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Report

Seatonomy applied in operational analysis of an autonomous net cleaning robot

NetClean 24/7 report for work package H1.1: Operational analysis and overall system design

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ABSTRACT
This report presents an analysis of the autonomous cleaning operations handled in the NetClean 24/7 project. The analysis was conducted using the Autonomous Job Analysis (AJA) concept introduced in the Seatonomy method. This includes the identification of the autonomous capabilities that a tetherless cleaning robot needs to conduct simultaneous net cleaning and inspection, as well as system design requirements and specifications related to equipment, sensors, actuators, architecture, error management and safe modes.

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APPENDICES

1 Background

1.1 Introduction

Biofouling, the unwanted growth of organisms such as algae and hydroids, is a challenge for salmon farming worldwide [1], [2]. Biofouling organisms blocking the water flow through the cage net can lead to decreased oxygen levels within cages, net deformation, and increased stress on mooring systems, while the presence of pathogens among biofouling organisms may impact fish health. Moreover, in Norway and Scotland where cleaner fish are used as biological sea lice control agents, farmers are concerned that the presence of biofouling as feed source for cleaner fish may decrease their delousing performance [1], [2]. As preventative measures such as biocidal coatings have only limited efficacy [3], biofouling removal using in-situ net cleaning is currently the main strategy employed in European salmon farms.

In Norway, net cleaning is usually conducted every 2-4 weeks, but may take place weekly from June to November [4]. These operations are weather dependent, costly, and time-consuming, typically occupying 2 operators per cage for 1-8 hrs (SINTEF, unpublished data). Existing net cleaning units may measure up to 3 m, meaning that they must be operated using a dedicated service vessel with a crane, onboard pumps and a control room in an operation that is very energy consuming and at best semi-autonomous.

In addition to economic challenges, the cleaning waste released during net cleaning poses a number of risks for fish health and welfare [5]. The released fragments of biofouling organisms [6] have been shown to negatively impact gill health [7], [8] and farmers report reduced appetite in salmon and increased mortality among cleaner fish in connection to cleaning operations. In addition, high-pressure cleaning has repeatedly been accused of causing damage to the net resulting in fish escapes [9] and has been shown to lead to abrasion of the antifouling coatings often used on the nets, significantly reducing their functionality and life span [10] and contributing to the annual release of approximately 1000 t of copper in Norwegian waters [11]. There is clearly a need for alternative net cleaning technology.

The collection of environmental data at fish farms in Norway is typically conducted via sensors located at the feed barge that log temperature, salinity and oxygen. Although variability between individual cages with regard to e.g. water currents [12] or oxygen [13] can be substantial, individual cages are usually not outfitted with sensor equipment beyond a feeding camera. Furthermore, in the event that data is collected, the analysis of these is commonly conducted manually based on the subjective interpretation of the individual farmer. Similarly, net inspection to ensure structural integrity and the absence of holes that fish could escape through, is conducted manually. Nowadays, ROVs (Remotely Operated Vehicles) are the most widely used solution for net inspection, requiring specially trained and experienced ROV pilots. Akin to net cleaning, net inspections are conducted every 2-4 weeks, and are tedious and time consuming while leaving very little room for error.

1.2 NetClean 24/7 project

The goal of the NetClean 24/7 project is to develop an autonomous, untethered robot for prevention of biofouling and inspection of net integrity. The permanently installed robot will be small, energy efficient, have its own docking station and it will conduct continuous net cleaning, data gathering through integrated sensors and inspection operations in fish farms. By cleaning continuously, the robot will prevent the establishment of a biofouling community on the net and thus the release of harmful cleaning waste, likely improving fish health and welfare. The sensors on the robot will allow a closer monitoring of cage conditions, enabling the optimisation of farming processes. Automation of the cleaning and inspection process will support farming in remote locations and under difficult weather conditions.

The NetClean 24/7 project aims to develop novel technology and build an advanced self-actuated robot, permanently installed inside each cage, see Figure 1. By developing new control and management strategies that do not impact fish health, the project aims to make the salmon farming industry more sustainable.

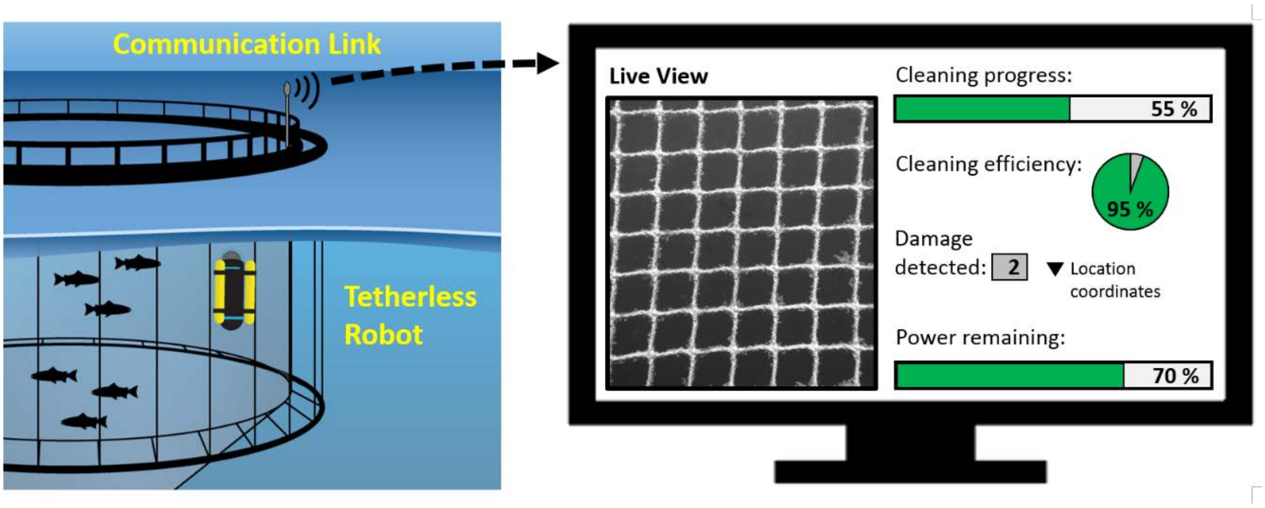

Figure 1 Permanently installed, autonomous and tetherless robot for simultaneous daily cleaning and inspection operations

The developed robot is built on new knowledge generated within automation and biofouling management and will enable the salmon industry to improve farming control and productivity while reducing costs and risks related to cleaning operations. Furthermore, the developed robot carries an integrated sensor consisting of cameras and environmental sensors. Computer vision algorithms enable the robot to detect holes in the net and thereby help reduce the numbers of fish escaping the cages.

1.3 SEATONOMY – Autonomous Job Analysis (AJA) and the AJA Canvas

SEATONOMY describes a methodology that provides a structured approach for design, development and validation of mobile autonomous maritime operations and systems [14, 15]. The goal is to achieve this by providing system developers of autonomous systems with suitable guidelines, principles, best practices and tools. The SEATONOMY methodology provides a structured way for design, development and validation of *autonomous functionality*. The main purpose of the AJA method is 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. The focus on autonomy is introduced early in the design phase. The AJA method can be summarized by the following steps:

- 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.

The Autonomous Job Analysis consists of the following steps:

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 (HMI)”, “Other premises/requirements” and “Notes and comments”. The last two rows are to allow for additional information, which do not fit into the other categories.

<u>The following steps are required during post processing and performing the AJA, preferably in an AJA meeting with all involved stakeholders:</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 [16]. 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* – where 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 NetClean 24/7 project, the AJA concept from the Seatonomy method [14, 15] was used to analyse the autonomous operations. Figure 2 shows the block diagram of the iterative approach adapted to perform the Seatonomy method in this report.

