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Report

Seatonomy applied in an operational analysis and overall system design for an autonomous underwater vehicle operating in fish cages

CageReporter report for workpackage H3.1 - Operational analysis and overall system design

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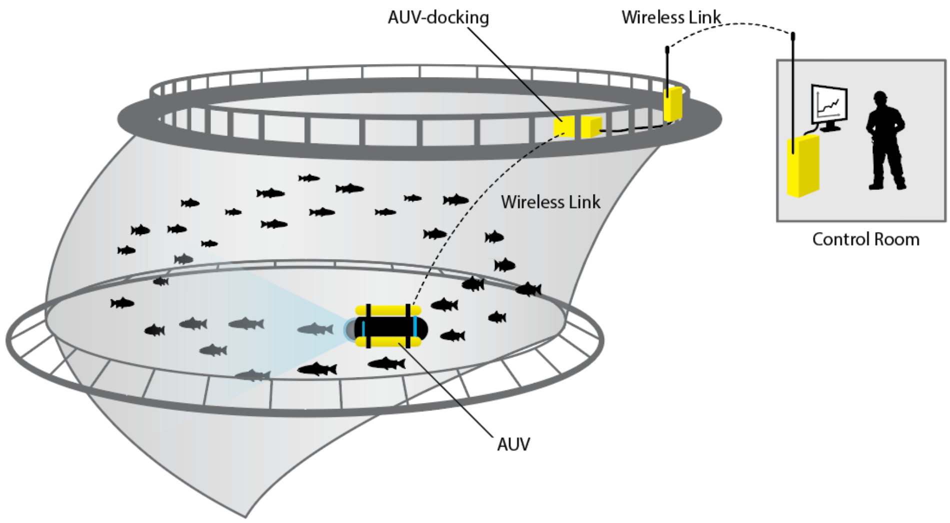

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ABSTRACT
This report presents results obtained by applying the Seatonomy concept for analysing autonomous operations handled in CageReporter project. The analysis results in this document are based on the Autonomous Job Analysis (AJA) concept introduced in the Seatonomy method. This includes analysis to identify autonomous capabilities that the system must possess for the various operations related to A) Fish conditions, B) Cage inspection and C) Production environment. Furthermore, the activity includes system design with focus on architecture, error management and safe mode.

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1 Background

The goal of the CageReporter project is to be able to utilize an autonomous and tetherless underwater vehicle, which is equipped with vision and environmental sensors for data capturing. After the completion of the operation the obtained relevant data are transferred from the vehicle to a central unit and to the operator (Figure 1). In particular, the underwater vehicle will collect data on the condition of the cage and the fish from the whole volume of the fish cage. The vehicle that will be used in this project is commonly referred to as Autonomous Underwater Vehicle (AUV), and is characterized by its self-propelled nature, but it also has contact with the operator using wireless underwater communication. The overall aim of the project is to develop solutions that allow the autonomous vehicle to operate in interaction with the biomass (bio-interactive navigation), which, in combination with real-time quality control, will ensure the acquisition of high-quality data. Therefore, the project will utilize the use of a permanent resident vehicle in each cage, for continuous high-quality data capture. The project idea will be based on the use of low-cost technology for wireless underwater communication, vehicle positioning and camera systems for 3D vision. The degree of innovation in the project is considered very high, where information about the condition in the cage are obtained in a completely new way, using AUV, for high-quality data capture.

The project addresses several challenges of the aquaculture industry linked to lack of accuracy and control in fish farms, using technological solutions to obtain high-quality data that can be used to quantify the condition in the fish cage by introducing the use of advanced technological solutions such as underwater robotic systems (Balchen, 1991). The following three main conditions are investigated: **A) Fish conditions**, **B) Cage inspection** and **C) Production environment**. Generally, the aim of the CageReporter project is to ensure close follow-up of the conditions in the fish cage that are beneficial to the fish by introducing the use of a permanent resident AUV as the 'eye' of the operator and/or the farmer in the cage. Note that the use of a permanent AUV gives the farmer far better control over the dynamic and complex farming situation, and thus it will be key technology that facilitates sustainable growth in aquaculture. In summary, this project provides a system for high-quality data capture for fish cages by using a resident solution permanently present in the fish cages that is able to perform autonomous inspection and monitoring of underwater operations. The provided system is a low-cost solution and it adapts the existing technology for use in the aquaculture industry.

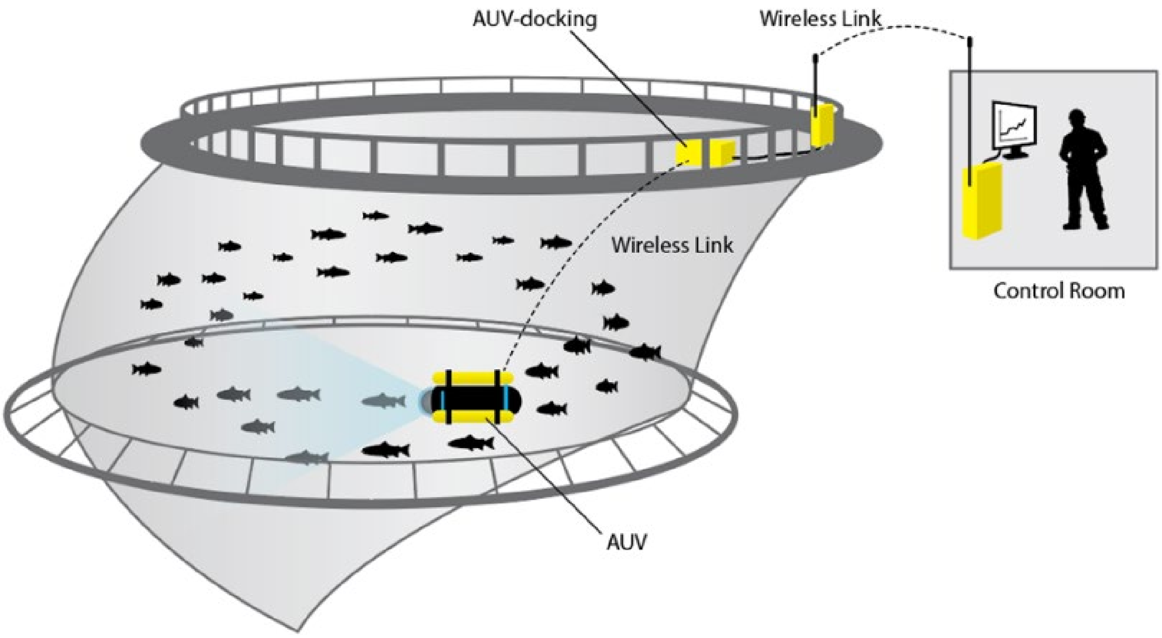

Figure 1 Illustration of the CageReporter project with AUV for high-quality data capture via wireless communication to a land-based control room

In order to realize the CageReporter concept, research related to autonomous functions, such as adaptive and bio-interactive operational planning, is required. It is crucial to develop solutions where the AUV largely performs on its own and only exceptionally receive assistance from the operator. A typical farming site has 4-16 cages, and a single operator, at a land-based control center, must be able to handle all the vehicles on the site. A high level of autonomy will also ensure that data can be obtained with a higher degree of repeatability and objectivity, which is an important component of high-quality data capture. Autonomy is also considered necessary to perform bio-interactive data capture. The main goal of the following analysis will therefore be to develop methods and perform operations by controlling the vehicle's motion that do not affect the fish during daily inspection and monitoring operations in fish cages.

2 Seatonomy – Autonomous Job Analysis (AJA) – AJA canvas

2.1 Introduction

Seatonomy describes a methodology that provides a structured approach for design, development and validation of mobile autonomous maritime operations and systems (Grøtli et al., 2015a,b). The goal is to achieve this by providing system developers of autonomous systems with suitable guidelines, principles, best practices and tools. The Seatonomy method provides a structured way for design, development and validation of *autonomous functionality*. Seatonomy regards the problem from three *viewpoints*:

a) ***The operational viewpoint:*** This viewpoint concerns the overall design and specification of the operation. This means analysing the operation(s) the system is intended to execute, without considering the physical system in detail. The reasoning behind this viewpoint is both to facilitate a common understanding between system designers and end-users, as well as making sure that the system design will be grounded by the actual operation it is intended to solve.
b) ***The system viewpoint:*** The system viewpoint concerns the realization and composition of autonomous functionality in the physical system. This viewpoint focuses on specifying the needs and requirements for how to create a working autonomous system. Requirements in terms of hardware and software are taken into account in order to accomplish the system's design and implementation. Within this viewpoint, details of the agent and system itself will be analysed.
c) ***Verification and validation***: The verification and validation viewpoint is concerned with how to make sure both system and operation behaves according to requirements (verification) and according to reason (validation). Validation by smart testing and operational scenarios is emphasized in the Seatonomy methodology as a way to counteract the challenges of analysing infinite states and responses.

The three categories or viewpoints must all be covered to make a design in accordance with the Seatonomy methodology. These viewpoints should not be considered isolated from the others. Instead the workflow should be incremental and iterative, as illustrated by Figure 2.

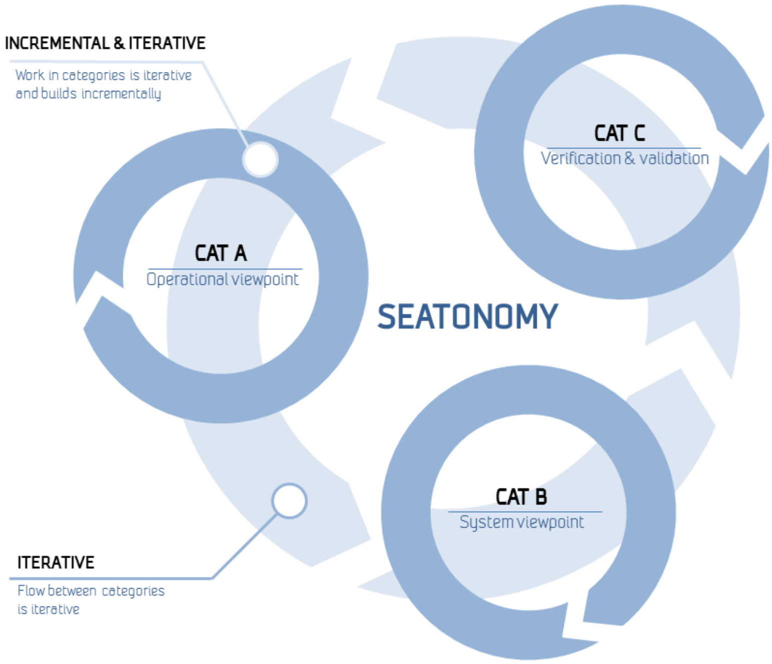

Figure 2 Seatonomy workflow

One of the suggested tools in the Seatonomy method is the Autonomous Job Analysis (AJA), a structured approach for design, development and validation of autonomous functionality. The purpose of AJA is to guide the design of autonomous marine operations. As such, the AJA method aims to aid the design of autonomous marine operations by uncovering the overall operational modes and design challenges as well as needs and limitations related to autonomous behaviour by breaking down operations into sub-operations and tasks and analyzing these tasks individually. AJA breaks down the operation and focuses on autonomy early in the design phase. The purpose of the AJA method is to:

- Analyse and break down an existing operation, or an operation which is to be designed into manageable sub parts.
- Uncover overall operational modes, design challenges, needs and limitations regarding autonomous behaviour.
- Force the designer to consider autonomy critical aspects early on, e.g. communication, safe-states, human machine interface, etc.

<u>The AJA consists of the following steps:</u>

1 Describe the main goal of the operation.
2 Divide into sub-goals, based on e.g. sequence, parallel behaviour or choices.
3 Answer the list of AJA questions in AJA Table.
4 For each sub-goal, go to step 2 and repeat until goals become trivial tasks.

The AJA table consists of rows representing goals and sub-goals, as well as the questions to facilitate a detailed analysis of the operation under evaluation. Each row corresponds to the categories “Communication”, “Perception”, “Success Criteria”, “What can go wrong”, “What is the operational safe state”, “Human-Machine Interaction”, “Other premises/requirements” and “Notes and comments”. The last two rows are to allow for additional information that does not fit into the other categories.

<u>The following steps are required during post processing and performing the AJA analysis where a meeting with all the involved people is required - AJA meeting:</u>

1 The details from the AJA meeting should be processed and distributed among the stakeholders.
2 The stakeholders give feedback for possible subsequent iterations.

The AJA canvas is a new tool that has been created in order to facilitate the application of AJA. It is a graphical representation of the AJA table and it contains the categories of the AJA method on a single page format - *the canvas*- and each category is supported with questions to be asked during the design procedure. The canvas should be printed out, one copy for each sub-operation to be treated, and used in meetings between customers, operation designers and field experts (e.g. experts in risk management, robotics, autonomy, instrumentation etc.). This way, they can jointly start sketching and discussing the autonomous operation. The canvas idea is based on the business model canvas approach and the scope is to gather the essential information needed for the design of an autonomous operation into a single page document. This facilitates the applicability of the method and gives the users the possibility to carefully design and analyse the operation in a structured manner.

To accomplish the vision and objectives of the CageReporter project, the Autonomous Job Analysis (AJA) concept from the Seatonomy method (Grøtli et al., 2015a,b) was used to analyse autonomous operations. Figure 3 summarizes the necessary steps that were investigated with respect to the theoretical analysis, simulations and experiments. Figure 4 shows the block diagram of the iterative approach adapted to perform the Seatonomy method in this report.

