DLR

Institute of Space Systems
System Analysis Space Segment

Feasibility Study
PELADIS

Concurrent Engineering Study Report

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Study Team and Responsibilities

Team Leader	Volker Maiwald, Rosa París Lopéz	DLR RY-SR
Customer	Hendrik Müller	MARUM
Systems	Dominik Quantius/ Hendrik Müller	DLR + MARUM
Science	Hendrik Müller	MARUM
Instruments/ Communication	Chrsitian Hilgenfeldt	MARUM
Data Handling	Carl Treudler	DLR RY-AY
CEF Software	Volker Schaus, Philipp Fischer	DLR BS-SC
n/a		
Configuration	Wiebke Wenzel	DFKI
Structure	Siebo Reershemius	DLR RY-SR
ACS	Markus Schlotterer	DLR RY-NR
Power	Andy Braukhane	DLR RY-SR
Operations/ Propulsion	Leif Christensen	DFKI
Hydrodynamics	Rodion Groll	ZARM

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Deutsches Zentrum für Luft und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

Institut für Raumfahrtsysteme
Systemanalyse Raumsegment (SARA)

Volker Maiwald

Robert-Hooke-Str. 7
D-28359 Bremen
Telefon 0421 24420-251
Telefax 0421 24420-150
E-Mail mailto: Volker.Maiwald@DLR.de
Internet http://www.dlr.de/irs/

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1. Introduction

Exploration and research activities related to marine mineral resources for the strategic mineral planning gains much importance due to rising commodity prices. However, effective methods to locate the mostly heterogeneous and often deeply covered, shallow marine ore deposits are absent.

In order to evaluate the profitability, one needs to access the spatial extend, the quality and the inner structure of a resource. Mining rights can only obtained from the International Seabed Authority (ISA) on the basis of precise prospection data to justify the required high investment and mining costs. Established marine exploration methods are only of limited suitability to explore Submarine Massive Sulphides (SMS), manganese nodules, phosphorites or heavy mineral placer deposits. In contrast, Controlled Source Electromagnetic (CSEM) imaging is ideal to detect marine resource of contrasting electrical conductivity and/or magnetic properties. However, the marine CSEM induction method demands spatially stable, operational robust and highly mobile sensor geometries of relatively large diameters, which has not been realized so far, especially not for deep-sea setting.

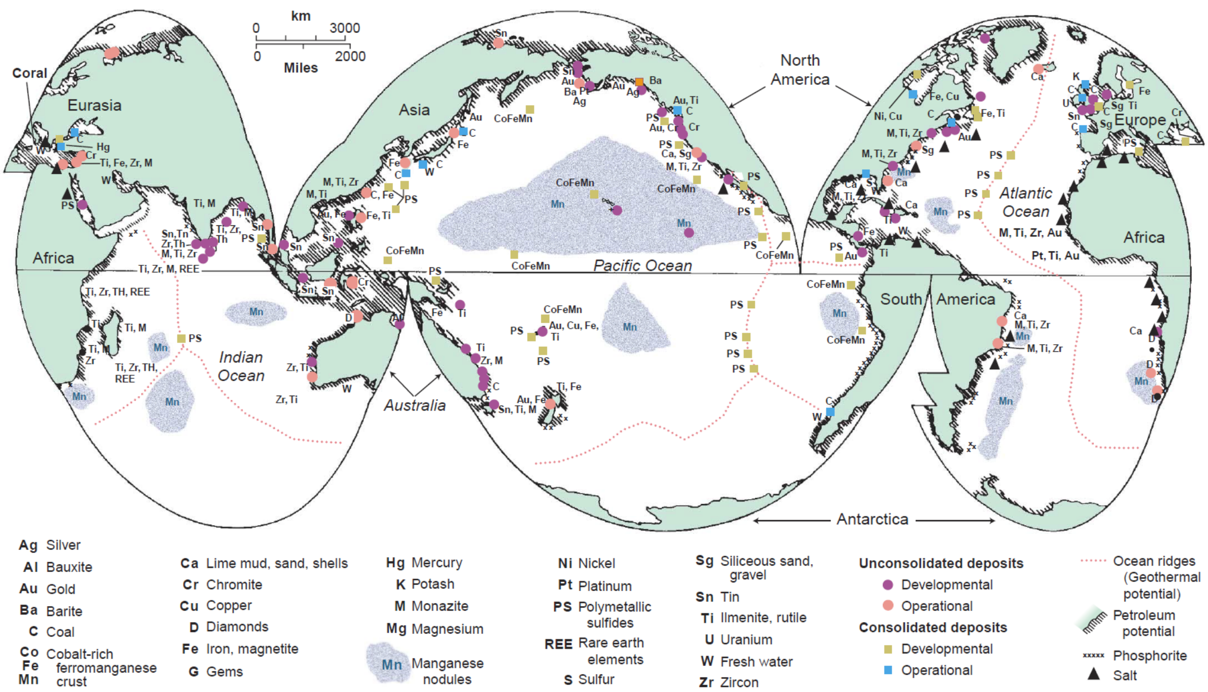


Figure 1-1: Global distribution of marine mineral resources [RD 1].

An EM Profiler, PELADIS, has been investigated during the 30th CE Study at the DLR Bremen. PELADIS satisfies the previously described, high demands and furthermore monitors the surrounding ecosystem and possible damage caused to the environment by mining activities. The studied EM Profiler will focus on PS, Mn, Fe, Ti and Phosphorite exploration and monitoring issues (s. Figure 1-1). Two elements have been considered as part of the PELADIS mission:

- Element #1: PELADIS ROV Sensor Module (PSM), attached to ROV as payload and connected via cable and winch. It has the necessary manoeuvre capability to prevent collisions and to provide attitude stability.

- Element #2: PELADIS ROV Interface Module (PIM), mounted below ROV. It serves as service part for the PSM.

The objectives of the study have been:

- Definition of the mission scenarios (deployment, terrain following, recovery)
- Preliminary design of PELADIS sensor module
- Budgets (e.g. mass, power) on equipment level for both elements
- Accommodation of required instruments
- Adequate size of PSM steering wings
- Analysis of interfaces to carrier vehicles
- Definition of autonomous terrain following capabilities

The CE study for PELADIS took place from 11th to 15th June 2012 in the Concurrent Engineering Facility of the DLR Bremen. The subsystem domains and disciplines have been taken by DLR Bremen staff, MARUM (Center for Marine Environmental Sciences), ZARM (Center of Applied Space Technology and Microgravity) and DFKI (German Research Center for Artificial Intelligence).

1.1. Mission Overview

The conceptual design study of PELADIS aims to develop an innovative ElectroMagnetic (EM) deep-sea profiler to explore near surface mineral resources in rough terrain and buried below sediments or lava flows. The envisaged deep-towed induction coil (sensor) module glides with well controlled ground distance even over rough terrains and allows high resolution EM mapping of the electric conductivity and the magnetic susceptibility of the subsurface, as well as optically and acoustically captured seafloor structure and biota.

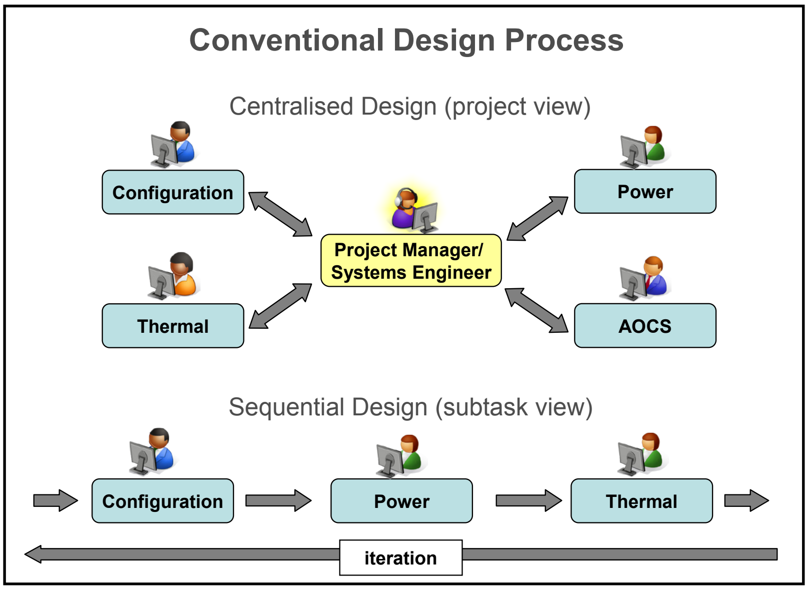
The envisaged EM profiler utilizes as leading technology a concentric assembly of a transmitter, receiver and compensation coil (development of Geophex Ltd. USA) that allows to receive secondary, rock-induced EM fields only, while continuously transmitting and receiving EM fields between 1 and 10 000 Hz at 25 Hz sampling rates. Several frequencies can be combined and jointly inverted to utilize a frequency dependent depth penetration: the lower the frequency, the deeper the penetration.
The sensor development will focus in its first stage to explore SMS deposits at passive hydrothermal vent sites in deep sea settings of up to 4 000 m water depth. Due to rough seafloor topography and often buried SMS structures, the EM profiler has to provide both, a safe ground distance of 1 to 4 m and a sufficient vertical penetration depth to quantify the quality and thickness of sulphide deposits up to 30 m below seafloor. Finite element and numerical models revealed that a vertical magnetic dipole induction sensor with concentric coplanar transmitter and receiver coils of 5 m transmitter diameter is needed to fulfil these requirements while still being deployable from standard research vessels. However, the theoretical models are only applicable, as long electromagnetic stray fields maintain below 3 mA/(m·√Hz) close to the receiver coil and metallic frame constructions should be avoided wherever possible, to provide sensitive EM measurements.

Two operation modes of the EM Profiler have been envisaged during the study: (1) a Remotely Operated Vehicle (ROV) coupled sensor module for rough terrains (e.g., hydrothermal vent sites at mid ocean ridges and back arc basins), and (2) a towed sensor body to cover wide areas at speeds up to 4 kn (e.g., heavy mineral (Fe, Ti) placers, phosphorites or manganese nodules).

1.2. Concurrent Engineering Approach

To investigate and define the technical concept of the PELADIS a Concurrent Engineering (CE) Study at DLR Bremen has been conducted. The CE-study comprised the analysis and the development of all subsystems necessary for PELADIS i.e. configuration, instruments, structure design, data handling, power, propulsion and operations, hydrodynamics and AACS.

The applied Concurrent Engineering (CE) process is based on the optimization of the conventional established design process characterized by centralized and sequential engineering (see Figure 1-2 top). Simultaneous presence of all relevant discipline's specialist within one location and the utilization of a common data handling tool enable efficient communication among the set of integrated subsystems (see Figure 1-2 bottom).



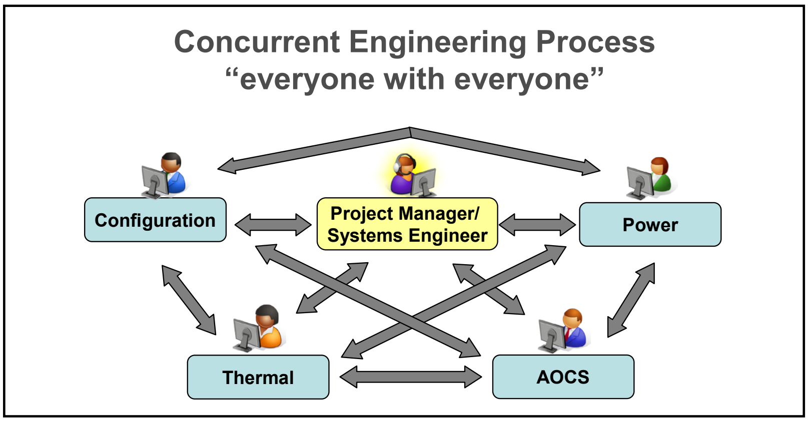


Figure 1-2: The Concurrent Design approach compared to projections of conventional design process.

The CE-Process is based on simultaneous design and has four phases ("IPSP-Approach"):

1. Initiation Phase (starts weeks/months before using the CE-facility):

- Customer (internal group, scientists, industry) contacts CE-team
- CE-team-customer negotiations: expected results definition, needed disciplines

2. Preparation Phase (starts weeks before using CE-facility):

- Definition of mission objectives (with customer)
- Definition of mission and system requirements (with customer)
- Identification and selection of options (max. 3)
- Initial mission analysis (if applicable)
- Final definition and invitation of expert ensemble, agenda definition

3. Study Phase (1- 3 weeks at CE-Facility in site):

- K/O with presentations of study key elements (goals, requirements)
- Starting with first configuration approach and estimation of budgets (mass, power, volume, modes, …) on subsystem level
- Iterations on subsystem and equipment level in several sessions (2- 4 hours each); trading of several options
- In between offline work: subsystem design in splinter groups
- Final Presentation of all disciplines / subsystems

4. Post Processing Phase:

- Collecting of Results (each S/S provides Input to book captain)
- Evaluation and documentation of results
- Transfer open issues to further project work

The DLR's Concurrent Engineering Facility in Bremen is derived from the Concurrent Design Facility at ESA's ESTEC (European Space Research and Technology Centre), which has already been in operation for more than ten years. Bremen's DLR-CEF has one main working room where the whole design team can assemble and each discipline is supplied with an own working station for calculations and interaction with the Virtual Satellite (VirSat), a design software tool developed by DLR. Three screens, one of them interactive, allows display of data in front of the team. Further working positions are provided in the centre of the working area and are usually reserved for customers, PIs, guests and also the team leader and possibly the systems engineer. Two more splinter rooms provide the design team with separated working spaces where sub-groups can meet, discuss and interact in a more concentrated way.

Figure 1-3: Concurrent Engineering Facility main room (lefthand) and working during CE-study phase (righthand) at DLR Bremen.

The major advantages of the CE-process are:

- Very high efficiency regarding cost & results of a design activity (Phase 0, A)

- Assembly of the whole design team in one room facilitates direct communication and short data transfer times
- The team members can easily track the design progress, which also increases the project identification
- Ideas and issues can be discussed in groups, which brings in new viewpoints and possible solutions; avoidance and identification of failures and mistakes

1.3. Document Information

This document summarizes the progress and results of the DLR Concurrent Engineering study about the PELADIS mission, which took place from 11th to 15th June 2012 in the Concurrent Engineering Facility of the DLR Institute of Space Systems in Bremen.
The single subsystems or domains as investigated during the study are covered in individual chapters, which explain the study progress, elaborate on decisions and tradeoffs made during the study and also design optimizations.

2. System

The following sections describe the framework for the study, i.e. the mission objectives and requirements as well as the system requirements. Furthermore a complete overview of the system is given as introduction to the following chapters that deal with the detailed subsystem descriptions.

2.1. Mission Objectives

The objectives as defined in Table 2-1 have been the frame for the PELADIS study and have been the basis for the mission and system requirements.