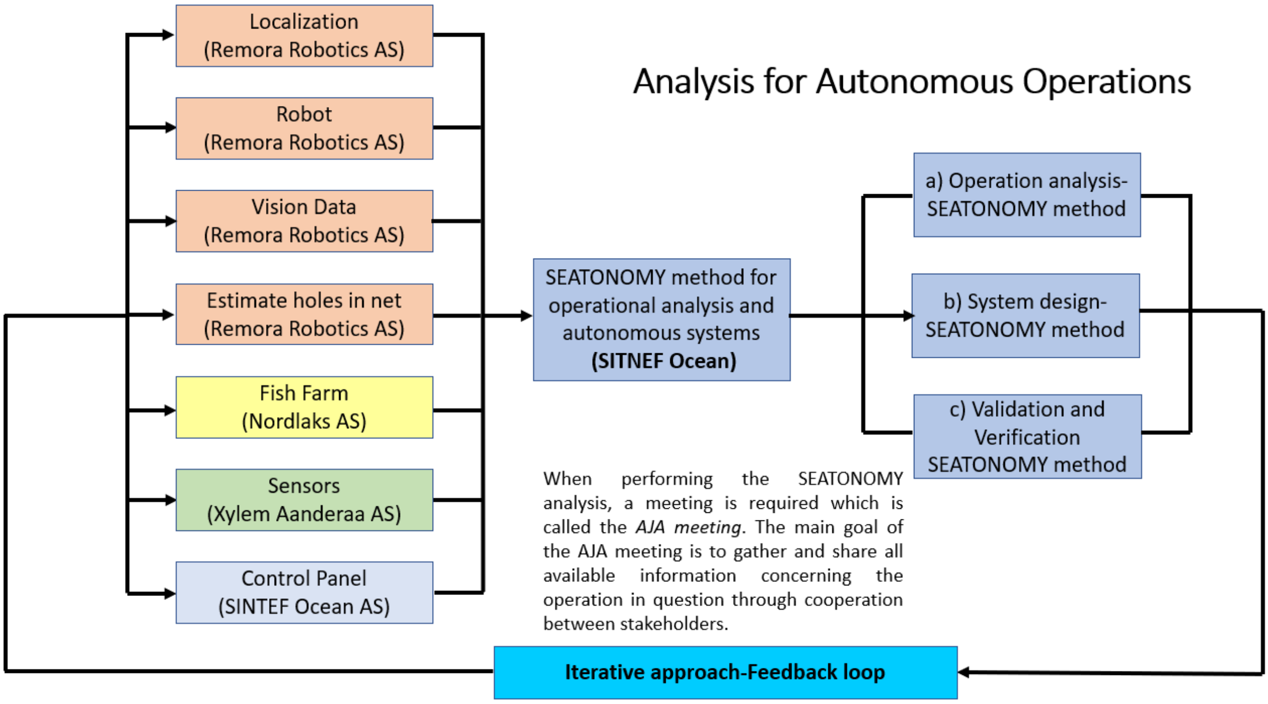

Figure 2 Seatonomy method adapted for autonomous operations analysis in NetClean 24/7

2 Use-case: Tetherless robot for biofouling prevention and inspection in salmon farming

In this report, we apply the AJA methods to solve the challenges present when an underwater vehicle is used as an autonomous, permanent resident vehicle for cleaning and inspection of fish nets. Table 1 shows the operations that have been analysed based on the AJA method. Some of the operations will be demonstrated in full-scale field trials. The robot will autonomously clean the cage nets, detect holes in the net and measure relevant environmental variables, all while ensuring optimal operation based on battery capacity, cleaning efficiency and environmental conditions. The robot will be able to determine if it is safe to perform a mission based on the environmental conditions and if a full, or partial mission should be carried out based on the battery capacity. The robot will use computer vision algorithms to determine its position, to detect holes in the nets and to accurately inform the operators about the locations of the holes. The positioning system will also allow the operators to gain knowledge about the level of biofouling and environmental conditions at different locations of the net. The analysis was conducted based on the Remora version of September 2020.

Table 1 Operations and sub-goals

Main goal: Tetherless robot for biofouling prevention and inspection				
Operations	Environmental condition monitoring	Net and biofouling inspection	Cleaning/prevention	Docking
Main sub-goal	Measure temperature, oxygen, pressure, water currents etc.	Detect and verify net conditions	Clean the cage net	Accomplish docking

The autonomous operations A) Environmental condition monitoring, B) Net and biofouling inspection, C) Cleaning/prevention and D) Docking are described by the following stages:

Stage 0: Deployment of robot and installation of docking station inside the fish cage
- **Actors**: Robot and support vessel
- **Actions to be done**: The robot and the docking station are deployed and permanently installed inside the fish cage using a support vessel.

Stage 1: Daily mission planning related to the cleaning and inspection operations
- **Actors**: Operator of the fish farm
- **Actions to be done**: The operator decides the mission that the robot should perform and is able to cancel, change or re-plan the mission depending on the conditions and data exchange between the control centre and the robot/docking station.

Stage 2: Perform autonomous inspection and intervention operation
- **Actors:** Robot
- **Actions to be done:** The robot is able to do autonomous cleaning and can, by obtaining high quality data through cameras and other environmental sensors, extract parameters related to A) environmental conditions and B) net cleanliness and integrity. The robot is 'crawling' on the cage net and collects data from the whole net, while at the same time preventing biofouling by brushing the net.

Stage 3: Data transfer to the docking station
- **Actors:** Robot
- **Actions to be done:** The robot sends data to the docking station via a high bandwidth communication link and/or transmits the obtained data after each mission by docking to the docking station.

Stage 4: 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.

The main goal, operations and main sub-goals are shown in Table 1.To accomplish the main goal, the robot must perform four different operations (simultaneously or individually). Each operation consists of one main sub-goal and several lower level goals which in many cases are overlapping. For instance, the 'Accomplish docking' and 'Follow path' low level goals are common for all operations, but 'Accomplish docking' is the main sub-goal in the Docking operation. The other operations depend on this sub-goal in order to be fully successful.

Table 2 shows an overview of all sub-operations and sub-goals and their dependencies. Since many sub-goals are shared between the operations, the sub-goals are only defined in one operation.

Table 2 Dependencies of operations and sub-goals

		Defined in operation				Used in operation			
		O1	O2	O3	O4	O1	O2	O3	O4
Measure temperature, oxygen, water currents etc.	1.1	X				X			
Mission planning	1.2	X				X	X	X	
Move robot to starting point…	1.3	X				X	X	X	X
Obtain real-time pos. measurement	1.4	X				X	X	X	X
Follow pre-planned path/route	1.5	X				X	X	X	X
Robot recovery operation	1.6	X				X	X	X	X
Robot manual operation	1.7	X				X	X	X	X
Battery capacity mode	1.8	X				X	X	X	X
Emergency mode	1.9	X				X	X	X	X
Planned return to docking	1.10	X				X	X	X	
Unplanned return to docking	1.11	X				X	X	X	
Real-time comm. of critical data	1.12	X				X	X	X	X
Visualization of obtained data	1.13	X				X		X	
Future prediction of env. cond.	1.14	X				X	X	X	
Navigation and control of robot	1.15	X				X	X	X	X
Detect and verify net conditions	2.1		X				X	X	
Obtain high quality image data	2.2		X			X	X	X	X
Determine abundance of biofouling	2.3		X				X	X	
Verify integrity of cage net	2.4		X				X	X	
Detect holes and get position of hole	2.5		X			X	X	X	
Future prediction of biofouling	2.6		X				X	X	
Visualization of biof. and holes	2.7		X				X	X	
Clean the cage net	3.1			X				X	
Verify efficiency of cleaning	3.2			X				X	
Accomplish docking	4.1				X	X	X	X	X
Detect docking station	4.2				X				X
Calculate traj. to docking station	4.3				X				X
Follow traj. to docking station	4.4				X				X
Charge robot and send data	4.5				X				X
Transfer data to docking station	4.6				X	X	X	X	X

2.1 Operation 1 (O1): Environmental condition monitoring

This operation considers all requirements for the robot to measure the environmental conditions. The robot will be equipped with sensors capable of measuring e.g., temperature, oxygen levels and pressure at different locations. As monitoring of environmental conditions is essential for the control of fish welfare, it is necessary to measure these values as frequently as possible and report to the fish farm operators. The gathered data will provide the operators with a good overview of the environmental conditions at locations other than those of the stationary sensors. Furthermore, the wealth of additional measurements enables the operator of the fish farm to make even better-informed decisions regarding possible intervention operations aiming to preserve the optimal conditions for the fish.

As this is the first operation to be considered, several common sub-goals will be presented here. The AJA is presented in Table 3.

Table 3 Autonomous Job Analysis, Operation 1: Measure environmental conditions.

Autonomous Job Analysis		
	Main goal of operation:	**Environmental condition monitoring**
1.1	**Description of main sub-goal**	Measure temperature, oxygen, pressure, water currents etc.
	Communication	Sensors must communicate with on-board algorithms/storage unit. Appropriate sampling time for the sensors and communication with on-board algorithms/storage unit must be chosen.
	Perception	The robot should know its own position so that the measurements can be connected to a certain position. The on-board algorithms should tell the robot if the environmental conditions are too harsh to operate in. Robot should also know its own battery capacity and the battery capacity of the sensor.
	Success criteria	Environmental condition measured with to be determined (TBD) accuracy.
	What can go wrong?	Sensor failure, battery capacity too low, sensor drift/bad calibration, storage unit is full.
	What is operational safe state?	Notify operators by sending a distress signal through an underwater communication network. The robot should idle in the current position or go to a safe area/to the docking station/to the surface. Operators may need to retrieve the robot for repairs.
	Human Machine Interface (HMI)	Operators will determine the path the robot should follow prior to the start of the mission. After the mission is finished the operators can monitor the gathered data through a graphical user interface (GUI). The operators can send a command signal to the robot through an underwater communication network and order it to stop, go to a safe area or return to docking.
	Other premises or requirements for successful execution	The necessary sensors are mounted on the robot and underwater communication is available between the robot and the operators. The robot is equipped with on-board algorithms for processing of data.
	Notes and comments	Main sub-goal. This operation relies on following sub-goals from other operations: 2.2, 2.5, 4.1, 4.6-4.10.
1.2	**Description of sub-goal**	Mission planning
	Communication	Operators communicate the mission to the robot. Either as a path, a set of waypoints or other relevant mission parameters.

