Pipefish AUV:
The flight style AUV delivering small, purpose built, hover capable AUVs

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***Abstract*—A current challenge for AUV missions is to combine long endurance with high manoeuvrability. The proposed Pipefish AUV is a long endurance AUV capable of high quality survey missions that can deliver multiple hover capable AUVs to sites of interest. The Pipefish AUV and the small vehicles can perform cooperative tasks and reach remote locations without the need for a monitoring surface vessel. It is shown that an endurance of six days can be achieved, whilst transporting smaller AUVs of a volume of almost two cubic metres.**

***Index Terms*—auv, flight style, hover capable, long endurance, cooperation.**

I. INTRODUCTION

Autonomous Underwater Vehicles (AUVs) have allowed access to areas of our Oceans that have previously been out of human reach. However, in current work with AUVs, a choice between two vehicle styles needs to be made: Hover capable and thus very manoeuvrable but with and endurance limited to few hours (e.g. TUNA SAND, [1]) - or flight style with several days endurance (e.g. Autosub Long Range, [2]) but manoeuvring limitations (see Fig. 1 for a subjective comparison).

Two solutions for this dilemma are possible: building an AUV that combines the two abilities, or design vessels of differing capability to cooperate. The first approach can be found with various existing vessels, e.g. the hover capable, flight style AUV Delphin2 or the thruster extension of REMUS600 [3].

Pipefish proposes and alternative: Instead of building one complex vessel, it proposes one vehicle with high endurance and reliability that can safely deliver smaller but more complex vessels to their mission location (see Fig. 7 for a component overview). As an existing example for the delivery of smaller AUVs, only the Talisman(TM) M vehicle was found. It is designed to deliver up to 500 kg of payload, which can include small AUVs [4]. The proposed Pipefish AUV can more than triple this payload whilst also delivering high quality science data over several days.

II. OBJECTIVES

The objectives for the Pipefish AUV are:

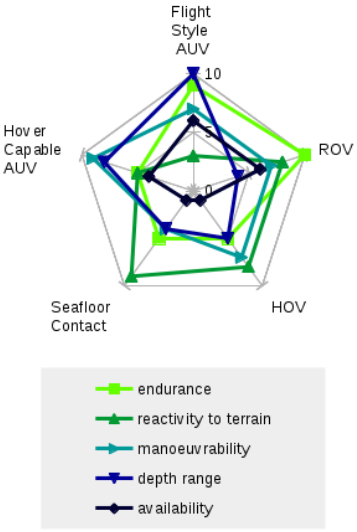


Fig. 1. Subjective comparison of the capabilities of various methods for seafloor surveys, higher rating corresponds to better capability.

1) High reliability
2) Accurate positioning
3) Long endurance
4) Detection of marker measurand
5) Delivery of one or multiple purpose built independent vessels (Minion AUV)
6) Data exchange with Minion AUV before release
7) Safe release of Minion AUV
8) Optional monitoring of Minion AUV

Due to its long endurance, the Pipefish AUV can be deployed both from a research vessel (fig. 2) or from shore (fig. 3).

Mission locations for the Minion AUV can be pre-defined coordinates, e.g. an offshore position at depth, where the Minion AUV will be released after navigating there and performing the time consuming descend and localisation manoeuvres. It can also be situation based, e.g. when the flight

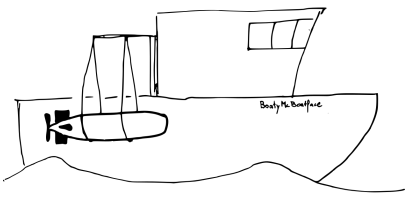


Fig. 2. Deployment from research vessel.

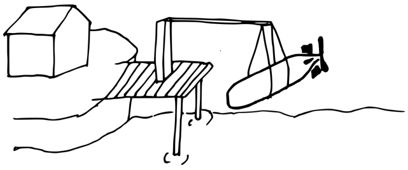


Fig. 3. Deployment from shore

style Pipefish performs a low altitude mission and encounters a cliff (Fig. **??**). If an area would be missed due to its ascend for obstacle avoidance, the Pipefish AUV can release a Minion AUV to survey the area (see Fig. 5). Additional sensors on Pipefish can be used to detect chemical signatures, temperature and salinity changes or escaping oil or gas from leaks in a pipeline (see Fig. 6).

