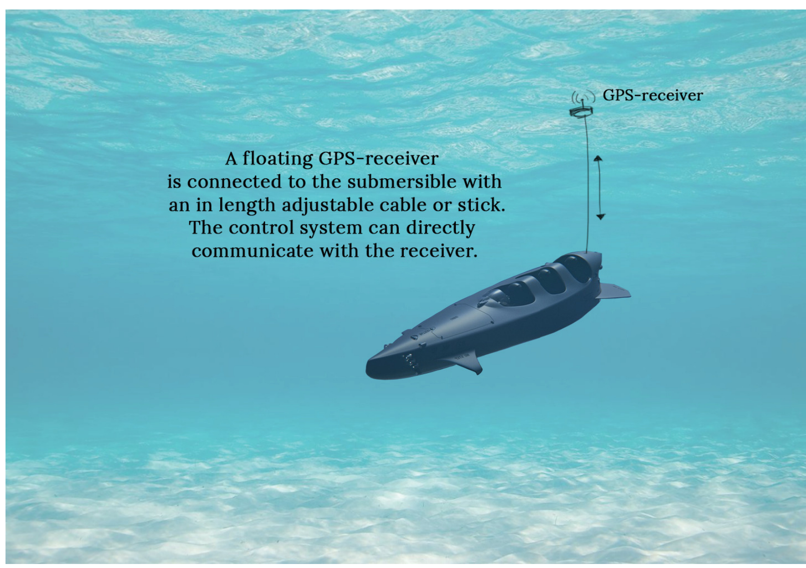


Figure 15 - *Terrain Aided Navigation*

6

Suitability considerations

The various underwater positioning systems have different characteristics concerning range, accuracy, methodology, and price. The optimal underwater positioning system is therefore purpose and environment dependent.

When building underwater infrastructure, for example, it is likely that the submersible is present in the same operational area for many days. Besides, these operations require much more accuracy compared to exploration tours, for example. In this case, applying an LBL or other acoustic system would make more sense. The installation and calibration time of the equipment can be neglected when it can be installed for a longer period of time.

For wreck diving, acoustic systems are less likely to be convenient, because the wreck itself will block the incoming signals. In this case, an inertial measurement unit would be a good option. For some exploration purposes, the range of the submersible can go up to 200 kilometres. A possible solution for reaching high accuracy on such distances is using geophysical identification techniques (only if there are enough reference points and nearby infrastructure).

Furthermore, most current underwater positioning systems use more than one method to locate itself. The vehicle that is currently used for marine applications, the Diver Propulsion Device (DPD) created by STIDD, uses an INS system, a DVL and sonar to find its location underwater (STIDD Systems, 2016).
The challenge here is, that Ortega's submersibles will be operational in all kinds of underwater activities, with many different purposes. For both short and long range operations, accuracy has to be high. Floaters are not always desirable, as there can be surface vessels. The time-consuming necessity to install acoustic systems can be counter-effective in cases where ranges are long, or when diving location changes every dive.

The most elegant and easy-to-use solution would be a navigation system that can be used for most of the underwater activities. Most attractive is the inertial navigation system, where the submersible can measure its location underwater by measuring displacements from within, and therefore without being restricted by environmental issues. Because of accumulative errors, the accuracy of such a system decreases over time. Therefore, the INS system is mostly used in combination with other aiding methods. A DVL can increase the accuracy of an INS system tremendously, up to less than 0,1% of the total distance travelled. This will be enough accuracy for the MK1C, and therefore an INS and DVL combination will be further elaborated in thris report. The system's accuracy will cover for most underwater activities, but when higher accuracies are required, the system can be upgraded with acoustic beacons or terrain aided navigation.

7

Market availability and considerations

WHAT IS AN INS

An INS, consisting out of gyroscopes, accelerometers and compasses that can measure its displacement from within. To derive distance from acceleration, the measurement has to be integrated twice, whereby the measurement error will be integrated as well. Because the system derives its position by adding measured displacements to the previous calculated position, the error ranges are also accumulative. To achieve acceptable accuracies with this method, high quality sensors are a necessity. Sensory data will be fused with a fusion algorithm. The Extended Kalman filter the most common algorithm, but algorithms with learning capabilities are used as well. Most INS systems can be upgraded with aiding sensors like DVL, GPS, sonar, acoustic systems and many more. The sensory data of the aiding sensor will be included in the fusion algorithm.

An INS could be built from separate sensors, but there are many ready-to-use systems available on the market. These systems are compact in size, and show great performance. The sensors have to be connected with a computer, where the sensor fusion algorithm will be executed by included software. In this chapter, an overview of various cur-

INS	Equinox U (SBG Systems, 2016)	Spatial FOG (Advanced Navigation, 2015)	MTi-G-710 (Xsens, 2016)	Micron INS (Tritech, n.d.)	SPRINT500 (Sonardyne, 2016)
Picture					
Roll/Pitch/Yaw	0,05˚/ 0,05˚ / 0,05˚	0,01˚ / 0,01˚ / 0,25*sec. latitude	0,25˚ / 0,25˚ / 1,0˚		0,01˚ / 0,01˚ / 0,1˚
DVL-aided accuracy	0,3% of TD	0,08% of TD		0,7% of TD	0,1% of TD
Aiding sensors	Multiple input possibilities	3 * RS232; 1 * RS422	Multiple input possibilities	2 * RS232; Ethernet	RS232
Depth range	200 m or 6000 m	4 m	1 m	500 m	5000 m
Included additional sensors	Pressure sensor	Pressure sensor; GNNS receiver	Pressure sensor; GNNS receiver	Pressure sensor	
Communication quality	Good	Very good	No response	No response	Very good
Costs	20k - 32k	30k			

Table 1 - *INS*

rently available INS and DVL sensors on the market is constructed, together with their most important specifications. The results are illustrated in Table 1.

While searching for the sensors, it was notable that most suppliers were not so eager to give away information about the product, nor were there any prices available. Therefore, e-mail contact with these suppliers was required. Pleasant communication with a company you have to work with, is almost as important as technical specifications of a product. Therefore, information about the communication quality is also implemented in Table 1.

INS SELECTION CONSIDERATIONS

The most appealing INS sensor is the Spatial FOG, designed by Advanced Navigation. There are several reasons why this sensor seems to be most suitable.

First of all, it is one of the most accurate INS systems available on the market. When looking at the accuracy in Roll, Pitch and Yaw you see it shows the least amount of deviation compared to other sensors.

Furthermore, with DVL aiding, the sensor reaches an accuracy of 0,08 % of the total distance travelled, which is more accurate than the other sensors. This accuracy statement however, is probably only true in very stable and optimal environments, and will therefore turn out lower in real life. Besides, the value is strongly dependent on the accuracy of the DVL sensor as well.

The INS has multiple input possibilities, meaning it is possible to add even more aiding sensors to the system, like an acoustic system, to make it even more accurate.

Another important advantage is that the spatial FOG is a bare INS that comes without casing and is meant to be integrated in other products. Most other sensors have a titanium casing that can withstand surrounding pressures up to 6000 m. This is way more than the submersible will ever come, but these casings are expensive to make, and will increase the product's price. Most subsea vehicles use pressure tight casings in their system already for other electronics, and the INS could be easily integrated into them.

Finally, the e-mail contact with Advanced Navigation was pleasant: Communications were clear, and useful responses were given. Besides, extensive datasheets and 3D models are with all the information about the product. This in in contradiction with other companies, who only had a double-sheet flyer with the most important information about the product. Advanced Navigation, among other companies, has an integrated INS and DVL systems available as well, but these are very expensive. The Sublocus DVL, is an INS and DVL system wherein the Spatial FOG is implemented, costs 120 k, which is much more than a separate INS and DVL would be. Besides, it is harder to implement a combined systems, as it is bigger and not custom shaped, and are therefore not considered as solution.

DVL OPERATING FREQUENCIES

Most companies selling DVL sensors had two different operating frequencies available: 500 kHz or 1 MH. The 1 MH systems achieve higher accuracies in some cases, but operational altitudes would become much lower. This is perfect for coastal operations, but a great part of the ocean requires higher altitude. To be able to strive the goal of making the navigation system suitable for as many cases as possible, the maximum distance between the submersible and seafloor has the be at least 100 m. All systems above 1MH are therefore neglected in Table 2.

DVL SELECTION PROCESS

The table shows there are two DVL systems that have significantly higher operational altitudes than the other two: The Syrinx DVL and Nortek DVL. Most favourable is the Syrinx DVL, because this sensor has a little higher accuracy than the Nortek DVL, and the communication quality was better: e-mails were extensive and clear. Somehow, a quotation was not yet received from both companies, even after elaborated contact. This DVL will be implemented in the submersible. Differences between the DVLs are small though, therefore it is advisable to retrieve the costs of both products and let this be an important decision factor.