	Perception	The position of the robot in each time step should be known (self-localization) and water current/wave estimations should be known *a priori*.
	Success criteria	The environmental conditions and the visibility must be good enough for the robot to perform the mission. Hardware and software are working, and robot is operational.
	What can go wrong?	Communication/hardware/software failure. Low visibility or rough environmental conditions.
	What is operational safe state?	Cancel or postpone the mission.
	HMI	Operator should confirm that everything is working properly and verify the environmental conditions. The operator should have the responsibility to cancel the autonomous mission and take over control of the robot.
	Other premises or requirements for successful execution	Optimal path planning algorithms based on cleaning efficiency and battery capacity.
	Notes and comments	Used in operation 1, 2 and 3.
1.3	**Description of sub-goal**	Move robot to starting point of planned path/route
	Communication	Communicate own position and velocity to the on-board navigation and control system. Receive control inputs from the on-board control system and measurements of the environmental conditions from the on-board sensors.
	Perception	The robot must know its own position and velocity as well as the docking station position and the starting point position. It must also measure the environmental conditions that may affect the operation, i.e., the water currents and wave disturbances. The visibility must be good enough for the cameras.
	Success criteria	Robot reaches the starting point with TBD meters accuracy.
	What can go wrong?	Environmental conditions are too harsh for the robot to operate in. Navigation and control system fail. Other hardware and software failures.
	What is operational safe state?	Notify operators by sending a distress signal through an underwater communication network. The robot should idle in the current position or go to a safe area/to the docking station/to the surface. Operators may need to retrieve the robot for repairs.
	HMI	Operators must be notified in case the robot signalizes that something is wrong. The operators can send a command signal to the robot through an underwater communication network and order it to stop, go to a safe area or return to docking.
	Other premises or requirements for successful execution	Stable and robust control system. Positioning system (sub-goal 1.4).
	Notes and comments	Used in operation 1, 2 and 3.
1.4	**Description of sub-goal**	Obtain real-time position measurement of the robot
	Communication	The on-board camera is used to navigate accurately on the net by detecting the net mesh and landmarks such as ropes and chains. Appropriate sampling time must be chosen.
	Perception	N/A
	Success criteria	Position measurement is correct with TBD meters accuracy

	What can go wrong?	The camera is unable to detect landmarks due to low visibility. Hardware and software failures.
	What is operational safe state?	Notify operators by sending a distress signal through an underwater communication network. The robot should idle in the current position or go to a safe area/to the docking station/to the surface. Operators may need to retrieve the robot for repairs.
	HMI	Operators must be notified in case the robot signalizes that something is wrong. The operators can send a command signal to the robot through an underwater communication network and order it to stop, go to a safe area or return to docking.
	Other premises or requirements for successful execution	Read camera images and estimate position through machine vision algorithms. Absolute necessity for autonomous operation. A positioning system must be developed/determined. Sufficient computing power.
	Notes and comments	Used by all operations. Receives input from sub-goal 2.2. Underwater positioning system based on acoustics may be necessary to obtain position.
1.5	**Description of sub-goal**	Follow pre-planned path/route
	Communication	Communicate own position and velocity to the on-board navigation and control system. Receive control inputs from the on-board control system and measurements of the environmental conditions from the on-board sensors. Position measurement from camera.
	Perception	The robot must know its own position and velocity as well as the docking station position and the starting point position. It must also measure the environmental conditions that may affect the operation, i.e., the water currents and wave disturbances. The visibility must be good enough for the cameras.
	Success criteria	The robot is able to follow the path with TBD meters accuracy.
	What can go wrong?	Robot is unable to follow the path due to adverse environmental conditions, sensor failure, software failure or other unexpected events. Robot is not able to transmit/receive data. Robot runs out of battery.
	What is operational safe state?	Notify operators by sending a distress signal through an underwater communication network. The robot should idle in the current position or go to a safe area/to the docking station/to the surface. Operators may need to retrieve the robot for repairs.
	HMI	Operators must be notified in case the robot signalizes that something is wrong. The operators can send a command signal to the robot through an underwater communication network and order it to stop, go to a safe area or return to docking.
	Other premises or requirements for successful execution	Stable and robust control system. Positioning system (sub-goal 1.4). Battery capacity must be sufficient.
	Notes and comments	Used in all operations. Receives input from sub-goal 2.5.
1.6	**Description of sub-goal**	Robot recovery operation
	Communication	Communicate robots' position and that a recovery is necessary through an underwater communication network.
	Perception	Able to detect if a recovery operation is needed by identifying hardware/software errors and own ability to move, i.e., if the robot gets stuck in a rope.
	Success criteria	Robot correctly signals the operators that something is wrong, and it needs to be recovered.

	What can go wrong?	Robot incorrectly signals the operators that something is wrong. Robot does not signal operator that something is wrong. Acoustic network is not working.
	What is operational safe state?	If signal is sent to operators the robot should idle in current position, drive to the surface or release from the net and float to surface. If signal cannot be sent the robot should drive to surface or release from the net and float to the surface.
	HMI	Operators must be notified in case the robot signalizes that something is wrong. The operators can send a command signal to the robot through an underwater communication network and order it to stop, go to a safe area or return to docking. Operators/divers may have to recover the robot.
	Other premises or requirements for successful execution	
	Notes and comments	Used in all operations
1.7	**Description of sub-goal**	Robot manual operation
	Communication	An underwater communication network is used to send simple control signals to the robot (stop, continue, go to surface etc.).
	Perception	N/A
	Success criteria	Robot is able to act based on the manual signals.
	What can go wrong?	The underwater communication network is down, i.e., the robot may not receive a stop signal from the operator. The operator orders the robot to drive into something, so it gets stuck.
	What is operational safe state?	If the underwater communication network is down the robot should automatically stop. The robot can potentially go to a safe area/to the docking station/to the surface.
	HMI	Operator controls the robot and can see the position of the robot using a graphical user interface. Low resolution camera images can be sent over the underwater communication network.
	Other premises or requirements for successful execution	
	Notes and comments	Used in all operations.
1.8	**Description of sub-goal**	Battery capacity mode
	Communication	The robot should notify the operators through the underwater communication network that it is switching to battery capacity mode (lower speed).
	Perception	Robots own position, battery capacity, distance to docking station.
	Success criteria	Robot is able to determine that battery capacity mode is necessary and turn off the correct functions. Robot returns to docking station.
	What can go wrong?	Robot is unable to detect that battery capacity mode is necessary. Robot is unable to turn off functions that drain power. Hardware/software errors.
	What is operational safe state?	Try to notify operators through the underwater communication network. Idle in current position or go to surface/safe area. Robot may have to be retrieved if it cannot reach the docking station.
	HMI	Operator should monitor the operation and can at any point order the robot to go to the surface or to the docking station by sending a signal through the underwater communication network.

	Other premises or requirements for successful execution	
	Notes and comments	Used in all operations.
1.9	**Description of sub-goal**	Emergency mode.
	Communication	Send an emergency message to the operators.
	Perception	Robot should detect that something critical has happened, e.g., robot falls off the net.
	Success criteria	Robot successfully sends a signal when something critical happens.
	What can go wrong?	Robot does not send signal. Robot sends the signal when it is not necessary. Hardware/software errors.
	What is operational safe state?	Carry on as usual.
	HMI	Operators supervise the operation and can at any point send a signal to the robot via the underwater communication network.
	Other premises or requirements for successful execution	
	Notes and comments	Used in all operations.
1.10	**Description of sub-goal**	Planned return to docking
	Communication	Notify operators that a planned return to docking is initiated.
	Perception	Robots own position, position of docking station, battery capacity, environmental conditions, mission status.
	Success criteria	Robot returns to docking station by following a path with TBD meters accuracy.
	What can go wrong?	Hardware/software errors, battery capacity too low, environmental conditions too harsh.
	What is operational safe state?	Notify operator of problems. Idle in current position. Go to safe area or to the surface.
	HMI	Operators must be notified in case the robot signalizes that something is wrong. The operators can send a command signal to the robot through an underwater communication network and order it to stop, go to a safe area or return to docking.
	Other premises or requirements for successful execution	Sufficient battery capacity to return to docking station.
	Notes and comments	Used in operations 1, 2 and 3.
1.11	**Description of sub-goal**	Unplanned return to docking
	Communication	Notify operators that unplanned return to docking is necessary.
	Perception	Robots own position, position of docking station, battery capacity, environmental conditions, mission status.
	Success criteria	Robot returns to docking station by following a path with TBD meters accuracy.
	What can go wrong?	Hardware/software errors, battery capacity to low, environmental conditions too harsh. Underwater communication network not working.
	What is operational safe state?	Notify operators. Idle in current position or go to a safe area or to the surface.
	HMI	Operators must be notified in case the robot signalizes that something is wrong. The operators can send a command signal to the robot