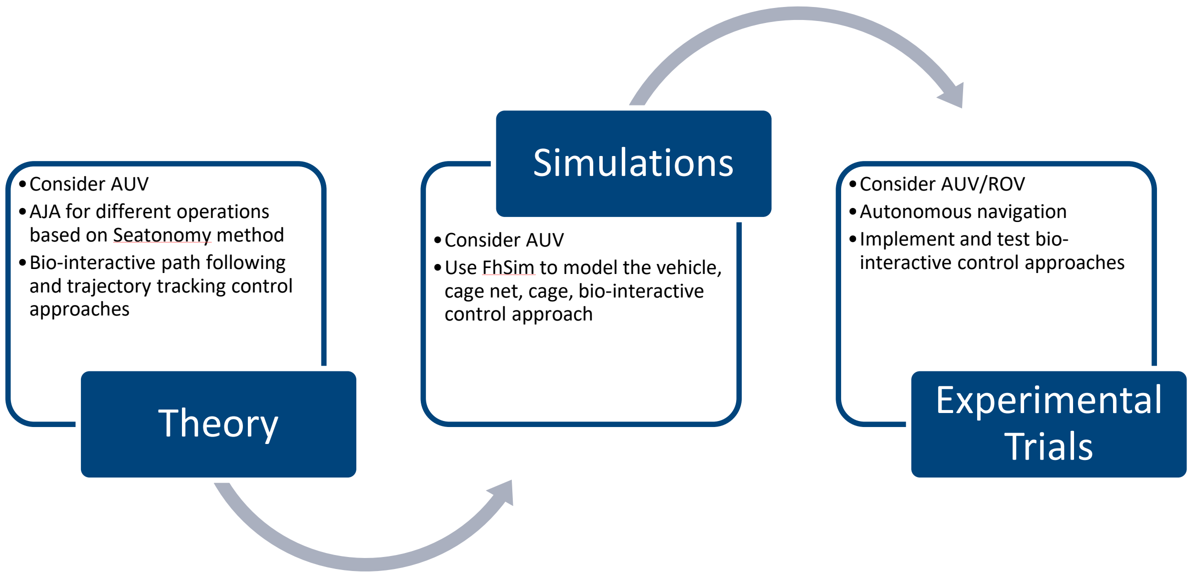

Figure 3 Summary of the concept adapted in CageReporter project

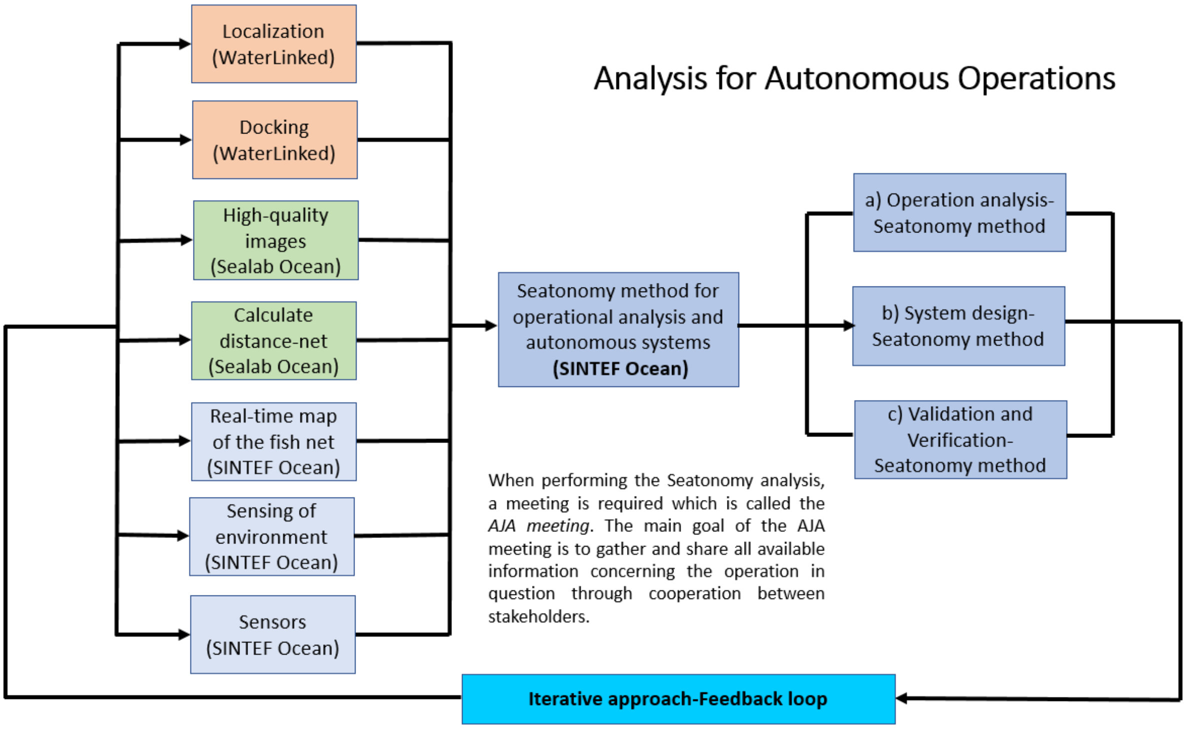

Figure 4 Seatonomy method adapted for autonomous operations analysis in CageReporter

2.2 Use – case: Autonomous permanent resident vehicle for a high-quality real-time low-cost data capture system for subsea monitoring of fish cages

This report documents the application of the Autonomous Job Analysis (AJA) table and AJA canvas methods to solve the challenges underwater vehicle meet when used as an autonomous permanent resident vehicle for a high-quality real-time low-cost data capture system for underwater inspection and monitoring operations in fish cages. Table 1 shows the operations that have been analysed based on the AJA method. Note that all the operations will be analysed based on AJA concept and some of the described operations presented in Table 1 will be demonstrated in full scale field trials. In order to investigate this concept, the underwater vehicle will autonomously navigate inside the fish cage to collect necessary data. By integrating a precise underwater positioning system with a high-quality data capture system, it is possible to navigate autonomously and obtain necessary data from fish cages, which are essential for the conditions in fish cages. The AUV as a permanent resident underwater vehicle with autonomous functionality will be used to perform different operations and collect relevant data in daily base for the conditions in fish cage. The AUV will be able to autonomously perform the planned mission inside of the cage without operator's input, while the operator of the fish farm will be responsible to plan the daily base missions of the AUV. An underwater positioning system will be used in order to obtain the position of the vehicle, the net relative distance and estimation of the fish cage structure based on estimation methods combined with the obtained measurements. In addition, the AUV will send the obtained data to the docking station via a high bandwidth communication link or transmit the obtained data after each mission by docking to the docking stations. In particular, the autonomous daily inspection and monitoring operations related to the A) Fish condition, B) Cage Inspection and C) Production environment will be described through the next stages:

Stage 0: Deployment of AUV and installation of docking station inside the fish cage

- **Actors**: AUV and Support Vessel (SV)
- **Actions to be done**: The AUV and the docking station is deployed and permanently installed inside the fish cage using a Support Vessel.

Stage 1: Installation of low-cost underwater positioning system

- **Actors**: AUV

- **Actions to be done**: The underwater positioning system is installed inside the fish cage in order to be able to obtain the position measurements of the vehicle in each time step during the daily operations in fish farms.

Stage 3: CageReporter´s daily mission planning related to the different operations

- **Actors**: Operator of the fish farm
- **Actions to be done**: The operator decides the mission which the AUV should perform and is able to cancel, change or re-plan the mission depending on the conditions and data exchange between the control center and the AUV.

Stage 4: Perform autonomous operation

- **Actors:** AUV
- **Actions to be done:** AUV is able to do autonomous operations by obtaining high-quality data which will be used to extract parameters related to the A) Fish conditions, B) Cage inspection and C) Production environment either by camera recognition, if possible, or by other sensors. The AUV navigates inside the fish cage and collect autonomously data from the most relevant sub-volumes.

Stage 5: Data transfer to the docking station

- **Actors:** AUV
- **Actions to be done:** The AUV sends data to the docking station via a high bandwidth communication link or transmit the obtained data after each mission by docking to the docking station.

Stage 6: Share information between docking station and the control room

- **Actors:** Docking station
- **Actions to be done:** Data is sent from the docking station to the control room.

Table 1 Analysis of operations in fish farms based on the AJA concept

MAIN GOAL: ***Autonomous permanent resident vehicle for high-quality real-time low-cost data capture system for underwater inspection and monitoring operations in fish cages***		
Sub-operation (1): **Fish conditions**	**Sub-operation (2):** **Cage inspection**	**Sub-operation (3):** **Production environment**
1.1. Counting of observed fish	2.1. Net inspection and identification of holes	3.1. Monitoring of temperature and oxygen levels in the cage
1.2. Parasite detection such as sea lice	2.2. Inspection of equipment inside the fish cage	3.2. Current and wave impact measurements and estimation
1.3. Behavioural indicators for fish welfare	2.3. Inspection of biofouling condition on the cage net	
1.4. Detection of physical injuries and wounds in fish		
1.5. Monitoring of fish feeding and feed waste		
1.6. Biomass estimation, average weight estimation and weight distribution		
1.7. Documentation of dead fish		

Sub-operation (1): Fish Conditions

Development of autonomous systems for *A) Fish conditions*, is considered as the most demanding task, since the AUV must collect data without affecting (e.g., scaring, agitating) the fish, as well as detecting where relevant data should be obtained. Considering that the vehicle's motion could potentially affect the fish response, the AUV must have bio-interactive ability to collect data without the fish "noticing" it. The main factors deciding the duration and the conclusion of a mission are the distance between the vision system and the target of observation (e.g., the fish, the net), the camera's field of view (FOV), the light conditions and AUV velocity. These factors will be considered during mission planning. The system must also be able to document that the entire fish cage area is inspected. Furthermore, the mission planning approach must cope with structures inside the cage volume (i.e., ropes, cleaner fish shelter) and avoid disturbing the fish during the motion. This challenge will be addressed by implementing adaptive bio-interactive mission planning and real-time evaluation of path following performance and collision avoidance.

1.1. Counting of observed fish

Computer vision techniques provide an attractive tool for developing a more robust and versatile fish counting systems relevant for several operations in fish cages. An interesting task during the operations performed in fish cages is to obtain information regarding the number of fish visible to the underwater vision system attached on the AUV during each operation. This information could be used during the daily operation in order to provide inputs for the estimation of biomass, the average weight, etc. Autonomous counting of salmon observed in front of the vision system will be obtained during AUV operations based on image processing techniques which can, for instance, intensify the eye of the fish or the whole shape of it. By using this obtained information, it is possible to count the number of fish visible in front of the camera during each operation.

1.2. Parasite detection such as sea lice

Sea lice are considered one of the greatest challenges for the aquaculture industry. Effective and environmentally responsible control of sea lice depends on an accurate estimate of the lice population in a fish cage. This is currently achieved only by close manual inspection of anaesthetised fish. When using AUVs, the lice population in fish cages will be calculated using machine vision algorithms based on the high-quality images obtained from the underwater camera system. During this operation, the AUV will traverse the whole volume of the fish cage and the lice on the exterior of the fish will be detected by using image processing techniques and a stereo vision system to capture 3D images of the fish. During daily inspection operations, the computer vision system attached to the AUV will automatically detect and count lice on fish swimming freely in the fish cage, allowing an estimate of the lice population on which intervention decisions can be based.

1.3. Behavioural indicators for fish welfare

Early warning systems that monitor and identify the behavioural condition of the fish during daily operations in fish farms will allow early intervention/adaptation to improve welfare and reduce stress responses in fish. Nowadays, methods for assessing stress related parameters are typically based on blood chemistry analyses. However, identifying behavioural indicators correlating to the stress related parameters will provide essential information that could benefit the fish farm production. Several daily operations in fish cages may be considered welfare-critical in the sense that they may act as significant stressors to the fish. Potential behavioural indicators for fish welfare are flight response, increased swimming speed, tail beat frequency and respiratory frequency (measured as opercular movements). By including the analysis of such inputs into operations, the performance of operations with the AUV could be less stressful for the fish. During each daily operation with the AUV, the computer vision system of the vehicle will be able to identify the behavioural indicators using image processing algorithms that are able to calculate the swimming speed of the fish, the tail beat frequency and respiratory frequency and adapt the motion of the vehicle autonomously to avoid any increase of the stress level on fish.

1.4. Detection of physical injuries and wounds in fish

Injuries to the cultured fish can be potentially deleterious to aquaculture production performance and welfare. Several types of injuries and wounds can be diagnosed on live fish in a fish farm. The detection of physical fish injuries and wounds in fish inside the fish cages will be identified using machine vision algorithms based on the high-quality images obtained from the underwater camera system. During this operation, the AUV will traverse the whole volume of the fish cage and the physical injuries and wounds, and their rate of occurrence on the exterior of the fish, will be detected by using image processing techniques. During daily inspection operations, the AUV computer vision system will automatically detect and identify injuries and wounds on fish swimming freely in the fish cage. The image processing algorithms will be able to locate a fish injury or/and wound and determine its surface area and the position of it on the fish.

1.5. Monitoring of fish feeding and feed waste

In the case of finfish aquaculture, it is challenging to verify in a visual and permanent way the amount of feed that is consumed by the fish. As it is impossible to verify the consumption in real-time, two main problems arise: 1) the economic loss because of the feed that is not consumed and 2) the negative environmental impact the wasted feed causes. As an example, in an industrial scale salmon farm, the feed costs represent about 60% of the total production costs. Therefore, the optimization in the use of the feed may significantly influence the economic result of the company. Daily operations using an AUV that is able to monitor the non-consumed feed in fish cages and inform the operator of the fish farm in order aide decision-making processes regarding feeding is quite essential. During this operation, the AUV will traverse the volume of the fish cage which represents the feeding related volume and the non-consumed feed will be detected by using image processing techniques. During daily inspection operation, the AUV computer vision system will automatically detect and identify non-consumed feed and thus provide useful information to the operator in order to take decision regarding the feeding process in addition to feeding camera input.

1.6. Biomass estimation, average weight estimation and weight distribution

Computer vision and video processing could be considered as alternative techniques for the estimation of biomass in fish farms, avoiding the manual handling of the fish required for the sampling and weighting of the fish population in tanks and cages. During daily operations in fish cages with the AUV, the biomass estimation, the average weight estimation and weight distribution will be obtained based on stereo camera systems and image processing algorithms that are able to obtain the 3D shape of the fish by using 3D computer vision techniques. Good light conditions and a stereo camera system are essential to obtain this information. During biomass estimation operation, the AUV will traverse the whole volume of the fish cage and, by using a vision sensor based on cameras, will obtain high-quality images for biomass estimation. In particular, the computer vision system will use image processing techniques in order to calculate the size of the fish and calculate the weight distribution. By combining this information with the output of the task *''1.1 Counting of observed fish"* it is possible to estimate the biomass inside the fish cage.