DVL systems	**Explorer (Teledyne RD Instruments, 2015)**	**Nortek DVL (Nortek AS, n.d.)**	**Syrinx DVL (Sonardyne, 2016)**	**Navquest 600 micro (Link-quest, 2009)**
Picture				
Dimensions (mm)	320 L * 12,4 D	225 L * 186 D	200 L * 200 D	174 L * 126 D
Long-term accuray	0,3% / 0,2cm/s	0,2% / 0,1cm/s	0,12% / 0,1cm/s	0,1% / 0,1mm/s
Extra sensors		Pressure and temperature	Temperature	
Operation frequency	614 kHz	500 kHz	600 kHz	600 kHz
Min/max altitude	0,5m / 81m	0,3m / 180m	0,4m / 175m	0,3m / 110m
Communication quality	No response	Fast response	Useful and fast response, but is very slow with quotations	Fast response
Costs				10 690 euro

Table 2 - *DVL comparison*

8

Gathering more information

CAUSES FOR DVL DYSFUNCTION

There are many environmental issues that can decrease the DVL's accuracy. The fact that the transducer head has to be in direct contact with water, brings a lot of challenges. In Table 3, common problems are listed. By clever implementation of the DVL, higher accuracies can be achieved and measurement errors can be prevented.

In-hull mounting

With in-hull mounting the transducer head is placed inside a hull, often called a sea chest (Figure 16). This can keep the transducer head safe from debris in the water, air bubbles and flow noise. A vent pipe is required to release the air bubbles that have gathered in the hull.

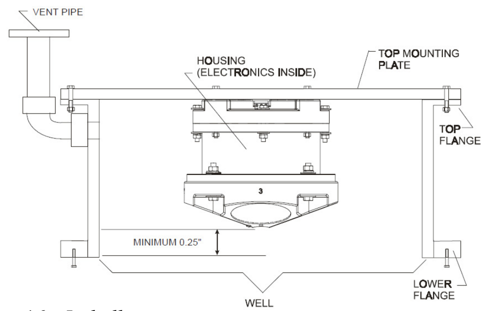


Figure 16 - *In-hull mounting*

Fairing

A fairing is a structure that produces a smooth outline and reduces drag or water resistance. The structure can be mounted underneath the submersible, and is used to guide the debris in the water, air bubbles and flow away from the transducer head. Because of its protruding structure, it is easy to implement a fairing without having to sacrifice space in the submersible. A fairing however, will have an impact on the hydro-

Obstacles or floating objects	If the transducer head protrudes the bottom of the submersible, it can easily be damaged by obstacles on the seafloor or objects in the water
Flow noise	Water flowing directly over the transducer faces increases the acoustic noise level.
Air bubbles	Air bubbles attenuate the signal strength and reduce the profiling range. Bubbles mostly get trapped in the flow layer, which is usually within the first two feet below the hull.
Corrosion	Although the DVL is made out of rust-proof material, it will still rust eventually.
Barnacle growth	The hard shells of barnacles can cut through the transducer faces and is the number one cause of failure of transducer beams.
Ringing	Side-paths of the transmitted pulse can come in contact with the metal of the transducer beam or other items in the water, causing the system to resonate at the transmit frequency. If the DVL is in receive mode while still ringing, it receives both frequencies, resulting in a bias. Because most DVLs only ring for a certain amount of time, a blanking period is introduced, where the DVL does not receive any data.
Signal interference	When a DVL is placed nearby other acoustic sensors, these can interfere with each other.

Table 3 - *DVL comparison*

dynamic structure of the submersible, resulting in more water resistance. Furthermore, it is impossible to 'park' the submersible on the seafloor or shore: the extending parts will make it roll over. A fairing can be used in combination with in-hull mounting as well. The protruding structure gets much smaller, and is only used to guide the air bubbles and flow away from the sensor.

Acoustic window

Generally, an acoustic window is used in addition to in-hull mounting. A 6mm-thick plate consisting out of a material with a refractive index close to water, is placed on top of the hull to 'close' the chest. The hull will still be filled with water, and will reduce signal noise produced by flow or air bubbles. The hull can be filled with fresh water as well, which cancels out corrosion and barnacle growth too. Nevertheless, acoustic windows also have disadvantages: The transponders' pulses can reflect against or be absorbed by the window. This phenomenon results in a tremendously decreased profiling range (up to 50 m of range loss), and can cause ringing problems. Acoustic windows are an option when there is known to be a lot of debris in the water. In most other cases, it is not worth the loss in range (Advanced Navigation, 2015).

Morphological scheme

Most design solutions listed above solve more than one environmental dysfunction cause, but can have a negative effect on other issues. In-hull mounting for example, has a positive effect on problems concerning obstacles, flow noise and air bubbles, but has a negative effect on ringing. To give a clear overview, a morphological scheme is shown in Table 4. For each dysfunction cause, possible solutions are given. It is possible to use the solutions solely and in addition to each other.

In the next phase, this table will be used to design several concepts, using different solutions.

	Solution 1	**Solution 2**	**Solution 3**	**Solution 4**
Obstacles	In-hull mounting	Fairing		
Flow noise	In-hull mounting	Fairing	Acoustic window	
Air bubbles	In-hull mounting	Fairing	Acoustic window	Place head further below surface
Corrosion	Rinsing after use	Coating	Acoustic window	Anode protection
Barnacle growth	Rinsing after use	Anti-fouling	Acoustic window	
Ringing	No in-hull mounting	Gaskets	No acoustic window	Increase blanking period
Interference	Let other sensors operate in different frequencies	Place as far away from other acoustics as possible	Transmit signal at the same time	

Table 4 - *Morphological scheme*

SENSOR PLACEMENT

Below, requirements are stated for each sensor concerning the sensors location in the submersible.

INS requirements

The Spatial FOG comes without a casing, and therefore the sensor has to be placed in a watertight casing that can withstand pressures up to 11 bar. To reach optimum measurement results, the INS should be aligned properly in x, y, and z direction, and mounted near the centre of gravity of the submersible. If this requirement is not met, it is possible to manually set an offset, but this still has a slight effect on the measurement results. The GNSS antenna that is included in the kit, requires a watertight casing as well, and should be mounted onto the submersible with an unobstructed view of the sky (Advanced Navigation, 2015).

DVL requirements

The Syrinx DVL has to be placed into the submersible, such that the transducer head is aligned downwards, having a reflection free clearance of 15 degrees around each beam. The sensor has to be placed close to the submersible's fore-to-aft centreline, but far away from other acoustic devices, thrusters and motors (RD Instruments, 2001).

System architecture

In Figure 17, an overview of the parts is illustrated together with their preferred placement. If highlighted areas overlap, it is possible to integrate the sensors into one compact unit to simplify the architecture and subsequently, reduce the costs.

It is not highlighted in the figure, but the GNSS antenna can be mounted in-between the passengers as well. The INS shows an overlap with both the DVL and the GNSS antenna, but the DVL and GNNS can never fuse.

Ortega's new requirements

The company had made a slight change of plans: the navigation system will not be implemented in the three-seater they are currently working on anymore. Instead, they wanted a modular system that can be integrated with all Ortega's submersible types. This opened up the possibility to make some adjustments in the current submersible design. To optimize the sensor placement, the shell could be altered in shape for example, or existing parts could be displaced. The navigation system will be sold separately, as an extra feature. Therefore, if a consumer wants to buy the submersible without it, it should have no negative consequences on the design.

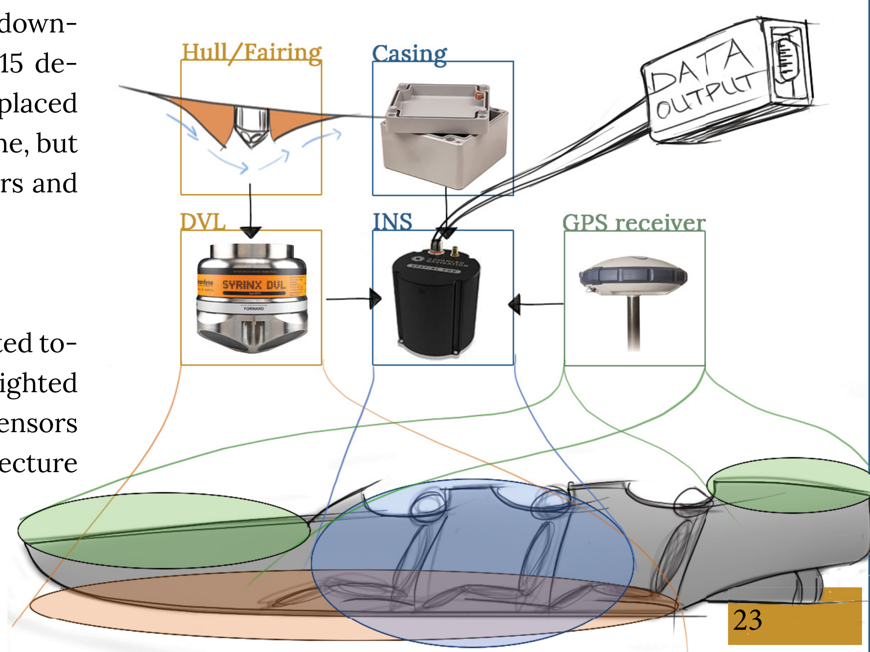


Figure 17 - *System architecture options*

ORTEGA'S INSIGHTS ON WATERPROOF CASINGS

The INS requires a waterproof casing to be operational below four metres of depth. The submersible already has several types of waterproof casings wherein electronics are stalled. These casings are already tested on depth and proved to be suitable, and therefore it would be logical to use the same standards.