		through an underwater communication network and order it to stop, go to a safe area or return to docking.
	Other premises or requirements for successful execution	
	Notes and comments	Used in operations 1, 2 and 3.
1.12	**Description of sub-goal**	Real-time communication of critical data
	Communication	Send critical data to operators. Critical data could be sudden changes in temperature, oxygen levels and position, inefficient cleaning (e.g. brushes worn out) or hole in net detected.
	Perception	Temperature, oxygen, environmental conditions etc. Robots own position and status of sensors and other hardware.
	Success criteria	Robot successfully sends critical data.
	What can go wrong?	Robot does not send critical data. Communication errors.
	What is operational safe state?	Try to send critical data until operators confirm that they are received. Send data when in docking station instead.
	HMI	Operators must be notified in case the robot signalizes that something is wrong. The operators can send a command signal to the robot through an underwater communication network and order it to stop, go to a safe area or return to docking. Acknowledge received critical data message.
	Other premises or requirements for successful execution	Underwater communication network is necessary.
	Notes and comments	Used in all operations. Receives input from sub-goal 1.1, 2.2, 2.3 and 2.5.
1.13	**Description of sub-goal**	Visualization of obtained data
	Communication	N/A
	Perception	N/A
	Success criteria	Postprocessing and visualization of gathered data through a graphical user interface.
	What can go wrong?	Data not received. Analysis of data did not provide useful information.
	What is operational safe state?	N/A
	HMI	A user interface for visualization of data.
	Other premises or requirements for successful execution	N/A
	Notes and comments	Visualization done in control room using specific software.
1.14	**Description of sub-goal**	Future prediction of environmental conditions
	Communication	Predictions can be used when planning missions.
	Perception	N/A
	Success criteria	Successful predictions of environmental conditions.
	What can go wrong?	Unsuccessful predictions of environmental conditions.
	What is operational safe state?	N/A
	HMI	Operators can feed the model with weather forecast data.
	Other premises or requirements for successful execution	Requires model for predictions of temperature, oxygen levels etc. Need to know when the models can be used in predictions and how to use them in the planning of robot missions.

	Notes and comments	May provide significant value to fish farmers. Able to predict when operations are safe to perform and thus improve planning of operations (when to hire boats/when to start preparing fish for mechanical delousing etc.). Used in all operations
1.15	**Description of sub-goal**	Navigation and control of robot
	Communication	The robot should communicate its own position and velocity to the on-board control system. The on-board control system provides inputs to the actuators on the robot.
	Perception	The control and navigation system knows the position and velocity of the robot, the environmental conditions, and the battery capacity.
	Success criteria	The control and navigation systems are able to bring the robot to the desired position with TBD meters accuracy.
	What can go wrong?	Loss of communication between on-board computer and actuators/sensors on the robot. Control system is improperly tuned.
	What is operational safe state?	Stop the robot in the current position or bring the robot to the surface/to docking/to a safe area.
	HMI	Operators can monitor the operation and may at any time send a stop signal to the robot.
	Other premises or requirements for successful execution	
	Notes and comments	Used in all operations.

The AJA canvas formulation for the Autonomous Job Analysis is presented in Figure 3 for Operation 1 (O1): Environmental condition monitoring.

Autonomous Job Analysis Canvas

SINTEF SEATONOMY

Communication

What key information needs to be communicated?

- Environmental conditions (pressure, temperature, oxygen, salinity, turbidity, ocean currents etc.).
- Position of robot.
- Status of robot (battery capacity, other error messages).

What are the communication restrictions and limitations?

Under water communication of data is still under development and may present challenges and limitations on bandwidth.

What communication infrastructure can be used?

- Underwater communication network for communication between the robot and the operators during missions.
- The robot will send all the data through ethernet when connected to the docking station.
- The desired path is sent to the robot while in the docking station. Robot has onboard control system and computer vision algorithms for positioning.

Human Machine Interaction (HMI)

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

- Prior to the operation the operator requires a map of the cage to place the waypoints for the desired path or enter a desired position for the robot to go to.
- During operation the operator requires information about the robots' position and status
- After an operation the operator requires graphical representation of the gathered data (environmental data, camera images etc.).
- The role of the human is to provide the robot with a path to follow or a position to go to.
- A user interface showing timeseries data is required.

Perception

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

- Vision Sensors-Cameras for high quality images.
- Underwater positioning system for 2D/3D self-localization of the vehicle.
- Sensors to measure the environmental conditions.

Sub-Operation Description

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

Overall objective:
Measure environmental conditions such as temperature, pressure, oxygen levels and ocean currents.

Qualitative description:
Environmental conditions are essential for the welfare of fish. Measuring them frequently will give the farm operators a good overview of the conditions and enable discussions regarding intervention operations to preserve the desired standards.

Preconditions:

- Have a fully functioning robot.
- Have an underwater positioning system to obtain the position of the robot.
- Have sensors capable of measuring the relevant conditions.
- Autonomous navigation and control of the robot.

Success Criteria

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

- The robot is able to measure the environmental conditions with the desired accuracy and at the locations specified by the operator.
- The criterias are evaluated by the operators after an operation is finished.
- The measurement intervals, path following algorithms and control algorithms may require tuning and updates based on the feedback from the operators.

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 robot 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 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:

- Path cannot be followed due to battery capacity or hardware failure.
- Hardware failure: Robot brakes down, thrusters stop working.
- Human error: Wrong pre-planned path is designed, or misleading commands are sent to robot.
- Sensor failure.
- Underwater communication network failure.
- Emergency alert due to failure of the operation.

External events:

- Obstacles.
- Robot gets stuck in a rope/in the net.
- 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

Notes/Comments

Environmental condition monitoring
Operation 1

Figure 3 AJA Canvas for Operation 1 (O1): Environmental condition monitoring

2.2 Operation 2 (O2): Net and biofouling inspection

Ensuring net integrity to prevent escape of fish is one of the most important concerns in salmon farming (Føre & Thorvalsen, 2021). Biofouling of aquaculture nets may negatively affect both cage integrity as well as fish health and welfare. Therefore, both net integrity and biofouling need to be monitored closely. The operation described below considers all requirements necessary for the robot to perform a net and biofouling inspection operation using the onboard camera. The main sub-goal of this operation is to detect and verify the net condition. To achieve this, the operation relies on several sub-goals from Operation 1, hence, these are not included in the AJA for this operation but mentioned in the notes of the main sub-goal. The AJA for this operation is listed in Table 4.

Table 4 Autonomous Job Analysis, Operation 2: Net and biofouling inspection

Autonomous Job Analysis		
	Main goal of operation:	**Net and biofouling inspection**
2.1	**Description of main sub-goal**	Detect and verify net conditions
	Communication	Sensors must communicate with onboard operating system/storage unit. Appropriate sampling time must be chosen. Underwater communication network operational so that signals can be sent to operators if necessary.
	Perception	Robot should know its own position so that the measurements can be connected to a certain position. Robot must be able to detect the net integrity and biofouling through computer vision algorithms. Robot should also know its battery capacity.
	Success criteria	Robot is able to detect and verify net integrity and biofouling abundance.
	What can go wrong?	Sensor failure, battery capacity too low, camera images not good enough, storage full, software errors.
	What is operational safe state?	Notify operators and idle in the current position or go to the surface/to docking/to safe area. Retrieve the robot for repairs.
	HMI	Operators must be notified in case the robot signalizes that something is wrong. The operators can send a command signal to the robot through an underwater communication network and order it to stop, go to a safe area or return to docking. Operators will investigate the gathered data through a GUI after a mission has been completed.
	Other premises or requirements for successful execution	
	Notes and comments	Main sub-goal. This operation relies on following sub-goals from other operations: 1.2-1.15, 4.1, 4.6-4.10.
2.2	**Description of sub-goal**	Obtain high quality image data
	Communication	High quality cables such that no data is lost during data transfer. Camera images synchronized with other sensors (position sensor etc).
	Perception	N/A
	Success criteria	High quality camera installed on the robot. Image quality is sufficient for computer vision algorithms.
	What can go wrong?	Too low light for good pictures, lack of contrast between net and background, camera obscured, e.g. by biofouling growth. Camera failure.

	What is operational safe state?	N/A
	HMI	Operator can view the camera images in the GUI after data has been transferred. Processed, down-sampled data can be sent via the underwater communication network.
	Other premises or requirements for successful execution	Assumes that camera suitable for use with computer vision algorithms is installed on the robot. Lighting system able to provide proper light conditions for cameras. Sufficient data storage.
	Notes and comments	Objective criteria for data quality to be defined (TBD). Used in all operations. Provides input to sub-goal 1.4 and 4.2.
2.3	**Description of sub-goal**	Determine biofouling abundance and main species
	Communication	Send position of robot and of the biofouling occurrence in cage relative coordinates via the underwater communication network.
	Perception	Robots own position and position of the biofouling occurrence.
	Success criteria	Successful determination of biofouling abundance measured as intensity (e.g. level of fouling, % cover, or % net-aperture occlusion) and distribution (area [m^2] affected by biofouling).
	What can go wrong?	Unable to detect biofouling when it is present. Over/underestimation of abundance of biofouling. Wrong identification of biofouling species.
	What is operational safe state?	Signal the operators through the underwater communication network if the computer vision algorithms fail.
	HMI	Operators can verify detected levels and type of biofouling. Operators must supervise the operation in case the robot signalizes that something is wrong. The operators can send a command signal to the robot through an underwater communication network and order it to stop, go to a safe area or return to docking.
	Other premises or requirements for successful execution	Requires computer vision algorithms capable of determining the levels and species of biofouling, and a sufficiently powerful on-board computer to perform the calculations.
	Notes and comments	Used in operation 2 and 3. Provides input to sub-goal 1.12
2.4	**Description of sub-goal**	Verify integrity of cage net
	Communication	Communicate the overall integrity of the cage net.
	Perception	N/A
	Success criteria	The integrity of the net is verified.
	What can go wrong?	Integrity is not verified or verified erroneously.
	What is operational safe state?	N/A
	HMI	Operators can verify or deny the suggested integrity. Operators must supervise the operation in case the robot signalizes that something is wrong. The operators can send a command signal to the robot through an underwater communication network and order it to stop, go to a safe area or return to docking.
	Other premises or requirements for successful execution	Algorithms to determine the integrity of the cage net must be developed. Sufficient capacity to store images.
	Notes and comments	Objective criteria for net integrity to be defined (TBD).
2.5	**Description of sub-goal**	Detect holes and identify position of holes in net
	Communication	Communicate that a hole is detected and the position of the hole in cage relative coordinates. Communicate position of the robot. Size of the hole (e.g. area of the hole in m^2 or number of broken mesh strands).