The Pipefish is not reduced to the delivery of the Minion AUV. Based on successful and well tested AUVs like the Autosub vessels [5], it is still a fully capable flight style AUV that can either survey the mission area of the Minion AUV or conduct separate studies. Since a recovery mechanism is not yet planned, after completion of their shared or independent missions all AUVs resurface and transmit their GPS position via Iridium messages where they are collected with a suitable research vessel.

The first version of the Pipefish AUV is designed for the mesopelagic zone, covering the continental shelf region up to 1000 m depth. This gives a large range of applications whilst keeping the depth demand in a range where experience from many existing AUVs can be relied on.

Whilst the Pipefish itself stays mostly the same for all missions, it contributes to a whole range of new, more complex missions. With its long endurance, deployment further from

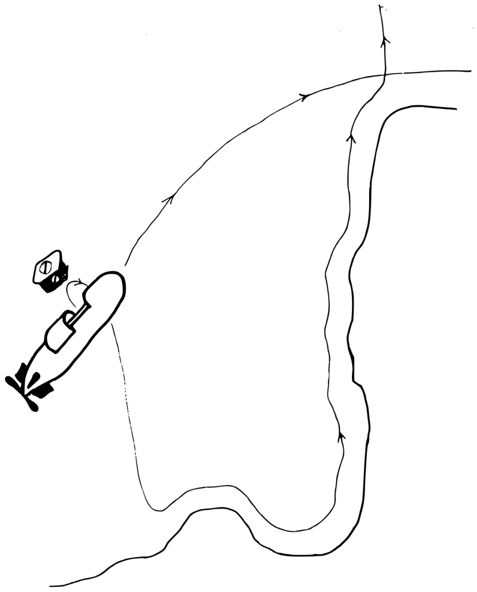


Fig. 5. During a steep ascend, a Minion AUV can be released for additional monitoring.

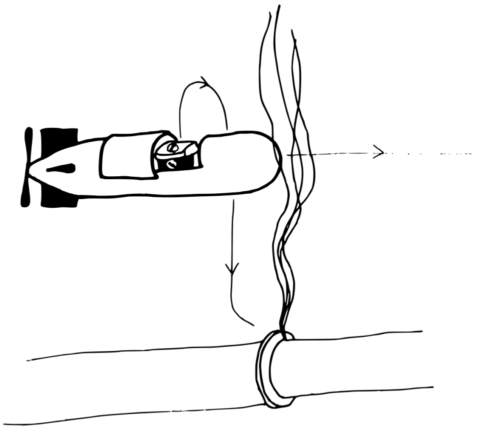


Fig. 6. After detection of a chemical marker, a Minion AUV can be released.

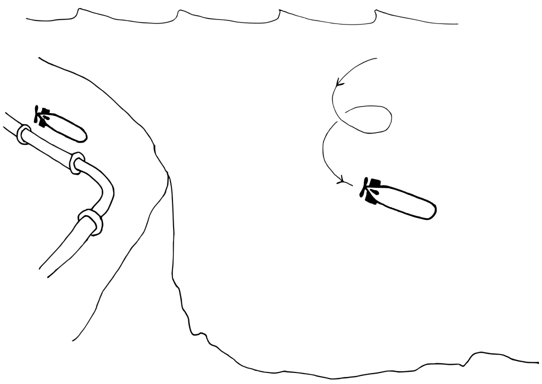


Fig. 4. Surveying and transit to the mission location of the Minion AUV.

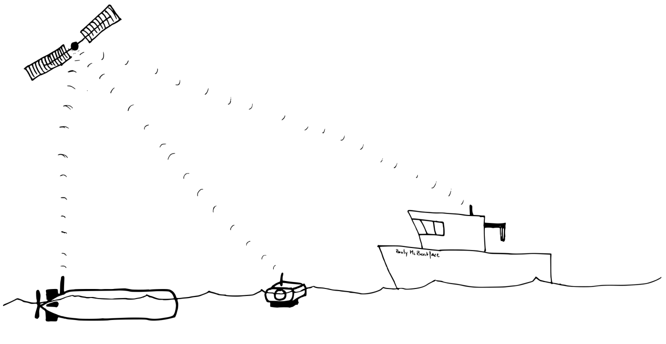


Fig. 8. Recovery of the Pipefish and Minion AUV with a surface vessel.