1.7. Documentation of dead fish

Computer vision techniques and image processing algorithms will be used to autonomously count the dead fish observed in front of the vision system, document their position and their conditions related to degradation. Therefore, during the daily operation, the computer vision system installed on the AUV will be used to count the dead fish observed in front of the camera and document their position and conditions. The sub-operation *1.1: Counting of observed fish* will run in parallel to provide inputs regarding the observed number of dead fish. The AUV will be programmed to perform this operation several times during the day and inform the operator on fish mortality.

Sub-operation (2): Cage inspection

For use case study *B) Cage inspection*, the complexity will be lower than for *A) Fish conditions*, but the system must still be able to retrieve images of structures in fish cages with sufficiently high quality. This means that different visibility- and light conditions in the water, and the occlusion of the cameras by passing fish must be handled.

2.1. Net inspection and identification of holes

In modern aquaculture using gravity net cages, holes in the net and other types of net failures constitute a challenge with respect to fish escapes. It has been reported that more than two thirds of the registered escape incidents are related to holes in the net. One important measure established to reduce escapees is a mandatory daily net inspection. Net inspection and identification of holes will be assessed using machine vision algorithms based on the high-quality images obtained from the underwater camera system. During net inspection, the AUV will traverse the net at a predefined distance and heading relative to the net and detect damages/holes using image processing algorithms such as pattern recognition of the cage net grid.

2.2. Inspection of equipment inside the fish cage

In addition to the net inspection and hole identification, it is necessary to perform daily inspection of the equipment inside the fish cage in order to report possible damages on the structures. This is an important factor for the fish cage structure maintenance. Inspection of equipment inside the fish cage and identification of possible damages will be assessed using machine vision algorithms based on the high-quality images obtained from the underwater camera system. During this operation, the AUV will traverse the whole volume of the fish cage and detect damages by using image processing techniques and comparing the obtained images with the priori available images of the fish cage during the installation stage.

2.3. Inspection of biofouling condition on the cage net

Biofouling of aquaculture nets causes serious maintenance and operational problems. Biofouling can cause a reduction of the mesh opening and a decrease in water circulation through the cage, resulting in reduced water exchange and oxygen available to the fish. This results in a significant reduction in carrying capacity and may lead to increased mortalities of the fish. Biofouling may also act as a reservoir for parasites and disease and certain fouling species, such as hydroids, are capable of inflicting harm through stinging cells that can damage the gills of the fish. In addition, farmers are concerned that the cleaner fish used as biological control against sea lice reduce their delousing efficacy when biofouling is available as an alternative food source. Therefore, it is important to know the conditions of biofouling and report when it is necessary to perform cleaning of the cage net. Inspection of the biofouling conditions in fish cages will be performed on a daily basis and the results will be assessed using machine vision algorithms based on the high-quality images obtained from the underwater camera system. During net inspection, the AUV will traverse the net from a predefined distance and heading relative to the net and by using image processing algorithms such as pattern recognition of the cage net grid shape will be able to estimate the biofouling conditions, i.e. the extent to which the openings of a net are occluded by fouling organisms. The output of this operation will allow the calculation of the percentage net-aperture occlusion (PNO) and provide information to the operator regarding when it is necessary to perform cleaning of the cage net. PNO is a method that was developed and repeatedly refined specifically to quantify biofouling on nets. For the calculation of this parameter using image processing algorithms it is important to keep constant distance from the net and have very good lightning conditions during the collection of the vision data.

Sub-operation (3): Production environment

The case study *C)Production environment* is the area with the lowest standards of autonomy level, as the quality of the measurements of the sensors used will not be affected by the dynamic conditions in the fish cage in the same way as for *A) Fish conditions* and *B) Cage inspection*. The requirements for autonomy levels will therefore be far lower, and the vehicle can, in principle, follow a pre-programmed path to obtain measurement from the sensors at specified points of the investigated volume inside the fish cage.

3.1. Monitoring of temperature and oxygen levels in the cage

It is well known that the environmental conditions related to the temperature of the water and the oxygen level are essential for the welfare of fish. Therefore, it is necessary to measure these values as frequently as possible and report to the fish farm operators. During the daily operations, the AUV will collect the measurements related to the temperature and oxygen level from the whole volume of the fish cage and report possible differences from different areas inside the fish cage. In addition, based on these measurements, the operator of the fish farm can take discussions regarding possible intervention operations necessary to preserve the desired standards for the fish conditions. During this operation, the AUV will traverse the whole volume of the fish cage and will obtain measurements using environmental sensors.

3.2. Current and wave impact measurements and estimation

For successful daily base autonomous inspection and monitoring operations in fish farms it is necessary to know the environmental conditions such as ocean current and waves impact. This is an important factor which is necessary for precise and autonomous navigation of the AUV for daily operations. For the estimation of ocean currents and the waves impact, environmental sensors installed on the AUV will be used. The current measurements can be obtained using commercially available mechanical, electromagnetic, acoustic or optical sensors. In addition, the estimation techniques could alternatively be used to estimate the current profile during the operations. For the wave impact estimation commercially available wave sensors measuring the sea motion will be used.

In the following section, the AJA method will be applied for operation analysis and overall system design for each of the operations described in this section in order to define the requirement of developing an autonomous system able to perform daily base inspection and monitoring operations in fish cages.

2.2.1 Autonomous Job Analysis for operations related to the A) Fish conditions

Autonomous Job Analysis		
	Main goal of operation:	**Operation 1.1. Counting of observed fish**
ID	**Question**	**Answer**
1.1.1	**Description of sub-goal**	Counting the number of salmon visible from the vision sensors
	Communication	AUV communicates its new position based on measurements from the underwater positioning system and the real-time map of the cage net at regular intervals so that the robot is able to perform autonomous navigation and the operator is able to supervise the movement.
	Perception	Information about sea-current and waves impact are valuable (but not necessary) in order to compensate for the forces acting on the AUV. Vision sensor based on cameras in order to obtain high-quality images for counting the number of fish visible to the vision sensors. Complex case: condition identification of each individual fish in the fish cage. Simple case: condition identification only the fish visible to the cameras by counting for instance either eye or tail shapes.
	Success criteria	Speed control of the AUV in order to obtain a sufficient number of images for the operation to be successful. Precise position measurements. Fish visible to the cameras. Real-time algorithms for image processing. Use of single camera under sufficient/good light conditions and slow motions.
	What can go wrong?	The sea current is too strong for the AUV to follow the pre-planned path/route. The vehicle is heading in a different direction than initially expected. The AUV is lost. The AUV is not able to transmit/receive data. The sensor fails to obtain sufficient data for salmon counting in fish cage.

	What is the operational safe-state?	If there is a communication problem or not enough fish visible during the operation from the cameras, try to inform the operator, otherwise autonomously go to the surface and wait for new commands. If failure happened, to be defined (TBD) meters close to cage net or stuck/collision with other infrastructure, then power shutdown and wait for manual recovery of the vehicle (i.e. operator take over the mission as *a super user* and perform manual recovery of the AUV) to avoid any fish and/or net damage.
	HMI	Operator should be able to monitor the AUV's position and status at all times. Operator should have the ability to intervene at any time (abort or change mode) as *a super user*.
	Other premises/requirements	What is the battery capacity of the AUV? What is the capacity of memory for saving high-quality images?
	Notes/comments	This sub-goal runs in parallel with the **sub-goals 1.1.2-1.1.11.** The output of **sub-goal 3.2.1** is an input to **sub-goal 1.1.1.**
1.1.2	**Description of sub-goal**	Mission Planning (Robots point of view)
	Communication	Ability to communicate with the control station and the operator, knowledge of the position of the vehicle for real-time control, knowledge of the distance to the net and the global position of the vehicle with respect to the cage net, localization and navigation, distribution of the path to be followed: either as a trajectory, or a pre-specified area that the vehicle is going to move in or pre-planned route, provide information regarding real-time weather conditions (sea current etc.) and fish behaviour (flight response if vehicle is too close to the fish).
	Perception	The position of the vehicle and the position of the fish cage in each time step should be known (self-localization), the camera system should be functioning to provide high-quality images, current/wave estimations should be known *a priori*.
	Success criteria	Hardware and Software are working correctly, and all test information has been transmitted and received correctly. Make sure to keep/adapt the distance to not 'scare' the fish (consider fish behaviour during mission planning).
	What can go wrong?	Communication/hardware/software malfunctioning, sensor failure, emergency alert, bad weather, unexpected obstacles that could lead to operation failure.
	What is the operational safe-state?	If the vehicle/robot is not able to perform the path planning then consider different cases depending on the situation: 1) Power shutdown and do not move in order to perform manual recovery if close to net to avoid any damage, 2) go to safe area or home if not risking destroying the net or harm the fish, 3) try to communicate and obtain the position measurements in case of bad communication.
	HMI	Human should confirm that everything is working properly. The operator should have the responsibility to cancel the autonomous mission and take over as a *super user*.
	Other premises/requirements	Specifications on how fast the robot can move while ensuring that a sufficient number of images are captured for the operation to be

		successful, are to be defined (TBD). Consider bio-interactive criteria such as flight response when performing motion planning operation. What is the battery capacity of the AUV?
	Notes/comments	This stage only considers what is related to the vehicle mission planning. The output of **sub-goal 3.2.1** is input to **sub-goal 1.1.2**.
1.1.3	**Description of sub-goal**	Move AUV to starting point of planned path/route
	Communication	AUV communicates its new position at regular intervals based on underwater positioning system installed in the fish cage so that the operator is able to supervise the operation. The AUV needs to make sure to be on the range of the underwater positioning system during the operation. The AUV must be able to know the distance to the net in each time step and be able to self-localize to avoid any collision with the cage net, the cage structure or other infrastructure in fish cage.
	Perception	The initial position of the vehicle and the position of the fish cage in each time step should be known *a priori*. The current and the wave impact information should be known *a priori*.
	Success criteria	AUV is at starting point with to be defined (TBD) meter accuracy. Enough power required to compensate for environmental disturbances are to be defined (TBD).
	What can go wrong?	Sea current/wave impacts too large to arrive at position, collision with other structures in the fish cage or with the fish, communication breakdown, AUV got stuck in the cage net or other infrastructure in fish farm.
	What is the operational safe-state?	Automatically go to the surface in case any error condition occurs, try to communicate any problem to the operator, turn off thrusters, and let AUV slowly ascend unless it is too close to cage net or to the fish. Power shutdown and proceed to manual recovery (i.e. operator take over the mission as *a super user* and perform manual recovery of the AUV) if the AUV is close to the net or got stuck/collision with fish, fish cage or other infrastructure in fish farms.
	HMI	AUV moves autonomously to starting point of planned path/route under supervision of operator. The operator is able to take over to manually transport the vehicle to starting point as a *super user*.
	Other premises/requirements	The safe range for the starting point to be defined (TBD). What is the battery capacity of the AUV?
	Notes/comments	The output of **sub-goal 3.2.1** is an input to **sub-goal 1.1.3**.
1.1.4	**Description of sub-goal**	Obtain real-time position measurements of the vehicle
	Communication	Proper communication between transmitter and receivers. Make sure that the range of communication is respected. The position and the number of transmitter and the receivers should be specified to obtain a range of the communication that covers the fish cage.
	Perception	The initial position of the vehicle and the position of the fish cage in each time step should be known *a priori*. Sufficient numbers of transmitters and receivers are available. Other relevant sensors to be defined (TBD). Use of underwater positioning system

		combination with numerical methods to realize a position reference system. Used in the SBL (Short Base Line) configuration with four acoustic receivers attached to the cage and an acoustic transmitter placed on the vehicle to measure the position of the vehicle relative to the cage. There is no 'blocking' of the signal sent from the transmitter and that the receivers are on the range to receive the position signals. Cage-relative position reference system that reports the vehicle's position relative to the net.
	Success criteria	Precise positioning system that ensure stable real-time communication.
	What can go wrong?	The setup between transmitter and the receivers fails. Problem with the transmitter or with one or several receivers.
	What is the operational safe-state?	Automatically go to the surface in case of not receiving any signal from the transmitter, try to communicate any problem to the operator, turn off thrusters, and let AUV slowly ascend unless it is strictly below a surface vehicle or close to cage net. Power shutdown and proceed to manual recovery of the vehicle (i.e. operator take over the mission as a *super user* and perform manual recovery of the AUV) if the AUV is too close to the net or got stuck/collision with fish cage or other infrastructure.
	HMI	The operator makes sure that the positioning measurements have been obtained in real-time so that the AUV can move autonomously to the starting point of a planned path/route under supervision of the operator. The operator is able to take over and manually bring the vehicle to the starting point as a *super user* in case that there is a failure in the positioning system.
	Other premises/requirements	Extra demanding task, compared with conventional operations on fixed structures, since the cage net is deformed by waves and currents, and the operations are performed inside of cage with moving fish.
	Notes/comments	The output of this sub-goal is essential for the successful accomplishment of the following sub-goals. This sub-goal is an input to almost all the other operations. The output of **sub-goal 3.3.1** is an input to **sub-goal 1.1.4**.
1.1.5	**Description of sub-goal**	Follow pre-planned AUV path/route
	Communication	AUV communicates its new position (self-localization) and the sensor data measurements at regular intervals so the operator is able to supervise the movement. The AUV is always on the range of the underwater positioning system and is able to receive real-time measurements of the relative distance to the net based on a realistic real-time map of the cage net.
	Perception	Information about sea-current and waves impact are valuable (but not necessary) in order to compensate for the forces acting on the AUV. Avoid obstacles and collisions with fish cage infrastructure or/and fish.
	Success criteria	The AUV follows the pre-defined trajectory with an accuracy of to be defined (TBD) meters. Speed control in order to make sure to obtain sufficient data for image processing.