Air-filled casings

The LED displays that show information to the user, are embedded in a waterproof. The casings are CNC milled out of aluminium, and have a wall thickness of 15mm. They can be closed by screwing a transparent, acrylic plate with a thickness of 15mm onto it. Pressure tests have been executed by Ortega themselves, and proved to be waterproof to at least 30 bar: This was the maximum pressure setting of the testing equipment. As you can see in Figure 18, the mounting surface has a little groove. In here, a rubber ring is placed before mounting the lid. This is the key to prevent water from seeping through into the casing.

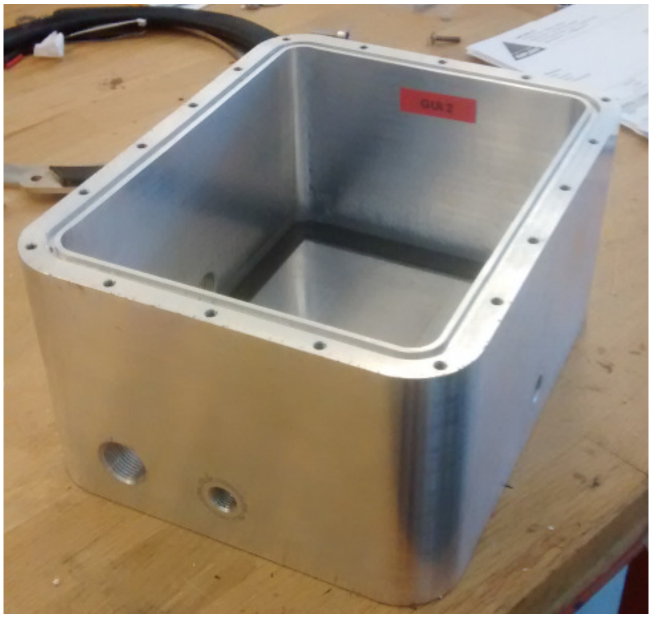


Figure 18 - *Display casing*

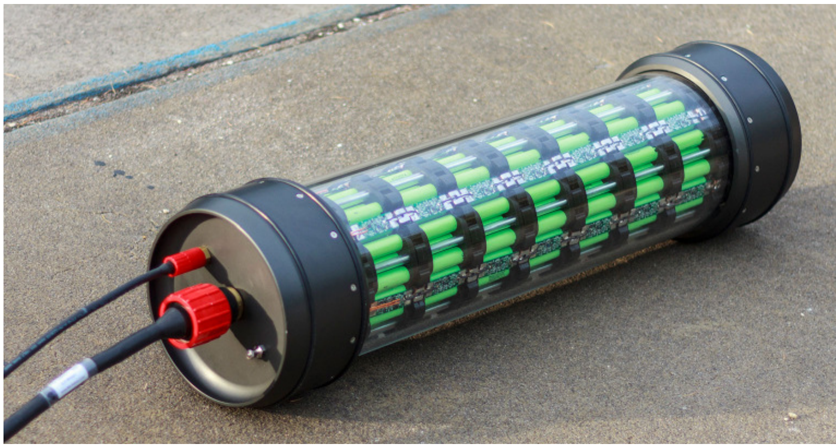


Figure 19 - *Battery casing*

The battery is placed in a cylindric casing, consisting of an acrylic plastic with a thickness of 20mm, and aluminium caps on both sides with some connectors attached to it. Even though the volume of the casing is quite big, it does not give any problems in high pressure surroundings, because the shape gives the structure its strength.

Oil-filled casings

The motor controller housing is the biggest casing in the submersible, and houses the majority of the electronics. Higher voltages coming straight from the battery are transformed and fed to other subsystems. It is the enclosure that houses the system's control computer as well. The aluminium casing has a wall thickness of only 2mm, and can be closed with an acrylic plastic plate that is screwed onto it. The whole cabin is filled with oil, because this non-conductive liquid does not compress as much as a gas would, when exposed pressure. This provides a counter-pressure, and therefore the casing itself does not have to withstand the compression force and can be produced much cheaper. The surrounding pressure however, cannot just disappear, but will be passed on to the electronics, crushing most of the gas-filled elements. The capacitor, part of the basic components in electronics, is one of them. To prevent these elements from crushing, it is possible to soak the electronics in polyurethane, sealing it forever by creating a hard and protective layer. In some cases, it is possible to find electronics without capacitors. Until now, all the components in the motor controller box are capacitor free.

Cable connectors

The cable connectors that Ortega uses, are bulkheads made from rubber, that can be disconnected and reconnected at depth without leaking. The number of required pins can be calculated, and the amount of current that flows through the system has to be determined to choose the right size bulkhead. These connectors, as shown in Figure 20, are used for the battery casing, among other things, and can be ordered at www.macartney.com.

Figure 20 - *McCartney Subconn Circular series*

Aluminium type 4

The specific aluminium type is type 4, carefully chosen because of its rust-proof properties, but also for its ability to let trough radiation and electrical impulses. The GNSS receiver requires a watertight casing, and could be easily integrated in this type of aluminium too. The submersibles' hull also has the property of passing through GPS signals. A requirement for the GPS receiver is to have a clear view of the sky, but if the obstruction can pass through the signal, technically the GNSS receiver still has a 'clear' view. However, it is still useful to place the antenna as high as possible, because when submerged, it won't receive any signals. The DVL operates at a minimum altitude of 0,4 m, and to obtain high accuracies, it would be profitable to have the DVL working before losing the GNSS signal.

Figure 24 - *DVL dimensions (Sonardyne, 2016)*

SENSOR SIZES

INS dimensions

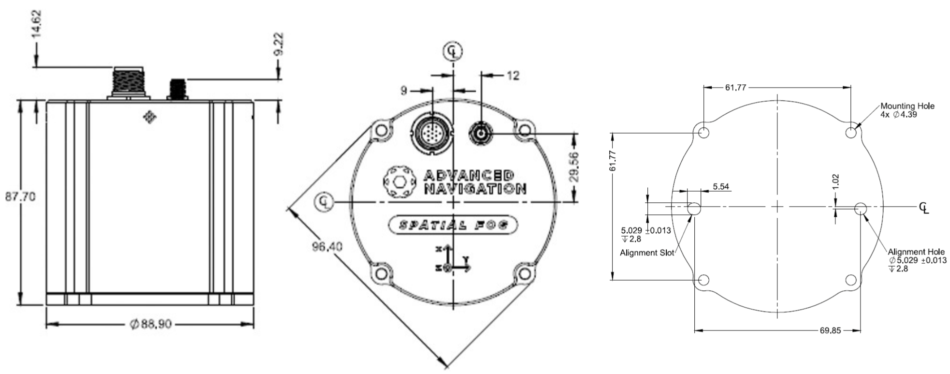


Figure 21 - *INS dimensions (Advanced Navigation, 2015)*

Figure 22 - *GNSS dimensions (Advanced Navigation, 2015)*

DVL dimensions

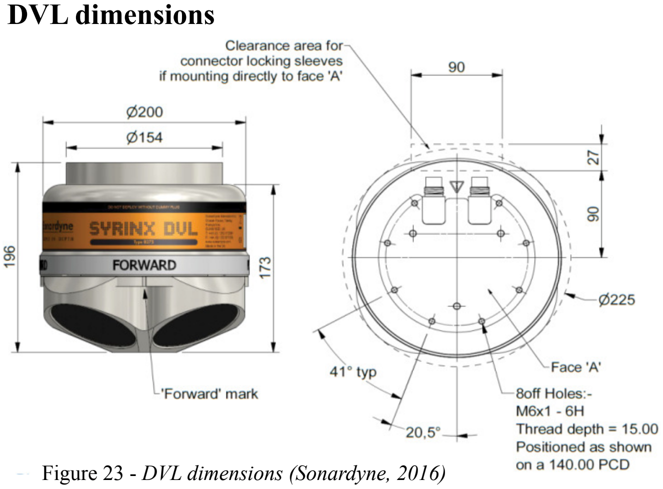


Figure 23 - *DVL dimensions (Sonardyne, 2016)*

As can be derived from Figure 21, the INS has a total height of 100 mm and a diameter of approximately 90 mm. Figure 23 shows that the DVL has a height and diameter of approximately 200 mm, and is therefore more than twice as big as the INS (Figure 24). The exact dimensions of the GNNS antenna could not be derived, but in Figure 22, you can see that it has the same diameter as the Spatial Fog (the white unit compared to the black unit in the box). The mounting illustration shows that the antenna is approximately 25 mm thick.