	Perception	Robots own position and position of the hole. Able to see the net through the camera. Covered by sub-goals 1.4 and 2.2.
	Success criteria	Holes are detected correctly, and the position is within TBD meters accuracy.
	What can go wrong?	Holes are not detected. Holes are detected but do not exist. Announce wrong position for the hole.
	What is operational safe state?	N/A
	HMI	Operators can double check the camera images or run the obtained camera images through computer vision algorithms on a computer with more capacity than the on-board computer. Operators must supervise the operation in case the robot signalizes that something is wrong. The operators can send a command signal to the robot through an underwater communication network and order it to stop, go to a safe area or return to docking.
	Other premises or requirements for successful execution	Computer vision algorithms capable of detecting holes in nets must be applied/developed. Positioning system is necessary. Sufficiently powerful on-board computer to perform the calculations.
	Notes and comments	Used in operation 1, 2 and 3. Provides input to sub-goal 1.5 and 1.12.
2.6	**Description of sub-goal**	Future prediction of biofouling conditions
	Communication	Predictions can be used when planning missions.
	Perception	N/A
	Success criteria	Successful predictions of biofouling conditions.
	What can go wrong?	Unsuccessful predictions of biofouling conditions.
	What is operational safe state?	N/A
	HMI	Operators can feed the model with biofouling data from other locations.
	Other premises or requirements for successful execution	Requires model for predictions of biofouling conditions. Need to know when the models can be used in predictions and how to use them in the planning of the robot missions.
	Notes and comments	Operators can use the models to better plan the missions, i.e., the number of missions may be reduced and hence one can save energy.
2.7	**Description of sub-goal**	Visualization of biofouling conditions and holes in net
	Communication	The collected data is transferred to the control room through the docking station. High quality cables between docking station and control room/wireless transmitter are necessary so that no data is lost.
	Perception	N/A
	Success criteria	Proper visualization of gathered data.
	What can go wrong?	Data not received. Analysis of data did not provide useful information.
	What is operational safe state?	N/A
	HMI	A user interface for visualization of data.
	Other premises or requirements for successful execution	N/A
	Notes and comments	Visualization done in control room using specific software.

The AJA canvas formulation for the Autonomous Job Analysis is presented in Figure 4 for Operation 2 (O2): Net and biofouling inspection operation.

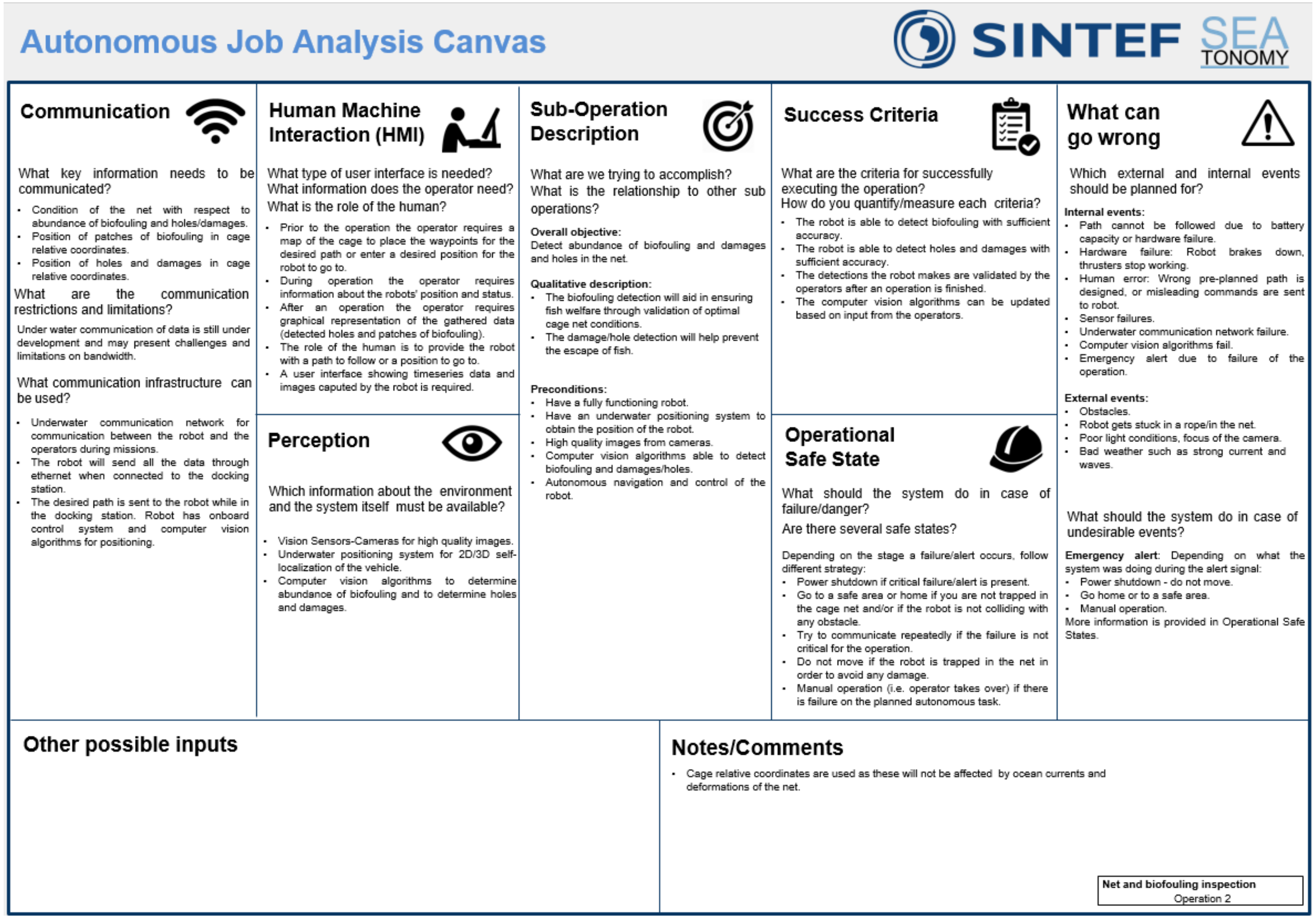

Figure 4 AJA Canvas for Operation 2 (O2): Net and biofouling inspection operation

2.3 Operation 3 (O3): Cleaning and prevention of biofouling

This operation considers all necessary requirements for the robot to clean the nets and prevent biofouling. The robot is equipped with brushes and will move along the cage net on a pre-defined path. Furthermore, the robot will be able to re-plan the path considering factors such as battery capacity and abundance of biofouling. This operation relies on the inspection operation in order to verify that the net has been sufficiently cleaned. Since many of the sub-goals in this operation are already defined for other operations, only two sub-goals need to be defined for this operation. Table 5 shows the AJA for this operation.

Table 5 Autonomous Job Analysis, Operation 3: Cleaning/prevention of biofouling

Autonomous Job Analysis		
	Main goal of operation:	**Cleaning/prevention of biofouling**
3.1	**Description of sub-goal**	Clean the cage net
	Communication	The robot communicates its position, velocity and other relevant parameters.
	Perception	Own position (sub-goal 1.4), biofouling abundance and taxonomic composition (sub-goal 2.3), cleaning efficiency (sub-goal 3.2).
	Success criteria	Robot successfully disturbs the net and prevents biofouling from growing.
	What can go wrong?	Brushes are broken/worn out/overgrown with biofouling. Insufficient disturbance frequency causes biofouling to establish.
	What is operational safe state?	Notify operators through the acoustic network. Idle in current position or go to docking station/safe area/surface. Retrieve robot for maintenance.
	HMI	Check camera images after data transfer and verify net cleanliness. Operators must supervise the operation in case the robot signalizes that something is wrong. The operators can send a command signal to the robot through an acoustic underwater network and order it to stop, go to a safe area or return to docking.
	Other premises or requirements for successful execution	Cleaning robot with tether already exists.
	Notes and comments	Main sub-goal. This operation relies on following sub-goals from other operations: 1.2-1.15, 2.1-2.7, 4.1, 4.6-4.8.
3.2	**Description of sub-goal**	Verify cleaning efficiency
	Communication	If cleaning efficiency is insufficient, notify through sub-goal 1.12.
	Perception	Amount of biofouling before and after cleaning. Ideally, biofouling is never present on the net due to successful prevention through constant disturbance from the robot.
	Success criteria	Successfully verifies cleaning efficiency.
	What can go wrong?	Unsuccessful verification of cleaning efficiency.
	What is operational safe state?	N/A
	HMI	Operators can verify cleaning efficiency. Operators must supervise the operation in case the robot signalizes that something is wrong. The operators can send a command signal to the robot through an acoustic underwater network and order it to stop, go to a safe area or return to docking.
	Other premises or requirements for successful execution	Requires a computer vision algorithm capable of determining if the net is sufficiently clean and a sufficiently powerful on-board computer.