Table 2-1: Mission objectives for PELADIS.

Objective	Description
MI-OJ-0010	Deploy EM sensing loops (Ø TX1 = 5 m, TX2 = 1.2 m, RX = 0.5 m) horizontally (gravitational), 1-4 m above ground
MI-OJ-0011	Determine composition of the seafloor (depth ≤ 4000 m) with preference to ferrous ore deposits
MI-OJ-0020	Determine burial depth, thickness and electric conductivity of ore deposit
MI-OJ-0030	Measure size and shape of ore deposit
MI-OJ-0040	Mark potential targets for supplementary investigations
MI-OJ-0050	High-precision imaging of seafloor bathymetry
MI-OJ-0060	Preprogrammed flight path and autonomous terrain following

2.2. Mission Requirements

In preparation for the CE-study the following mission requirements were defined to allow the mission definition:

Table 2-2: Mission requirements for PELADIS.

Requirement	Description
MI-PE-0010	Operate above rough terrain with bottom water currents up to 1 m/s (water temperature: -2 to 18°C)
MI-PE-0011	Control and maintain ground elevation of the sensor within 0.1 m (favored: autonomous terrain following)
MI-PE-0020	Precisely control and maintain Roll-Pitch-Yaw and absolute position of sensor, including compensation of ship motion and side currents
MI-PE-0030	Over ground speed of the sensor of 0.5 - 1.0 m/s (speed in water up to 2.0 m/s)
MI-LA-0010	Deploy and recover system from carrier ship
MI-PE-0010	Operate above rough terrain with bottom water currents up to 1 m/s (water temperature: -2 to 18°C)
MI-PE-0011	Control and maintain ground elevation of system within 0.1 m (favored: autonomous terrain following)

2.3. System Requirements

In order to dimension the subsystems and to fulfill the science constraints the following system requirements have been predefined before the study:

Table 2-3: System requirements for PELADIS.

Requirement	Description
ST-DE-0010	Low-noise electromagnetic signatures of sensor platform (e.g. fiberglass) and instrumentation at EM receiver in the center of the system (< 3 mA/(m√Hz))
ST-DE-0020	All power consumption based on 24 V DC
ST-DE-0030	Minimize size and mass to keep core system to 20-foot shipping containers (inner-space (LxWxH): 5.898 x 2.300 x 2.380 m, 18 t load capacity)
ST-DE-0031	Deploy system via A-Frame or side beam of standard research vessels
ST-DE-0032	The vehicle shall be mountable onboard the carrier ship
ST-DE-0040	The vehicle shall have a system for enabling recovery in case of emergency
ST-PE-0010	The vehicle shall have autonomous terrain following capabilities and systems for obstacle avoidance

2.4. Baseline Design

PELADIS as primarily investigated during the study consists of two vehicles, i.e. the sensor module (PSM) and the interface module (PIM). The former is depicted in Figure 2-1.

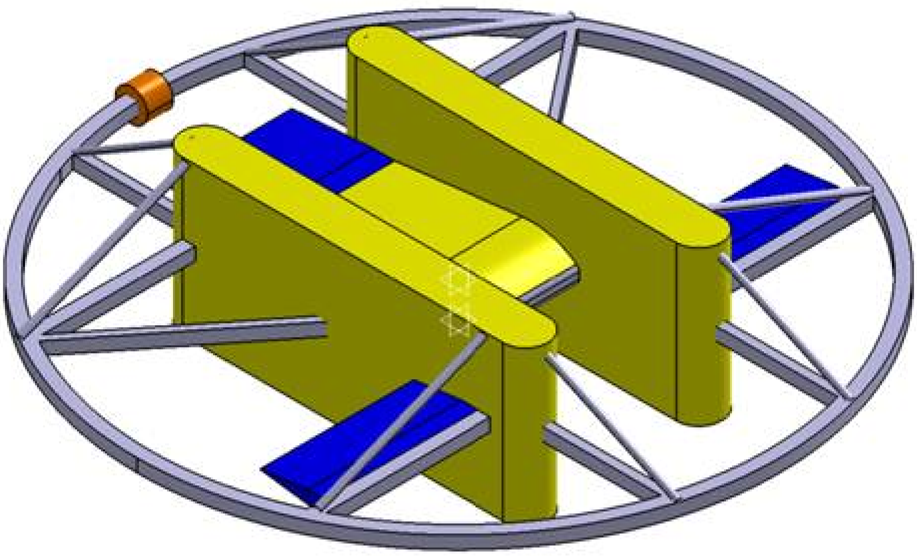


Figure 2-1: General configuration of PELADIS' sensor module.

It primarily consists of a framework structure that holds the sensor coil, while two vertical housing structures hold the equipment needed for operation partly in pressure tanks, partly not. Three large flaps are considered for steering and a small propeller at the aft-section of the coil is used for the rotation around the yaw-axis. The layout and power and data interfaces between ROV, PIM and PSM are depicted in Figure 2-2 and Figure 2-3.

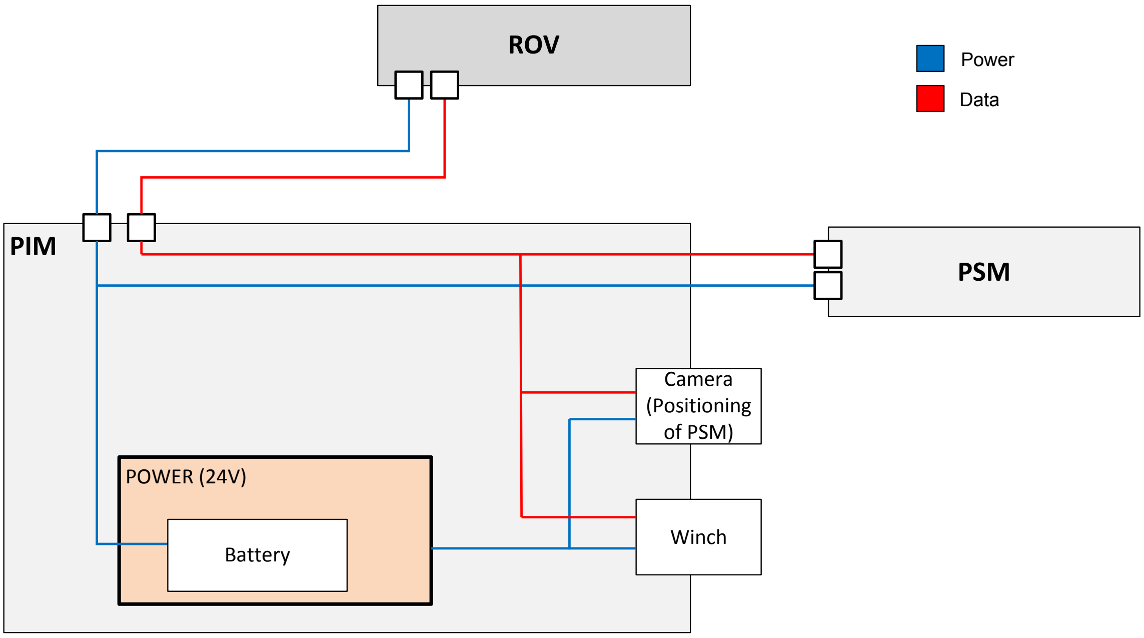


Figure 2-2: Interface diagram of PELADIS' interface module.

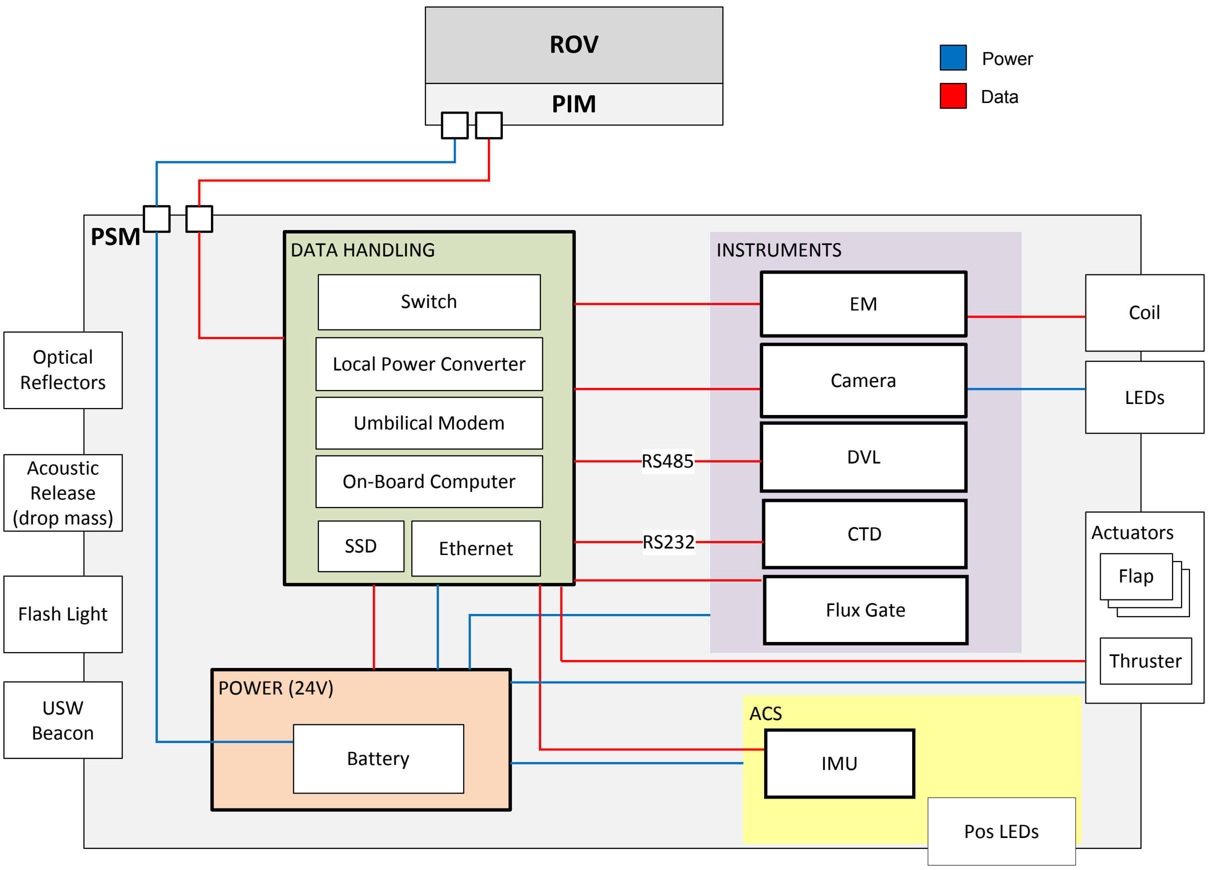


Figure 2-3: Interface diagram of PELADIS' sensor module.

2.5. To be studied / additional Consideration

There are some issues that are open and need to be addressed in future phases of the project. The open issues identified during the CE-study are:

- Computer architecture: The architecture of the computer systems needs to be designed in more detail to estimate performance and component requirements

- Detailed accommodation of components in CAD model: The identified components need to be accommodated in the vertical housings/ pressure tanks to reassure that they all match the design envelope

- Determination of mechanical connection between PIM and ROV: The mechanical interface between these two elements needs to be defined and considered for the design of the PIM framework

- Release and Docking of PIM at PSM: The mechanical and procedural docking of these two modules, especially for deployment and recovery needs to be investigated

- Testing of Terrain Following coordination: The interaction of two active steered vehicles, i.e. the sensor module and the Remotely Operated Vehicle (ROV) for terrain following (s. Section 3.2) has to be tested to optimize the complex system for the actual usage in the sea

- Include Cabling/ Harness: Currently cabling between the components of each subsystem needs to be addressed in the mass budget more extensively and in more detailed, currently this is only foreseen via margins on the actual subsystem mass

- Structure mass optimization via profile usage: The structure mass of the sensor module is currently estimated under the assumption of a bulk structure, usage of lightweight profiles should be investigated for mass savings

- Adapt the central structure to improve vertical movement: The central structure of the design is currently optimized for horizontal movements, vertical movement would be considerately hindered and therefore openings in the structure should be foreseen to reduce drag

- Interference between instruments (e.g. sonar/DVL) has to be prevented: As the sonar and DVL use acoustic signals, possible interferences by this system need to be prohibited by either coordinated operation in sequence or frequency selection

2.6. Summary

The total mass of the combined modules, i.e. PSM and PIM, is 1545 kg. The power demand for the sensor module is 366 W, for the interface module 118 W. A total displaced volume of about 1,13 m³ adapted by buoyant bodies (see Figure 8-5) ensures the PSMs underwater mass goal of 100 kg and at the same time creating a lift of 10 kg without the emergency masses of 110 kg being dropped off in a failure case. During the study the major topic has been the sensor variant that is attached to an ROV via the PIM. The initial investigations regarding the option that is towed directly by the research ship, revealed that the changes would be minor.

2.6.1. Mass budget

Table 2-4: Mass summary of Element 1 (PSM).

MassSummary

This part shows a configurable mass summary.

	Mass w/o margin [kg]	Margin [%]	Margin [kg]	Mass with margin [kg]	% of total dry mass
Attitude_Control	161.35	10.00	16.13	177.48	18.65
Data_Handling	16.25	19.85	3.23	19.48	2.05
Instruments	124.24	10.00	12.42	136.66	14.36
Power_PSM_E1	15.00	18.67	2.80	17.80	1.87
Structure	500.00	20.00	100.00	600.00	63.06

	Mass w/o margin [kg]	Margin [%]	Margin [kg]	Mass with margin [kg]	% of total dry mass
Total dry mass:	816.84			951.42	
System margin:		20.00		190.28	
Total dry mass with system margin:				**1141.71**	
Drop-off mass:				110.00	
Launch Mass:				**1251.71**	
Max launcher capacity:				1500.00	
Buffer to launch mass:				248.29	

Table 2-5: Mass summary of Element 2 (PIM).

MassSummary

This part shows a configurable mass summary.

	Mass w/o margin [kg]	Margin [%]	Margin [kg]	Mass with margin [kg]	% of total dry mass
Instruments	12.00	10.00	1.20	13.20	5.39
Power_PIM_E2	119.00	10.76	12.80	131.80	53.80
Structure	80.00	25.00	20.00	100.00	40.82

	Mass w/o margin [kg]	Margin [%]	Margin [kg]	Mass with margin [kg]	% of total dry mass
Total dry mass:	211.00			245.00	
System margin:		20.00		49.00	
Total dry mass with system margin:				**294.00**	
Drop-off mass:				0.00	
Adapter mass:				0.00	
Launch Mass:				**294.00**	
Max launcher capacity:				1500.00	
Buffer to launch mass:				1206.00	

Table 2-6: Overall mass summary of the PELADIS system.