THE SUBMERSIBLE'S ARCHITECTURE

To find a suitable location for the sensors, it is necessary to know about the submersible's architecture. Figure 25 shows a clear overview of the subsystems that occupy significant space.

Above the trimming control tank, there is some free space to bring cargo. All the way to the back and in the front, mechanisms are installed to adjust the fins. They are controlled by the steering mechanism of the navigator.

9

Cabling solutions

INS PIN ALLOCATION

The INS has a thirteen-pin connector that consists out of multiple signal connections and power supply. Table 5 shows the pin allocations and their communication possibilities.

Pin	Colour	Function
1	Black	GPIO 1
2	Brown	GPIO 2
3	Red	Signal ground
4	Orange	Power ground
5	Yellow	Power supply (24 V)
6	Green	Primary RS422 Rx(+) / RS232 Rx
7	Blue	Primary RS422 Rx(-)
8	Violet	Primary RS422 Tx(+) / RS232 Tx
9	Grey	Primary RS422 Tx(-)
10	White	Auxillary RS232 Tx
11	White / Black	Auxillary RS232 Rx
12	White / Brown	GNNS RS232 Rx
13	White / Red	GNNS RS232 Tx

Table 5 - *Pin allocation INS connector (Advanced Navigation, 2015)*

what you can see, the connector has six pins reserved for communications that use the RS232 protocol. This is a standard binary-data communication between computers and peripherals (Domoticx, 2016). RS232, in this case, uses two pins to communicate. There are three connection possibilities: The INS will communicate with the DVL and with the submersible's main computer using RS232, and there will be more room for another aiding sensor in the future. One of the RS232 connections can also be used for RS422, which is a similar protocol, but requires four pins for communication.

Some aiding sensors use GPIO pins in addition to RS232. This communication type uses a single pin that can be turned on and off using software, and the state of the pin can be read (Breseman, 2015).

Furthermore, the connecter uses three pins for the power cable. The INS requires an input voltage between 9 V and 35 V. This voltage supply will be available in submersible's main computer casing.

The INS has a separate two-pin coaxial connection for the GNSS receiver that comes with the package.

DVL PIN ALLOCATION

Table 6 illustrates the pin allocation of the DVL connector. The DVL uses three pins to communicate with the INS: RS232 Primary and Signal ground. Two pins are reserved for power ground and supply. The auxiliary and GPIO pins will remain disconnected.

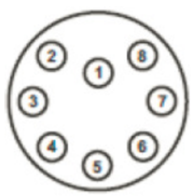
Pin	Function	Connector face
1	RS232 Rx Primary	
2	Power ground	
3	RS232 Tx Primary	
4	Power supply (24 V)	
5	Signal ground	
6	GPIO	
7	AUX RS232 Rx	
8	AUX RS232 Tx	

Table 6 - *Pin allocation INS connector (Advanced Navigation, 2015)*

IMPLEMENTATION

With the previous information, suitable connectors could be determined to fit into the aluminium casing. First of all, the number of pins that go from the INS to the motor controller box, where the submersible's main computer is stalled, can be combined into a single cable. The number of pins will be five in total. There are three pins for data communication (two for RS232 and a GPIO pin, just in case), and two pins for power.

The DVL requires three pins for RS232 communication with the INS, and two for power. It can get its power supply either from the motor controller directly, or via the INS casing. There is already a cable present between the DVL and GPS, and to minimize system parts it would be logical to let the DVL receive its power through the INS casing. In this case, the DVL and INS have to be connected with a 5-pin connector. Final decisions however, can vary between concepts.

The remaining connector will have five pins as well. One GPIO pin, two RS232 pins, and another two pins to use RS422 instead. This connector will be implemented, but remain empty until other aiding sensors are deployed. If another aiding sensor is applied without using RS422, the two empty pins can be used for the power supply of the aiding sensor as well.

The GNSS antenna uses a separate connector. This coaxial cable uses two pins for communication.

Table 7 gives an overview of the four connectors that will be used in the casing.

Connector	Number of pins	Cable destination
1	5 (Power, RS232, GPIO)	Motorcontroller box
2	5 (Power, RS232, Signal Ground)	DVL
3	5 (RS232 or RS422, GPIO)	Empty
4	2	GPS antenna

Table 7 - *INS casing connectors (Advanced Navigation, 2015)*

The connector with cable that is included with the INS, can be requested in any length as unterminated cable (Advanced Navigation, 2016). The electrical wires that come out of the connector can be identified by colour (Figure 21) and connected to the right waterproof connector pin in the casing. A render of the 5-pin male connector is shown in Figure 26.

A rule of thumb is, that where the power leaves the casing, the connectors have to be female. The INS casing will have two 5-pin male connectors (connector 1 & 3), and one 5-pin female connector, connected to the DVL.

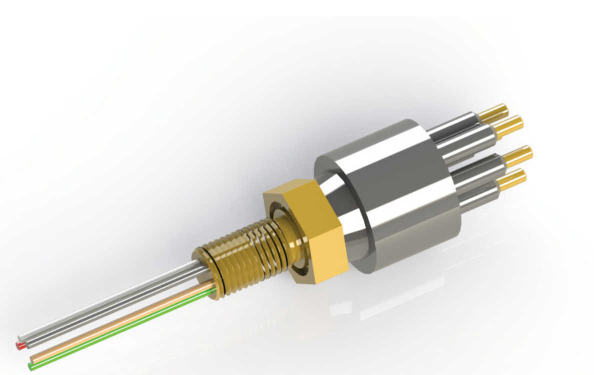


Figure 26 - Render of *McCartney's 5-pin male connector*

10

Concept design

Based on all the retrieved information, various concepts could be constructed. In this chapter, three concepts are elaborated and in the end, a concept will be chosen to further elaborate in this project.

CONCEPT 1

In this concept, the INS and DVL are combined into one compact package, and placed in the front of the submersible (Figure 27). The INS has an extra thick shell to withstand surrounding pressure, and the DVL has a thinner shell, just for steady mounting. The GPS receiver is integrated into the main computer box, such that is placed as high as possible. The motor controller box as it is now, has to experience some changes in shape to realize this. Because this box is filled with oil, the electronics of the GPS receiver have to be capable of withstanding pressure. The main advantage of this design is, that there is just one cable to install. If the GNNS antenna cannot be submerged in oil, another possibility is to include the GPS receiver into the display casing of the middle or last person. These casings are air-filled and placed in the middle top of the submersible, but will require additional cables.

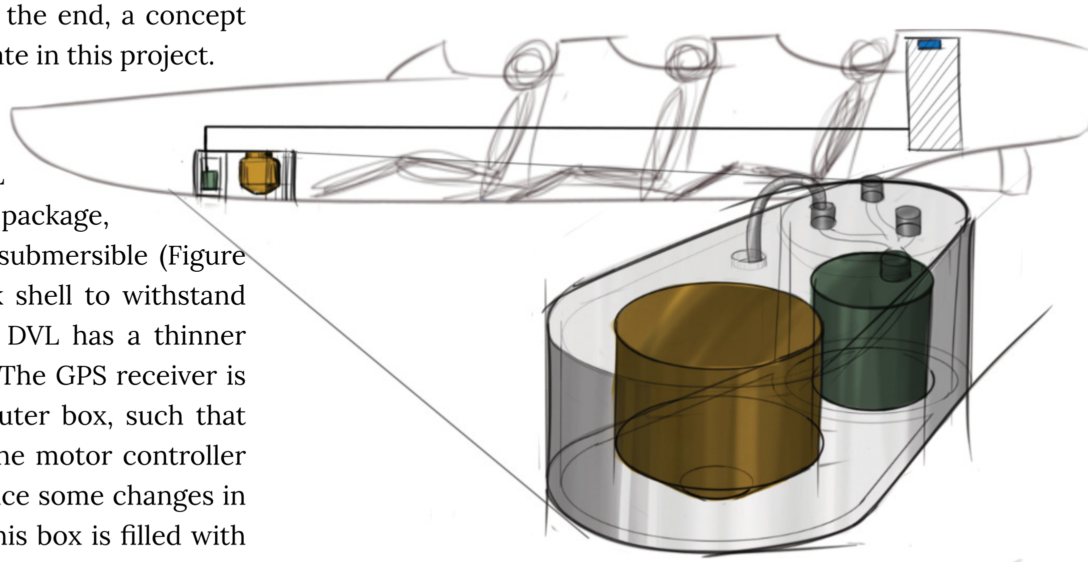


Figure 27 - *Concept 1 - DVL & INS combined, in-hull mounted*

CONCEPT 2

This concept is similar with concept 1, because the DVL and INS are integrated into one compact unit. The only difference is, that the hull is now a fairing (Figure 28). The main advantage is that with a fairing the INS can be placed more to the centre of gravity of the submersible, which is one of its requirements. It is possible though, to manually set an offset value if this requirement cannot be met. Another advantage is that it is not necessary to make big, complex holes in the submersible's shell, which will make it easier to implement. The GNSS receiver is placed within the display case, or in a separate enclosure.