	Notes and comments	Takes input from sub-goal 2.2 and 2.3. Provides input to sub-goal 1.12.

The AJA canvas formulation for the Autonomous Job Analysis is presented in Figure 5 for Operation 3 (O3): Cleaning/prevention of biofouling.

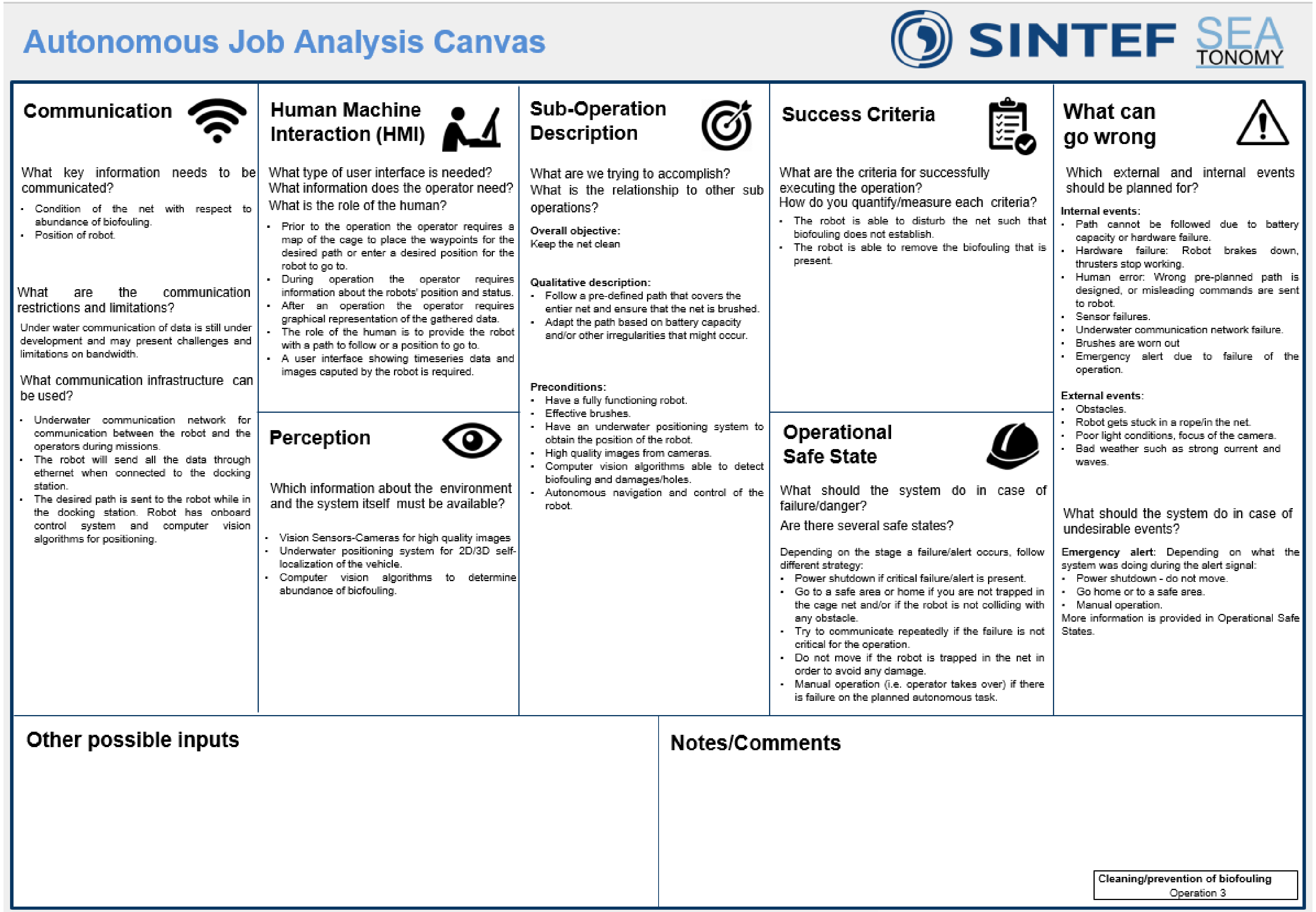

Figure 5 AJA Canvas for Operation 3 (O3): Cleaning/prevention of biofouling

2.4 Operation 4 (O4): Docking

This operation considers all requirements necessary for the robot to perform the docking and data transfer. While in the docking station, the robot will charge the batteries and transfer and receive data to and from the control room. Some of the gathered data can be used to create models of biofouling growth and environmental models. These models can give fish farmers valuable insight into cage conditions with relevance to fish welfare parameters, which may be used as predictive tools for operation planning. Table 6 contains the AJA for this operation.

Table 6 Autonomous Job Analysis, Operation 4: Docking

Autonomous Job Analysis		
	Main goal of operation:	**Docking**
4.1	**Description of sub-goal**	Accomplish docking
	Communication	Communicate position and velocity of the vehicle and the position of the docking station.
	Perception	Robot must know its own position and velocity, the position of the docking station and the path it should take. Robot must also know its own battery capacity and that it has successfully docked.
	Success criteria	The robot successfully docks. Charging and data transfer is possible.
	What can go wrong?	Unsuccessful docking. Damaged connectors. Growth on connectors.
	What is operational safe state?	Notify operators if the docking procedure fails (robot cannot enter docking station/battery is empty etc.). Retrieve robot or docking station for repairs.
	HMI	Operators must supervise the operation in case the robot signalizes that something is wrong. The operators can send a command signal to the robot through an acoustic underwater network and order it to stop, go to a safe area or return to docking. Camera on docking station for live video feed of robot when it is close to docking station.
	Other premises or requirements for successful execution	Requires positioning system and docking station with all necessary connections. Vision system to detect docking station (4.2) and subsea docking system for automatic launch and recovery of the robot. Conceptual study on docking station. Inspiration from existing docking station systems will serve as basis.
	Notes and comments	Main sub-goal. Used in all operations. This operation relies on the following sub-goals: 1.3-1.9, 1.12, 2.2, 4.2, 4.3, 4.4
4.2	**Description of sub-goal**	Detect docking station
	Communication	The robot communicates that the docking station is detected and within range of a docking procedure.
	Perception	Robots own position and velocity. Position of docking station. Distance to docking station and a path from the robot to the docking station.
	Success criteria	The robot detects the docking station and the distance with TBD meters accuracy.
	What can go wrong?	Robot fails to detect the docking station. Robot detects the docking station when it is not there.
	What is operational safe state?	Notify operators. Idle in current position. Retrieve robot for repairs.
	HMI	Operators can verify that the robot has detected the docking station. Operators must supervise the operation in case the robot signalizes that something is wrong. The operators can send a command signal to the

		robot through an acoustic underwater network and order it to stop, go to a safe area or return to docking.
	Other premises or requirements for successful execution	Requires computer vision algorithms for detection of docking station and a sufficiently powerful on-board computer.
	Notes and comments	Takes input from sub-goal 2.2.
4.3	**Description of sub-goal**	Calculate trajectory to docking station
	Communication	N/A
	Perception	Robots own position. Position of docking station. Possible obstacles. Battery capacity. Shortest path to docking station.
	Success criteria	The robot calculates a feasible trajectory to the docking station while regarding battery capacity.
	What can go wrong?	Robot fails to calculate a trajectory to the docking station.
	What is operational safe state?	Signal operators through the acoustic network. Retrieve robot. Send signal that the robot should move to another location and try again. Go to safe area or to the surface.
	HMI	Operators must supervise the operation in case the robot signalizes that something is wrong. The operators can send a command signal to the robot through an acoustic underwater network and order it to stop, go to a safe area or return to docking.
	Other premises or requirements for successful execution	Requires a trajectory planning algorithm. Robot will ensure that it always has enough battery capacity to reach the docking station.
	Notes and comments	
4.4	**Description of sub-goal**	Follow trajectory to docking station
	Communication	Robot position and velocity. Distance to docking station. Path parameters or waypoints.
	Perception	Robot position and velocity. Distance to docking station. Battery capacity.
	Success criteria	Robot follows the trajectory with TBD meters accuracy.
	What can go wrong?	Robot fails to follow trajectory. Environmental conditions are too harsh. Hardware and software errors. Acoustic network stops working.
	What is operational safe state?	Signal operators. Go to safe area or to the surface.
	HMI	Operators must supervise the operation in case the robot signalizes that something is wrong. The operators can send a command signal to the robot through an acoustic underwater network and order it to stop, go to a safe area or return to docking.
	Other premises or requirements for successful execution	Requires a control algorithm capable of following a given trajectory.
	Notes and comments	
4.5	**Description of sub-goal**	Charge the robot and send data to control room
	Communication	Send signal that the robot is properly docked. Send battery level while charging and notify when fully charged. Send signal to operators that data transfer is possible.
	Perception	The robot should know that it has docked and that data transfer is possible.
	Success criteria	Robot successfully starts charging batteries. Data transfer to control room is carried out successfully.