MassSummary

This part shows a configurable mass summary.

	Mass w/o margin [kg]	Margin [%]	Margin [kg]	Mass with margin [kg]	% of total dry mass
PELADIS_ROV_Interface_Element_2	211.00	16.11	34.00	245.00	20.48
PELADIS_ROV_Sensor_Element_1	816.84	16.48	134.58	951.42	79.52

	Mass w/o margin [kg]	Margin [%]	Margin [kg]	Mass with margin [kg]	% of total dry mass
Total dry mass:	1027.84			1196.42	
System margin:		20.00		239.28	
Total dry mass with system margin:				**1435.71**	
Drop-off mass:				110.00	
Adapter mass:				0.00	
Launch Mass:				**1545.71**	
Max launcher capacity:				1500.00	
Buffer to launch mass:				-45.71	
massUnderwaterWithMassDropoff				190.00	

2.6.2. Power budget

Table 2-7: Power summary of Element 1 (PSM).

System Component	Parameter	Unit	Default
⊟ PELADIS_ROV_Sensor_Element_1	powerAvgWithMarginWith...	watt	439.680
⊟ PELADIS_ROV_Sensor_Element_	powerAvgWithMargin	watt	366.400
⊞ Attitude_Control	powerAvgWithMargin	watt	21.000
Communication	powerAvgWithMargin	watt	16.800
Data_Handling	powerAvgWithMargin	watt	3.000
⊞ Instruments	powerAvgWithMargin	watt	292.000
Operations	powerAvgWithMargin	watt	16.800
Power_PSM_E1	powerAvgWithMargin	watt	0.000
Propulsion	powerAvgWithMargin	watt	16.800
Structure	powerAvgWithMargin	watt	0.000
PELADIS_ROV_Sensor_Element_	marginSystem	percent	20.000

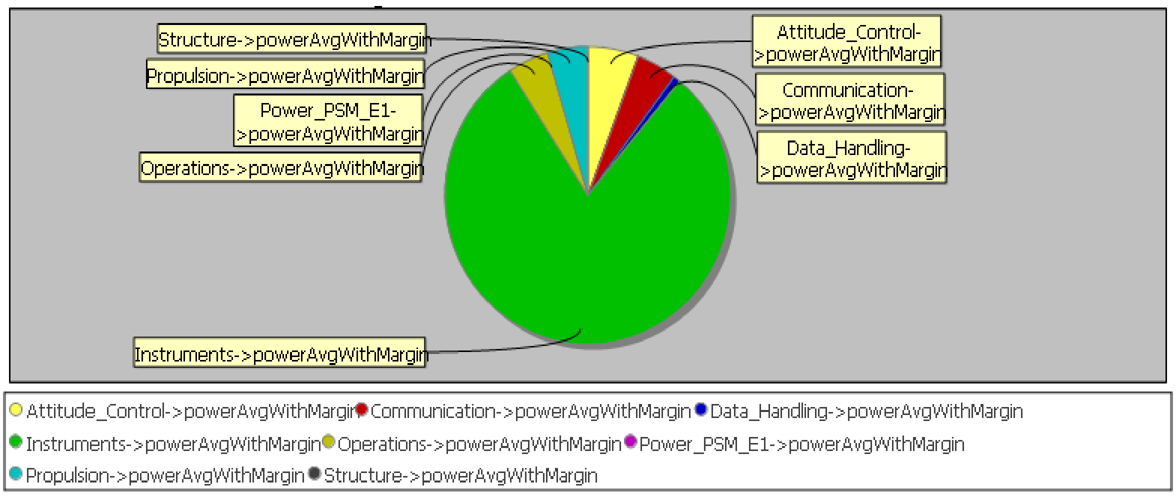


Figure 2-4: Power contribution diagram of Element 1 (PSM).

Table 2-8: Power summary of Element 2 (PIM).

System Component	Parameter	Unit	Default
⊟ PELADIS_ROV_Interface_Element_2	powerAvgWithMarginWith...	watt	141.960
⊟ PELADIS_ROV_Interface_Elemer	powerAvgWithMargin	watt	118.300
⊞ Instruments	powerAvgWithMargin	watt	80.800
Power_PIM_E2	powerAvgWithMargin	watt	37.500
Structure	powerAvgWithMargin	watt	0.000
PELADIS_ROV_Interface_Elemer	marginSystem	percent	20.000

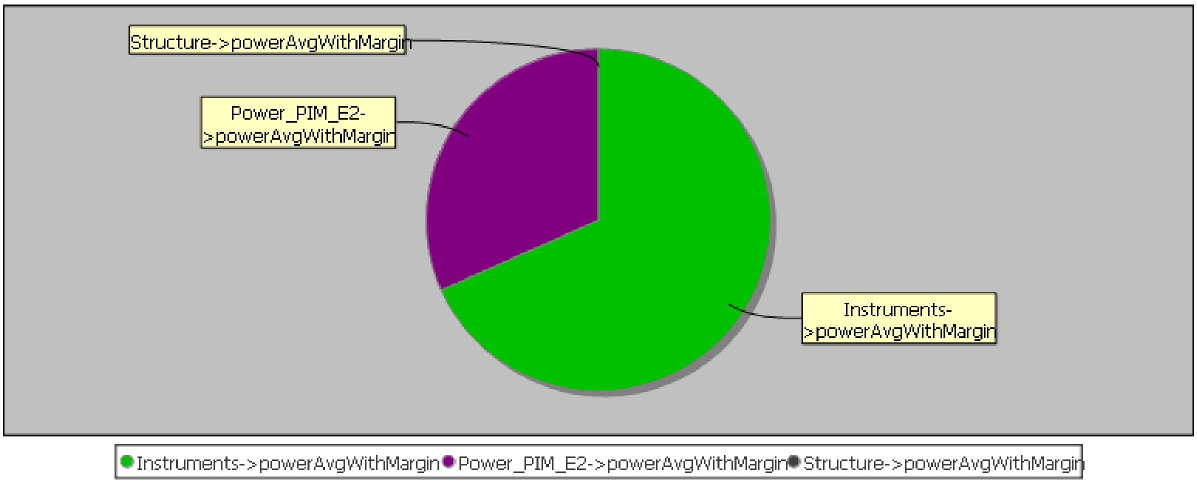


Figure 2-5: Power contribution diagram of Element 2 (PIM).

3. Use Cases

3.1. Deployment/ Recapture

The deployment of the sensor module will occur while it is attached to the interface module, which itself is mounted onto the ROV. For transport the PSM is disassembled and stored into a container (standard 6 feet), reassembly will occur onboard the science vessel.
After operation the sensor module will be hauled towards the PIM via winch for retrieval onboard the ship.

3.1.1. Requirements

The major requirement or design driver for this use case has been the assumed maximum width of the crane booms (A-frame) of 4 m, through which the sensor module has to be transferred into or from the water, see Figure 3-1.

Figure 3-1: Example of ROV deployment [Source: MARUM].

Other requirements are the ability to handle the system on-board a moving ship and also during rough seas.

3.1.2. Effects on Design/ Options

The primary concern for deployment is the 5 m diameter of the sensor coil, which makes direct transfer through the before mentioned crane impossible. Consequently it has been discussed during the study to make the sensor structure foldable.
This option would introduce joints within the coil, either to fold the front and aft sections or side sections. Preferably deployment should occur in the moving direction of the ship,

considering the risk of the sensor swinging back and forth, reduction of the overall length of the sensor seemed reasonable.
During transport and after capture these “wings” would have to be attached to the PIM. Especially the attachment of the foldable structure during capture, with possible rough sea, is difficult. Mechanisms to secure the structure on the PIM need to be included, motors to move the structure as well or more likely divers have to attach the structures in the water. Further disadvantages are possible vibrations and the introduction of weak spots in the coil. Consequently this option has been ruled out for the remainder of the study.
Instead application of an extra crane/ side-beam has been selected. While this increases the costs and the effort of transporting the equipment, it allows keeping the bulk coil without introduction of weak spots or joints. Another disadvantage is the difficulty of handling the 5 m sensor in the cramped space of a small research ship.

3.2. Terrain Following

3.2.1. Requirements

The relevant requirements for the terrain following are ST-PE-0010, which prescribe terrain following capabilities for the system, MI-OJ-0060, which states the need for autonomous terrain following capabilities and MI-PE-0010 clarifying the accuracy to be 0.1m regarding ground elevation.
Generally collisions between ground structure and the sensor as well as the ROV are also to be prevented.

3.2.2. Effects on Design/ Options

In all cases it has been decided that the winch which is part of the PIM, should be able to tauten the cable connection between PIM and PSM at all times, mostly to prevent accidents with the ROV and to have a secure and determined distance between the two modules.
The first option investigated has been that the ROV exclusively handles the ground elevation and no actuators of any kind are installed on the PSM. Two questions arose that made this solution currently not useful. Due to the larger mass and therefore inertia it has been unclear whether or not the ROV can do the terrain following sufficiently fast. Also since the winch can only act in an upward manner, only the weight force can move the PSM downwards if no actuators of any kind are installed. It is questionable if this suffices to actually achieve sufficient terrain following capabilities.
The opposite set-up would be active control on both the ROV and the PSM. Usage of propellers would allow control independent of external forces but would increase mass and power budget significantly as well as introduce electromagnetic disturbances in the sensor coil’s vicinity. Additionally difficulties in sight due to soil being raised by the propellers might arise.

During the study the application of flaps has been discussed in detail (see Chapter 7). The major drawback of this method is that a forward movement is needed for them to have a steering effect.

Generally the combination of two active systems that have to work in a coordinated manner to achieve terrain following is challenging and needs testing. To prevent accidents and collisions it has been decided that the ROV has to have knowledge of the cable length between PIM and PSM (max. 20 m, measured via winch), its own distance to the sensor module (via LED detection on-top of the PSM using a camera) and of the distance between PSM and the ground. Therefore the ROV can have information about its own distance to the ground without using sonar detection that is likely to be disturbed by the PSM below the ROV. Without knowledge of the length of the cable or distance between ROV and PSM, it could occur that the ROV sinks down more than the cable length would allow and thus the PSM could sink onto the ground.

For the remainder of the study it has been assumed that the necessary data is fed to the research vessel and processed into a steering strategy by the ROV pilot – autonomous control has not been considered, in difference to the previously mentioned requirements.

4. Instruments

The instrumental payload of the PELADIS Sensor Module is described in the general PSM diagram (Figure 4-1) and can be grouped in two subclasses: instruments for Scientific & Navigational purposes (Figure 4-2) that are directly linked to PSM's power supply and data handling and thereby accessible to the operator via ROV telemetry, and Safety Instruments (Figure 4-3) that come with own battery and communication structure, independent from the general operation procedures and accessible even after loss of ROV based communication to recover the PSM.
Instruments on the PELADIS Interface Module (PIM; Figure 4-4) are directly linked to the ROV telemetry (power and communication). The PIM instrument facilitates heave up and down maneuvers utilizing a submersible electronic winch and a downward looking camera (same model as on PSM) to localize the PSM via position LED-lights attached on the top side of the PSM.

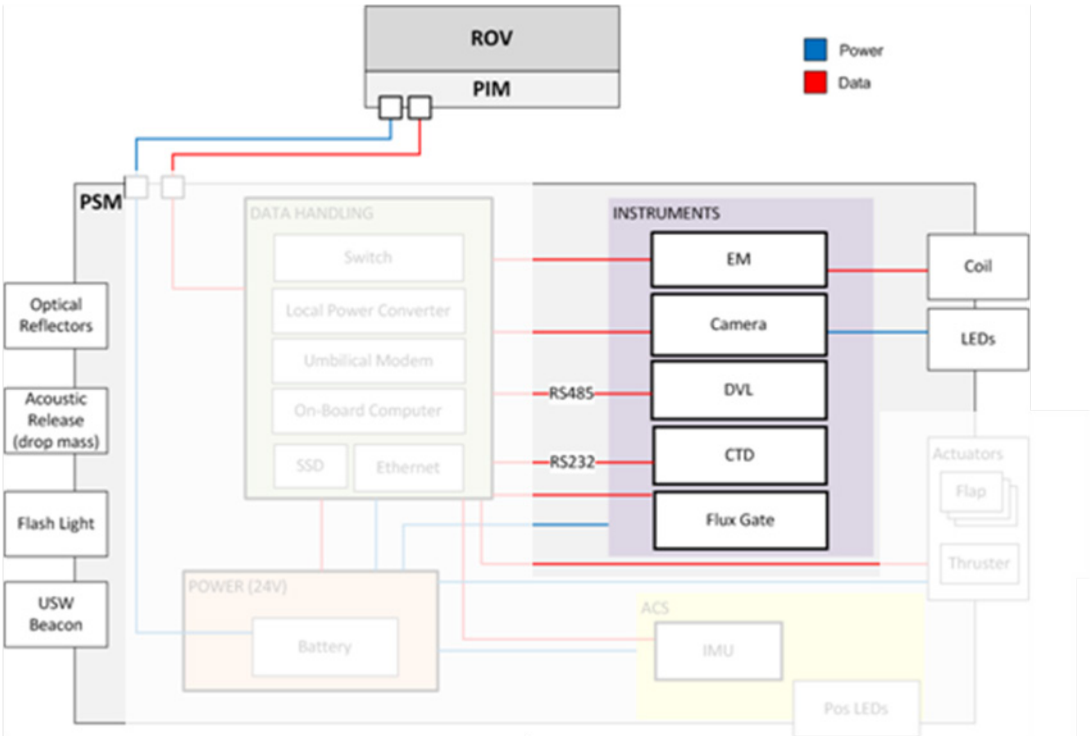


Figure 4-1: Instruments of Peladis Sensor Module (PSM).

4.1. Instrument description

This section summarizes the different instrument in continuous order, following the sensor grouping according to Figures 4-2 to 4-4.