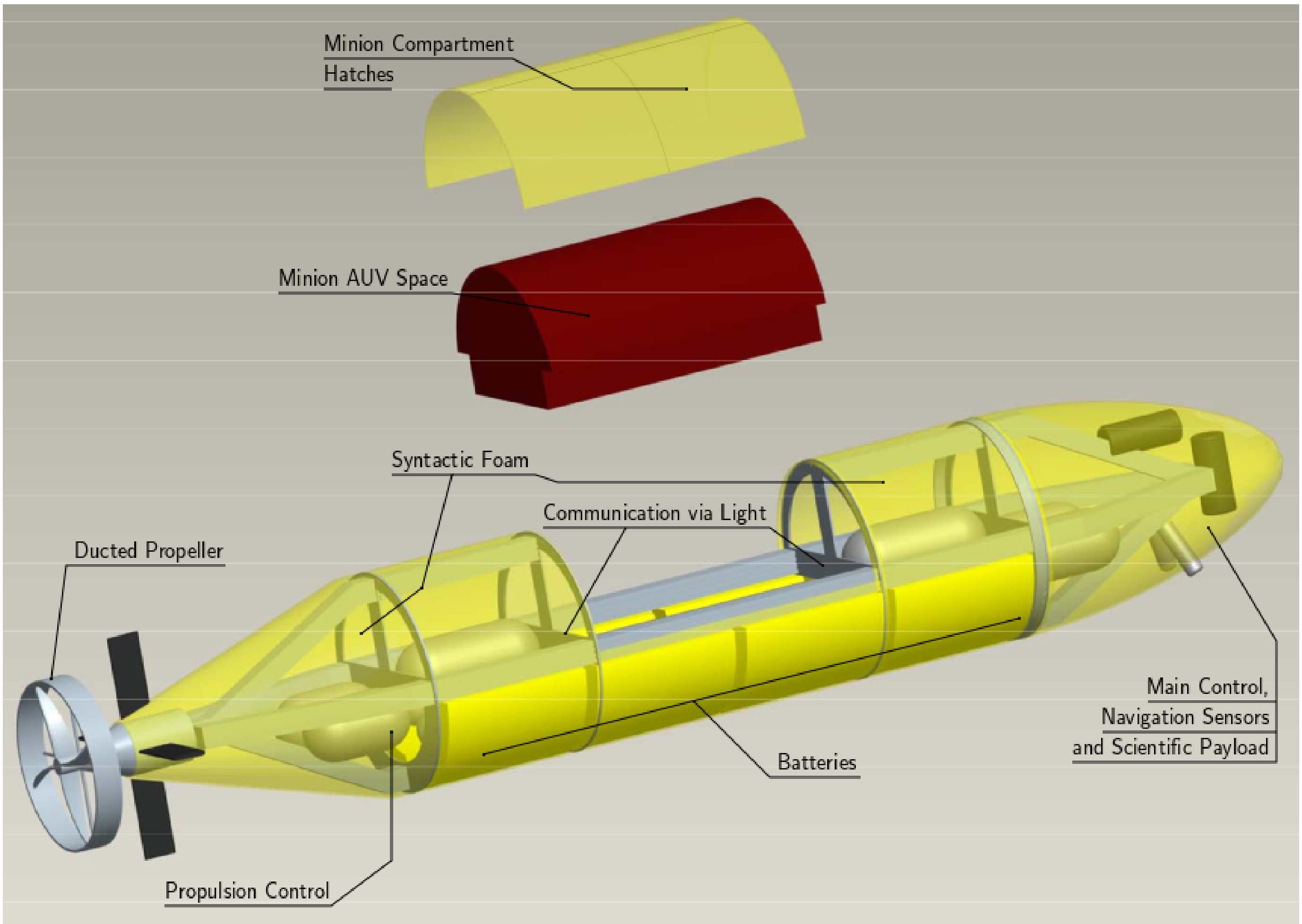


Fig. 7. Sketch of the main components of the Pipefish AUV.

the mission site, or towards an unknown sensor event are possible. The smaller vessels ('Minion AUV') can be redesigned for each mission. Since they are small, new designs can be developed quickly in small testing facilities.

III. DESIGN METHODOLOGY

The main novelty of the Pipefish AUV is the release of Minion AUV during the mission. The new mission steps add previously unknown mission requirements and risks. In the design this needs consideration in the overall layout, so suitable space for the Minion AUV is available and vital components are kept safe.

Next, all necessary sensors and actuators for the vehicle are outlined to get an estimate of their power consumption and mass. It is assumed that the power consumption and mass of the Minion release system is small compared to the overall system so they are not considered in detail.

After defining the main measurements, sensors and actuators of the vehicle, the space that can be filled with batteries and the necessary amounts of syntactic foam are estimated. This gives an estimate for the vehicle mass and endurance.