	What can go wrong?	The sea current is too strong for the AUV to follow its trajectory. The AUV is heading in a different direction than initially expected. The AUV is lost and it is not able to finish the operation. The AUV cannot find/observe any fish in the specified time window, then report and move to **sub-goal 1.1.3**: "Move AUV to starting point of planned path". AUV collision with fish or other infrastructure in fish cage. AUV is not able to transmit/receive data.
	What is the operational safe-state?	If there is a communication problem try to inform the operator, otherwise autonomously go to the surface or starting point and wait for new commands. If failure happened to be defined (TBD) meters close to cage net or stuck/collision with other infrastructure, then power shutdown and wait for manual recovery of the vehicle (i.e. operator take over the mission as *super user* and perform manual recovery of the AUV) to avoid any fish and/or cage net damage.
	HMI	Operator should be able to monitor the AUV all the time, position and status. Operator should have the ability to intervene at any time (abort or change mode) as *a super user*.
	Other premises/requirements	What is the battery capacity of the AUV?
	Notes/comments	The AUV should perform several rounds. The output of **sub-goals 1.1.4, 1.1.11 and 3.2.1** are inputs to **sub-goal 1.1.5**.
1.1.6	**Description of sub-goal**	Underwater docking
	Communication	AUV communicates its new position based on measurements from the underwater positioning system and the real-time map of the fish cage structure at regular intervals so that the AUV is able to perform autonomous navigation and the operator is able to supervise the movement. The initial position of the docking station is *a priori* known.
	Perception	Information about sea-current and waves impact are valuable (but not necessary) in order to compensate for the forces acting on the AUV. Vision sensor based on cameras in order to obtain high-quality images for docking station detection. Subsea docking systems for automatic launching and retrieval of the vehicle, as well as inductive battery charging, and transmission of the large data quantities obtained must be developed.
	Success criteria	Sensor and control systems for safe and robust launch and recovery operation and autonomous docking of the vehicle. Transmit the required vision data to the control station for offline processing.
	What can go wrong?	The sea current and waves are too strong for the AUV to manage successful docking. The AUV is heading in a different direction than initially expected. The AUV is lost and not able to finish the docking. The AUV cannot find/observe the docking station in the specified time window, then report and move to **sub-goal 1.1.3**: "Move AUV to starting point of planned path". AUV collision with fish or other infrastructure. The AUV is not able to transmit/receive data.
	What is the operational safe-state?	If there is a communication problem or it is not possible to find the docking station, try to inform the operator, otherwise autonomously go to the surface or starting point and wait for new

		commands. If failure happened TBD meters close to cage net or stuck/collision with other infrastructure, then power shutdown and wait for manual recovery of the vehicle (i.e. operator take over the mission as *super user* and perform manual recovery of the AUV) to avoid any fish and/or net damage.
	HMI	Operator should be able to monitor the AUV all the time, position and status. Operator should have the ability to intervene at any time (abort or change mode) as *a super user*.
	Other premises/requirements	Requirements specification to be defined (TBD) and conceptual study should be developed for a docking system adapted for use in fish cages. Inspiration will be obtained from existing docking systems used for other application areas as a basis for developing requirement specifications and conducting a conceptual study of a subsea docking system for use in sea cages.
	Notes/comments	
1.1.7	**Description of sub-goal**	No detection or partial detection of fish, net, feed or structure: Autonomously re-plan according to new commands and specifications
	Communication	AUV communicates its new position based on measurements from the underwater positioning system and the real-time map of the cage net at regular intervals so that the robot is able to perform autonomous navigation and the operator is able to supervise the movement.
	Perception	Information about sea-current and waves impact are valuable (but not necessary) in order to compensate for the forces acting on the AUV. Vision sensor based on cameras in order to obtain high-quality images to perform the desired operation.
	Success criteria	The path is re-planned and the AUV is able to detect useful information using the vision sensors.
	What can go wrong?	The sea current is too strong for the AUV to follow the pre-planned path/route. The vehicle is heading in a different direction than initially expected. The AUV is lost. AUV is not able to transmit/receive data. The sensor fails to obtain sufficient data for the planned inspection operation inside the fish cage.
	What is the operational safe-state?	If there is a communication problem or not enough fish visible during the operation by the cameras, try to inform the operator, otherwise autonomously go to the surface and wait for new commands. If failure happened to be defined (TBD) meters close to cage net or stuck/collision with other infrastructure, then power shutdown and wait for manual recovery of the vehicle (i.e. operator take over the mission as *a super user* and perform manual recovery of the AUV) to avoid any fish and/or cage net damage.
	HMI	Operator should be able to monitor the AUV all the time, position and status. Operator should have the ability to intervene at any time (abort or change mode) as *a super user*.
	Other premises/requirements	What is the battery capacity of the AUV? Does any alternative path exist? What is the capacity of memory for saving high-quality images?

	Notes/comments	AUV needs to have vision contact using the camera/s for necessary inspection of an object of interest for a to be defined (TBD) minutes or return to **sub-goal 1.1.3.**
1.1.8	**Description of sub-goal**	Obtain high-quality images from cameras
	Communication	AUV communicates its new position based on measurements from the underwater positioning system and the real-time map of the cage net at regular intervals so that the robot is able to perform autonomous navigation and the operator is able to supervise the movement. Good communication in order to obtain synchronized high-quality images from the cameras with the rest of the measurements.
	Perception	Vision sensor based on cameras in order to obtain high-quality data. Camera system for 3D vision to capture relevant data for several operations. Development of real-time algorithms. Lighting systems that provide adequate picture quality under varying light and visibility conditions in the water.
	Success criteria	High-quality vision data obtained using underwater camera system. Image processing algorithms in combination with other numerical methods to assess whether the data meets the predetermined quality criteria.
	What can go wrong?	The sea current is too strong for the AUV to follow the pre-planned path/route. The vehicle is heading in a different direction than initially expected. The AUV is lost. The AUV is not able to transmit/receive data. The sensor fails to obtain sufficient data to capture high-quality images due to the close proximity of fish, focus problems, poor light- and water quality conditions. Insufficient bandwidth to obtain online transmission of high-quality images required for online image processing relevant to several operations.
	What is the operational safe-state?	If there is a communication problem or insufficient visibility during the operation from the cameras, try to inform the operator, otherwise send signal to the AUV in order to autonomously go to the surface and wait for new commands. If failure happened TBD meters close to cage net or stuck/collision with other infrastructure, then send signal to the AUV to proceed to power shutdown and wait for manual recovery of the vehicle (i.e. operator take over the mission as a *super user* and perform manual recovery of the AUV) to avoid any fish and/or net damage. In case of doubt, the operator shall assess the data quality and give command of the next move.
	HMI	Operator should be able to monitor the AUV all the time, position and status. Operator should have the ability to intervene at any time (abort or change mode) as *a super user*. The operator should be able to decide if the obtained images are sufficient.
	Other premises/requirements	Special focus on developing fully integrated and robust camera technology with low-cost for use in aquaculture. What is the battery capacity of the AUV? Does any alternative path exist? What is the capacity of memory for saving high-quality images?
	Notes/comments	Objective criteria for data quality to be defined (TBD).
1.1.9	**Description of sub-goal**	AUV recovery operation

	Communication	N/A
	Perception	Position system to be working so that AUV moves to the recovery point.
	Success criteria	AUV recovered safely.
	What can go wrong?	Strong current. High waves. AUV did not reach the recovery point. AUV got stuck or collision with fish, the cage net or other infrastructure.
	What is the operational safe-state?	N/A
	HMI	Abort command. Map positions.
	Other premises/requirements	N/A
	Notes/comments	Starts at timeout or abort command from operator.
1.1.10	**Description of sub-goal**	AUV manual operation
	Communication	Receive operator commands, report back position and status.
	Perception	Underwater positioning system for AUV's own positioning, depth sensor for depth mapping and collision avoidance with fish, net and/or other infrastructure.
	Success criteria	Operator has full control of a single AUV.
	What can go wrong?	Collision with fish, net or other infrastructure, communication errors, hardware/software malfunctioning, unexpected weather conditions. AUV got stuck in the cage net or lying at the bottom of the fish cage.
	What is the operational safe-state?	Go to the surface in case any error condition occurs, try to communicate any problem to the operator and keep safe distance to the net and fish in order to avoid any damage.
	HMI	Operator should be able to give manual commands. Operator should be able to monitor the AUV all the time, position and status. Operator should have the ability to intervene at any time (abort or change mode) as *a super user*.
	Other premises/requirements	The operator should be able to manually control the AUV having the proper skills in case of emergency or failure of autonomously planned tasks. Divers should take over in case of extreme emergency for instance when being stuck on the cage net or lying at the bottom of the fish cage.
	Notes/comments	This operation will run in every emergency by giving *a super user* role to the operator.
1.1.11	**Description of sub-goal**	Estimation of the deformation and reconstruction of the cage net structure
	Communication	AUV communicates its new position based on measurements from the underwater positioning system and the real-time map of the cage net at regular intervals so that the robot is able to perform autonomous navigation and the operator is able to supervise the movement. The positions of the locators have been received regularly from the receivers installed on the fish cage.
	Perception	Information about sea-current and waves impact are valuable (but not necessary) in order to compensate for the forces acting on the

		AUV and consider these information/inputs to identify the net deformation. Vision sensor based on cameras in order to obtain high-quality images for cage net deformation. Case 1: Use of Mono SLAM with one camera to get point cloud under the condition that there is not much net deformation. Case 2: Use of Stereo Cameras combined with two Green Lasers for 3D construction of deformable cage net. Case 3: Estimation techniques using underwater locators in different points of the cage. For the estimation of the cage net, two locators can be located at the bottom ring and at the bottom of the fish cage. In addition, another locator needs to be located in the middle of the cage for verification purposes. The positions of the locators will be obtained using a receiver located at the top of the fish cage. The positions relative to the top of the fish cage will be used to estimate the current profile which will be combined with the *a priori* available information about the shape of the fish cage to estimate the deformation in each time step. For the estimation of the deformation the discrete finite element method will be used.
	Success criteria	Speed control of AUV in order to obtain a sufficient number of images for the operation to be successful. Precise position measurements. Cage net visible to the cameras. Real-time algorithms for image processing. Not much deformation and good lighting conditions during the operation when using the underwater camera system. Precise estimation of current profile and *a priori* knowledge of the initial structure of the fish cage for the estimation of the deformation of the net based on measurements from the locators installed in the fish cage.
	What can go wrong?	The vision sensor platform fails to obtain sufficient data to calculate the 3D map of the cage net. The deformation is too rapid and the implemented image processing algorithms fail to reach a conclusion and construct the 3D map of the cage net. offish occluding the camera and thus not possible to take proper images of the cage net. Imprecise measurements of the locators' position which leads to poor estimation of the current profile and thus not possible reach conclusion regarding the deformation of the cage net.
	What is the operational safe-state?	If there is a communication problem between the installed transmitter and the receivers or not enough cage net visible during the operation from the cameras try to inform the operator, otherwise autonomously go to the surface and wait for new commands. If failure happened to be defined (TBD) meters close to cage net or stuck/collision with other infrastructure, then power shutdown and wait for manual recovery of the vehicle (i.e. operator take over the mission as *a super user* and perform manual recovery of the AUV) to avoid any fish and/or net damage.
	HMI	Operator should be able to monitor the AUV all the time, position and status. Operator should have the ability to intervene at any time (abort or change mode) as *a super user*.
	Other premises/ requirements	What is the battery capacity of the AUV? What is the capacity of memory for saving high-quality images?

	Notes/comments	This sub-goal runs in parallel with the **sub-goals 1.1.2-1.1.11.** The output of **sub-goal 3.2.1** is an input to **sub-goal 1.1.11.** The output of this sub-goal could provide relevant information for real-time map **sub-goal 1.1.4**.
	Main goal of operation:	**Operation 1.2. Parasite detection such as sea lice**
ID	**Question**	**Answer**
1.2.1	**Description of sub-goal**	Estimation of the lice population on a fish cage
	Communication	AUV communicates its new position based on measurements from the underwater positioning system and the real-time map of the fish cage at regular intervals so that the robot is able to perform autonomous navigation and the operator is able to supervise the movement.
	Perception	Information about sea-current and waves impact are valuable (but not necessary) in order to compensate for the forces acting on the AUV. Vision sensor based on cameras in order to obtain high-quality images for estimation of lice population.
	Success criteria	Speed control of AUV to obtain sufficient number of images for the operation to be successful. Precise position measurements. Fish visible to the cameras for estimation of lice population. Real-time algorithms for image processing.
	What can go wrong?	The sea current is too strong for the AUV to follow the pre-planned path/route. The vehicle is heading in a different direction than initially expected. The AUV is lost. The AUV is not able to transmit/receive data. The sensor fails to obtain sufficient data to calculate the lice population.
	What is the operational safe-state?	If there is a communication problem or not enough fish visible during the operation of the cameras, try to inform the operator, otherwise autonomously go to the surface and wait for new commands. If failure happened to be defined (TBD) meters close to cage net or stuck/collision with other infrastructure, then power shutdown and wait for manual recovery of the vehicle (i.e. operator take over the mission as *a super user* and perform manual recovery of the AUV) to avoid any fish and/or net damage.
	HMI	Operator should be able to monitor the AUV all the time, position and status. Operator should have the ability to intervene at any time (abort or change mode) as *a super user*.
	Other premises/requirements	What is the battery capacity of the AUV? What is the capacity of memory for saving high-quality images? For general parasite detection inputs from biologists required.
	Notes/comments	This sub-goal runs in parallel with all the **sub-goal 1.1.2-1.1.11**. The output of **sub-goal 3.2.1** is an input to **sub-goal 1.2.1.**
	Main goal of operation:	**Operation 1.3. Behavioural indicators for fish welfare**
ID	**Question**	**Answer**