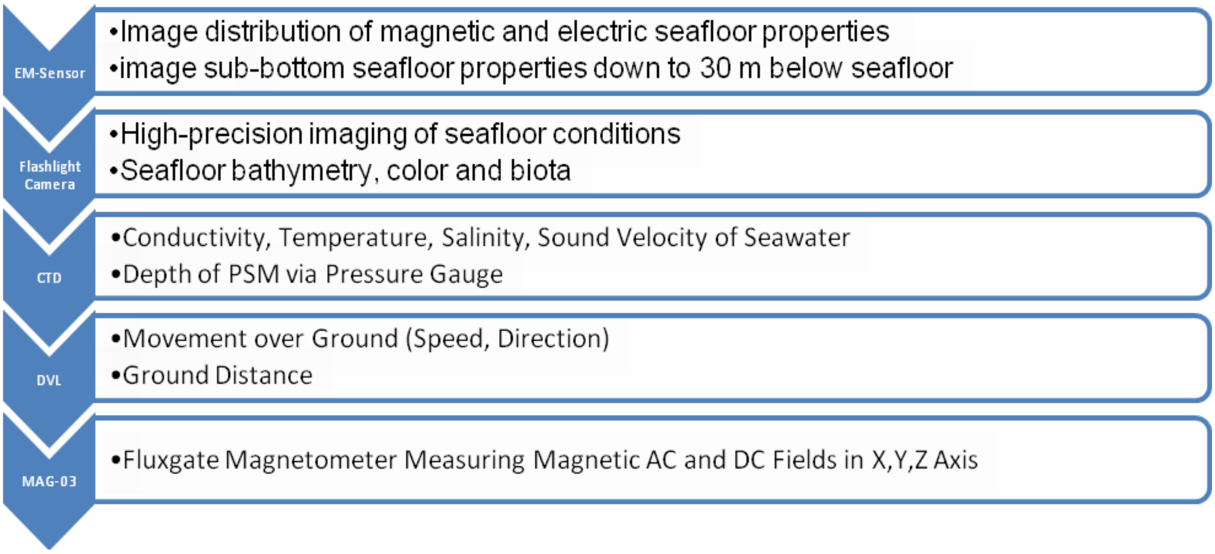


Figure 4-2: Scientific and Navigational Instruments of Peladis Sensor Module (PSM).

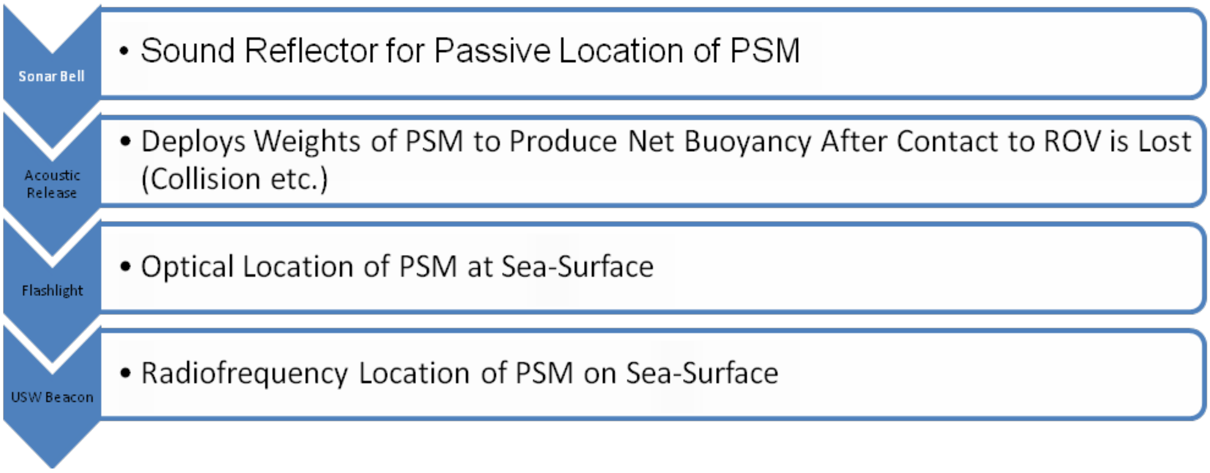


Figure 4-3: Safety Instruments of Peladis Sensor Module (PSM).

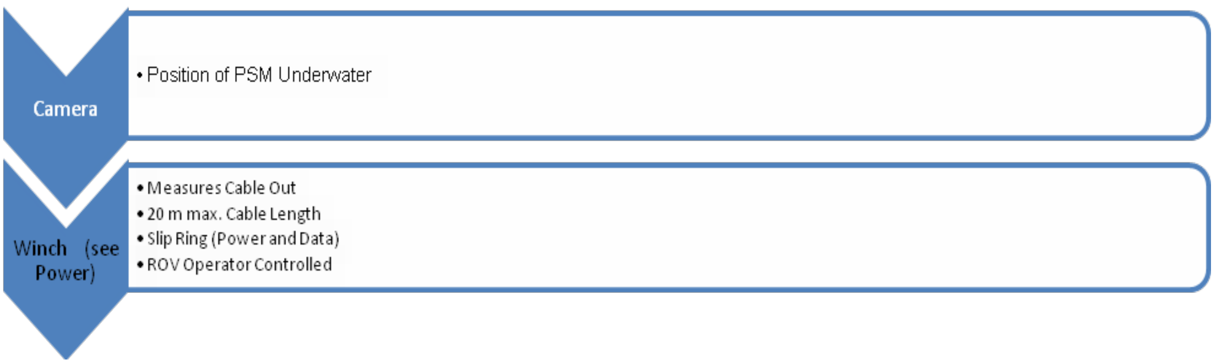
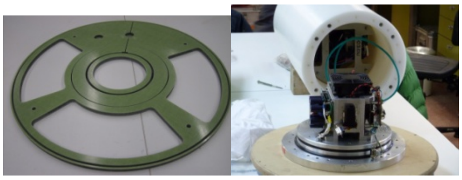


Figure 4-4: Instruments of Peladis ROV-Interface Module (PIM).

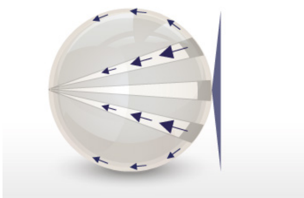
4.1.1. Instrument Parameters

Table 4-1: Scientific and Navigational Instruments of PELADIS Sensor Module (PSM).

(1) GEM-3 Broadband Electromagnetic Sensor	**• Image distribution of magnetic and electric seafloor properties • image sub-bottom seafloor properties down to 30 m below seafloor**	
	Manufacturer:	Geophex Ltd. (Aeroquest Sensortech, USA), Develogic (housing)
	Mass:	43.2 kg
	Power:	240 W (24V, 10A)
	Volume:	0.025 m³ (5 m transmitter coil diameter)
	Reference:	[RD 13]
(2) MAG-03 Fluxgate Magnetometer	**• Fluxgate Magnetometer Measuring Magnetic AC and DC Fields in X,Y,Z Axis**	
	Manufacturer:	Bartington Instruments (UK), National Instruments (A/D converter), Develogic (housing)
	Mass:	4.0 kg
	Power:	4.4 W
	Volume:	0.012 m³
	Reference:	[RD 17]
(3) Manta G-504B/C Still Flash Camera	**• High-precision imaging of seafloor conditions • Seafloor bathymetry, color and biota**	
	Manufacturer:	Allied Vision Technologies (D), PC, Develogic (housing)
	Mass:	12 kg
	Power:	40.4 W
	Volume:	0.012 m³
	Reference:	[RD 14]
(4) CTD 60M Conductivity-Temperature-Depth probe	**• Conductivity, Temperature, Salinity, Sound Velocity of Seawater • Depth of PSM via Pressure Gauge**	
	Manufacturer:	Sea and Sun Technology (D)
	Mass:	4.0 kg
	Power:	4.4 W
	Volume:	0.001 m³
	Reference:	[RD 15]

(5) Workhorse Navigator Doppler Velocity Log (DVL) 1200 kHz	• Underwater navigation (Speed over Ground, Direction) • Ground Distance	
	Manufacturer:	Teledyne RD Instruments
	Mass:	13.6 kg
	Power:	2.8 W
	Volume:	0.008 m³
	Reference:	[RD 16]

Table 4-2: Safety instruments of PELADIS Sensor Module (PSM).

(1) Sonar Bell Acoustic reflector	Sound Reflector for Passive Location of PSM	
	Manufacturer:	SALT – Subsea Asset Location Technologies
	Mass:	1.0 kg
	Power:	0 W (passive)
	Volume:	0.006 m³ (100 mm diameter sphere)
	Reference:	[RD 18]
(2) Sonardyne DORT Acoustic Release Transponder	• Releases Weights of PSM to Produce Net Buoyancy by External Transponder Signal	
	Manufacturer:	Sonardyne (UK)
	Mass:	44.0 kg (2 units)
	Power:	0 W (internal battery)
	Volume:	0.022 m³
	Reference:	[RD 19]
(3) NOVATECH ST-400 Xenon-Flasher	• Optical Location of PSM at Sea-Surface	
	Manufacturer:	MetOcean Data Systems (Ca)
	Mass:	1.7 kg
	Power:	0 W (internal battery)
	Volume:	0.001 m³
	Reference:	[RD 20]

(4) NOVATECH AS-900A ARGOS Beacon	• Radiofrequency Location of PSM on Sea-Surface	
	Manufacturer:	MetOcean Data Systems (Ca)
	Mass:	1.6 kg
	Power:	0 W (internal battery)
	Volume:	0.001 m³
	Reference:	[RD 21]

4.1.2. Open Issues and further trade-offs

A safety concept has been assessed during the PELADIS study in case of loss of communication with the PSM. The following safety equipment (s. Table 4-2) is necessary: acoustic reflector, acoustic release transponder, optical beamer (flashlight) and USW transmitter. Other safety elements to be considered are drop masses (controlled externally through the acoustic release transponder) and a grappling tether (cable blinders).
The following open issues were identified at the end of the study:

- The DVL has to be tested; if it cannot provide velocity data in water and over ground at the same time, a further sensor is needed.
- The interference between instruments (e.g. sonar/DVL) has to be prevented by either coordinate operation or frequency selection.
- The terrain following coordination has to be tested.
- The prices between instrument providers have to be compared.
- The corrosion protection has to be considered in further analyses.

4.2. Summary

The next figures show the mass summary and percentage mass contribution of the PELADIS' equipment in Element 1 (PSM).

Table 4-3: Mass summary of PELADIS' equipment in PSM.

MassSummary

This part shows a configurable mass summary.

	Mass w/o margin [kg]	Margin [%]	Margin [kg]	Mass with margin [kg]	% of total dry mass
Accoustic_Release_Transponder	44.00	10.00	4.40	48.40	60.41
Camera	12.00	10.00	1.20	13.20	16.47
CTD	4.00	10.00	0.40	4.40	5.49
DVL_Teledyne	13.60	10.00	1.36	14.96	18.67
EM_Coil	43.24	10.00	4.32	47.56	59.36
Flash_light	1.70	10.00	0.17	1.87	2.33
FluxMagnetometer	4.00	10.00	0.40	4.40	5.49
UKW_Beacon	1.70	10.00	0.17	1.87	2.33

	Mass w/o margin [kg]	Margin [%]	Margin [kg]	Mass with margin [kg]	% of total dry mass
Total dry mass:	72.84			80.12	

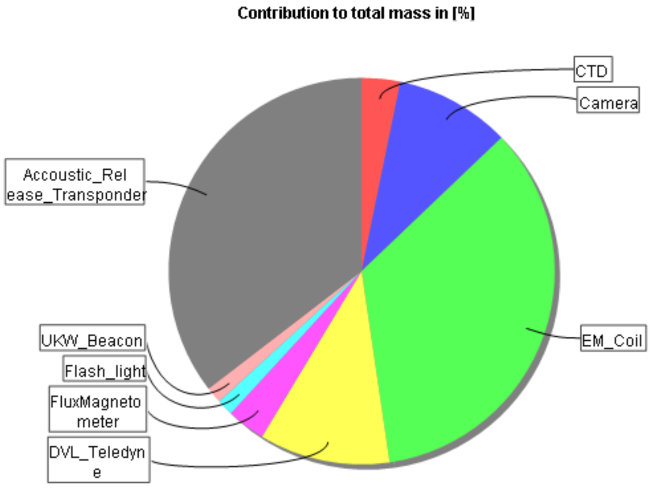


Figure 4-5: Mass contribution diagram of PELADIS' equipment in PSM.

Table 4-4: Power summary of PELADIS' equipment in PSM.

System Component	Parameter	Unit	Default
⊟ Instruments	powerAvgWithMargin	watt	292.000
⊞ Camera	powerAvgWithMargin	watt	40.400
CTD	powerAvgWithMargin	watt	4.400
DVL_Teledyne	powerAvgWithMargin	watt	2.800
EM_Coil	powerAvgWithMargin	watt	240.000
FluxMagnetometer	powerAvgPerUnitWithMargin	watt	4.400

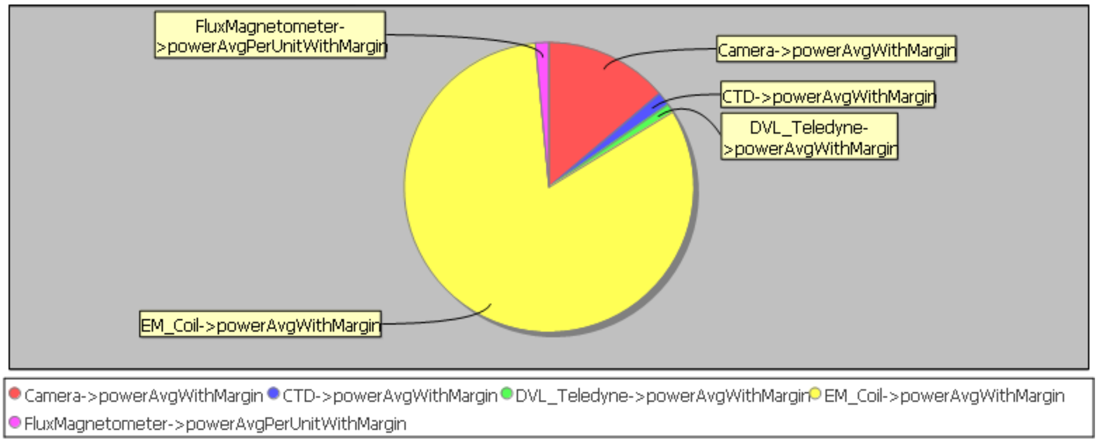


Figure 4-6: Power contribution diagram of PELADIS' equipment in PSM.

Table 4-5 and Table 4-6 expose the mass and power summaries of the PELADIS' equipment in Element 2 (PIM).

Table 4-5: Mass summary of PELADIS' equipment in PIM.

MassSummary

This part shows a configurable mass summary.

	Mass w/o margin [kg]	Margin [%]	Margin [kg]	Mass with margin [kg]	% of total dry mass
Camera	12.00	10.00	1.20	13.20	100.00

	Mass w/o margin [kg]	Margin [%]	Margin [kg]	Mass with margin [kg]	% of total dry mass
Total dry mass:	12.00			13.20	

Table 4-6: Power summary of PELADIS' equipment in PIM.

System Component	Parameter	Unit	Default
⊟ Instruments	powerAvgWithMargin	watt	80.800
⊞ Camera	powerAvgWithMargin	watt	80.800

5. Data Handling System

The main purpose of the Data Handlings System (DHS) is to process and to store the science and auxiliary data generated on-board the PSM. Collected data is stored inside the DHS memory, and transmitted to the operator as bandwidth permits.