The mechanism for opening the Pipefish and releasing a Minion needs to be newly designed. For the time of the release, safety and stability considerations need to be made: The vehicle will significantly change its physical properties by opening and releasing its content and during the release there is a risk of a collision between the Minion and the Pipefish. After the release of the Minion, the AUV will have a larger flooded section than previously, but will otherwise be very similar to other widely used flight style AUVs.

A. *New Risks*

In addition to existing vehicle risks, new risks specific to the pipefish missions need to be considered. The highest new mission risk is expected from the deployment process. At this point, the resistance of the hull increases significantly in one location, and the Minion getting stuck during release can be detrimental for both vehicles. To make this mission step fast, a spring loaded release mechanism for the Minion AUVs is planned. During the release, a large amount of drag is added due to the open hatches. This drag will induce a pitching moment. For vehicle safety it was therefore chosen to have the opening hatch at the top rather than the bottom of the Pipefish, so the vehicle would pitch upwards during the release. To increase the vehicle safety after the release, a duct is added to the propeller and the control surfaces are designed similar to ailerons on airplanes. Their leading edge is stationary, so it can be reinforced to reduce the damage sustained from potential collisions with Minon AUV. To protect the antennas for satellite communication at the surface, they are integrated in the top rudder.

B. Length and Diameter

For vehicle transport, release, and recovery, it is important that the AUV can be handled with standard equipment. As a limitation, the standard length of a shipping container, 6 m was chosen. To allow for some room, an overall length of 5.6 m was chosen for the Pipefish AUV. To increase the space available for the Minion AUV, the length over diameter ration L/D was chosen as 4.5, based on the Autosub LR vehicles [6]. The resulting diameter is 1.2 m.

C. Layout

To keep a large area for the Minon AUV, the mid-section of the AUV is filled mainly with batteries and syntactic foam. Fig. 9 shows a cross section of the planned mid-section of the Pipefish AUV. Besides the batteries and the free top section, the space for the main structure of the AUV is indicated in grey. Space is also planned for easily accessible data connections and separate power connections. All other components are placed in the front and tail section. The mid-section is chosen at a length of 3.0 m. Its bottom area is filled with batteries as shown in Fig. 9. To make the vehicle positively buoyant, some areas of the upper section need to be reserved for syntactic foam (see detailed buoyancy section). As a result, a 1.7 m length of the mid section remains for the Minion compartment. This section has two separate hatches which can be opened individually, allowing the separate release of smaller vehicles or the release of a single larger Minion AUV. The hatch opens from the top of the AUV by rotating the upper half of the hull into the lower half. Figure 9 shows the two segments that are opened in yellow and their position during the Minion release in dashed brown.

D. Batteries

Whilst for most parts no direct components were chosen, Lithium Ion batteries were selected from SubCtech [7]: The batteries make a large part of the AUV's mass and volume, knowing their measurements and capacity allows a better estimate of the vehicle range and endurance. Compared to other available batteries suited for 1000 m depth, the large diameter and length of the "Big Jim" batteries allows the use of fewer batteries, but also well filling the volume of the Pipefish. Four 630 mm long batteries are stacked behind each other, their horizontal alignment is shown in Fig. 9, the batteries are represented by red circles. With this method a total of 36 batteries can be placed in the centre section. It would be possible to add a fifth set of shorter batteries within the 3 m length of the centre section, but instead some space space for the battery connectors and hatch opening mechanism were allowed. At an individual weight of 38 kg in air and a capacity of 3.5 kW h, the total dry weight is 1400 kg and the total capacity is 127 kW h.