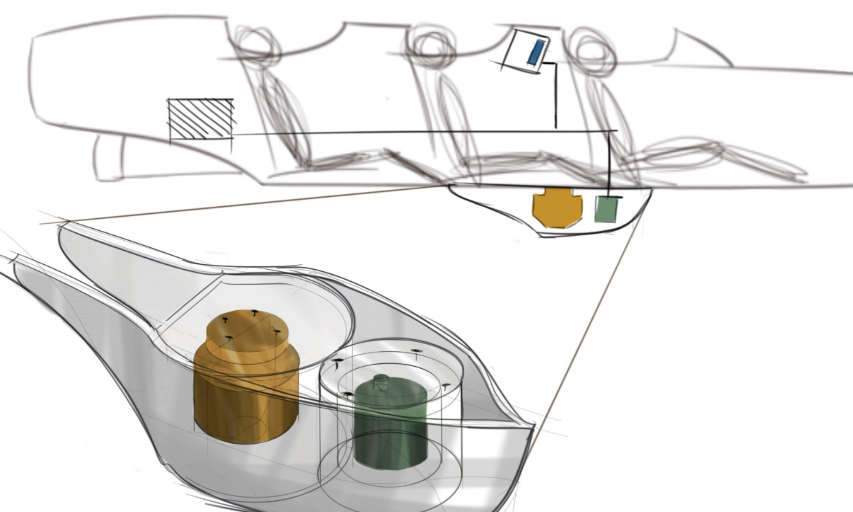


Figure 28 - *Concept 1 - DVL & INS combined in a fairing*

CONCEPT 3

Figure 29 shows how the INS and GPS are integrated into a cylindrical watertight casing, that is placed both at altitude and near the centre of gravity of the submersible. Because of fusing the two subsystems together, there are only three connectors required to attach to the INS casing. There are also only two cables for the whole system: A cable that leads to the main computer box (located at the back of the submersible), and one to the DVL, which is mounted in-hull in front of the first person. The hull of the DVL does not have to withstand much pressure, because the separate structure will be flooded with water, and can therefore be constructed out of any material.

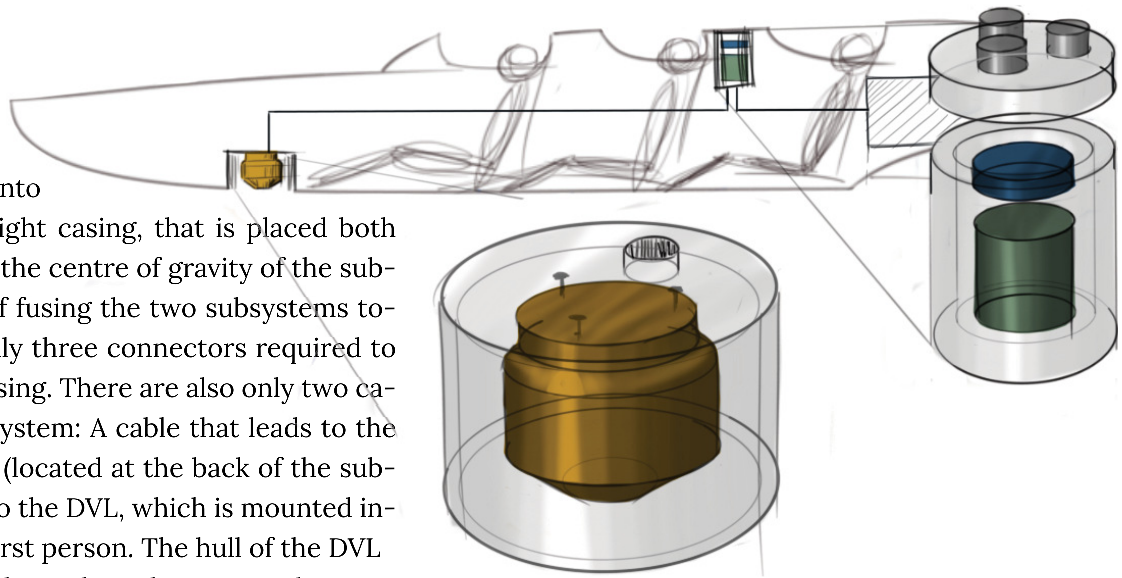


Figure 29 - *Concept 1 - INS & GNSS conbined, DVL in-hull*

CONCEPT CHOICE

To decide what concept is most suitable, the choice has to be made bad on the system's requirements. Table 8 shows the requirements that are relevant in this stage of the design, and these will be rated per concept. The scores vary from zero to three, where zero points is means that the design does not comply with the requirements at all, and three points indicate that the requirement accomplished.

The INS and GPS integrated into one cylindrical watertight enclosure is the concept that meets the requirements the most. It is visible, that the third concept scores far above the other two. The system is modular because no integration is required with other existing systems. The casings are made out of easy shapes, making them suitable for production and assembly. The DVL is placed far away from the thrusters, the GPS antenna is placed at altitude and the INS near the centre of gravity. In the next chapter, this concept will be elaborated more extensively.

Requirement	**C1**	**C2**	**C3**
Spatial FOG at centre of gravity	**1**	**2**	**3**
GNNS antenna placed at altitude	2	2	2
DVL at fore-to-aft centreline	3	3	3
DVL away from motors and thrusters	3	2	3
Minimize cable length	3	1	2
Minimum amount of parts / elegance	2	1	3
Modular system	1	2	3
Total	*15*	*13*	*19*

Table 8 - *Concept rating by relevant requirements*

11

Detailed engineering

INS AND GNNS

Ortega produces their aluminum casings by CNC milling. This is efficient, because strong, custom-made enclosures can be produced fast and conveniently: By sending a 3D model. The casing is cylindric of shape, because this uniformly spreads the pressure, making it very strong. The wall thickness of the casing could be decreased, compared to the cubic shaped casings that Ortega uses.

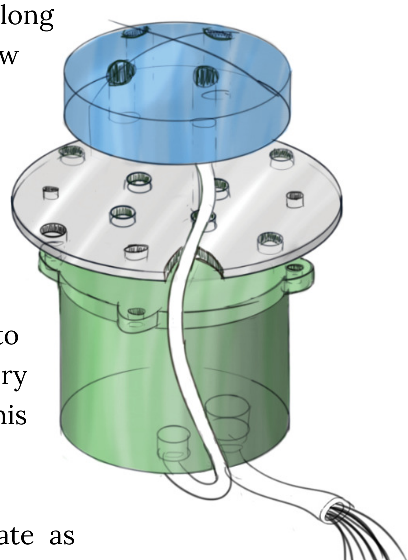
How to lock the INS and GNNS into the casing

The GNSS antenna has to be placed on top of the structure, to minimize signal obstruction. The INS can be placed pointing either upwards or downwards into the cylinder. Even though correct alignment is a requirement, an offset can be manually indicated as well. For installation purposes, it would be most logical to first mount the INS onto a mounting plate, and then to lock it upside down into the cylinder on the same mounting plate. If pointed upwards, long screws would be required to be able to screw the INS in the cylinder.

Another advantage of this alignment is that the connectors can be conveniently installed on the bottom of the casing. If they were placed on top, the GNSS would have some obstruction, and it is not convenient to have all the cables connected with the lid. Every time you open it all the wires will move, and this can only cause damages.

The GNSS antenna requires a mounting plate as well, and by placing the INS upside down, these two mounting plates can be combined into one. The plate will consist out of a circle with thirteen holes: Four holes to install the INS, four holes for fixing the plate into the cylinder, then another four for mounting the GNSS antenna, and one bigger gap to pass the coaxial cable trough. As derived from the mechanical drawings of the INS, all screws are of type M4 (Figure 22). The mounting plate can be produced by a laser cutter.