	What can go wrong?	Robot fails to dock. Damaged connectors/growth on connectors. Power outage. Wires disconnected.
	What is operational safe state?	Signal operators. Retrieve robot and/or docking station for repairs.
	HMI	Operators monitor the operation and can send a signal to the robot via the acoustic network or through the docking station cables. Can verify that the robot has docked, and that the data is transferring. The operators can access the software on the robot when it is docked.
	Other premises or requirements for successful execution	Assumes that a docking station exists.
	Notes and comments	

The AJA canvas formulation for the Autonomous Job Analysis is presented in Figure 6 for Operation 4 (O4): Docking.

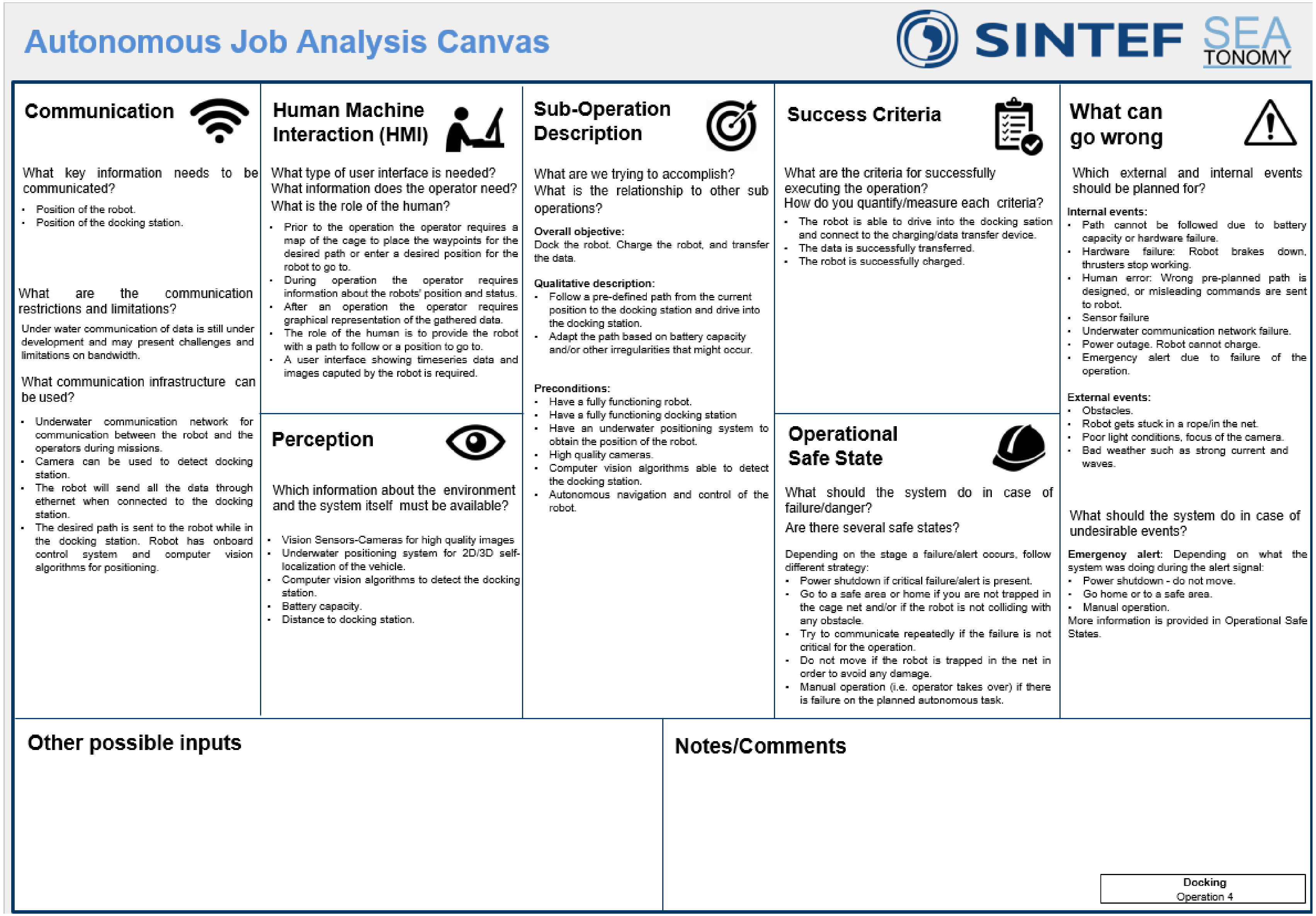

Figure 6 AJA Canvas for Operation 4 (O4): Docking

3 Requirement matrix

Based on the AJA method a requirement matrix for the operations has been developed. In the requirement 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 against it. Each requirement **shall** only contain one "**shall**" or "**should**".

The requirements are grouped according to the following definitions:

- VEH – Vehicle requirements, i.e. Remora Robot.
- 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 7 Requirement matrix

Req. no.	Description	Comment
	VEHICLE (VEH)	
VEH-1	The robot **shall** have the ability of self-localization with a **TBD** accuracy *Comment: The accuracy will probably be given by the equipment available, not by demonstrator needs.*	
VEH-2	The robot **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 robot **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 the hardware requirements are too extensive and a second on-board computer is needed.*	
VEH-5	All sensor data **shall** be stored in the vehicle for retrieval after the mission is finished. *Comment: Consider redundant storage in case of failures.*	
VEH-6	The vehicle **shall** be able to operate for a minimum of **TBD** minutes.	
VEH-7	The robot **should** have a hydroacoustic underwater communication link.	
VEH-8	The robot docking station **should** deploy a wireless modem for communication with the control room.	
VEH-9	The robot **shall** be equipped with sensors for detecting the • Cage: net, equipment, biofouling condition, etc. • Environment: temperature, oxygen, water current, waves, etc. • Docking station.	
VEH-10	The robot **shall** have machine vision sensors (mono or stereo camera).	
VEH-11	The robot **shall** support docking capabilities.	
	Use Interface/Control Station (HMI)	
HMI-1	The operator **should** be able to interfere with the operation. *Comment: This could be to abort the operation, change modes etc. Modes are described elsewhere. Requires acoustic underwater communication.*	
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. Requires acoustic underwater communication.*	
HMI-5	The operator **should** see the vehicle position in a cage map. *Comment: Requires acoustic positioning system.* *Comment: Requires acoustic underwater position.*	
HMI-6	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-7	The operator **shall** be able to configure/change the safe state of each vehicle. *Comment: see INT-7*	
HMI-8	The operator **shall** be able to configure the battery threshold. *Comment: See INT-6*	
HMI-9	The operator **shall** be able to configure what information/data is presented in the HMI.	
HMI-10	The operator **shall** have the opportunity to store the collected sensor data	
COMMUNICATION (COM)		
COM-1	The vehicle **should** be able to send time critical messages directly to the control station. *Comment: Requires acoustic underwater communication.*	
COM-2	There **should** be a possibility to detect and cope with bandwidth problems.	
COM-3	The robot **shall,** as a minimum, be able to transmit the following data when in the docking station: - 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 and Kalman filter	
COM-4	The robot **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-5	Underwater protocols **should** allow robot localization.	
COM-6	The robot **shall** be able to send data about the cage net and the environmental conditions and its position to the control station.	
Distributed Intelligence (INT)		
INT-1	The following general modes **shall** be implemented in the robot: - Manual mode - Go to docking station - Go to safe state - Autonomous path following - Go to position - Battery save mode *Comment: This requirement looks like a design decision. However, the functionality is needed. Battery save mode is not necessary for the demonstration. It can encompass reduced speed, disabling of unused sensors etc.*	
INT-2	The following modes **should** be implemented in the robot: - Go to surface	

INT-3	Upon loss of communication for **TBD** minutes, the robot **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 robot **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 robot **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 docking station/surface, the battery threshold should be such that the vehicle can go to the docking station/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 docking station/surface and report position for retrieval, but this might vary depending on the operation and environmental conditions.*	
INT-8	Reaction to collision with infrastructure **should** be implemented if required sensors are available.	
INT-9	The robot **shall** be able to inspect the cage net condition (biofouling, holes, damages etc.)	
INT-10	The robot **shall** be able to inspect the environmental conditions in fish cages.	
General (GEN)		
GEN-1	The robot **shall,** as a minimum, be able to perform a cleaning operation.	
GEN-2	The docking station **shall** be designed in such a way that it is easy to maneuver into.	