5.1. Assumptions

The following assumption has been made to setup the DHS design baseline:

- Provide data-storage for all sensor data.
- Provide communication to the PIM / surface vessel.
- Electronics are housed inside a pressure hull.
- Besides handling the data the DHS will also run the ACS software on its computer system.
- Commercial of the shelf (COTS) components and industry standard-interfaces are the preferred solution.
- The uplink to the surface vessel or the ROV will either be an ADSL-type modem or 100BaseT Ethernet.

5.2. Data Volume Requirements

Data volume and rate requirements are driven by the camera which is capturing high-resolution (5M pixels) images at a frame-rate of approximately 7 to 10fps.
Depending on the cameras mode of operation, the data interface between the DHS and the camera becomes a bottleneck. The interface's maximum speed of 1GBit/s is assumed to be the sensors data-rate in the baseline design.
The EM-sensor and all other non-camera sensors generate a comparably small amount of data, in the order of 100 Byte/s. The total data originating from all sources other than the camera is assumed to be 1 Mbit/s on average.
For an 8 hour mission these requirements cause the following data storage requirements:

Table 5-1: Data storage requirements for PELADIS.

Data source	Rate	Total for an 8h mission
Camera	125 MByte/s	3.6 TByte
All low-rate Sensors	1 Mbit/s	3.6 GByte
Total:		3604 GByte

5.3. Interfaces

Interfaces between the DHS and other subsystems are either serial point-to-point style connections (RS-232, RS-422 and similar) or are Ethernet based. The point-to-point connections can be served with dedicated interface-converters. For the Ethernet based Interfaces an Ethernet- switch is required inside the DHS. The Uplink to the ROV or surface vessel is either an ADSL-type modem, connected via Ethernet, or a direct Ethernet connection.

5.4. Conclusions

The data rate and volume generated by the camera drives many aspects of the design, especially the selection of an appropriate data-storage. The embedded PC and Ethernet components must also be selected with respect to the data-rate. Other subsystem-interfaces are be covered by standard interface-adapters, readily available on the market.
Storing the camera data requires a high-volume data-storage. Appropriate technologies available today are either arrays of hard-disk drives (HDD) or solid state disks (SSD). For the baseline design SSDs are assumed because of their wider environmental operating range.
Embedded PC systems available on the market providing sufficiently fast and numerous interfaces, mainly Gigabit-Ethernet and multiple SATA interfaces, are thought to be sufficiently powerful computationally-wise to cover the control and data-handling tasks required for the mission.

5.5. Baseline Design

The following Figure depicts the functional components of the Data Handling System, the main function groups are:

- Data storage
  This is handled by an array of SSDs, depending on the individual size of the SSDs it might be necessary to add more SATA interfaces to the mainboard or use a dedicated RAID controller / SATA Port multiplier. Depending on the time available between missions the SSDs might need to be swappable, to avoid the time consuming transfer over Ethernet.

- Communication with ROV / surface vessel
  For the short connection to the ROV an Ethernet connection is used. ADSL is required for the longer connections.

- Communication with Subsystems
  Sensors and other Subsystems are connected to the DHS. If the mainboard doesn't provide the specific interface an additional converter is added. Ethernet based interfaces are run connected to the Ethernet switch.

- Local Power Conversion
  COTS embedded components come with different requirements regarding their power supply. To ease the outside harness and gain overall flexibility the required supplies are generated locally by the DHS. This Module also includes the EMI-filters for the DHS.

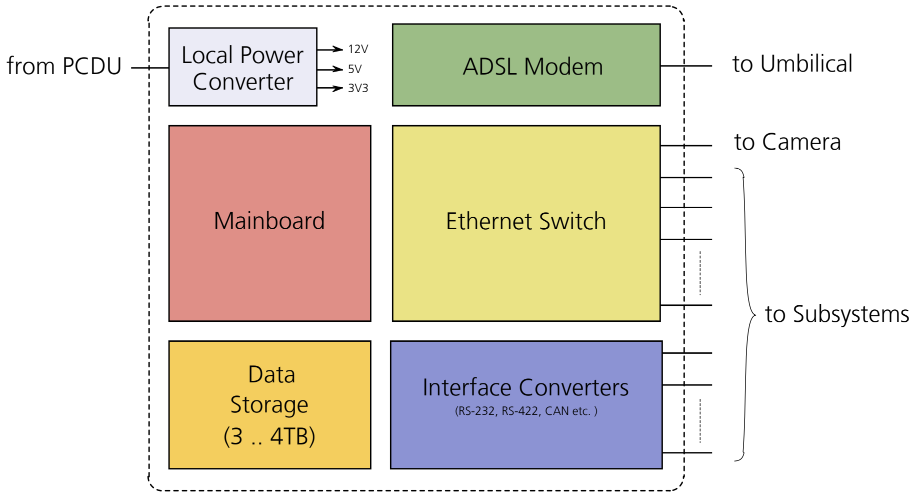


Figure 5-1: Data Handling structure.

5.6. List of Equipment Mass and Power Budget

5.6.1. Mass Budget

Table 5-2: Mass summary of PELADIS' data handling subsystem.

MassSummary

This part shows a configurable mass summary.

	Mass w/o margin [kg]	Margin [%]	Margin [kg]	Mass with margin [kg]	% of total dry mass
Local_Powerconverter	3.00	20.00	0.60	3.60	18.49
Mass_memory	3.00	20.00	0.60	3.60	18.49
OBC_electronics	10.00	20.00	2.00	12.00	61.62
Umbilical_Modem	0.25	10.00	0.03	0.28	1.41

	Mass w/o margin [kg]	Margin [%]	Margin [kg]	Mass with margin [kg]	% of total dry mass
Total dry mass:	16.25			19.48	

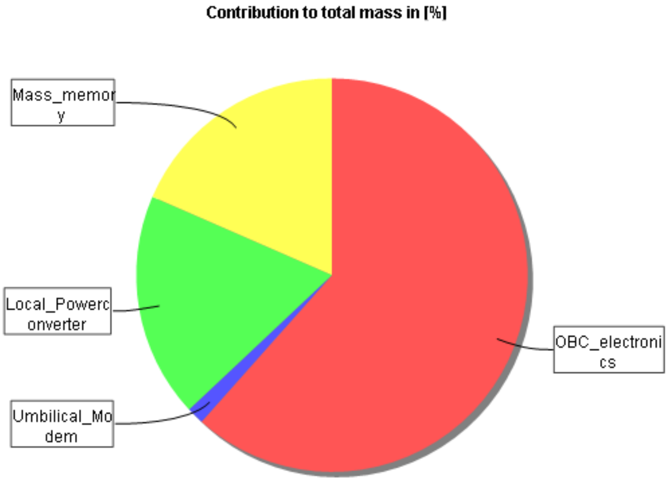


Figure 5-2: Mass contribution diagram of the data handling subsystem.

5.6.2. Power Budget

Table 5-3: Power Budget of the data handling subsystem for PELADIS.

Equipment	Power [W]
DHS Electronics (incl. mainboard, eth.-switch, internal wiring, structural and thermal support)	80
ADSL Modem	3
Data Storage	25
Local Power Converter (incl. Input Filter) [Power according to 80% Efficiency]	21
Total	129

5.7. Summary

The proposed design is modular in its approach and COTS based. It is expected to satisfy the currently identified requirements and should be adaptable to future expansions and changes. The high data-rate of the camera constrains the selection of the components today, but future hardware is likely to reduce the impact on the required power and size again.

6. Power

6.1. Requirements and Design Drivers

Relevant system requirements for the design of the Power subsystem for the PELADIS elements are:

- ST-DE-0010 Low-noise EM signal on sensor platform
- ST-DE-0020 All Power consumption based on **24 V DC**
- ST-DE-0030 5.9 x 2.3 x 2.38 m3; 18 t
- ST-PE-0030 Sensor ops time > 8 h

Further recommendations, goals and design drivers are:

- Use of Digital Telemetry System (DTS) as interface (I/F) to ROV
    - for Element 2/1 supply
    - 30 A, 24 V, 1 Gbit, 16 ports
- Winch required for PSM / PIM connection
- Re-use of experience and use of available equipment desired

As an initial additional assumption, the following architecture which can be seen in Figure 6-1 has been considered as a baseline for the elements and subsystems/equipment relevant for the power domain.

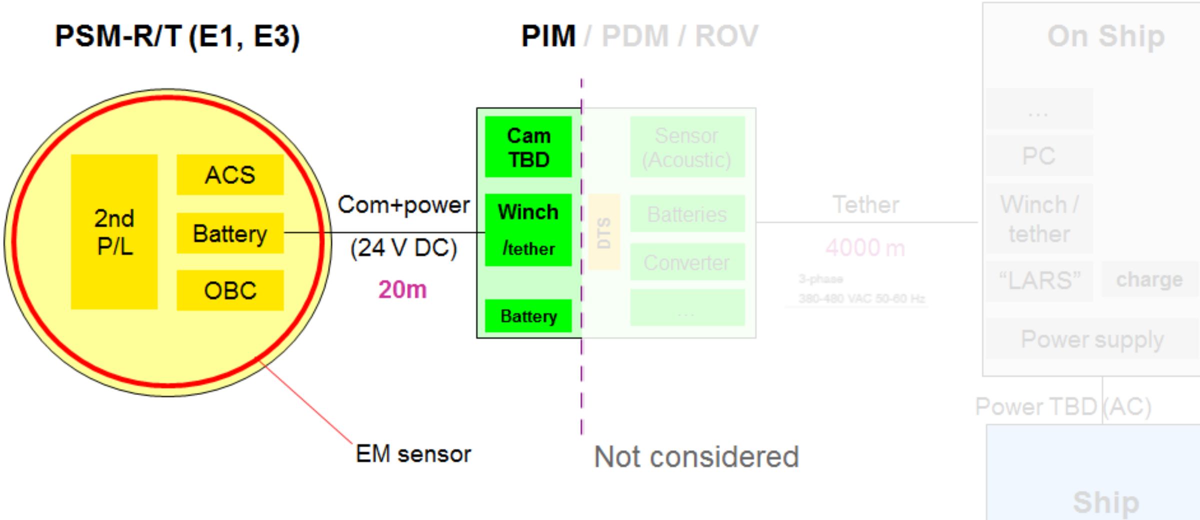


Figure 6-1: Overview of involved and considered equipment in the PSM/PIM power supply chain.

One of the main design drivers is the power demand of all the components related to the involved subsystems and will be described in 6.3.

6.2. Modes of Operation

For the PELADIS study there has only been one default mode defined for initial assessments which can be considered as the 'science mode'. No mode-dependent power budget has been generated but overall peak and average numbers have been considered. For more information see 6.5.3.

6.3. Power and Energy Demand

The main driver for the power supply unit sizing is the demand of all different payloads and equipment over the operation time. Table 6-1 shows the demand for the PSM.

Table 6-1: PSM Power Demand.

	Equipment	avg. [W]	S/S [W]	[Wh] (t=8h)
P/L	DVL	2,8		
	Emcoil	240		
	Cam	40		
	CTD	5		
	Flux	5	292,8	2342,4
DHS	OBC	80		
	Umb Mod	3		
	Pow Conv	21		
	Memory	25	129	1032

	Equipment	avg. [W]	S/S [W]	[Wh] (t=8h)
ACS	IMU	10		
	Yaw thruster	16		
	Actuator	12	38	304
System Margin (20%)			91,96	
Total average consumption			**551,76**	**4414,08**

The PIM average demand has not been studied in such level of detail but can be assumed as:

- ~750 W (peak)
- ~650 Wh

whereas the winch (see also section 6.4.3) contributes with 325 Wh with a maximum power demand of about 650 W for only 0.5 h (0.25 h for each, release and recovery of PSM) and the Camera (similar to the one installed on the PSM, see 4.1) with continuously requiring 40 W for 8 h with a maximum demand of about 90 W. The numbers given here for the PIM are w/o margin and only present the order of magnitude.

6.4. Baseline Design

The PELADIS modules (PIM and PSM) receive via the DTS a total current of 30 A, distributed over the different connectors, as well as 24 V DC. This results in 720 W (5780 Wh) power and covers the average energy demand of all equipment.

6.4.1. Options

The following options came up during the design of the power subsystem and have been iterated:

- **Energy storage**
  - (1) None (fully / directly powered by ROV)
  - *(2) Buffer @PSM (E#1) → for PSM peak power demand*
  - (3) Buffer @PIM (E#2) → for PSM peak power demand
- **Winch for umbilical cable**
  - (4) On PSM
  - *(5) On PIM*
- **Winch motor**
  - (6) Electrical → using DTS ROV I/F
    - *i. Battery on PIM → for PIM peak power demand (motor)*
  - (7) Hydraulical → additional hydraulic I/F to ROV req.

The final selection of the options stated above with respect to the different units is marked with green font color and italic font style. The trades which have been performed are described in the following to sections.

6.4.2. Battery design

Although it adds complexity to the lean design desired for the sensor module (Element #1; PSM) it is recommended to equip this vehicle with an internal battery unit which acts as a buffer for the main power supply provided by the ship, converted by the ROV and routed through the PIM. This battery allows continuing with the payload operations for a certain time even if the central modules (i.e. ROV, PIM) face problems or if the umbilical cable gets damaged. Furthermore it ensures the provision of the desired current and voltage due to the almost direct connection.

A voltage of 24 V is required for all equipment. Since there might be a lower voltage available at the PSM umbilical connector than provided by the DTS, two battery of 12 V connected in sequence comply with the requirement. Due to the high energy density and the comparably constant provision of high voltages when discharging the batteries, Lithium-ion (Li-ion) packs are favoured. There are several 12 V packages on the market which consist of 4x3.6 V cells and provide a nominal voltage of 14.4 V (12 V average). Since the most demanding component for the power system of the PSM will be the EM coil, the battery has to cope with a 10 A demand for a certain time.

Considering also the discharge rates of Li-ion batteries of 0.2 C [A/Ah] and the limitations of the pressure tanks for -4000 m operations, smaller battery packs with less Ah should be selected (see also Table 6-2).

Table 6-2: PSM / PIM battery back design.

Parameter	Value	Unit	Remark
Charge current rate	0,75	C	[A/Ah]
Discharge current rate	0,2	C	[A/Ah]
Constant Current	6	A	tbc
Charge	8	Ah	(2s)
Nominal voltage	12	V	(2s)
"Capacity" (1Battery)	20	Ah	
Capacity (1 Batty)	240	Wh	
No of batteries	4	n	2x2
Capacity (n Batt)	960	Wh	
DOD	80,00%		
Available Capacity	768	Wh	
Mass incl. Adapters	3		
Mass total	12	kg	
Energy density	80	Wh/kg	

For the current design the following batteries (or similar) are recommended. These batteries [RD 3] provide 12 V with a ‘capacity’ of 20 Ah. The mass is 2.6 kg each (3 kg incl. margin) and have following dimensions, suitable for the preferred pressure tanks: 230 mm * 120 mm * 75 mm. An example is shown in Figure 6-2:

Figure 6-2: Lithium-Ion battery pack example [RD 3].