Figure 30 illustrates the inside of the cylindric casing. Four pillars are coming out of the bottom circle with threaded holes in them. This is where the INS can be mounted onto. In between the INS and the mounting plate, some gaskets are placed to damp the system, reducing noise, and to



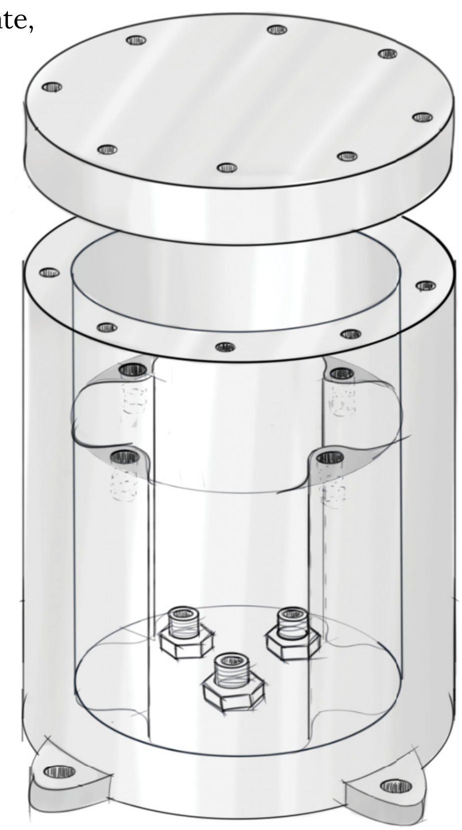


Figure 30 - *INS*

gain some space for the screws of the GPS to pass through later on. The gaskets and screws are not included in Figure 30.

Before mounting the INS and the mounting plate into the casing, the cable connectors have to be tightened into the frame. All the wires coming out of the INS connector have to be attached to the right pin on the pin connectors. The wires will be long enough to achieve this without too much effort. In between the bottom of the casing and the INS will be enough space to stack the wires when everything is put into place. The coaxial cable must be lead through the gap on the side of the mounting plate to connect with the GNSS receiver.

The GNSS antenna can be screwed onto the mounting plate. At last, the casing can be sealed by placing an aluminium disc on top of the it or other signal-passing material that does not easily deform. The mounting surface of the casing has a groove milled into it, to put in a rubber ring that has a little bigger diameter than the groove its depth. When the lid is concealed, this rubber ensures water tightness. This however, is not shown in Figure 30. The lid can be tightened with eight M4 bolts. Bolts are used instead of screws, because more torque can be applied when tightening them. Hex screws would be a suitable solution as well.

Casing placement in the submersible

Behind the second seat, in the raised area, there is some space left for the INS and GNNS antenna casing. This is a very ideal place, because it is one of the

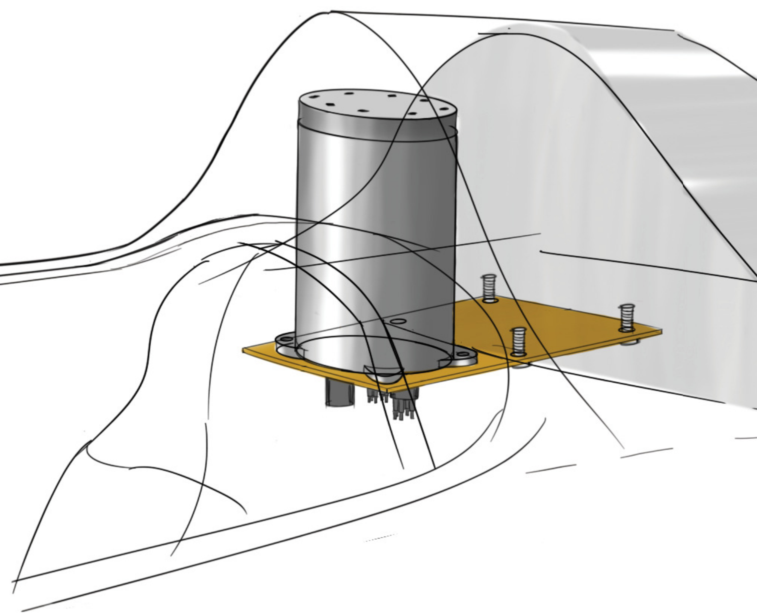


Figure 31 - *Casing attachment*

highest locations in the submersible, and still near the centre of gravity. Approximately half of this area is stuffed with foam, and enclosed by a plastic. This is a hard material that lines the whole interior of the submersible. In Figure 31, the grey area represents the part that has been stuffed. The surrounding material is hard enough to attach parts onto it, and is therefore a very suitable place to hang the casing.

The casing will be fixed onto a mounting plate before implementing. The mounting plate requires some holes for the bolts that will lock the casing, but also for the connector heads to pass through.

Then, the mounting plate is attatched to the bottom of the suffed part, such that the casing is located in the raised part behind the seat. The connectors are then facing downwards. The space can easily be accessed by taking out the seat out in front of the raised part, or via the opening of the seat behind.

3D model

In Figure 32, the system is demonstrated as an autocad model, with the casing set to slightly transparent. This view shows clearly show how the parts are connected, and how they fit in the casing. As you can see, there is enough space between the INS and bottom of the casing to stack some wires. The cable connected to the INS, and the correct wiring is not shown in this model.

The design is a little adjusted compared to the drawings: Instead of protruding flanges attached on the side of the casing, there are now four threaded holes made in the cylinder. With this adjustment, the mounting plate ended up smaller, and milling costs could decrease.

The outer diameter of the casing is 139 mm. The casing's height, with the connectors included, is 240 mm.

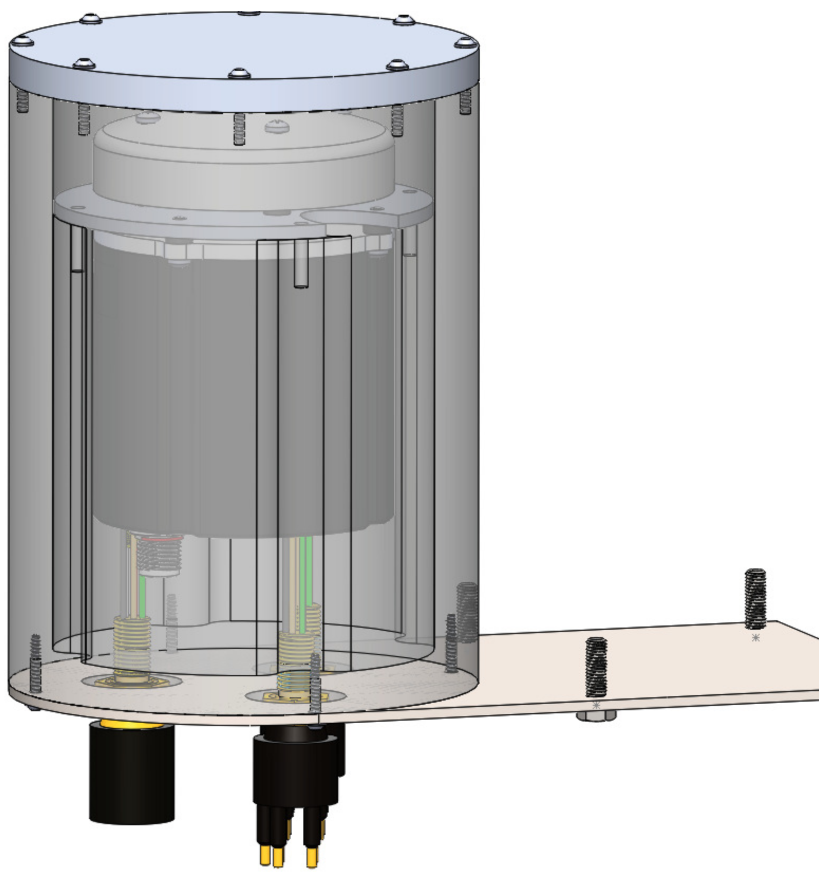


Figure 32 - *INS casing*

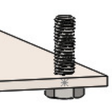
THE DVL'S HULL

The DVL requires a 15-degree free space around every transducer head, and therefore the casing has to be bigger than the outer diameter of the DVL. The structure is 350 mm wide, and 220 mm high. The shape of the hull is created such, that the water that flows under the submersible will not be intercepted by it. This can cause the water inside the hull to swirl and creates hydrodynamic resistance (Figure 33).

The hull has four flanges with holes attached to the outer shell, to fix the hull in the submersible. Although this part, as shown in Figure 34, seems simple, but requires several steps to produce. The shape itself can be laser-cut, but then, a threaded hole has to be milled in there manually. The flanges are placed with a little offset from the bottom, which will make the hull coincide with the outside of the submersible's shell.

A hole is drilled on top of the hull pass the cable that connects the DVL with the INS. In Figure 34, the bottom of the hull is perfectly straight. The submersible, on the other hand, has a shell that is slightly curved. This is countered for in Figure 34. The bottom contour is designed such that two big circles can be drilled into the submersible, and the space in-between can be removed by sawing.

In between the hull and the DVL a gasket will be placed to increase the system's damping, subsequently reduce signal noise and ringing problems. These gaskets however, are not shown in Figure 33.