1.3.1	**Description of sub-goal**	Calculation of rapid fish escape, swimming speed, tail beat frequency and respiratory frequency
	Communication	AUV communicates its new position based on measurements from the underwater positioning system and the real-time map of the cage net at regular intervals so that the robot is able to perform autonomous navigation and the operator is able to supervise the movement.
	Perception	Information about sea-current and waves impact are valuable (but not necessary) in order to compensate for the forces acting on the AUV. Vision sensor based on cameras with at least two cameras (i.e. stereo cameras) to obtain high-quality images for calculation of parameters related to flight response of fish, swimming speed, tail beat frequency and respiratory frequency.
	Success criteria	Speed control of AUV in order to obtain sufficient number of images for the operation to be successful. Precise position measurements. Fish visible to the stereo cameras. Real-time algorithms for image processing and analysis of fish motion possibly based on optic flow techniques and calculation of swimming speed relative to cameras. Implementation of real-time algorithms to track the head, the tail or the gills of the fish. Possible minimum distance close to net to be defined (TBD).
	What can go wrong?	The sea current is too strong for the AUV to follow the pre-planned path/route. The vehicle is heading in a different direction than initially expected. The AUV is lost. The AUV is not able to transmit/receive data. The sensor fails to obtain sufficient data to calculate the parameters related to the behavioural indicators.
	What is the operational safe-state?	If there is a communication problem or not enough fish visible during the operation from the cameras try to inform the operator, otherwise autonomously go to the surface and wait for new commands. If failure happened to be defined (TBD) meters close to cage net or stuck/collision with other infrastructure in fish cage, then power shutdown and wait for manual recovery of the vehicle (i.e. operator take over the mission as *a super user* and perform manual recovery of the AUV) to avoid any fish and/or net damage.
	HMI	Operator should be able to monitor the AUV all the time, position and status. Operator should have the ability to intervene at any time (abort or change mode) as *a super user*.
	Other premises/requirements	What is the battery capacity of the AUV? What is the capacity of memory for saving high-quality images?
	Notes/comments	This sub-goal runs in parallel with the **sub-goals 1.1.2-1.1.11.** The output of **sub-goal 3.2.1** is an input to **sub-goal 1.3.1.**
	Main goal of operation:	**Operation 1.4. Detection of physical injuries and wounds in fish**
ID	**Question**	**Answer**
1.4.1	**Description of sub-goal**	Identification of physical fish injuries and wounds in fish
	Communication	AUV communicates its new position based on measurements from the underwater positioning system and the real-time map of the cage net at regular intervals so that the robot is able to perform

		autonomous navigation and the operator is able to supervise the movement.
	Perception	Information about sea-current and waves impact are valuable (but not necessary) in order to compensate for the forces acting on the AUV. Vision sensor based on cameras to obtain high-quality images for detection and identification of fish injuries and wounds in fish inside the fish cage.
	Success criteria	Speed control of AUV to obtain sufficient number of images for the operation to be successful. Precise position measurements. Fish visible to the cameras. Real-time algorithms for image processing. Depth information is essential for the operation. Image processing algorithms to segment the fish against the background in order to find the shape of the fish (for a known background it is sufficient with only one camera) and identify possible injuries and wounds.
	What can go wrong?	The sea current is too strong for the AUV to follow the pre-planned path/route. The vehicle is heading in a different direction than initially expected. The AUV is lost. The AUV is not able to transmit/receive data. The sensor fails to obtain sufficient data to detect and identify fish injuries and/or wounds. Camera too close to the fish.
	What is the operational safe-state?	If there is a communication problem or not enough fish visible during the operation from the cameras try to inform the operator, otherwise autonomously go to the surface and wait for new commands. If failure happened to be defined (TBD) meters close to cage net or stuck/collision with other infrastructure in fish cage, then power shutdown and wait for manual recovery of the vehicle (i.e. operator take over the mission as *a super user* and perform manual recovery of the AUV) to avoid any fish and/or net damage.
	HMI	Operator should be able to monitor the AUV all the time, position and status. Operator should have the ability to intervene at any time (abort or change mode) as *a super user*.
	Other premises/requirements	What is the battery capacity of the AUV? What is the capacity of memory for saving high-quality images?
	Notes/comments	This sub-goal runs in parallel with the **sub-goals 1.1.2-1.1.11.** The output of **sub-goal 3.2.1** is an input to **sub-goal 1.4.1.**
	Main goal of operation:	**Operation 1.5. Monitoring of fish feeding and feed waste**
ID	**Question**	**Answer**
1.5.1	**Description of sub-goal**	Inspection of feeding process and calculation of feed waste in fish cage
	Communication	AUV communicates its new position based on measurements from the underwater positioning system and the real-time map of the cage net at regular intervals so that the robot is able to perform autonomous navigation and the operator is able to supervise the movement.
	Perception	Information about sea-current and waves impact are valuable (but not necessary) in order to compensate for the forces acting on the AUV. Vision sensor based on cameras in order to obtain high-quality

		images for inspection of feeding process and calculation of feed waste in fish cage.
	Success criteria	Speed control of AUV in order to obtain sufficient number of images for the operation to be successful. Precise position measurements. Fish and feed visible from the cameras. Real-time algorithms for image processing. It is necessary to use set of cameras for this operation. The level of temperature and oxygen desired for feeding process should be known *a priori*.
	What can go wrong?	The sea current is too strong for the AUV to follow the pre-planned path/route. The vehicle is heading in a different direction than initially expected. The AUV is lost. The AUV is not able to transmit/receive data. The sensor fails to obtain sufficient data to detect the feeding process.
	What is the operational safe-state?	If there is a communication problem or not enough fish and feed visible during the operation from the cameras try to inform the operator, otherwise autonomously go to the surface and wait for new commands. If failure happened to be defined (TBD) meters close to cage net or stuck/collision with other infrastructure, then power shutdown and wait for manual recovery of the vehicle (i.e. operator take over the mission as *a super user* and perform manual recovery of the AUV) to avoid any fish and/or net damage.
	HMI	Operator should be able to monitor the AUV all the time, position and status. Operator should have the ability to intervene at any time (abort or change mode) as *a super user*.
	Other premises/requirements	What is the battery capacity of the AUV? What is the capacity of memory for saving high-quality images? Investigate if fish has a specific swimming pattern during feeding.
	Notes/comments	This sub-goal runs in parallel with the **sub-goals 1.1.2-1.1.11.** The output of **sub-goal 3.2.1** is an input to **sub-goal 1.5.1.** The desired values of temperature and oxygen level for feeding process to be defined (TBD) based on the outputs of the **sub-goal 3.1.1.**
	Main goal of operation:	**Operation 1.6. Biomass estimation, average weight estimation and weight distribution**
ID	**Question**	**Answer**
1.6.1	**Description of sub-goal**	Estimate the biomass and average weight and weight distribution in fish cage
	Communication	AUV communicates its new position based on measurements from the underwater positioning system and the real-time map of the cage net at regular intervals so that the robot is able to perform autonomous navigation and the operator is able to supervise the movement.
	Perception	Information about sea-current and waves impact are valuable (but not necessary) in order to compensate for the forces acting on the AUV. Vision sensor based on cameras in order to obtain high-quality images for biomass estimation. Use image processing techniques in order to calculate the size of the fish and then it is possible to obtain the weight distribution. By combining this information with the

		output of the **sub-goal 1.1.1** it is possible to get the biomass estimation inside the fish cage.
	Success criteria	Speed control of AUV in order to obtain sufficient number of images for the operation to be successful. Precise position measurements. Fish visible to the cameras. Real-time algorithms for image processing.
	What can go wrong?	The sea current is too strong for the AUV to follow the pre-planned path/route. The vehicle is heading in a different direction than initially expected. The AUV is lost. The AUV is not able to transmit/receive data. The sensor fails to obtain sufficient data to estimate the biomass, the average weight and the weight distribution of fish in fish cage.
	What is the operational safe-state?	If there is a communication problem or not enough fish visible during the operation from the cameras try to inform the operator, otherwise autonomously go to the surface and wait for new commands. If failure happened to be defined (TBD) meters close to cage net or stuck/collision with other infrastructure, then power shutdown and wait for manual recovery of the vehicle (i.e. operator take over the mission as *a super user* and perform manual recovery of the AUV) to avoid any fish and/or cage net damage.
	HMI	Operator should be able to monitor the AUV all the time, position and status. Operator should have the ability to intervene at any time (abort or change mode) as *a super user*.
	Other premises/requirements	What is the battery capacity of the AUV? What is the capacity of memory for saving high-quality images?
	Notes/comments	This sub-goal runs in parallel with the **sub-goals 1.1.2-1.1.11.** The output of **sub-goal 3.2.1** is an input to **sub-goal 1.6.1.** The detection of size is related to **sub-goal 1.4.1**: Detection of physical fish injuries and wounds.
	Main goal of operation:	**Operation 1.7. Documenting dead fish**
ID	**Question**	**Answer**
1.7.1	**Description of sub-goal**	Calculation of the dead fish number in fish cage
	Communication	AUV communicates its new position based on measurements from the underwater positioning system and the real-time map of the cage net at regular intervals so that the robot is able to perform autonomous navigation and the operator is able to supervise the movement.
	Perception	Information about sea-current and waves impact are valuable (but not necessary) in order to compensate for the forces acting on the AUV. Vision sensor based on cameras in order to obtain high-quality images for detection and calculation of number of dead fish by using image processing algorithms that are able to detect head and tail parts of the fish.
	Success criteria	Speed control of AUV in order to obtain sufficient number of images for the operation to be successful. Precise position measurements. Dead fish visible to the cameras. Real-time algorithms for image processing. Possibly use of other type of sensors to be defined (TBD).

	What can go wrong?	The sea current is too strong for the AUV to follow the pre-planned path/route. The vehicle is heading in a different direction than initially expected. The AUV is lost. The AUV is not able to transmit/receive data. The sensor platform fails to obtain sufficient data to detect and count dead fish.
	What is the operational safe-state?	If there is a communication problem or not enough fish visible during the operation from the cameras try to inform the operator, otherwise autonomously go to the surface and wait for new commands. If failure happened to be defined (TBD) meters close to cage net or stuck/collision with other infrastructure in fish cage, then power shutdown and wait for manual recovery of the vehicle (i.e. operator take over the mission as *a super user* and perform manual recovery of the AUV) to avoid any fish and/or net damage.
	HMI	Operator should be able to monitor the AUV all the time, position and status. Operator should have the ability to intervene at any time (abort or change mode) as *a super user*.
	Other premises/requirements	What is the battery capacity of the AUV? What is the capacity of memory for saving high-quality images?
	Notes/comments	This sub-goal runs in parallel with the **sub-goals 1.1.2-1.1.11.** The output of **sub-goal 3.2.1** is an input to **sub-goal 1.7.1.** The question to be answered is: Do we find dead fish or not during this operation based on the information available from the sensors and we are able to obtain the number of dead fish and the level of degradation.

2.2.2 Autonomous Job Analysis for operations related to the B) Cage inspection

		Autonomous Job Analysis
	Main goal of operation:	**Operation 2.1. Net inspection and identification of holes**
ID	**Question**	**Answer**
2.1.1	**Description of sub-goal**	Detect holes and identify their location in the cage net
	Communication	AUV communicates its new position based on measurements from the underwater positioning system and the real-time map of the cage net at regular intervals so that the robot is able to perform autonomous navigation and the operator is able to supervise the movement.
	Perception	Information about sea-current and waves impact are valuable (but not necessary) in order to compensate for the forces acting on the AUV. Vision sensor based on cameras (sufficient to have single camera) in order to obtain high-quality images for detection and identification of holes and their exact positions in net inside the fish cage. Knowledge of the cage net deformation during the operation. Localization of the AUV relative to the net.
	Success criteria	Speed control of AUV in order to obtain sufficient number of images for the operation to be successful. Precise position measurements. Cage net visible from the cameras. Real-time algorithms for image processing. Good light conditions. Close enough to the cage net and slow motion of the vehicle to ensure sufficient overlap of the

		images. Image processing algorithms able to extract features for online or offline net inspection. Must be able to reference images in relation to a known point on the cage. AUV traverses the net from a predefined distance and heading relative to the net and detect damages/holes using image processing algorithms such as pattern recognition of the cage net grid.
	What can go wrong?	The sea current is too strong for the AUV to follow the pre-planned path/route. The vehicle is heading in a different direction than initially expected. The AUV is lost. The AUV is not able to transmit/receive data. The sensor fails to obtain sufficient data to inspect the cage net or the images are of bad quality. There is too much biofouling to see the net grid.
	What is the operational safe-state?	If there is a communication problem or not enough information/overlap visible during the operation from the cameras try to inform the operator, otherwise autonomously go to the surface and wait for new commands. If failure happened to be defined (TBD) meters close to cage net or stuck/collision with other infrastructure in fish cage, then power shutdown and wait for manual recovery of the vehicle (i.e. operator take over the mission as *a super user* and perform manual recovery of the AUV) to avoid any fish and/or net damage.
	HMI	Operator should be able to monitor the AUV all the time, position and status. Operator should have the ability to intervene at any time (abort or change mode) as *a super user*.
	Other premises/ requirements	What is the battery capacity of the AUV? What is the capacity of memory for saving high-quality images?
	Notes/comments	This sub-goal runs in parallel with the **sub-goals 1.1.2-1.1.11.** The outputs of **sub-goals 3.2.1** and **1.1.11** are inputs to **sub-goal 2.1.1.**
	Main goal of operation:	**Operation 2.2. Inspection of equipment inside the fish cage**
ID	**Question**	**Answer**
2.2.1	**Description of sub-goal**	Inspection and detection of damage of the cage infrastructure
	Communication	AUV communicates its new position based on measurements from the underwater positioning system and the real-time map of the cage net at regular intervals so that the robot is able to perform autonomous navigation and the operator is able to supervise the movement.
	Perception	Information about sea-current and waves impact are valuable (but not necessary) in order to compensate for the forces acting on the AUV. Vision sensor based on cameras in order to obtain high-quality images for detection and inspection of equipment in the fish cage.
	Success criteria	Speed control of AUV in order to obtain sufficient number of images for the operation to be successful. Precise position measurements. Relevant infrastructure visible from the cameras. Real-time algorithms for image processing. AUV traverses the whole volume of the fish cage avoiding colliding with the fish, the net and the infrastructure inside the cage and detect damages by using image processing techniques and comparing the obtained images with the

		a priori available images of the fish cage during the installation stage.
	What can go wrong?	The sea current is too strong for the AUV to follow the pre-planned path/route. The vehicle is heading in a different direction than initially expected. The AUV is lost. The AUV is not able to transmit/receive data. The sensor platform fails to obtain sufficient data to satisfy the inspection criteria to be defined (TBD). Camera occluded by fish and thus not able to record good images of the infrastructure for damage detection.
	What is the operational safe-state?	If there is a communication problem or not enough data available during the operation from the cameras try to inform the operator, otherwise autonomously go to the surface and wait for new commands. If failure happened to be defined (TBD) meters close to cage net or stuck/collision with other infrastructure in fish cage, then power shutdown and wait for manual recovery of the vehicle (i.e. operator take over the mission as *a super user* and perform manual recovery of the AUV) to avoid any fish and/or net damage.
	HMI	Operator should be able to monitor the AUV all the time, position and status. Operator should have the ability to intervene at any time (abort or change mode) as *a super user*.
	Other premises/ requirements	What is the battery capacity of the AUV? What is the capacity of memory for saving high-quality images?
	Notes/comments	This sub-goal runs in parallel with the **sub-goals 1.1.2-1.1.11.** The outputs of **sub-goals 3.2.1** and **1.1.11** are inputs to **sub-goal 2.2.1.**
	Main goal of operation:	**Operation 2.3. Inspection of biofouling condition on the cage net**
ID	**Question**	**Answer**
2.3.1	**Description of sub-goal**	Calculation of percentage net aperture occlusion (PNO)
	Communication	AUV communicates its new position based on measurements from the underwater positioning system and the real-time map of the cage net at regular intervals so that the robot is able to perform autonomous navigation and the operator is able to supervise the movement.
	Perception	Information about sea-current and waves impact are valuable (but not necessary) in order to compensate for the forces acting on the AUV and consider these information/inputs to identify the net condition and visibility. Vision sensor based on cameras in order to obtain high-quality images of the cage net.
	Success criteria	Speed control of AUV in order to obtain sufficient number of images for the operation to be successful. Precise position measurements. Cage net visible from the cameras. Real-time algorithms for image processing. Not much deformation and good lighting conditions during the operation. AUV traverses the net from a predefined distance and heading relative to the net and by using image processing algorithms such as pattern recognition of the cage net grid shape to estimate the biofouling conditions. Good lightning conditions during the collection of the vision data