They include a battery management system (BMS) and provide a 14 A discharge rate which is required for the EM coils. Each battery pack cost about 300 EUR and can be accommodated in a 2s2p (2 in series / 2 parallel) configuration. Therefore 2 batteries shall be installed in series within each tank. This configuration allows a supply 24 V and 40 Ah which is ~1/3 of the overall energy required by the PSM units. With a charge voltage of assumed 6 V and a rate of 0.75 C (see Table 6-2) the battery system is a robust buffer element for the peak power demands, constant voltage provision and emergency cases. Another example of batteries (12 V; 40 Ah) which are suitable for such application can be seen in [RD 4] but have dimensions exceeding the ones given by the selected pressure tanks.
The same batteries could be used in a similar configuration for the PIM, providing ~800 Wh in the 2s2p configuration which is already sufficient for the winch energy demand. This approach would also allow ordering the same battery pack / pressure tank set-up which reduces could the cost and ensures an easy exchange of the batteries amongst the modules.

6.4.3. Winch and Cable design

The distance between the PSM and PIM shall be 20 m. The operation depth is about 4000 m. In order to reduce complexity on the PSM, the **winch** which shall release and recover this element is installed on the PIM which is attached below the ROV.
Based on these constraints and assumptions the PIM shall be equipped with an underwater winch and engine as well as an umbilical cable for power and date transmission.
The most critical part is the motor. Several options are possible. Based on the available interfaces amongst the ROV and the PIM hydraulical and electrical variants could be possible. A hydraulic motor could make use of the hydraulical system installed already on the ROV, which reduces the PIM internal energy supply; an electrical motor reduces the interfaces (only the DTS is required) but needs an additional battery system or access to the AC voltage equipment.
In order to keep the degree of independency as high as possible, the baseline design includes an electrical DC engine which supports the winch. There are some winch/engine options on the market which – in a combined way – will meet the given requirements. Figure 6-3 shows some examples which act as references for the scaling of our required winch.

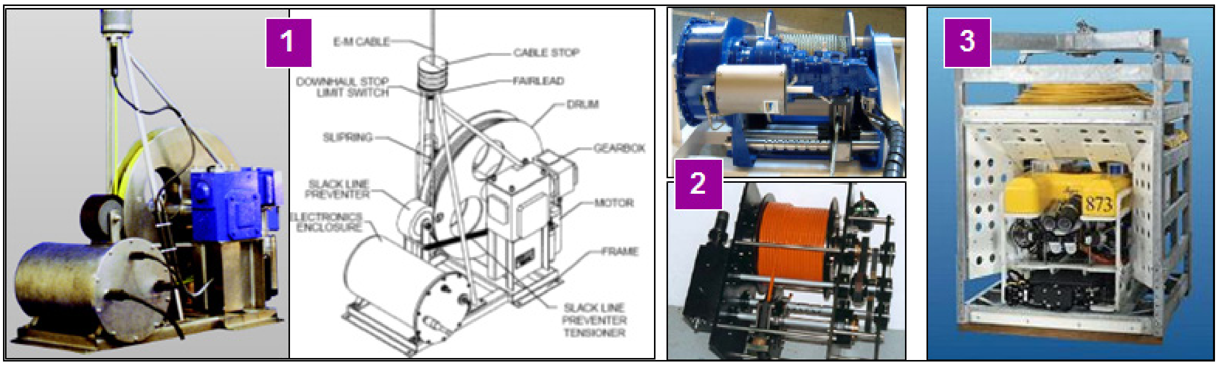


Figure 6-3: Winch & TMS options: (1) by Interocean [RD 6]; (2) by All Ocean [RD 5]; (3) by Saab [RD 7].

Classical underwater winches from e.g. « All Ocean » [RD 5] and especially « Interocean Systems » can provide 48V DC systems with maximum 730 W power demand [RD 6], which are used for 13 mm cable in a 300 m depth. Another example, the Tether Management System (TMS) for the Saab Seaeye [RD 7] has a mass of 450 kg which includes a 1.2 x 1.2 x 1.65 m^3 frame.

Based on this example one can scale down the systems to a 100 kg winch (~ 5 times smaller design than the SAAB version) with ~650 W max. power demand (similar to the Interocean System) which can be delivered by the given PIM battery ampere rate (i.e. 14 A, see 6.4.2). The 48 V DC could be ensured in a 4x series (4s) configuration of the proposed battery packs.

The **umbilical cable** selected for the PELADIS set-up is based on the Focus-2 ROV built by « Macartney » (see page 14 of [RD 8]). With an average weight of ~350 kg/km for a 20 m cable this costs 7 kg in terms of mass. Furthermore the cable ensures a safe working load of ~20 kN. Even more robust (and heavier) alternatives are given in [RD 9].

For the **PSM internal connection** traditional Ethernet cables [RD 10] are chosen which allow the transmission of power or data or both.

6.5. List of Equipment Mass and Power Budget

6.5.1. Mass Budgets for Element #1 (PSM)

Table 6-3 shows the different power subsystem components which contribute to the PIM mass budget:

Table 6-3: PSM mass breakdown of the power S/S.

MassSummary

This part shows a configurable mass summary.

	Mass w/o margin [kg]	Margin [%]	Margin [kg]	Mass with margin [kg]	% of total dry mass
Battery_12V_20Ah	12.00	20.00	2.40	14.40	80.90
Power_Harness	2.00	10.00	0.20	2.20	12.36
Umbilical_Connector	1.00	20.00	0.20	1.20	6.74

	Mass w/o margin [kg]	Margin [%]	Margin [kg]	Mass with margin [kg]	% of total dry mass
Total dry mass:	15.00			17.80	

Including margins the Power S/S has a total mass of about 18 kg total mass on PSM which is driven by the battery. The battery mass, however, is stated without the mass of the pressure tanks which are covered by the structure mass budget.
Furthermore the mass of the power harness is considered for the power S/S internal connection only and does not reflect the cables between the e.g. battery and the instruments.

6.5.2. Mass Budgets for Element #2 (PIM)

Table 6-4 shows the different power subsystem components which contribute to the PIM mass budget:

Table 6-4: PIM mass breakdown of the power S/S.

MassSummary
This part shows a configurable mass summary.

	Mass w/o margin [kg]	Margin [%]	Margin [kg]	Mass with margin [kg]	% of total dry mass
Battery_for_Winch_motor	12.00	20.00	2.40	14.40	10.93
Umbilical_Cable	7.00	20.00	1.40	8.40	6.37
Winch_for_PSM	100.00	9.00	9.00	109.00	82.70

	Mass w/o margin [kg]	Margin [%]	Margin [kg]	Mass with margin [kg]	% of total dry mass
Total dry mass:	119.00			131.80	

Due to the consideration of the winch within the power subsystem, the total mass, including margin for the PIM is 132 kg. The mass is mainly based on up- and downscaling of available components on the markets (see section 6.4.3). In contract to the PSM power design the (umbilical) cable in this budget includes also the communication harness together with the power harness since it is desired o have only one cable connecting PSM and PIM. Nevertheless, the winch does not include the overall framework which connects the different PIM equipment and attach it to the ROV but only the winch internal frame including motor and cable reel.

6.5.3. Power Budgets

The only device from the power subsystem which is a considerable contributor to the power budget is the winch, to be installed on Element #2 (PIM).

6.6. Summary

The design of the power subsystem provided here is mainly based on theory and shall be cross-check with respect to applicability with the real operational scenario. There is no final selection of the equipment but reasonable examples given in this section.
The mass and power values are first estimates (based on the available data sheets) but represent conservative numbers which can be considered as right order of magnitude.

7. Attitude and Altitude Control System

The Attitude and Altitude Control System (AACS) is responsible for controlling the attitude (Yaw, Pitch and Roll) and the altitude above ground. For that a measurement or estimation of the respective values is necessary as well as a path-planning task to control the altitude above the changing terrain.

7.1. Requirements and Design Drivers

The following requirements define the design of the AACS:

- Hold sensor module 1-4 m above ground in towed mode
  - Unclear if this is the range of the nominal altitude or the control accuracy

- Sensor should be controlled in a horizontal attitude
  - Attitude control accuracy for pitch and roll should be: ±5°

- Max. required altitude rate: 0.5 m/s @ 3 kn (~1.5 m/s)
  - Derived requirement, first guess by customer, should be verified from altitude accuracy requirement, max. horizontal velocity and worst case terrain profile

- Maximum vertical force: 1000 N ($c_w = 0.4, A = 20m^2, v_{vertical} = 0.5m/s$)
  - Derived by hydrodynamics from max. altitude rate requirement

- Same configuration for ROV (Element 1) and towed (Element 3) mode

- One suspension point

- Yaw control needed for small velocities in ROV mode
  - Change direction of sight for camera
  - Small velocities are velocities smaller than max. water current velocity

7.2. Options and Trades

7.2.1. Open Issues

Due to the fact that the current design represents the status of a pre-development phase there are still some open points to be investigated in more detail for the next design iteration:

- Detailed umbilical cable sizing and connectors

- How to share of DTS (→ PIM-ROV interface) capabilities (limits?)

- Need for 2nd battery tank (with 2x12 V) on PSM

- Winch design and (supplier) selection on PIM

- Winch motor selection, depending on:
  - Energy demand (in general) of the winch motor
  - Functionalities of the “Tether Management System (TMS)”
  - Forces/torques to withstand
  - ROV interfaces and options
    → Is hydraulic easily possible?
    → How to ensure the best re-use of PELADIS and ROV equipment

- Detailed Battery sizing and configuration on the PIM
  →Depending on motor selection

7.2.2. Active vs. Passive Stabilization of Attitude

A trade has been made between active and passive stabilization. Active stabilization includes the usage of thrusters or flaps to control the attitude in any case (even for small velocities). It also includes the measurement of the required values and a running onboard computer to run the control algorithms.

Passive stabilization can be guaranteed by configuration and is much simpler. Weights and lifting bodies have to be placed at the right position such that the center of buoyancy is above the center of mass. No active parts are needed. Passive horizontal stabilization within the required control accuracy even in moving water has to be proven by experiment or hydrodynamic simulation.

Passive Yaw stabilization can also be guaranteed hydrodynamic configuration for a minimum velocity. A necessary, but not sufficient condition is that the pressure point is behind the center of mass.

Passive stabilization has been chosen as it is much simpler and as it is assumed to be easily reachable for PELADIS. Only for the control of the Yaw angle an active control has been chosen for small velocities.

For higher velocities Pitch and Roll will be controlled actively.

7.3. Baseline Design

7.3.1. Control system architecture

The architecture of the AACS can be seen in Figure 7-1. The system consists of sensors (green), actuators (blue) and the Onboard Computer (OBC) to process the navigation, path-planning and control algorithms.
The sensors are:

- Doppler velocity log (DVL): It measures velocity in water and above ground as well as altitude above ground. Detailed description can be found in the instruments section.

- Inertial Measurement Unit: It consists of three accelerometers and three gyros to measure acceleration and attitude rate. It also provides a navigation solution by integrating attitude rates to angles.

- Fluxgate magnetometer: It measures three-dimensional magnetic field vector. Detailed description also in the instruments section.

- Sonar: The Sonar is only used in the towed mode and is mounted on the depressor module. It measures terrain profile and sends the data to the OBC of the sensor module.

The following actuators are used:

- 3 flaps (hydroplanes): To control altitude, Roll and Pitch. (See also configuration section). The flaps are controlled by electrical actuators, which are commanded by an analog voltage reflecting the attitude rate and which also send encoder readings reflecting the flap angle.

- Yaw thruster: Thruster to produce a torque around the vertical axis to control the Yaw angle.

The OBC has interfaces to all sensors and actuators as well as a data link to the operator. The OBC reads the measurements from all sensors, processes them and sends out commands to the actuators.

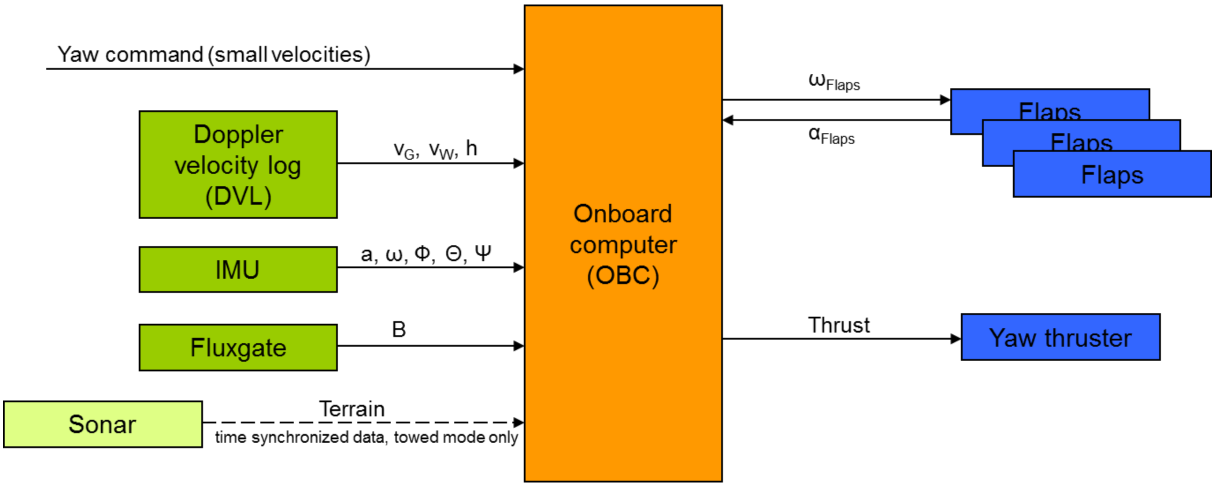


Figure 7-1: Control System architecture.

7.3.2. Control concept

As actuators 3 flaps and one thruster for Yaw control are used. For the control concept it has to be distinguished between ROV and towed mode.

ROV mode

In ROV mode the altitude above ground is controlled by the ROV. For the attitude it has to be distinguished between smaller and higher velocities.

For smaller velocities Pitch and Roll should be passively stable by configuration. The flaps do not show any effect, so they are not used. Yaw is not stable for small velocities but should be controlled to change the direction of sight of the onboard camera. For that a thruster is used (Yaw thruster) to produce a torque around the vertical axis.

For higher velocities the Yaw angle is passively stable and such it has not to be controlled actively. If the passive stabilization of the horizontal attitude is not sufficient when moving through the water with higher velocity, Pitch and Roll can be controlled actively using the flaps.

Altitude control, which is done by the ROV, can be supported with the flaps. This needs further investigation: It has to be clarified with the ROV pilot if dynamic loads are acceptable and within which range and the control algorithms have to be tuned such that the controller supports the ROV pilot and does not counteract against him.