The hull of the DVL does not have to withstand high pressures or have to be watertight, and therefore it can be very thin. For the same reason, it doesn't necessarily have to consist out of metal, but can be made out of some plastics. PVC for example, is a commonly used material for plumbing and outdoor furniture

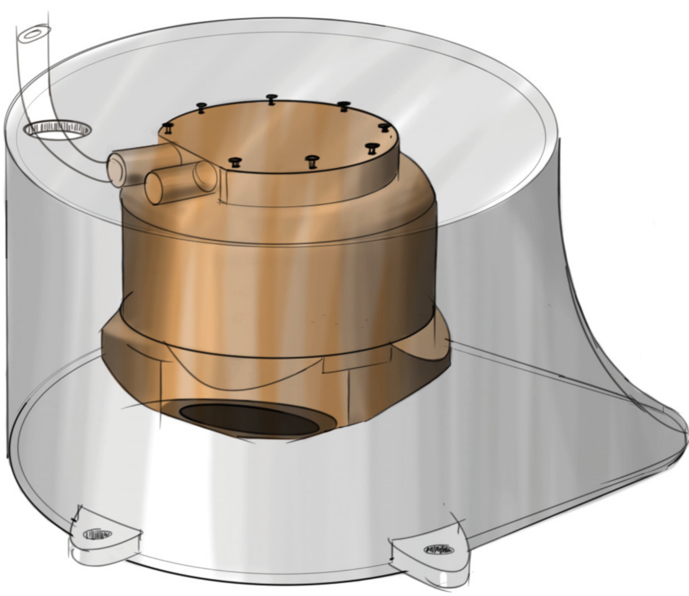


Figure 33 - *DVL hull*

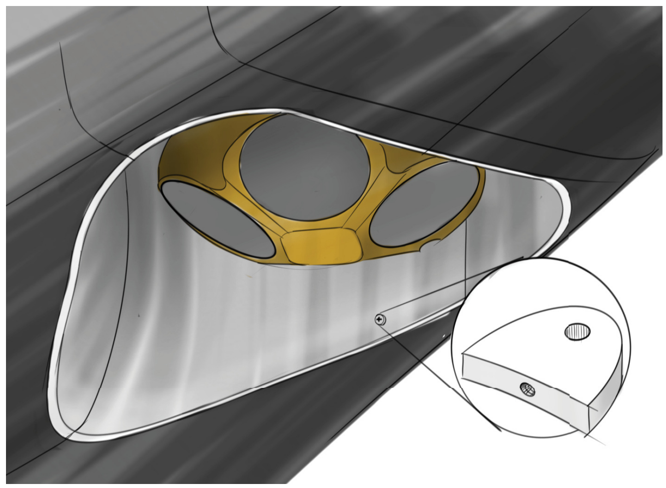


Figure 34 - *DVL hull*

because of its outdoor characteristics: it is chemically inert, corrosion and weather resistant. PET is an easy-to-mould material as well, that is among other things, used for aquaculture applications and plastic playground equipment. Another material called Isoplast, is unaffected by salt water, gasoline and many other chemicals. Besides, it is stronger than PVC and PET (Gerard, 2012).

The first hull will be produced by a CNC drilling machine, but when more units are implemented, the hull could be processed using compression moulding. This will reduce the amount of waste tremendously compared to the milling, and will be much cheaper to produce in higher amounts.

Although there is not directly space in the front of the submsersible, with a few adjustments in the current architecture, it must be possible for the DVL to fit in.

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Final design

DRAWING

In this overview, the casing, hull and submersible are displayed in their correct properpotions.

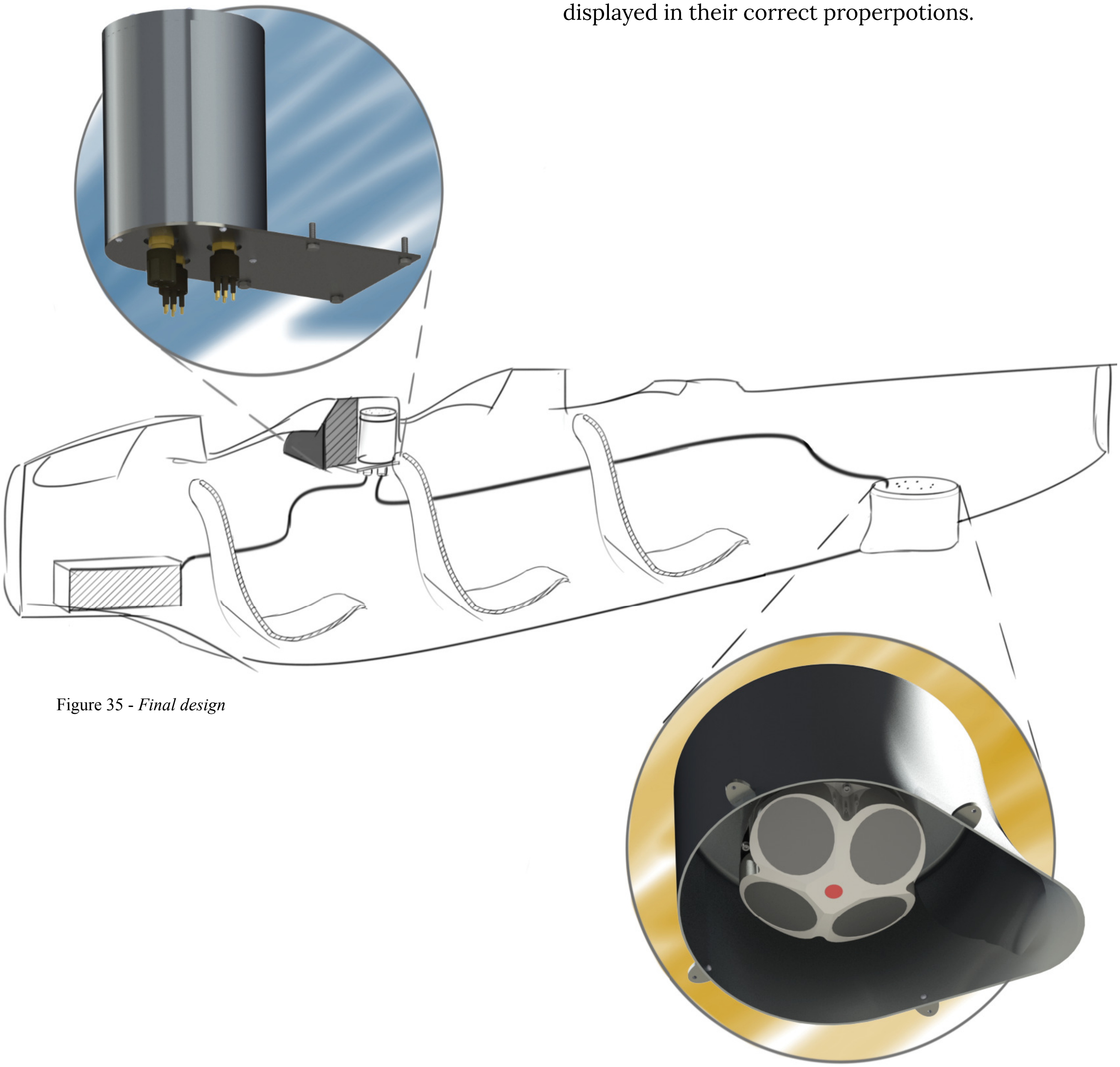

Figure 35 - *Final design*

PARTS LIST

Parts list INS	Amount
Bolt M6 200 mm	4
Cable coaxial	1
Cable INS connector	1
Casing	1
Connector BH5F	1
Connector BH5M	2
GNNS antenna	1
INS	1
Lid	1
Mounting plate external	1
Mounting plate internal	1
Screw M4 12 mm	8
Screw M4 30 mm	4
Screw M4 torx 20 mm	12
Parts list DVL	
DVL	1
Hull	1
Screw M4 12 mm	8
Screw M6 torx 20 mm	4
General parts	
Cable 5-pin male-female 3 m	1
Cable 5-pin male-female 4 m	1
Computer (motor controller box)	1

Table ? - *Parts list INS*

COSTS PREDICTION

In chapter 7 and 8, some inquiries were received by contacting several companies. The Spatial FOG INS costs 30.000,- euros, and in this kit, the GNSS antenna, connector cable and coaxial cable are included.

From the Syrinx DVL, there is still no inquiry received. The Navquest 600 Micro DVL has almost the same accuracy, but can only reach a bottom range of 110 m (instead of 175 m), and costs 10.690,- euros. It is likely, that the Syrinx DVL will not deviate too much from this value. It could be slightly more expensive, because it has a higher operational altitude. Costs are therefore estimated at 12.000,- euros.

Now, let's say that the remaining parts - the hull, casing, connectors and cables, mounting plates and screws - are approximately 1000,- euros. This estimation could be executed roughly, because the price is small enough to be insignificant compared to the total costs. The computer is neglected in this analysis, as this will be implemented in the next-built submersible anyway, regardless of the implementation of the navigation system.

The total costs of implementing this INS/DVL navigation system is therefore estimated to be 43.000,- euros.

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Conclusion and discussion

CONCLUSION

The most suitable underwater navigation system, applied to Ortega's submersibles, is a combination of an INS and a DVL. The navigation system has a predicted accuracy of 0,08 % of the total travelled distance. Although this score will be enough for most underwater activities, it is possible to add more aiding sensors, like sonar or acoustic systems to obtain a higher accuracy.