	What can go wrong?	The sea current is too strong for the AUV to follow the pre-planned path/route. The vehicle is heading in a different direction than initially expected. The AUV is lost. The AUV is not able to transmit/receive data. The sensor fails to obtain sufficient data to calculate the percentage net aperture occlusion. The deformation is too rapid, the quality of vision data not sufficient and the implemented image processing algorithms fails to reach a conclusion and detect the conditions of biofouling. Camera occluded by fish and thus not able to record good images of the infrastructure for damage detection.
	What is the operational safe-state?	If there is a communication problem or not enough cage net visible during the operation from the cameras try to inform the operator, otherwise autonomously go to the surface and wait for new commands. If failure happened to be defined (TBD) meters close to cage net or stuck/collision with other infrastructure, then power shutdown and wait for manual recovery of the vehicle (i.e. operator take over the mission as *a super user* and perform manual recovery of the AUV) to avoid any fish and/or net damage.
	HMI	Operator should be able to monitor the AUV all the time, position and status. Operator should have the ability to intervene at any time (abort or change mode) as *a super user*.
	Other premises/ requirements	What is the battery capacity of the AUV? What is the capacity of memory for saving high-quality images? The cameras will be used to show how much of the net is well-visible and the rest will be assumed to be seaweed.
	Notes/comments	This sub-goal runs in parallel with the **sub-goals 1.1.2-1.1.11.** The outputs of **sub-goals 3.2.1** and **1.1.11** are inputs to **sub-goal 2.3.1.**

2.2.3 Autonomous Job Analysis for operations related to the C) Production environment

		Autonomous Job Analysis
	Main goal of operation:	**Operation 3.1. Monitoring of temperature and oxygen levels in the cage**
ID	**Question**	**Answer**
3.1.1	**Description of sub-goal**	Evaluation of the environmental condition based on temperature and oxygen
	Communication	AUV communicates its new position based on measurements from the underwater positioning system and the real-time map of the cage net at regular intervals so that the robot is able to perform autonomous navigation and the operator is able to supervise the movement. The range of communication should be specified to measure and sent the measured values to the workstation/control room to be available to the operator.
	Perception	Target values of the temperature and oxygen level measurements *a priori* knowledge when starting an autonomous operation. The type of sensors necessary for temperature and oxygen level measurements to be defined (TBD).

	Success criteria	Target range values for oxygen and temperature are necessary for several sub-operations and especially for feeding process and behavioural response of fish. AUV collects the measurements related to the temperature and oxygen level from the whole volume of the fish cage and report possible divergence from target values for individual areas inside the fish cage.
	What can go wrong?	Not sufficient information about the measurements are available for proper accomplishment of other sub-operations. The sensor measurements are wrong and thus the welfare of fish and feeding process are affected rapidly. The AUV moves only in one part of the fish cage providing misleading measurements of the measured values.
	What is the operational safe-state?	Stop the mission if the measurements are not sufficient and avoid risking welfare of fish. In case of values measured for the temperature and oxygen below the target range inform operator and wait for new commands.
	HMI	*A priori* knowledge of optimal temperature and oxygen values. Operator should take a decision if the autonomous mission will start depending on *a priori* initial obtained measurements. Human make sure that proper sensors for measurements are available to obtain sufficient information for temperature and oxygen level measurements.
	Other premises/ requirements	Specifications of the optimal of temperature and oxygen level range for different operations are to be defined (TBD).
	Notes/comments	This sub-goal runs in parallel with all the **sub-operations (1) and (2)**
	Main goal of operation:	**Operation 3.2. Current and wave impact measurements and estimation**
ID	**Question**	**Answer**
3.2.1	**Description of sub-goal**	Estimation of current and wave impact on fish cages
	Communication	AUV communicates its new position based on measurements from the underwater positioning system and the real-time map of the cage net at regular intervals so that the robot is able to perform autonomous navigation and the operator is able to supervise the movement. The range of communication should be specified to measure and sent the measured values to the workstation/control room.
	Perception	Initial local current and wave impact values *a priori* knowledge. Development of proper estimation techniques providing accurate measurements of the current and wave impact values. Commercially available mechanical, electromagnetic, acoustic or optical sensors.
	Success criteria	Precise current and wave impact estimates in real-time.
	What can go wrong?	Current estimates are wrong and thus trajectories are wrong and the robot is unable to follow the pre-panned route.
	What is the operational safe-state?	If the current/wave impact is too strong then perform power shutdown and recover the vehicle manually (i.e. operator take over the mission as *a super user* and perform manual recovery of the AUV) to avoid damaging the cage net.

	HMI	*A priori* knowledge of the present conditions regarding currents and wave impacts. Necessary measurements should be obtained before starting any mission. Operator should take a decision of the autonomous mission will start depending on *a priori* initial current and wave measurements. The (human) operator needs to make sure that proper algorithms for estimation are implemented.
	Other premises/ requirements	Specifications of maximum current/wave impact values the vehicle can tolerate are to be defined (TBD).
	Notes/comments	This sub-goal runs in parallel with all the **sub-operations** (**1) and (2)**

An example of an AJA canvas formulation for the Autonomous Job Analysis is presented for the sub-operation 1.2: Parasite detection such as sea lice (Figure 5). Note that all the other sub-operations can be generated in a similar manner.

Autonomous Job Analysis Canvas

SINTEF SEATONOMY

Communication

What key information needs to be communicated?

Welfare/condition of fish by calculating the average number of sea lice per fish based on high quality images obtained either in real-time or processed after finishing the operation.

What are the communication restrictions and limitations?

The communication range should be specified to measure and sent the measured values to the work-station.

What communication infrastructure can be used?

- At least 2Gbit bandwidth of Ethernet communication for online processing or consider to compress images or adapt fiberoptic solution or, in the worst case, offline processing of the information obtained from the cameras due to the bandwidth restrictions.
- Limit the speed of the AUV in order to get sufficient number of images.
- The desired control signals are sent to the vehicle to ensure that sufficient localization data are received on time in order to track the desired pre-defined path or waypoints.
- Make sure that the emergency stop signal is received regularly.

Human Machine Interaction (HMI)

What type of user interface is needed?
What information does the operator need?
What is the role of the human?

During the operation, a control interface is needed to show the high-quality images obtained, the position of the AUV in real time and the calculation of the average number of sea lice per fish based on online image processing. In addition, a joystick for manual control of the AUV is needed so that the operator as Super User can take over control in emergency situations. The AUV should be able to explore the area of the cage autonomously based on the precise position measurements and following a 3D pre-defined path, while the operator should be able to take over in case of failure of the mission.

Perception

Which information about the environment and the system itself must be available?

- Vision Sensors-Cameras for high quality images
- Underwater positioning system for 3D self-localization of the vehicle
- Sensor to measure the environmental conditions such us current and waves in order to compensate for them during autonomous 3D path following
- Lice Detection based on image processing
- Synchronization of the sensor's outputs

Sub-Operation Description

What are we trying to accomplish?
What is the relationship to other sub operations?

Overall objective:
The overall goal is to provide information about the average number of sea lice per fish.

Qualitative description:
Using underwater cameras attached to an AUV inspect autonomously, using an appropriate underwater positioning system, the fish cage and calculate the average number of sea lice per fish.

Preconditions:

- Have a fully functioning AUV
- Have an underwater positioning system to obtain the position of the AUV
- Have cameras to obtain high quality images of the fish in the cage
- Autonomous navigation of the AUV
- Algorithms for online detection of lice on fish

Success Criteria

What are the criteria for successfully executing the sub-operation?
How do you quantify/measure each criteria?

Efficiency & Thoroughness: Depending on the operation decide if it is sufficient to obtain results for some parts of the fish cage in order to optimize the operation time. Define the criteria re: when is sufficient data collected to allow a decision regarding the need of a lice removal operation.
Constraints: Good localization of the vehicle and high-quality images in order to perform autonomous navigation and obtain sufficient data for online processing and calculation of lice detection percentage. Sufficient tether length in order to perform the operation.
Time bound: Full exploration of the fish cage at least ones or twice per day to calculate the average number of sea lice per fish.

Operational Safe State

What should the system do in case of failure/danger?

Are there several safe states?

Depending on the stage a failure/alert occurs, follow different strategy:

- Power shutdown if critical failure/alert is present.
- Go to a safe area or home if you are not trapped in the cage net and/or if the AUV is not colliding with any obstacle.
- Try to communicate repeatedly if the failure is not critical for the operation.
- Do not move if the robot is trapped in the net or very close to the fish in order to avoid any damage.
- Manual operation (i.e. operator takes over) if there is failure on the planned autonomous task.

What can go wrong

Which external and internal events should be planned for?

Internal events:

- Goal cannot be reached: too demanding tasks, too fast motion of the AUV
- Hardware failure: Robot brakes down, thrusters stop working.
- Human error: Wrong pre-planned path is designed, or mis-leading commands are sent to robot
- Sensor failure: localization sensor network failure, camera sensor failure
- Communication loss: not being able to receive position measurements or damage to the tether.
- Emergency alert due to failure of the operation

External events:

- Obstacles
- Poor light conditions, focus of the camera.
- Bad weather such as strong current and waves

What should the system do in case of undesirable events?

Emergency alert: Depending on what the system was doing during the alert signal:

- Power shutdown - do not move
- Go home or to a safe area
- Manual operation

More information is provided in Operational Safe States.

Other possible inputs

- The AUV will be launched from a support vessel where the control room allows the human operator to take over the operation in case of failure or emergency alert.
- Changes with respect to the camera choice such as lighting conditions, focus of the cameras, distance from the fish.
- Inputs from fish health specialists regarding the acceptable average number of sea lice per fish before confirming the command to proceed to lice removal operation.
- Investigate how fast the AUV can move without disturbing the environment and the fish while making sure to collect a sufficient number of images for lice detection.
- Changes to the system by possibly adapting the sensors by including green laser to obtain net relative localization in fish cage environment.
- Monitor how often the position measurements are available in order to perform autonomous exploration of the area.

Notes/Comments

Connection between different sub-operations: The output of the lice detection sub-operation can be input to the lice removal sub-operation.

Parasite-detection
Sub-goal 1.2

Figure 5 AJA Canvas for the sub-operation 1.1: Parasite detection such as sea lice

2.3 Requirements matrix

Based on the AJA method, a requirement matrix for the operations described in this section has been developed. In the requirements matrix the use of the word "**shall**" denotes requirements that must be met. Use of the word "**should**" denotes requirements that are desirable and must be met unless justification is provided for an alternative. Each requirement shall only contain one "**shall**" or "**should**". The wording TBC (To Be Completed) or TBD (To Be Defined) are used in order to write precise requirements even though not all details are in place yet.

The requirements are grouped according to the following definitions:

- VEH – Vehicle requirements. This refers to the AUV.
- HMI – User interface and control station requirements.
- COM – Communication requirements.
- INT – Distributed intelligence, typically mapping, cooperation algorithms etc.
- GEN – General requirements that does not fit into any of the other categories.

Table 2 shows the requirement matrix for the operations described in the CageReporter project.

Table 2 Requirement matrix for the operations conducted in the CageReporter project

Req. no.	Description	Comment
	VEHICLE (VEH)	
VEH-1	The AUV **shall** have the ability of self-localization with an accuracy minimum of **TBD** horizontally and **TBD** vertically. *Comment: The accuracy will probably be given by the equipment available, not by demonstrator needs.*	
VEH-2	The AUV **shall** detect and report internal faults and error states. *Comment: This includes the battery status.* *Comment: Reporting can be done with varying levels of detail and message priority depending on error criticality.*	
VEH-3	The AUV **shall** react to internal faults and error states. *Comment: Critical errors might invoke safe state.*	
VEH-4	The middleware in the vehicle **should** run on the same embedded computer with interface to the HW already on board the vehicle. *Comment: Unless it is considered easier to integrate into the already existing computer, considering all aspects incl. verification.*	
VEH-5	All sensor data **should** be stored in the vehicle for eventual retrieval after the mission is finished. *Comment: Rationale is for backup in case of communication failure.*	
VEH-6	The vehicle **shall** be able to operate for a minimum of **TBD** minutes.	
VEH-7	The AUV **shall** mount a hydroacoustic underwater communication link.	
VEH-8	The AUV vessel/docking station **shall** deploy a wireless modem for communication with the control room.	
VEH-9	The AUV **shall** be equipped with sensors for detecting the • Fish condition: Biomass estimation, growth and feeding, sea lice, fish behaviour, dead fish, etc. • Cage inspection: net, equipment, biofouling condition, etc • Environment monitoring: temperature, oxygen, current, waves, etc.	
VEH-10	The AUV **shall** support collision avoidance with fish and other infrastructure in fish cages.	
VEH-11	The AUV **shall** have machine vision sensors (mono or stereo camera).	
VEH-12	The AUV **shall** support docking capabilities.	
VEH-13	The AUV **shall** support bio-interactive capabilities.	