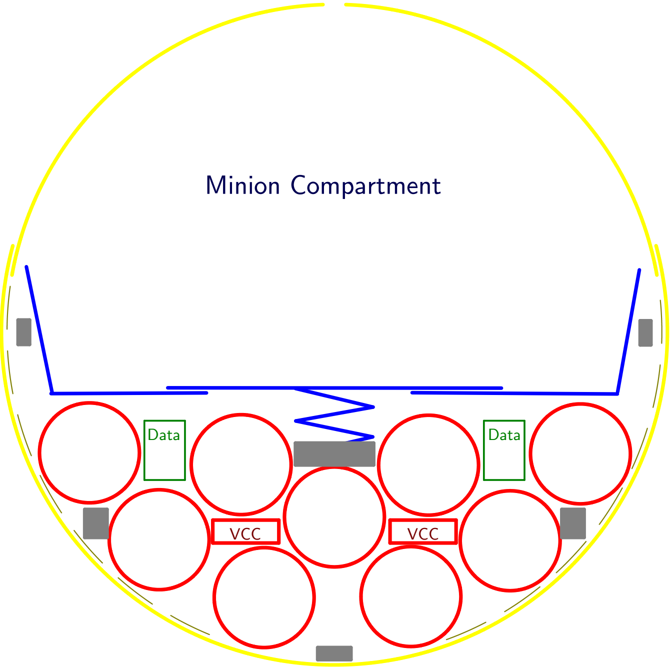


Fig. 9. Cross section view of the AUV mid section area. Marked in red are the batteries and the space for power distribution. In green the space for data wires is indicated. Blue outlines the Minion compartment and the ejection mechanism. In grey is the cross section through the mechanical structure of the AUV. Indicated in dashed is the open position of the Minion compartment hatches.

E. Actuators

For manoeuvring, the Pipefish has a main thruster and four actuated control surfaces. In addition to this, actuators for opening and closing the Minion area are needed. The hatch opening mechanism uses 2 rotational actuator per hatch, for two hatches four motors are needed. Whilst these motors need consideration in weight and space, their contribution to the power consumption is minimal since they are rarely used. It is assumed that the main power consumption comes from the main thruster, estimated at $\approx$ 350 W and that the consumption of the other actuators on average is below 11 W. The estimates for weight, volume and power consumption are listed in Tab. I.

F. Sensors & Computation

An important priority for the Pipefish AUV is its accurate navigation. For this purpose, a Doppler Velocity Log for bottom tracking and an optical Inertial Navigation System were chosen. If needed, the vehicle can communicate with a surface vessel via an acoustic modem. For obstacle avoidance a mechanical scanning sonar was chosen, since the vehicle will deploy Minion AUV in more complex environments and provide them with information about their environment whilst flying above them. The Pipefish is designed to still be capable of typical missions for flight style AUVs and needs to be able to monitor the Minion AUV if required. Its sensor system

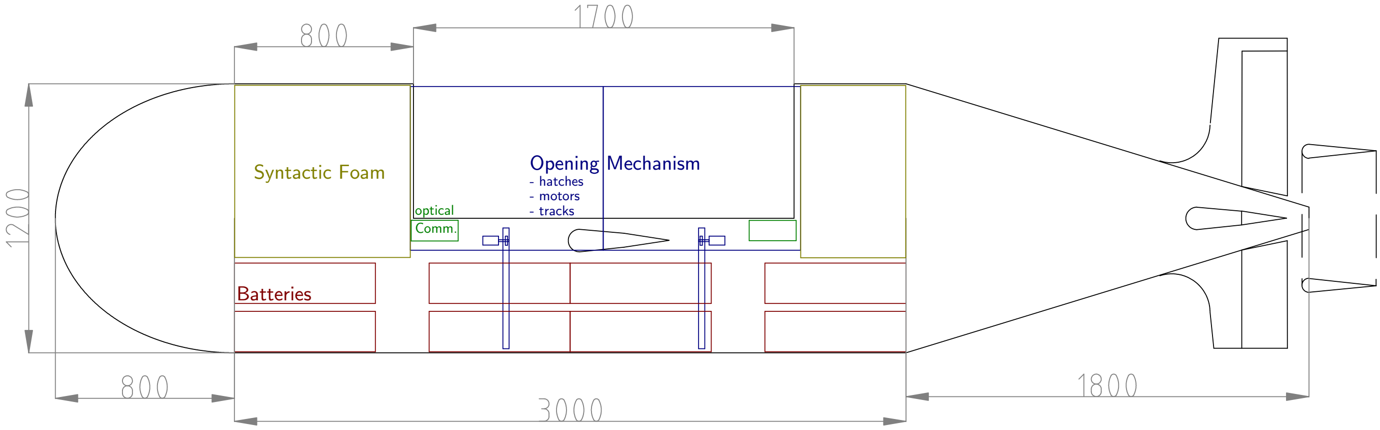


Fig. 10. Lengthwise drawing of the Pipefish with measurements in [mm] and details on the mid-section layout.

includes a multibeam sonar, a sidescan sonar, a subbottom profiler and conductivity, temperature and depth measurements. Before opening the Minion compartment, all relevant mission data is transmitted to the Minion AUV via a fast and energy efficient optical communication interface within the Minion compartment. After deployment of the Minion AUVs, the acoustic modem can be used for communication if required. At the end of the mission, the Pipefish is recovered using the GPS position transmitted via the Iridium Short Burst Data service as it is common practice.