The INS and GPS antenna will be placed in the raised area behind the second seat, because this is an ideal placement for both systems. Besides, they were both in need of a waterproof casing, which could now be integrated. With the help of a mounting plate, it could be attached to the bottom surface of the interior lining.

The DVL will be placed in front of the first seat at the fore-to-aft centreline. Here, it can be placed nicely within the shell of the submersible, instead of protruding. Besides, at this location the DVL is placed far away from motors, thrusters and other systems that could result in measurement noise. The hull has a drip-shaped rear, to guide the water away from the transducer head.

This navigation system has broad operational capabilities, because it is not limited by range, nor does it require installation time. It can therefore be employed in almost all underwater activities.

Time consuming or big-range operations, however, will experience low accuray over time, because errors are accumulative. The maximum range of the submersible is 200 km, and will result in a error of 160 metres in ideal conditions, which is quite a lot. If over this range high accuracies are required, it would be advisable to get to surface for a GNNS-fix occasionally.

Another option to obtain greater accuracy, is to upgrade the system with extra aiding sensors, which can be implemented without making adjustments in the design.

Another requirement was to make the system modular enough to be implemented as an option, and designed for all submersible types. This requirement is partially met, because the hull of the DVL is probably too big to implement in the one-and two seater types. It would be advisable to consider the placement of a smaller DVL, like the Navquest 600 micro.

If another sensor will be chosen to use in this navigation system, the report does not have to be discarded. It can still be generalized as a step-by-step guide of how to attack the challenges that come with the implementation of an underwater navigation system, and how to realize the implementation of these systems.

Although some inquires yet have to be received for cost calculation, the total price of the INS and DVL system is estimated to be 43.000 euro.

DISCUSSION

First of all, the software part of the system is mainly left out of this report. The INS sensor comes along with a software package that has to be installed on a computer. The software will read the sensory data and calculate global coordinates. This requires some processing power, and thus the minimum requirements for the computer system have to be checked.

Another point of interest is the communication between the INS and the DVL. The fact that they both communicate using RS232, does not necessarily mean they use the same data packages. For this matter, a sensor expert can be of use.

Sonardyne also has an INS sensor available, that has almost the same characteristics as the Spatial FOG. The reason that the Spatial FOG was chosen, was that it has no casing. A self-made casing would be easier to integrate, and it would reduce costs significantly. The inquiries of the Sonardyne systems were however, not yet retrieved from the company. If it turns out that the Sonardyne INS is only a little more expensive compared to the Spatial FOG, it would be more logical to integrate this INS. The systems are then produced by the same manufacturer, and therefore compatibility will be ensured. It is possible that Sonardyne has a 'casingless' version of its INS as well. It is therefore recommended to retrieve more information from the several companies, to obtain a more informed decision process.

Furthermore, the hull of the DVL is not yet optimized. The shape is chosen such that the flowing water underneath the submersible is lead away as smooth as possible, instead of being gulped by the hull and creating chaos inside of it. Another recommendation is therefore, to test the hull's shape on how flow will behave around the transducer heads.

The flanges, that connect the DVL with the submersible's shell, are very complex parts in comparison to their function. If the hull could be re-shaped such that angle brackets could be used for attachment, this would reduce production time and costs.

A recommendation for the user interface, is to enable the navigator to insert GNSS fixes manually, based on underwater objects or other recognition points whose coordinates are known. For longer operations, this could be of help.

At last, the completeness of this report can be doubted. But, as I am writing this there will be more en more sensors developed, or technical improvements on a new navigation system suddenly made another method suddenly more attractive. Completeness, in this case, in an illusion. The last reccomendation therefore is, when this report is used in the future, it is advisable to check the market possibilities.

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References

- Acedemy of Positioning Marine and Bathymetry. (n.d.). Underwater acoustic postitioning systems. Retrieved from Hydro International: http://www.hydro-international.com/files/3fb82f3961d1f9890fc2a475cf56d9ed.pdf
- Advanced Navigation. (2015). Spatial FOG. Retrieved from Advanced Navigation : http://www.advancednavigation.com.au/product/spatial-fog#specifications
- Advanced Navigation. (2016, April 27). Spatial FOG reference manual. Retrieved from Advanced Navigation: https://www.advancednavigation.com.au/sites/advancednavigation.com.au/files/Spatial%20FOG%20Reference%20Manual.pdf
- American Special Ops. (n.d.). Driver Propulsion Device (DPD). Retrieved from American Special Ops: http://www.americanspecialops.com/boats/diver-propulsion-device/
- Breseman, K. (2015, January 22). A web developer's guide to communication protocols (SPI, 12C, UART, GPIO). Retrieved from Tessel: https://tessel.io/blog/108840925797/a-web-developers-guide-to-communication-protocols#gpio
- CDL Intertial Engineering. (n.d.). MINIPOS3. Retrieved from Ashtead Technology: http://www.ashtead-technology.com/datasheets/CDL_MiniPOS3.pdf
- Chandler, J. (2016). The history of submarines. Retrieved from People of our everyday life: http://peopleof.oureverydaylife.com/history-submarines-8548.html
- Domoticx. (2016). Wat is een seriële poort (RS232)? Retrieved from Domoticx knowledge center: http://domoticx.com/wat-is-een-seriele-poort-rs232/
- Gerard, K. (2012, november 16). Top 5 reasons to use plastic marine fasteners. Retrieved from Craftech Industries: http://info.craftechind.com/blog/bid/181930/Top-5-Reasons-to-Use-Plastic-Marine-Fasteners
- Harris, B. (2015). The navy times book of submarines . Retrieved from Submarine History: http://www.submarine-history.com/NOVAfour.htm
- Jurgens, M. (2015). Stealth duikboot. Duiken, magazine van de onderwaterwereld, 27(1), pp. 80-83.
- Khan, R. R., Taher, T., & Hover, F. S. (2010). Accurate Geo-referencing Method for AUVs for Oceographic Sampling. IEEE, 1-5.
- Kuch, B., Butazzo, G., & al., e. (2012). GPS diving computer for underwater tracking and mapping. International Journal of the Society for Underwater Technology, 189-194.
- Link-quest. (2009, March). NavQuest 600 micro. Retrieved from Link-quest.
- Nortek AS. (n.d.). Nortek DVL Datasheet. Retrieved from Nortek AS: http://www.nortek-as.com/lib/brochures/nortek-dvl-datasheet-1/view
- Oceanology International. (2013). Recent advantages in doppler sonar technology for subsea navigation and current profiling. San Diego: Teledyne RD Instruments.
- Paull, L., Saeedi, S., & al., e. (2014, January). AUV Navigation and Localisation: A Review. IEEE Journal of Oceanic Engineering, pp. 131-149.
- RD Instruments. (2001, September). Navigator ADCP/DVL Installation guide. Retrieved from RD Instruments: https://web.duke.edu/robotics/html/pdf/dvl/nav_installation.pdf
- SBG Systems. (2016, July). Motion Sensing and Subsea Navigation - Equinox subea series. Retrieved from

SBG Systems: https://www.sbg-systems.com/docs/Ekinox_Subsea_Series_Leaflet.pdf
- Sonardyne. (2016). SPRINT – Subsea Inertial Navigation System. Retrieved from Sonardyne: https://www.sonardyne.com/product/sprint-subsea-inertial-navigation-system/
- Sonardyne. (2016). Syrinx - Doppler velocity log. Retrieved from Sonardyne: https://www.sonardyne.com/product/syrinx-doppler-velocity-log/
- SSI. (n.d.). Hoe de mens probeerde de onderwaterwereld te betreden. Retrieved from Open water diver: https://ems.divessi.com/ems/index.php?id=5036&L=7
- STIDD Systems. (2016). Recon-Navigation System (RNAV). Retrieved from STIDD Systems: http://stiddmil.com/recon-navigation-system-rnav/
- Teledyne RD Instruments. (2015, July). Explorer Doppler Velocidy Log (DVL) - Navigation performance in a compact package. Retrieved from RD Instruments.
- Tomczak, A. (2011). Modern methods of underwater postitioning applied in subsea mining. Górnictwo i Geoinzynieria.
- Tritech. (n.d.). Micron INS. Retrieved from Tritech: http://www.tritech.co.uk/media/products/micron-ins.pdf
- U-Boat Worx. (n.d.). C-Explorer 3 (3 Persons 300 M). Retrieved from U-boat Worx: http://www.uboatworx.com/C-Explorer_3.dhtml?lan=ENG
- Wikipedia. (2016, November 26). History of submarines. Retrieved from Wikipedia: https://en.wikipedia.org/wiki/History_of_submarines
- Xsens. (2016). MTi-G-710. Retrieved from Xsens: https://www.xsens.com/products/mti-g-710/