	Comment: Motion control algorithms should be implemented to account for bio-interactive motion during the operations in fish farms.	
Use Interface/Control Station (HMI)		
HMI-1	The operator **shall** be able to interfere with the operation. *Comment: This could be to abort the operation, change modes etc. Modes are described elsewhere.*	
HMI-2	Manual mode **shall** overrule automatic mode. *Comment: The operator has the role of a super user during the operations.*	
HMI-3	The data set **shall** be presented or visualized to the operator. *Comment: Design decision whether to use synchronized clocks and where data is to be timestamped.*	
HMI-4	The operator **shall** be given a warning if an abnormal situation occurs. *Comment: Could be an alarm and/or a visual indication.*	
HMI-5	The operator **shall** see the vehicle position in a cage map.	
HMI-6	The operator **should** be able to collect data from the vehicle manually after the operation. *Comment: Might not be necessary to implement for the demonstrators.*	
HMI-7	It **should** be possible to use data retrieved from local storage together with real-time collected data. This means they should have the same format and meaning. *Comment: See VEH-4* *Comment: For example, to present all data collected inside the same map.* *Comment: Might not be necessary to implement for the demonstrators.*	
HMI-8	The operator **shall** be able to configure/change the safe state of each vehicle. *Comment: see INT-7*	
HMI-10	The operator **shall** be able to configure the battery threshold. *Comment: See INT-6*	
HMI-11	The operator **shall** be able to configure what information/data is presented in the HMI.	
COMMUNICATION (COM)		
COM-1	One common communication stack **shall** be used for the underwater network, which preferably should consist of standardized protocols.	
COM-2	The vehicles **shall** be able to send time critical messages directly to the control station.	
COM-3	There **should** be a possibility to detect and cope with bandwidth problems. *Comment: This might, for example, imply to turn off camera live streaming.*	
COM-4	The AUV **shall,** as a minimum, be able to transmit the following data: - Self localization results (typically own position) - Sensor data - Self-test results (including battery status) - Actual Mode (see INT-1 and INT-2) - Speed - Heading - Relevant processed outcomes from image processing	
COM-8	The AUV **should,** as a minimum, receive the following data: - Mode selection - Path to be followed - Timing requirements - Task requirements - Environmental conditions - Manual control commands (in manual mode) - List of commands/info from mission planner	
COM-9	Underwater protocols **should** allow robot localization.	
COM-10	The AUV **shall** be able to send data about the fish, cage net and the environmental conditions and its position to the control station.	
Overwater RF-Communication		
COM-1-RF	The communication via air network between the docking station on the cage and the control station **should** preferably consist of standardized protocols.	

COM-2-RF	The communication subsystem **shall** support RF wireless communication infrastructure between the docking station on the cage and the control station.	
COM-3-RF	The RF communication subsystem **shall** support data transmission from the docking station on the cage to the control station.	
COM-4-RF	The communication subsystem **shall** support transmission of different data types. *Comment: Data types could be video streaming (compressed video), data, mission commands*	
Distributed Intelligence (INT)		
INT-1	The following general modes **shall** be implemented in the AUV: - Manual mode - Go to surface - Go to safe state - Autonomous bio-interactive motion planning *Comment: This requirement looks like a design decision. However, the functionality is needed.*	
INT-2	The following modes **should** be implemented in the AUV: - Stop/Hoover - Go to Position - Battery save mode. *Comment: Battery save mode is not necessary for the demonstration. It can encompass reduced speed, disabling of unused sensors etc.*	
INT-3	Upon loss of communication for **TBD** minutes, the AUV **shall** go to safe state. *Comment: This timeout should be configured by the operator. The safe state TBD to avoid damaging the cage net and harming the fish.*	
INT-4	Upon loss of communication for **TBD** minutes, the AUV **should** search for a position where communication is possible. *Comment: This timeout should be configured by the operator.* *Comment: This timeout should be shorter than that of INT-3.*	
INT-5	Upon low battery, the AUV **shall** go to safe state. *Comment: The battery threshold should be configurable by the operator.* *Comment: if the safe state does not entail going to the surface, the battery threshold should be such that the vehicle can go to the surface with the remaining energy when going to safe state.*	
INT-6	A timeout function activating safe state **shall** be implemented.	
INT-7	The safe state **shall** avoid damage to vehicle, cage net and harm the fish. *Comment: Often, the safe state will be to go to surface and report position for retrieval, but this might vary depending on the operation and environmental conditions.*	
INT-8	Reaction to collision with fish, cage net and the other infrastructure **should** be implemented if required sensors are available.	
INT-9	The AUV **shall** be able to inspect the fish condition.	
INT-10	The AUV **shall** be able to inspect the cage net condition.	
INT-11	The AUV **shall** be able to inspect the environmental conditions in fish cages.	
INT-12	Based on the measurements of the fish escape response, the AUV **shall** be able to determine the safe distance from the fish based on the bio-interactive path following control approach implemented.	
General (GEN)		
GEN-1	The AUV **shall,** as a minimum, support basic inspection tasks specified during the operation. *Comment: The task should be accomplished considering a bio-interactive motion planning control approach based on the escape response of the fish during the operation.*	

3 Recommendations and specifications obtained based on the Seatonomy method

In this section, we list the specifications of the underwater positioning system and the requirements for the camera system in order to obtain high-quality images. We have reached these conclusions based on the Seatonomy theoretical analysis conducted in earlier section. Based on this analysis, it is possible to specify the necessary tasks and specifications/conditions/requirements in order to achieve autonomous navigation of the vehicle and record high-quality images to detect and analyse the fish conditions and cage inspection related tasks. These parameters have been discussed with all the partners to avoid any misunderstanding and make sure that all partners are aware of the different sensors requirements, vehicle specifications, range of quality data capturing, needs for additional sensors, need for adaptations on the setup and the equipment, needs to consider special/more simple situations if the tasks too demanding etc. from the very beginning.

3.1 List of requirements to obtain high-quality images from the cameras

Details about the specifications needed to obtain high-quality images from the cameras can be found in Table 3. In this table, the desired specifications based on the Seatonomy analysis have been defined. The parameters related to the cameras/images/vision data specifications have been discussed with Sealab Ocean AS to ensure that the different sensors requirements, vehicle specifications, range of quality data capturing, need for additional sensors, need for adaptations on the setup and the equipment, consider special/more simple situations if the tasks too demanding, etc. are respected. Sealab Ocean AS have provided the actual system specifications (see Table 3). This information provides useful inputs regarding control function implementation for autonomous navigation and for the possible experimental trials in this project. Furthermore, it is essential to summarize the specifications of the camera system (Table 4) that will be used in CageReporter project for the possible showcase scenarios in field trials. This information is essential for the installation and the integration of the camera system on the underwater vehicle for the possible planned field tests related to A) Fish conditions and B) Cage inspection.

Table 3 List of requirements for obtaining high-quality images from the cameras (Sealab Ocean AS)

	Desired Specifications (Seatonomy)	**System Specifications (Actual)**
Lighting conditions	The exposure time should be small in order to avoid motion-blur in single frames. Exposure times <1/500s would be ideal. Exploit natural sunlight (likely best around 12:00 O'clock) and/or add artificial lighting.	The exposure time 1/500s is feasible but tests have shown that 1/300s is ideal and gives better depth in images. For lighting, 4 LED lights from Sealab Ocean, each 8000 Lumens, all dimmable from 0-100%, will be used. Lighting will be off axis to avoid backscatter. Total power required is approximately 300W.
Auto/manual focus	Manual and Auto focus should both be possible. Ideally, it should be possible to change the focus remotely.	This is feasible with the Sealab Ocean AS control software.
Capturing distance from net/fish	0.6m (if possible 0.1m) to 5m (if in-water visibility permits, 15m)	Approximately 0.5 meters to infinity (focus), but water conditions will limit how far you can see.
Number of Required Cameras	Stereo camera for direct metric measurements (=2 cameras). Baseline of the cameras adjustable. Other tasks may be sufficiently solved with a single camera.	Case 1: To keep the setup simple we would initially use a monoscopic camera in this case. Case 2: A 3D vision camera system is developed for more challenging operations.
Communication Bandwidth	Raw image transmission would be ideal. However, then the required bandwidth for 2 cameras would be quite high. To take a raw image size of 1288(H) x 964 (W) pixels and 3 bytes per pixel with a framerate of 60 (FPS) x 3(BPP), a bandwidth of 1288(H) x 964 (W) x 60 (FPS) x 3(BPP) => approx. 223.49 Megabytes/second is needed (for each camera). This corresponds to a desired	Sealab Ocean AS will provide a hybrid umbilical for both fiber communication and electric power delivery. NB! topside 16A 230VAC required!

	total bandwidth of ~3.6 Gigabit for both cameras combined.	
Image Resolution	Larger than 1280x800 pixels	1080p@25 8 bits per color
Etc. (which other parameters should be considered to make sure that the data obtained from the cameras are sufficient for the described operations for A) Fish conditions, B) Cage inspection).	Generally, the signal to noise ratio should be good (large=> low noise). Color cameras.	This is feasible with the developed solution from Sealab Ocean AS.

Table 4 Technical specifications of the camera system to be used in CageReporter

	Sealab Ocean AS Camera System
Total weight of cameras	Approximately 3Kg in air, 1.5Kg in water
Dimensions	Approximately 350x140mm
Connection requirements	Hybrid cable from surface to conjunction box. Size of box approximately of 450x200mm (cylinder), weight 5kg in air and 3kg in water.
Communication requirements	Provided by Sealab Ocean AS previous setup. Topside communication with underwater vehicle.
Position to mount on underwater vehicle	Very flexible and use of standardized mounting clams and fixtures.
Bandwidth requirements	1Gb/s
Include other relevant specifications	Monitoring and recording systems topside taken care of by Sealab Ocean AS.

3.2 List of requirements to obtain accurate position measurements

The list of requirements to obtain accurate position measurements are summarized in Table 5. WaterLinked AS have included the system specifications of the available position systems and how they can meet the desired requirements in Table 5. The parameters related to the underwater positioning data specifications have been discussed with WaterLinked AS to ensure that the different sensor requirements, vehicle specifications, range of quality data capturing, need for additional sensors, need for adaptations on the setup and the equipment, consider special/more simple situations if the tasks too demanding, etc. are respected. Details about the specifications can be found in Table 5. This information provides useful inputs when it comes to control function implementation for the autonomous functions, real-time estimation of net deformation and for the possible experimental trials. In addition, the technical specifications of the positioning system (Table 6) have been provided by WaterLinked AS and this information will be used to plan and showcase the planned field trials in the project.

Table 5 List of requirements to obtain precise position measurements (WaterLinked AS)

	Desired Specifications	**System Specifications**
Desired accuracy of position measurements (XYZ position)	±0.5 m in absolute distance (i.e. the norm of XYZ)	The current WaterLinked system has an accuracy of 1% of the distance from the receivers.
Estimated area of the cage to fully cover for the autonomous navigation of the vehicle	Diameter = 50 m Depth = 20 m Total volume = 40.000 m^3 Maximum distance of vessel from locator = ca. 54 m	This is feasible with the WaterLinked system.
Number and position of the receivers to be installed in the fish cage to have full coverage of the fish cage area necessary for proper navigation of the vehicle	Although one system per cage should be sufficient to obtain acoustic coverage, at least three systems will be needed when estimating the net structure for navigation purposes. This	To get good coverage, 4 receivers should be used. They need to be separated by 1-2 meters between each receiver. To help with triangulation, receives should be placed at different depths.

	is because the net estimator requires an absolute minimum of two position measurements in the net to estimate the net structure and shape (note that the net estimation procedure will be more accurate if we can go beyond two position measurements).	
Specify how often the position measurement should be updated for the real-time navigation purposes of the ROV	1-2 samples per second should be sufficient.	The WaterLinked system updates the position at 4 Hz.
Specify what the system should do in case of loss of position measurements (backup solution)	The AUV should be positively buoyant so that it surfaces when shut down. Shut off thrusters and actuators to avoid damaging the net or other cage components.	The system will always provide a position even when there is no Locator in the water. If there is no Locator in the water the position will jump around randomly. Therefore, there should be a backup navigation system such as an IMU.
Any additional information needed to obtain accurate and real-time position measurements	The precision will depend on the cage model that will be developed.	Adding an IMU on the underwater vehicle to support the positioning of it will facilitate providing a stable positioning of the vehicle.

Table 6 Technical specifications of the positioning system to be used in CageReporter

	Specifications for the underwater positioning system
Total weight of transmitter/receiver	Each receiver weights 36 g without cable, but additional weight should be added to keep them stable in the water. Locator weights from 30g to 52g, depending on the choice of Locator. The total weight of the system is around 4 kg.
Dimensions	Topside unit: 270 x 246 x 124 mm Receivers: 71 x 20 mm (cylindrical) Locator A1: 41 x 20 mm (cylindrical) Locator S1: 76,6 x 30 mm (cylindrical) Locator D1: 81 x 30 mm (cylindrical) Locator U1: 32 x 121 mm (cylindrical) Locator P1: 50 x 154,5 mm (cylindrical)
Connection requirements	The connection from the topside case is via ethernet with RJ-45 and power is 10-18V.
Communication requirements	From topside case the connection is ethernet.
Position to mount on ROV	A bracket is needed to mount the Locator. The Locator should be mounted high on the underwater vehicle. Preferably on top where the head of the Locator has minimal obstruction to send the signal.
Bandwidth requirements	The WaterLinked system uses frequencies from 100 kHz to 200 kHz (selectable)
Include other relevant specifications	Possible locators and requirements: • **S1:** Only needs power (10-18V) from the underwater vehicle but the depth of the vehicle needs to be provided to the software API. • **A1:** Need its own twisted pair in the umbilical connected to the top side case. The depth of the vehicle needs to be provided to the software API. • **D1:** Does not need any integration with underwater vehicle but needs its own cabled connected to the top side case. • **U1:** Does not need any integration with underwater vehicle. It is wireless (battery powered) and it has its own depth sensor. • **P1:** Same characteristics as S1. However, it is more powerful and thus it is suitable for use in very noisy environments. To get a better and more stable position, it is recommended to use an IMU with the acoustic positioning system, especially when using it to perform autonomous driving. The acoustic reference system is north-east-down with Y being north, X being east, and Z being down.