Towed mode

In towed mode the velocities are higher as such and an active Yaw stabilization is not necessary. Altitude control is done using the flaps. Active Pitch and Roll control with flaps may be necessary of the passive stabilization is not sufficient.

7.3.3. Navigation / Sensor Data Fusion

The values needed for control are the altitude, the three attitude angles (Yaw, Pitch and Roll) as well as their derivatives altitude and attitude rate.
Altitude is measured directly by the DVL, while the attitude rate vector is measured by the IMU. One can get attitude angles by calibrating the IMU at the beginning of the experiment and integrating the attitude rate during the measurement campaign. Due to the drift of the gyro measurement the attitude error may sum up to 90° during an 8 hour campaign (performance of typical fiber-optic gyros).
To get a better performance sensor data fusion is needed. An Extended Kalman Filter will be used to fuse measurements from the IMU (attitude rate and accelerometers), the velocity above ground from the DVL as well as the magnetometer readings. This would result in an attitude estimation accuracy of better than 1° when velocities above ground readings are available (best engineering estimate, depends on velocity measurement accuracy, simulations needed).
The Sensor Data Fusion would also improve the accuracy of the velocity estimate.

7.3.4. Path-Planning

While being in towed mode a path-planning for the altitude has to be done. The Sonar on the depressor module measures the profile of the terrain which will be reached be the sensor module some time later. From the terrain profile, the velocity and the horizontal distance between depressor and sensor module, the path-planning algorithm will compute an optimal path under the consideration of maximum possible vehicle dynamics and altitude requirements. The result is the nominal trajectory to be tracked by the control algorithm.
Control algorithms as well as path-planning and sensor data fusion run as different task on the OBC.

7.4. List of Equipment Mass and Power Budget

7.4.1. Inertial Measurement Unit

A possible IMU is the iVRU-FC from iMAR with fiber-optic gyros and MEMS accelerometers [RD 1]. Main design values are gyro bias and noise:

- Bias: 0.003 °/s (10 °/h)
- Noise: 0.1 °/√h

Other technical data are:

- Dimensions: 120 mm x 120 mm x 130 mm

- Mass: 1.85 kg
- Power: 10 W, 11-34V
- Interface: RS232 or RS422 or CAN or HDLC

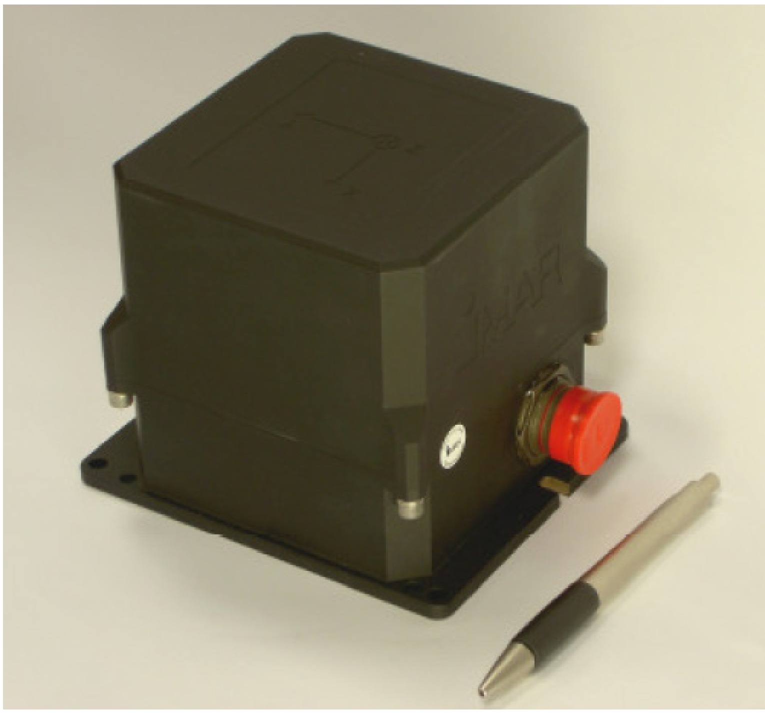


Figure 7-2: iVRU Inertial Measurement Unit [RD 1].

7.4.2. Flap actuator

Main design values for the flap actuators are torque and speed. The maximum torque on the flaps has been estimated by

$$T = F_z / 2 / \cos(45°) \cdot l$$

with the torque T, the maximum vertical force $F_z = 1000N$ and the lever arm $l \approx 0.1m$. This results in a maximum torque of $T = 70Nm$. The flap shall turn from maximum positive position ($+45°$) to maximum negative position ($-45°$) within 1s. So maximum speed should be $\omega_{flap} = 90°/s$.

The *Model 60* from Tecnadyne [RD 11] has been chosen with the following technical data:

- Max. torque = 81 Nm
- 100 - 350 W / 24 - 330 V
- +/- 5 V speed command

- Encoder output

Figure 7-3: Tecnadyne Model 60 flap actuator [RD 11].

7.4.3. Yaw thruster

Main design value for the Yaw thruster is the produced thrust. Required thrust can be estimated from a hydrodynamic simulation. Tecnadyne has thrusters of several sizes in its portfolio, e.g. the Model 540 [RD 12] with the following technical data:

- Thrust: +- 10 kg
- 1.9 kg
- 450 W / 24 – 330 V
- +/- 5 V speed command

Figure 7-4: Tecnadyne Model 540 thruster [RD 12].

7.4.4. Mass Budgets

Table 7-1: Mass summary of AACS.

MassSummary

This part shows a configurable mass summary.

	Mass w/o margin [kg]	Margin [%]	Margin [kg]	Mass with margin [kg]	% of total dry mass
Fins	60.00	10.00	6.00	66.00	37.19
FlapActuators	7.50	10.00	0.75	8.25	4.65
Flaps	90.00	10.00	9.00	99.00	55.78
IMU	1.85	10.00	0.19	2.04	1.15
LEDs	2.00	10.00	0.20	2.20	1.24
YawThruster	1.90	10.00	0.19	2.09	1.18

	Mass w/o margin [kg]	Margin [%]	Margin [kg]	Mass with margin [kg]	% of total dry mass
Total dry mass:	161.35			177.48	

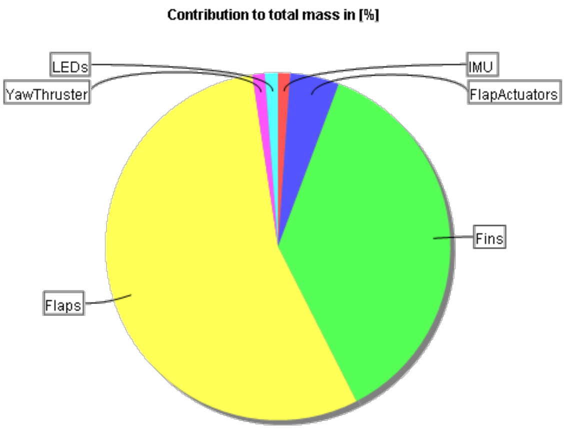


Figure 7-5: Mass contribution of AACS' equipment.

7.4.5. Power Budgets

Table 7-2: Power summary of AACS in PIM.

System Component	Parameter	Unit	Default
⊟ Attitude_Control	powerAvgWithMargin	watt	21.000
⊞ IMU	powerAvgWithMargin	watt	10.000
FlapActuators	powerAvgWithMargin	watt	9.000
LEDs	powerAvgWithMargin	watt	2.000

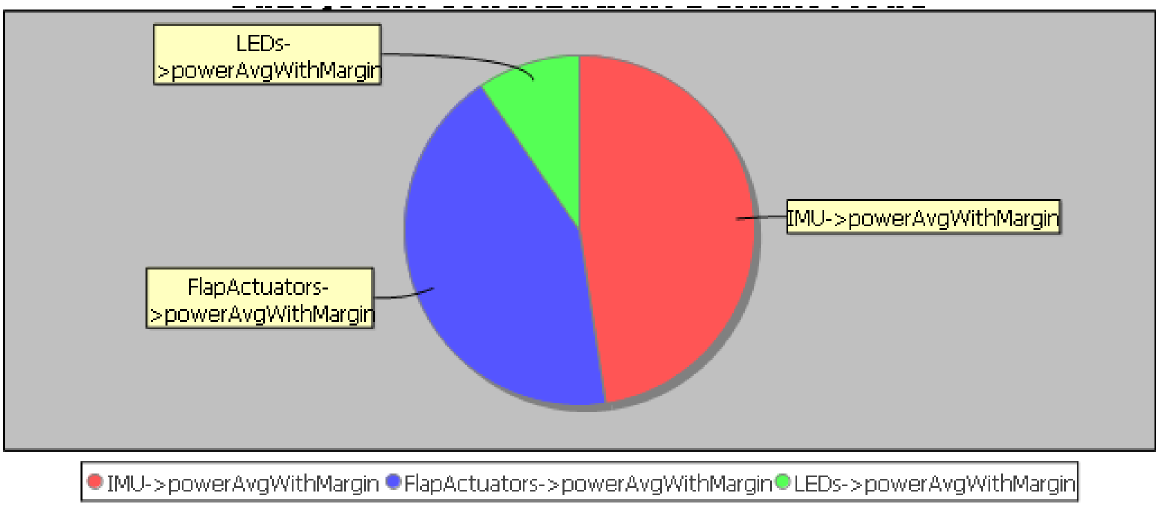


Figure 7-6: Mass contribution diagram of AACS in PSM.

7.5. To be studied / additional Consideration

The next steps shall be the development of a hydrodynamic simulation to proof passive stability for small velocities. For that worst case water current profiles are needed.
The hydrodynamic model is also needed to refine flap and actuator sizes. For that worst case terrain profiles are needed as they define the required dynamics of the vehicle (e.g. max. vertical velocity).
On the hardware side one should check costs and maximum water depth in cooperation with the manufacturer of the actuators.
Further steps are the design of the control algorithms, sensor fusion and path-planning algorithms. For the design of the control algorithms either a simulation with a sophisticated hydrodynamic model or experimental data is needed. The hydrodynamic model can be the result of a hydrodynamic CFD simulation campaign and should include forces and torques on vehicle and flaps, depending on flap position ($\alpha_{1..3}$), attitude rate of thruster ($\omega_{thruster}$), attitude rate of sensor module and velocity relative to the water:

$$[F_{Hydro}, T_{Hydro}, T_{Flaps}] = f(\alpha_{1..3}, \omega_{Thruster}, \omega, v_{Water}) .$$

The same model can be produced by making experiments with a scaled sensor module model in a water channel.

The third option is to design the control algorithm using experimental data from the real sensor module. But of course this is only possible when the module is already built. It may be also quite expensive as several test campaigns on a ship are needed.

8. Structure and Configuration

8.1. Requirements and Design Drivers

The main design driver of the Structure/Configuration was the Sensor Element (Element #1, PSM) which consists of a 5 m diameter outer ring, a 1 m inner ring and a receiver unit. From the configuration point of view it was necessary to accommodate all electrical elements far enough from the receiver unit, so it is guaranteed that the electromagnetic field of the elements do not influence the receiving and sending units. Also due to the sensitivity of the sensor element to metallic materials, it was also necessary to use non-metallic materials for the structure of the PSM.
In the following several further requirements are described:

- All electrical components have to be stored in standardized pressure tubes (MCH Large Housing).
- At least 3 flaps have to be accommodated (see Section 7 and Section 9).
- The ROV has to be stored on top of the PSM. Therefore at least four cutouts have to be provided, to give the opportunity to conduct for struts, which connect ROV and ship.
- The distance between the connection points of the rod, which connects ROV and Sensor element, and the CoG has to be adjustable.
- 2 frames and buoyant bodies for payload (similar to Nereus [RD 22])
- Payload includes:
  - Batteries
  - Camera
  - Inertia Measurement Unit (IMU)
  - Magnetometer
  - Doppler Velocity Log (DVL)

8.2. Baseline Design

The first conceptual design of the PSM (Figure 8-1 and Figure 8-2) consists of an outer sensor ring, an inner sensor ring and 4 flaps. 2 flaps are arranged one above the other to move the sensor up and down und 2 flaps are arranged next to each other (located behind the buoyant bodies) for movement around the yaw axis.

A framework should ensure the stability of the whole construction: An outer framework around the outer sensor ring and an inner framework housed in 4 buoyant bodies, which should accommodate the payload.

There were concerns because of stability of position with the up and down flaps while a dive. A possible solution is to use 2 flaps arranged next to each other instead of one above the other. This ensures correction of position stability by moving both flaps in opposite direction.

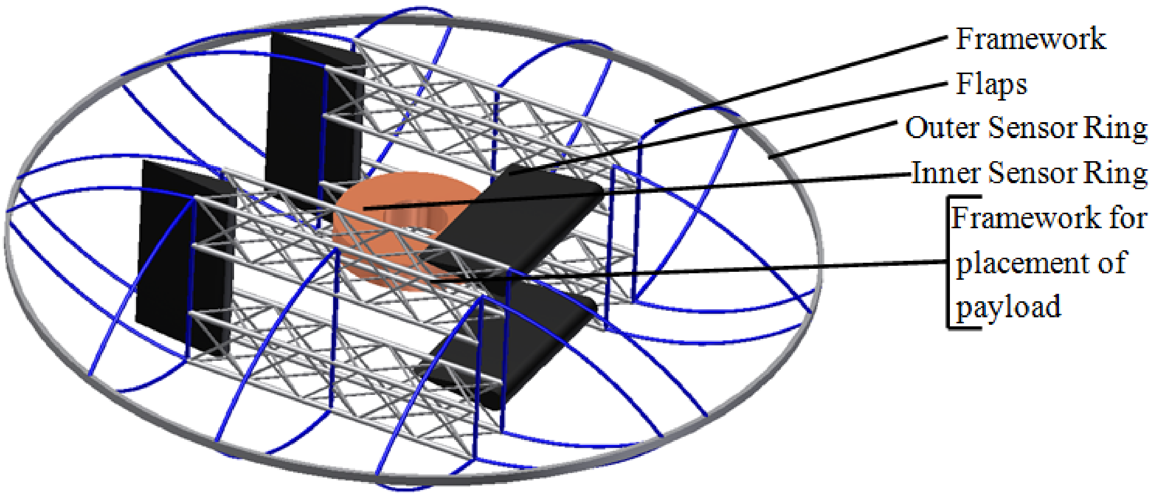


Figure 8-1: First PSM's conceptual design (without buoyant bodies).