For computation, a standard unit will be chosen for running a linux system with ROS. For redundancy, two systems are installed in separate pressure vessels. The recorded mission data is stored on hard drives that can be quickly replaced to get the vehicle ready to capture more data.

Based on the actuator, sensor and computation considerations, the part list in Tab. I was generated. Values are estimated based on author experiences, conversation with other engineers, the Autonomous Undersea Vehicle Applications Center (AUVAC) [8] and the product ranges from Ekinox, Klein Marine Systems Inc., Kongsberg, KVH FOG, LinkQuest, Seatronics, Sonardyne, Teledyne, and Tritech. For the choice of final products, more detailed information including cost and detailed data protocols need consideration. It was therefore decided to go with estimates and keep the choices open.

G. Buoyancy & Stability

With the component sizes and weights estimated in Tab. I, and the battery weight in seawater given at $22\,\mathrm{kg}$, the needed syntactic foam for zero buoyancy can be estimated and suitable space on the vehicle allocated for it. The weight of the components in seawater (density $1025\,\mathrm{kg\,m^{-3}}$) is $110\,\mathrm{kg}$. The weight of 36 batteries in seawater is $792\,\mathrm{kg}$. Adding a $10\,\mathrm{kg}$ emergency drop weight, a total of $912\,\mathrm{kg}$ need to be compensated by syntactic foam.

The syntactic foam for the mesopelagic zone described in [9] has a density of $385\,\mathrm{kg\,m^{-3}}$, one cubic metre of the foam can therefore compensate for $640\,\mathrm{kg}$ weight in water. To compensate $912\,\mathrm{kg}$, approximately $1.43\,\mathrm{m^3}$ of foam are necessary. In the mid section, the upper half is reserved to form the Minion compartment or to be filled with syntactic foam (see Fig. 9). Using a semicircle cross section, with a radius of $0.6\,\mathrm{m}$, and choosing a length of $1.3\,\mathrm{m}$, the volume of the foam reaches $1.47\,\mathrm{m^3}$, leaving a mid section length of $1.7\,\mathrm{m^3}$ and a volume of over $1.9\,\mathrm{m^3}$ for the Minion compartment.

Name	Mass $[kg]$	Volume $[m^3]$	Power consumption $[W]$
Doppler Velocity Log	10	0.005	100
Inertial Navigation System	1.5	0.001	5
Acoustic modem	5	0.004	2
GPS	<0.1	<0.001	<0.001
Iridium SBD	<0.1	<0.001	<0.001
Mech. scanning sonar	3	0.002	10
PC	1	0.002	20
Hard drives	1	0.002	5
Power distribution	1	0.002	5
Main thruster	6	0.006	350
Control surfaces	2	0.001	10
Hatch actuation	4	0.002	1
Optical communication	<0.05	<0.001	<0.001
Multibeam	60	0.015	150
Sidescan	60	0.015	60
Sub bottom profiler	20	0.005	100
CTD	2	0.003	1
Waterproof wires & connectors	2	0.003	1
Total	≈ 180	≈ 0.07	≈ 820

TABLE I
ACTUATORS, SENSORS AND OTHER ELECTRICAL COMPONENTS OF THE PIPEFISH AUV.

These calculations neglect the buoyancy that may be needed for structural components, however with additional space available in the tail and front of the vehicle, the small contributions of the structure can be compensated if needed. For aligning the centre of buoyancy above the centre of gravity, most of the sensors will be positioned at the front of the vessel, whilst additional foam will be added in the back. If this is not sufficient, the position of the Minion compartment can be shifted along the length of the mid-section.

Hover capable AUVs for great depth are regularly designed negatively buoyant to save energy [1], they are thus at an increased risk of vehicle loss. The Minion AUV can be positively buoyant since the costly ascend is performed by the more energy efficient Pipefish AUV. As typical for flight style AUVs, the Pipefish will also be positively buoyant. To increase its ability to dive, control surfaces are added at the side of the AUV at a position close to the centre of gravity. At the mission end, or in case of an electrical failure, all vehicles will automatically return to the surface. To avoid a large change in the position of the centre of gravity and the centre of buoyancy, the compartment is placed close to the position of the centre of gravity and the centre of buoyancy. It is recommended to keep the buoyancy of the Minion AUV positive but close to zero both to increase their endurance and to ensure that the release of the Minion AUV will not result in a large change in buoyancy.

Adding the protective duct to the propeller stabilises the zero pitch and yaw position of the vehicle [10]. To keep a good manoeuvrability, the size of both the vertical and the horizontal sternplanes is increased. To keep the lower vertical sternplane above the keel line of the vehicle, the dimensions of the upper sternplane are increased more. This has the positive side effect that the antennas, which are kept protected in the leading edge of the upper sternplane, are further out of the water when the vehicle is at the surface.