3.3 List of requirements for autonomous navigation of the vehicle in a fish cage

1. Specify the requirements for real-time mapping (e.g. estimation of net deformation) of the fish cage and discuss what kind of other sensors need to be used in order to develop the real-time map of the fish cage.
    a. This has been addressed in workpackage H1.2, where a detailed report of the obtained results is available.
    b. For the estimation of the cage net, two locators from WaterLinked AS have been located at the bottom ring and at the bottom of the fish cage. For verification purposes, an additional locator has been located in the middle of the cage. The positions of the locators have been obtained using a set of four receivers located at the top of the fish cage. The positions relative to the top of the fish cage have been used to estimate the current profile which was combined with the *a priori* available information about the shape of the fish cage to estimate the deformation in each time step. For the estimation of the deformation, discrete finite element methods have been used.
2. For the implementation of the autonomous navigation control functions, it is necessary to know the 3D position and the full range of position measurements.
    a. This has been addressed in H1.1, where a detailed report of the obtained results is available.
    b. The underwater positioning system from WaterLinked AS has been tested and it provides precise XYZ position measurements of the vehicle.
    c. The range of position measurements should be identified and how the presence of biomass influences the measurements during the motion of vehicles. Results are obtained and discussed in detail in the report of H1.1.
    d. Roll, Pitch, and Yaw measurements can be obtained using the onboard measurements available on the underwater vehicle.
3. Have an operational vehicle with the necessary sensors installed on it.
    a. Argus Mini ROV (Figure 6 and Figure 7) will be used instead of an AUV for the field trials in this project in order to demonstrate case studies relevant to A) Fish conditions, B) Cage inspection and C) Production environment.
    b. Necessary sensors have been installed to provide the required measurements for the planned operations in this project.
4. Attach the camera/cameras on the underwater vehicle and make sure to respect the desired bandwidth to obtain the data for image processing.
    a. The underwater camera system from Sealab Ocean AS has been installed on the Argus Mini ROV.
    b. The characteristics of the camera and the communication requirements have been presented in previous section.
5. Discuss which kind of sensors should be installed on the Argus Mini ROV in order to measure all relevant information (current, wave impact, oxygen saturation, temperature, etc.)
    a. A list of required sensors has been proposed based on the results from Seatonomy method.
    b. A list of the sensors to be installed on the Argus Mini ROV has been posted in section 3.4.
6. Specify which is the maximum payload that the robot could afford without impact on the behaviour of the vehicle.
    a. The maximum payload of the Argus Mini ROV is 15kg by removing gripper and onboard HD camera.
    b. The weight of the locator from WaterLinked and the weight of the underwater camera system from Sealab Ocean AS are given on the specification Tables in previous section 3.2.

7. Implement functions for a) path following, b) trajectory tracking, c) automatic reaching initial point, d) autonomous recovery e) speed control etc. considering ideal position measurements and the available 3D net map as inputs.
    a. This is related to the deliverable of H3, where the report described in detail the implemented functions for autonomous navigation.
    b. The control panel available for the operator to observe the autonomous mission should be implemented. The operator should be able to have a *super user* role and be able to cancel the mission anytime.
8. For simulations: implement vehicle, the sea environment, cage and cage net structure, wave and current impact and all the necessary functions for autonomous navigation functions mentioned in bullet 7.
    a. This is related to the deliverable of H3, where the complete simulation environment is described in detail.
9. Implement bio-interactive control approach based on simulations and considering that there is a detection of a change in fish behaviour due to the motion of the vehicle. Adapt the behaviour of the navigation and the vehicle based on this input.
    a. This is related to the deliverable of H3, where the bio-interactive control concepts developed are presented in detail.
    b. Figure 8 shows the illustration of the control strategies to be implements for both the inspection of the fish cage/fish/net and the navigation related control strategies of the vehicle.
10. Define the required information needed for a bio-interactive control approach (for instance, measurement of the rapid change of speed and turning motion of fish based on images processing, etc.).
    a. This is related to the deliverable of H2, where image processing techniques are developed to identify relevant inputs for bio-interactive control concept implementation.

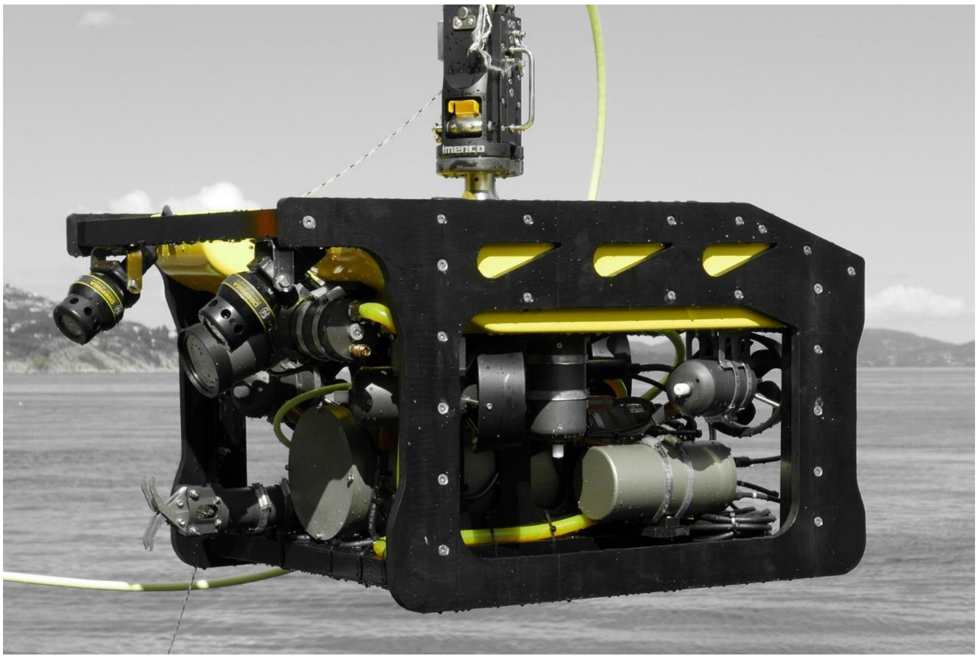

Figure 6 Argus Mini ROV

General

Dimensions:

Length	: 0.9m
Width	: 0.65m
Height	: 0.5m
Weight	: ca. 90kg
Payload	: 5kg
Frame	: Aluminum
Pods	: Hard anodised Aluminum
Connectors	: Subconn / Seaconn
Buoyancy	: Syntactic foam
Depth rating	: 300msw

Power requirements

ROV/HPU Power input	: 230VAC , 3kW , Single-phase
Thrusters	: 6 x electric, 4 Horizontal and 2 vertical

Performance

Bollard pull fwd	: 40kg
lat	: 28kg
vert	: 24kg
Speed fwd	: 2,5-3kn
vert	: 2kn

Surface controls

Power distribution panel	:Fitted LIMS for Power safety
Control Console	:Stand alone panel Integrated touch screen Surface Control box Argus Video overlay Hard Disk Recorder

Standard equipment fit

Lights	: 2 x Argus 130W LED Lights, gives 23 000 lumen, 4500 Kelvin in total
Tilt for camera	: 24VDC
Depth sensor	: 0-5V
Compass	: Fluxgate
Auto functions	: Auto Head Auto Depth Auto Altitude (if Altimeter fitted)

Optional equipment

Sonar	: Tritech, Mesotech or Blueview
Altimeter	: Tritech PA500
HDTV Camera	: 1080i camera
Manipulator	
Latch for launch and recovery	
Ethernet channel	

Figure 7 Technical specifications of Argus Mini ROV

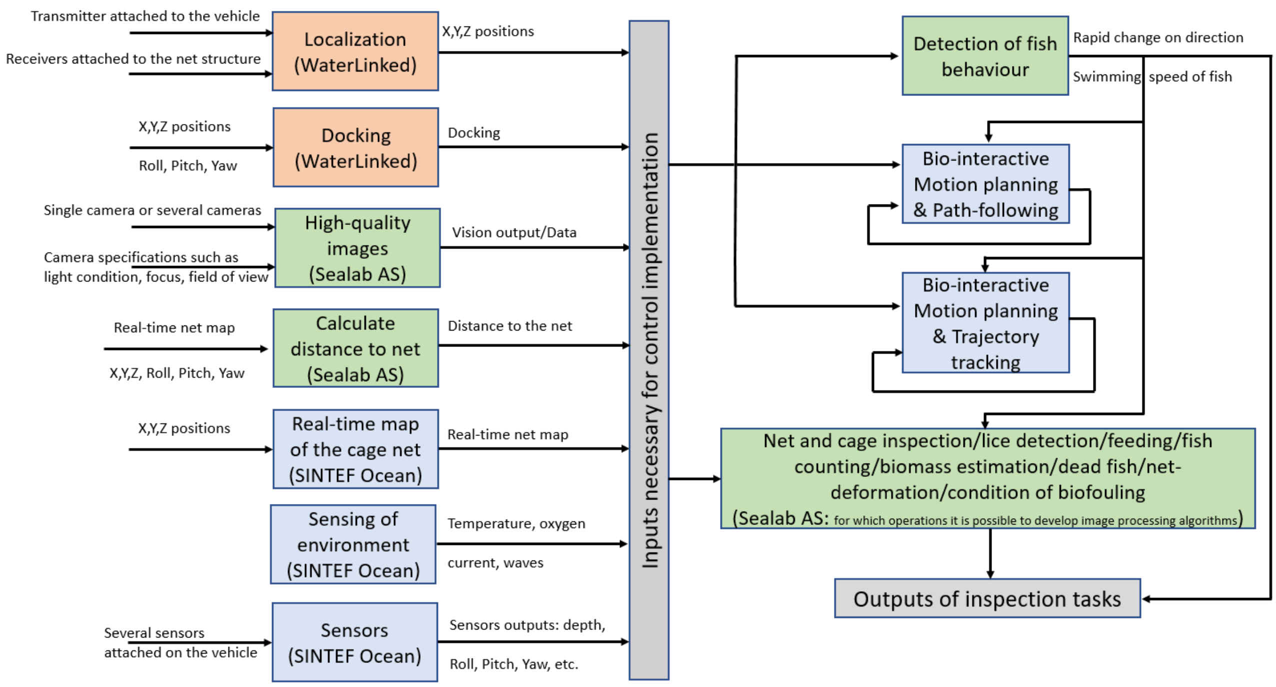

Figure 8 Illustration of the control strategies

3.4 Required sensors to be installed on the Argus Mini ROV

The list of required sensors to be installed on the underwater vehicle for the planned operations in this project have been listed below:

1. Wireless locator from WaterLinked AS: The specifications are given in Table 6.
2. Underwater vision system from Sealab Ocean AS: The specifications are given in Table 4.
3. IMU, depth sensor, etc: The specifications are given in Table 8.
4. Environmental sensors for temperature and oxygen level measurements: The specifications are given in Table 7.

Table 7 Technical specifications of the environmental sensors to be used in CageReporter

	Specifications for HOBO Pendat Temperature/light 64K Data Logger	**Specifications for miniDOT Logger**
Picture		
Total weight of the sensors	18g	340g
Dimensions	58 x 33 x 23 mm	50mm diameter x 187mm length
Connection requirements	n/a	n/a
Communication requirements	Data readout via Optic USB interface	Data readout via USB or SD-card
Position to mount on ROV	Can be mounted anywhere on the ROV due to its small size	Can be mounted anywhere on the ROV due to its small size
Include other relevant specifications	**Measurement range** Temperature: 20° to 70°C Light: 0 to 320,000 lux (0 to 30,000 lumens/ ft^2 **Accuracy** Temperature: ± 0.53°C from 0° to 50°C Light: Designed for measurement of relative light levels **Resolution** Temperature: 0.14°C at 25°C Drift: Less than 0.1°C/year **Battery:** CR2032 **Water depth range:** 30m from –20°C to 20°C **Environmental Rating:** IP68	**Measurement range** Temperature: 0 to 35°C Oxygen: 0 to 150% saturation **Accuracy** Temperature: +/- 0.1 °C Oxygen: +/- 5% of the measurement or +/- 0.3 mg/l **Resolution** Temperature: 10 millidegrees Oxygen:0.01 mg/l **Battery:** Two AA lithium batteries **Water depth range:** 100m **Sensor type:** Optical

Table 8 List of sensors that are available on the Argus Mini ROV

	Sensors installed on the Argus Mini ROV
Depth sensor	Keller PA-23SYEi/81821.05, Range 0-100bar, RS-232 connection
Fluxgate compass	OceanServer OS5000 Series, RS-232 connection
Pitch / roll sensor	OceanServer OS5000 Series, RS-232 connection
Camera	Focus Zoom Colour Camera with HD-SDI video output
LED lights	LED lights fitted are 130W, resulting in approx. 115000 lumens each

4 Conclusion

This report presented results on how the AJA method has been applied when designing the autonomous underwater vehicle concept in CageReporter project. After the main goal of each operation had been defined, the operation was broken down into sub-goals and sub-operations to reduce the complexity of the analysis, and questions related to the AJA categories were answered for each sub-operation. These categories include key aspects for autonomous systems such as human machine interaction, success criteria, safe states, perception, communication, failure modes and safety barriers. Through an iterative workflow, where complexity was added incrementally, the required tasks for each unit to achieve the overall inspection and monitoring goals were identified. This includes analysis to identify autonomous capabilities that the system must possess for the various operations related to A) Fish conditions, B) Cage inspection and C) Production environment. Solutions for autonomous navigation of the vehicle inside the fish cage were obtained as well, together with the technical specifications of the necessary equipment for sensing, localization, high-quality data capture and communication. The outcomes of this report will be used for the autonomous navigation concepts to be developed in H3 and the complete HW and SW system integration and demonstration in H4.

5 References

J. G. **Balchen**, *Possible roles of remotely operated underwater vehicles (ROV) and robotics in mariculture of the future, Model*. Identification Control, 1991.

E. **Grøtli**, T. Reinen, K. Grythe, A. Transeth, M. Vagia, M. Bjerkeng, P. Rundtop, E. Svendsen, Ø. Rødseth, G. Eidnes, *Seatonomy: Design development and validation of marine autonomous systems and operations*. In Proc. MTS/IEEE OCEANS'15 Washington DC, USA, 2015a.

E. **Grøtli**, M. Vagia, S. Fjerdingen, M. Bjerkeng, A. Transeth, E. Svendsen, P. Rundtop, *Autonomous job analysis a method for design of autonomous marine operations*. In Proc. MTS/IEEE OCEANS'15 Washington DC, USA, 2015b.

R, **Parasuraman**, T.B., Sheridan and C.D., Wickens, *A model for types and levels of human interaction with automation.* IEEE Transactions on systems, man, and cybernetics-Part A: Systems and Humans, 30(3), 2000.