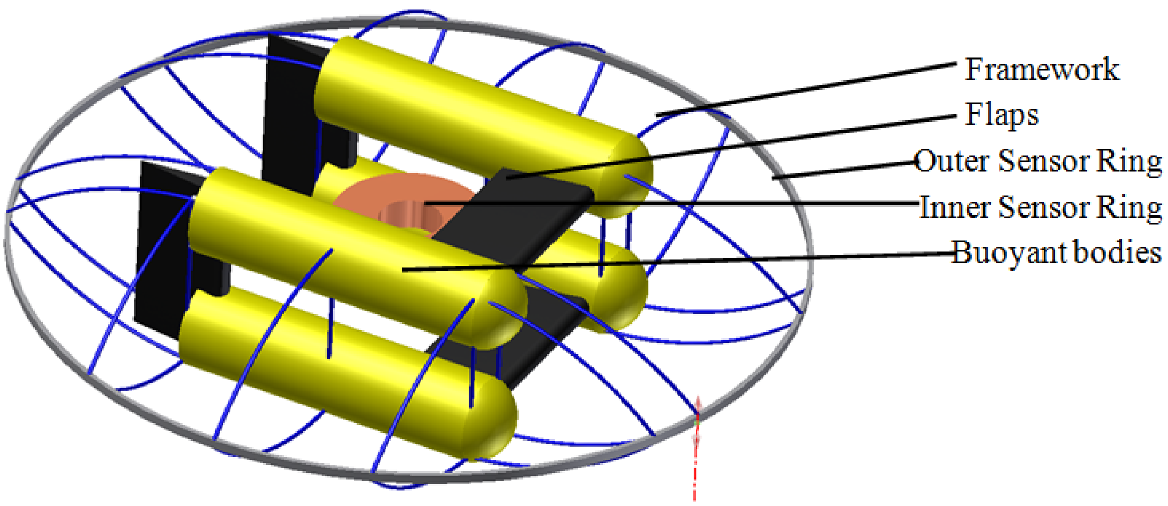


Figure 8-2: First PSM's conceptual design (with buoyant bodies).

A new arrangement of the flaps is shown in the second conceptual design (Figure 8-3). The flaps for moving around yaw axis were reduced to one flap. A thruster for moving around the yaw axis was added, too. Further considerations were to use a round basic plate (diameter = 5 m) with large notches to get a robust but lightweight framework.
A further decision was to use 2 buoyant bodies (instead of 4), which should be as small as possible.

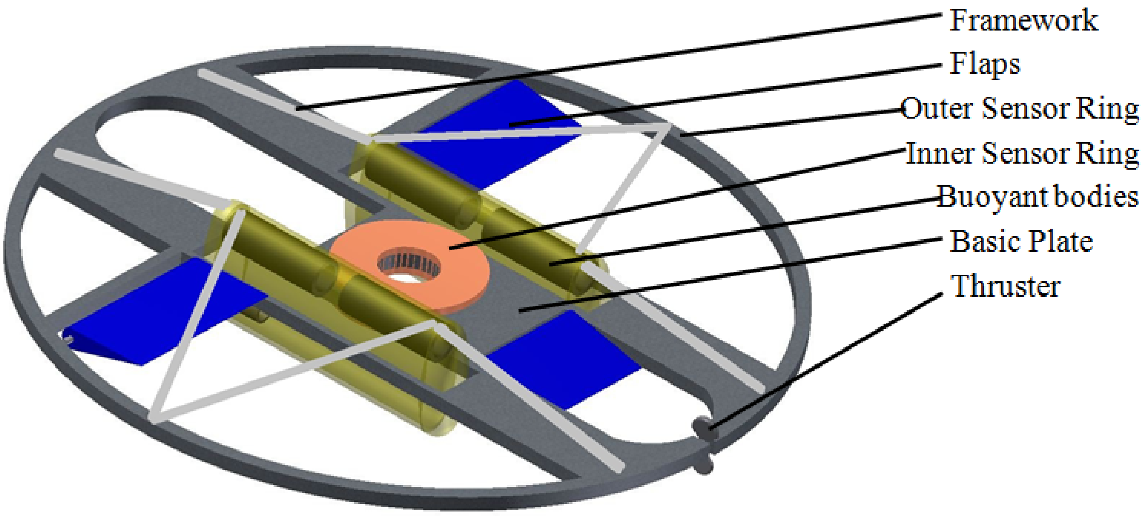


Figure 8-3: Second PSM's conceptual design.

The, for the present, last version (Figure 8-5 and Figure 8-6) consists of a lightweight framework without a basic plate. The inner sensor ring is placed in a flap housing (formed like a wing), where at the other end of which is a flap. Just there are 3 flaps for moving up and down and a thruster for moving around the yaw axis.
2 buoyant bodies contain the payload, e.g. pressured electrical compartment. An emergency mass is mounted close to the inner sensor ring.

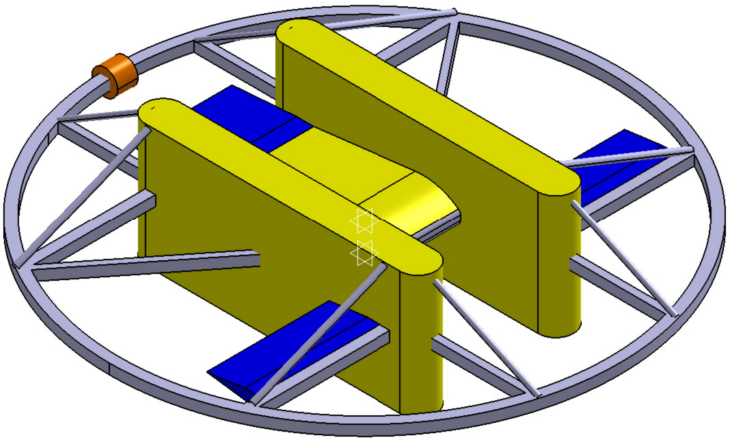


Figure 8-4: Third PSM's conceptual design.

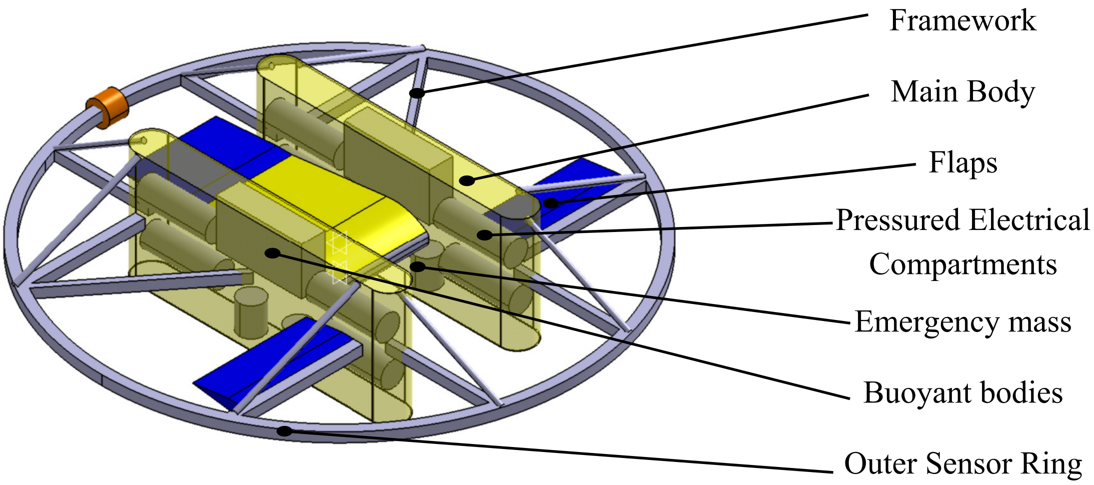


Figure 8-5: Third PSM's conceptual design (with inner configuration).

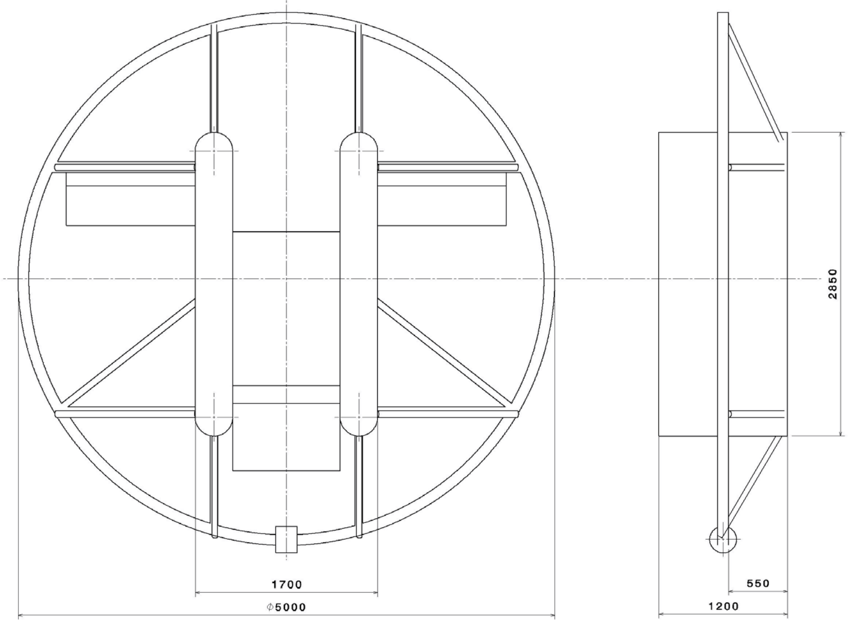


Figure 8-6: Top and side view of the PSM (third conceptual design).

8.3. To be studied / additional Consideration

For the further development it has to be studied whether a laminated or extruded glass fiber reinforced plastic should be used. It is recommended to execute a detailed finite element analysis or experiments to have a reliable base for the decision. For the current structure massive rods made out of plastics are used for the framework. To save mass it should be investigated whether it is possible to use hollow profiles instead.

The exact volume and mass of the buoyant bodies and the emergency masses has to be studied as well.

In case of emergency masses on the bottom side of the main body will be ejected. To ensure the ejection it is useful to use preloaded spring to accelerate the masses.

The mass distribution of design and placement of payload (instruments etc.) has to be well studied in order to achieve a balance point, which avoids tilting of the sensor element.

8.4. Summary

The current configuration delivers a good possibility to achieve valuable sensor data. All further investigation, which have to be studied are not identified as design drivers. The baseline configuration is based on a simple and cost-effective design, which leads to a short manufacturing and development time.

9. Hydrodynamics

9.1. Requirements and Design Drivers

The only possible approximation for lift and drag forces in vertical direction is defined by a model for the steering flaps at the sensor module.
Defining the working state lift forces and drag forces by a motion in the vertical direction should be equalized.

9.2. Baseline Design

The vertical drag D_v and lift L forces are computed by the following equations [RD 23],[RD 24]:

$$D_v = \frac{1}{2} \cdot \rho \cdot C_{Dv} \cdot V_y^2 \cdot A_y$$

$$L = \frac{1}{2} \cdot \rho \cdot C_L \cdot V_x^2 \cdot A_F$$

where is C_{Dv} is the vertical drag coefficient, C_L vertical lift coefficient, V_x horizontal velocity, V_y vertical velocity, A_y vertical cutting area, A_F complete flap area and ρ fluid density.

The constant values used for the calculations are:

Table 9-1: Hydrodynamic values for PELADIS.

Abb.	Definition	Value
C_{Dv}	Vertical drag coefficient	0.45
C_L	Vertical lift coefficient	0.5
V_x	Horizontal velocity [m/s]	1.5
V_y	Vertical velocity[m/s]	0.5
A_y	Vertical cutting area [m^2]	20
ρ	Fluid density [kg/ m^3]	1000

The flap area results with

$$A_F = A_y \cdot \left(\frac{A_y}{V_x}\right)^2 \cdot \frac{C_{Dv}}{C_L} = 2\, m^2$$

The approximated lift force would be 1125 N, and this would be the force on the sum of all flaps. With two small flaps (1 m width x 0,5 m length) and one large flap (1 m x 1 m) the mechanic moment on the small flaps would be app. 125-150 Nm and on the large flap app. 500-600 Nm [RD 25].

9.3. To be studied / additional Consideration

Furthermore the 3D behavior of the sensor should be investigated with a CFD study computing drag and lift forces and attaching moments.

9.4. Summary

With a summarized flap area of 2 m^2 and resulting lift forces of 1125 N the forces of the flap are not higher than 150 Nm on small flaps and 600 Nm of the large flaps.

10. Acronyms

Domain	Abbreviation	Comments
General		
	AACS	Attitude and Altitude Control System
	CEF	Concurrent Engineering Facility
	CE	Concurrent Engineering
	CSEM	Controlled Source Electromagnetic
	DLR	Deutsches Zentrum für Luft- und Raumfahrt
	EM	Electromagnetic
	ESA	European Space Agency
	P/L	Payload
	PELADIS	Pelagic Discoverer
	ROV	Remotely Operated Vehicle
	SMS	Submarine Massive Sulphides
	S/S	Subsystem
	TBC	To Be Confirmed
	TBD	To Be Defined
System		
	CTD	Conductivity, Temperature and Depth profiler
	DVL	Doppler Velocity Log
	EM	Electromagnetic
	IMU	Inertia Measurement Unit
	MI	Mission
	OJ	Objective
	PIM	PELADIS Interface Module
	PSM	PELADIS Sensor Module
	ROV	Remotely Operated Vehicle
	SSD	Solid State Disk
	USW	UltraSonic Wave
P/L	**Instruments**	
	AC	Alternating Current
	CTD	Conductivity, Temperature and Depth profiler
	DC	Direct Current
	DVL	Doppler Velocity Log
	EM	Electromagnetic
	GEM	Digital Electromagnetic sensor
	LF	Low Frequency

	PIM	PELADIS Interface Module
	PSM	PELADIS Sensor Module
	ROV	Remotely Operated Vehicle
DHS	**Data Handling System**	
	COTS	Commercial Of The Shelf
	HDD	Hard-Disk Drives
	OBC	On-Board Computer
	PIM	PELADIS Interface Module
	PSM	PELADIS Sensor Module
	RAID	Redundant Array of Independent Disks
	SATA	Serial Advanced Technology Attachment
	SSD	Solid State Disk
Power		
	AACS (ACS)	Attitude and Altitude Control System
	BMS	Battery Management System
	CTD	Conductivity, Temperature and Depth profiler
	DC	Direct Current
	DoD	Depth of Discharge
	DTS	Digital Telemetry System
	DVL	Doppler Velocity Log
	EM	Electromagnetic
	I/F	Interface
	IMU	Inertia Measurement Unit
	OBC	On-Board Computer
	P/L	Payload
	PIM	PELADIS Interface Module
	PSM	PELADIS Sensor Module
	ROV	Remotely Operated Vehicle
	TMS	Tether Management System
AACS	**Attitude and Altitude Control System**	
	DVL	Doppler Velocity Log
	IMU	Inertia Measurement Unit
	OBC	On-Board Computer
	ROV	Remotely Operated Vehicle
Structure and Configuration		
	AACS	Attitude and Altitude Control System
	EM	Electromagnetic
	ROV	Remotely Operated Vehicle
	CoG	Centre of Gravity

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