H. Robot Collaboration

Collaboration between AUVs is challenging due to communication often being limited to slow acoustic communication. However during the approach to a Minion release site, the vehicles can communicate via light whilst the Minion AUV is contained in the Pipefish AUV. This way Minion AUVs can be updated with mission information and a recently generated map of the area. If both vehicles are equipped with an acoustical modem, the Pipefish can then monitor the activities of the Minion AUV at a few hundred metres distance and the two vehicles can exchange further updates.

IV. SPECIFICATIONS

The table below gives the specifications of the Pipefish AUV, as derived in the design section. The dry mass is given as the mass without added Minion AUV, the wet mass is the mass for a flooded AUV without Minion AUV. However since it is recommended to design the Minion AUV to be only slightly positively buoyant, it can be assumed that the flooded mass with Minion AUV will be similar to the given wet mass.

V. DEVELOPMENT SCHEDULE

The development of the Pipefish can be split in building a flight style AUV relying on existing technologies and new developments needed for the release of Minion AUV. An important milestone in the development of the Pipfish is the definition of the Minion compartment, since this is needed for the development of Minion AUV.

A. Technologies

Existing technologies that will be relied on:

- Basic flight style AUV navigation & control
- Weight and buoyancy considerations for positively buoyant vehicles
- AUV release and recovery methods for Pipefish AUV
- Pressure compensated rechargeable batteries
- Pressure hull design for 1000 m depth
- Communication via light (before release)
- Acoustical communication (after release)

Pipefish AUV Specifications	
Depth rating	1000 m
Mass, dry	1600 kg
Mass, wet	3600 kg
Length	5.6 m
Diameter	1.2 m
L/D	4.5
Average speed	1 m/s
Battery capacity	127 kWh
Average power consumption	820 W
Expected endurance	155 h $\approx$ 6 days
Expected range	6000 km
Space for minion AUVs	1.7 m length, cross section 0.55 m radius

TABLE II
SPECIFICATIONS OF THE PIPEFISH AUV. FOR THE CROSS SECTION AVAILABLE FOR THE MINION COMPARTMENT, SEE FIGURE 9.

Newly developed technologies:

- Sliding door for minion release
- Vehicle ejection mechanism
- Protocol for information exchange before minion release
- Mission planning to include minion release
- Cooperative mission planning for Minion and Pipefish

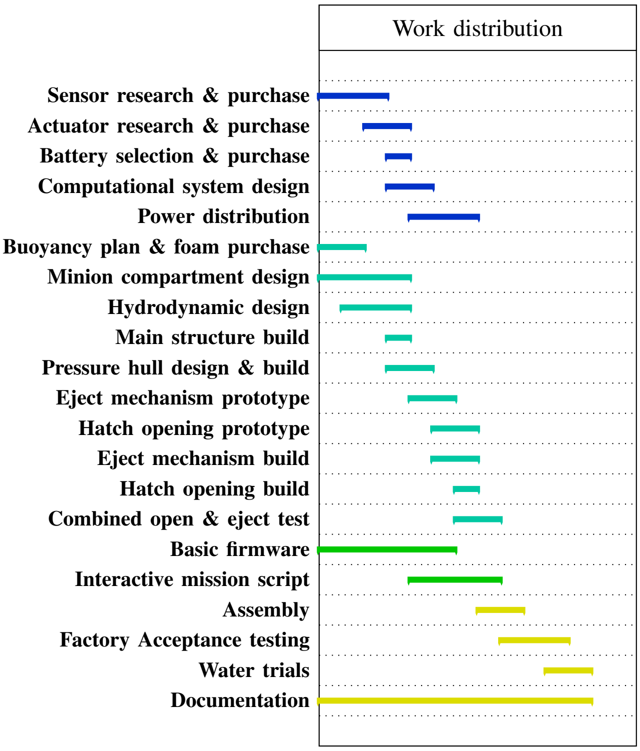
Table III gives an estimate for all work steps that were identified. It details for each task, how much of the time will require an engineering background in mechanical, electronic or software design.

Based on the split results for the work estimates, a possible work distribution for building the Pipefish AUV in three years would be three electrical engineers, three software engineers and five mechanical engineers.

Since the development time of the Pipefish largely depends on the number of people working on it, the below Gantt chart remains without units. It gives a timing overview of the tasks, and can be scaled over three years when using the 11 engineers outlined above. The different colours match the focus on different engineering aspects based on Tab. III. The last set of tasks (yellow) is the work that needs equal contributions from all areas.

Description	total	elec.	mech.	softw.
Sensor research & purchase	1	**0.6**	0.2	0.2
Actuator research & purchase	0.6	**0.3**	0.2	0.1
Battery selection & purchase	0.5	**0.4**	0.1	-
Computational system design	1.5	**1.1**	0.1	0.3
Power distribution	1.5	**1.2**	0.3	-
Buoyancy plan & foam purchase	0.6	-	**0.6**	-
Minion compartment design	1.6	0.4	**1.2**	-
Hydrodynamic design	1.4		**1.4**	-
Main structure build	1	-	**1**	-
Pressure hull design & build	0.6	0.2	**0.4**	-
Eject mechanism prototype	2.5	0.5	**2**	-
Hatch opening prototype	2	0.2	**1.8**	-
Eject mechanism build	1.5	-	**1.5**	-
Hatch opening build	1	-	**1**	-
Combined open and eject test	1.5	0.5	**1**	-
Basic firmware	4	-	-	**4**
Interactive mission script	3	0.2	0.2	**2.6**
Assembly	1.2	0.4	0.4	0.4
Factory Acceptance testing	2	0.6	0.6	0.8
Water trials	1	0.3	0.4	0.3
Documentation	2.5	0.7	0.7	1.1
Total	32.5	7.6	15.1	9.8

TABLE III
TIME FOR THE DEVELOPMENT STEPS OF PIPEFISH, SPLIT INTO WORK ON ELECTRONICS, MECHANICAL AND SOFTWARE WORK, ESTIMATED IN WORK YEARS. HIGHLIGHTED ARE THE PHASES WHERE A MAIN WORK AREA IS IDENTIFIED.



VI. BUDGET

The cost of the Pipefish is composed of the material cost, the cost for the sensor and actuator system and the cost for the engineering time. An estimate of the cost for sensor and actuator system as well as vessel and electronic systems materials is given in Tab. IV. The material cost for developing the hatch is considered within the budged for structure and hull material. The main cost for adding the new capabilities of the Pipefish come from the cost for development time.

Name	Cost order of magnitude [\$]
Doppler Velocity Log	$20 \cdot 10^3$
Inertial Navigation System	$150 \cdot 10^3$
Acoustic modem	$20 \cdot 10^3$
GPS	150
Iridium SBD	500
Mech. scanning sonar	$15 \cdot 10^3$
Multibeam	$200 \cdot 10^3$
Sidescan	$80 \cdot 10^3$
Sub-bottom profiler	$200 \cdot 10^3$
CTD	$60 \cdot 10^3$
PC	100
Hard drives	200
Power distribution	200
130 kWh LiIon batteries	$200 \cdot 10^3$
Main thruster	1000
Other actuators	2000
Syntactic foam	$30 \cdot 10^3$
Structure (material)	1500
Hull (material)	1000
4 pressure vessels (material)	$50 \cdot 10^3$
Waterproof wires & connectors	$25 \cdot 10^3$
Total	$1\ 056\ 650 \approx 10^6$

TABLE IV
COST ESTIMATES FOR THE MATERIALS AND COMPONENTS.

The work years required for developing and assembling the Pipefish were already estimated in the development schedule, Tab. III. Assuming the cost of one engineering work year at around \$ 100 000, the total work cost for the Pipefish AUV is \$ 3 250 000, combined with the material cost of \$ 1 056 650, the total cost is \$ 4 306 650. Additional costs for facilities and water trials still need including.

VII. CONCLUSION

The design considerations show that the Pipefish AUV can combine being a long endurance mapping and area scanning vessel with delivering purpose build hover capable AUVs to sites of interest. At a cost of \$ $4.5 \cdot 10^6$ it can be build within 3 years. Whilst an initial investment is needed, the savings from being able to quickly develop small, task specific AUVs and deliver them to remote sites are immeasurable. Building on the ability of the Pipefish AUV's capabilities, further development can turn the Pipefish into a more advanced supply vessel. Besides extending the depth range to 6000 m and beyond, a valuable development would be to enabling re-entry of Minion AUV for example by adding a rope mechanism or by choosing Minion actuators suitable for a docking manoeuvre. Then the Minion AUV could access even the most remote locations at great depth, under ice or in caves. Another purpose of docking small AUV on a further developed Pipefish could be recharging. A swarm of small robots could be supplied with power, information and control commands whilst performing extended work in remote areas.

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