4 List of requirements and specifications for new Remora robot design

The tethered version of Remora vehicle has already been developed and tested. Based in this, Table 8 lists the requirements for development of a tetherless and fully autonomous underwater vehicle for simultaneous inspection and cleaning operations in fish cages (Figure 7). These conclusions have been reached based on the Seatonomy theoretical analysis conducted in the earlier section. The Seatonomy results were used to specify the necessary tasks and conditions/requirements needed to achieve autonomous navigation of the vehicle, record high-quality images and obtain parameters related to environmental conditions [17]. These parameters have been discussed with all the partners to avoid any misunderstanding and make sure that all partners from the very beginning are aware of various important aspects like different sensors requirements, vehicle specifications, data capturing requirements, needs for additional sensors, need for adaptations on the setup and the equipment, and needs to consider special/more simple situations if the tasks are too demanding.

Figure 7 The tetherless underwater vehicle Remora.

Table 8 List of requirements for the tetherless Remora vehicle

Hardware	Software	Design
- Underwater communication system - Connection to docking station for battery charging and data transfer - Sensor package for measuring environmental conditions - Docking station - Battery	- Autonomous navigation software - Control system for autonomous operations - Manual control system - Computer vision algorithms - Mission planning and re-planning software - User interface - Sensor fusion algorithms for analysing sensor/camera data and estimate position	- Docking station design and localization - Docking station connection design and localization - Sensor package design and localization

4.1 Requirements for autonomous robot navigation along the net

The most important enablers for underwater navigation along the net are a positioning system and control functions for autonomous navigation. Precise underwater positioning systems are necessary to ensure effective brushing, as it is challenging to follow a planned path or trajectory without it. The positioning system can also determine the location of holes in the net and give location-bound environmental measurements. Based on the Seatonomy analysis, two positioning systems should be used: a local positioning system to determine the robots' position on the net and a global positioning system to determine the robots' position with respect to the docking station. The local positioning system is used by the robot to determine its position in the net-relative reference frame and is used for mission planning and hole localization. Since the net moves, the global positioning system cannot be used for these purposes. The global positioning system is used by the robot to determine the location of the docking station, by the operators to determine the position of the robot in the North-East-Down (NED) reference frame, and as a redundant positioning system by the robot if the primary positioning system fails. While the global positioning system can be realized using existing underwater positioning technology based on acoustics, the local positioning system needs to be developed. One suggestion is to use high-quality images from vision system and machine vision algorithms to count the mesh openings of the net and use the count to determine the position of the vehicle. Details about the desired specifications for positioning system can be found in Table 9. This information provides useful inputs when it comes to control function implementation for the autonomous functions and for the possible experimental trials. A potential candidate for an underwater positioning system based on acoustics that could be adapted in this project has been developed by WaterLinked AS and has been investigated in detail in the NFR project CageReporter [18]. In addition, the roll, pitch, and yaw measurements can be obtained using the onboard measurements available on the underwater vehicle.

Table 9 List of requirements to obtain precise position measurements based on acoustics or a machine vision approach

	Desired Specifications
Desired accuracy of position measurements (XYZ position)	±0.1 m in absolute distance (i.e. the norm of XYZ)
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
Number and position of the receivers to be installed in the fish cage to have full coverage of the fish cage area	One system per cage should be sufficient to obtain acoustic coverage
Specify how often the position measurement should be updated for the real-time navigation purposes	1-2 samples per second should be sufficient.
Specify what the system should do in case of loss of position measurements (backup solution)	Kalman filter or other position estimation techniques.
Any additional information needed to obtain accurate and real-time position measurements	

The robot requires a robust control system (Figure 8) in order to follow the specified mission path. The control system must handle varying environmental conditions such as water currents, waves, and other external disturbances. Furthermore, the control system must handle special cases such as unplanned deviations from the original path due to detections of holes, extra brushing in specific areas, low battery capacity or unplanned returns to the docking station. In particular, the control system should include a high-level motion planning algorithm (e.g. multi objective optimization, task priority approach), [19] that calculates the most effective brushing path based on battery capacity, measured environmental conditions and monitored brushing efficiency, i.e., the motion planning algorithm should be able to re-plan the path on-line. Table 10 shows the different control and navigation functions. A mathematical model of Remora (along with a 3D model) is implemented in SINTEFs simulation software FhSim. The simulation model is used to test different control strategies and to develop the optimization and path planning algorithms [19]. FhSim makes the transition between simulations and real world testing easy and effective as the same commands and environment can be used in both settings. The software can be used to communicate through serial interfaces, thus enabling real world testing. FhSim also contains models of fish cages, fish, and environmental conditions for realistic simulations.

If possible, the robot should also be manually controlled. Such a system is already implemented on the initial version of the robot and it is therefore suggested that this is applied to the new model. FhSim can be utilized in this context through the establishment of a connection to the external controller.

Table 10 List of control and navigation functions

Function	**Description**	**Importance**	**Status**
Speed control	Given a desired forward speed, the controller calculates the required torque on the wheels that	High	PI controller verified in simulations.

	ensures correct forward speed		
Heading control	Given a desired heading, the controller calculates the required torque on the wheels to ensure correct heading	High	PID controller verified in simulations
Line-of-sight (LOS) path following	Given two waypoints, the LOS algorithm calculates the desired heading. Input to the heading control	High	Verified in simulations
Task priority	Calculate the battery capacity and distance to docking station. If battery capacity is too low the robot returns to docking station	High	Verified in simulations
Optimal path planning	Given the shape of the net cage, calculate the optimal path based on energy usage, length of path etc.	Medium	Verified in simulations
Simulation model	A mathematical representation of the robot and its movement	High	An initial, simplified model exists. Complex model under development.

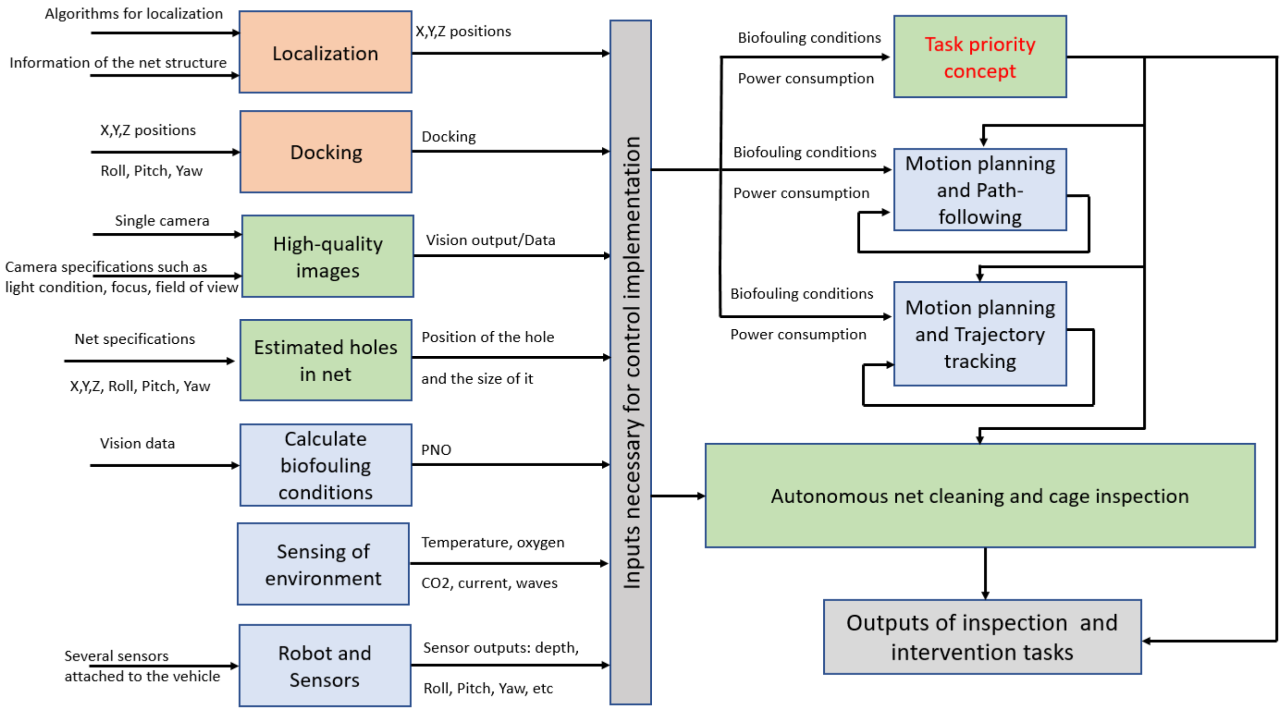

Figure 8 Illustration of the control system for autonomous navigation

4.2 Sensors for the new Remora robot

Required sensors for the underwater vehicle and its planned operations are listed below:

1. Underwater positioning system: The specifications are given in Table 9.
2. Sensors required for autonomous operation: Given in Table 11.
3. Underwater vision system: The specifications are given in Table 12.
4. Existing sensors on the Remora vehicle: Listed in Table 13.
5. Environmental sensors**:** Given in Appendix C.

Figure 13 shows the illustration of the Robot with all the integrated sensors.

4.2.1 Sensor requirements for autonomous operation

The robot requires a minimum set of sensors to autonomously operate and navigate on the cage net. The robot is built around the ArduSub solution which utilizes a Pixhawk microcontroller/autopilot. The Pixhawk has built-in IMU, compass, gyroscope, and pressure/depth sensor. An additional (external) pressure sensor is installed (Bar02 Ultra High Resolution). This sensor, however, is listed as not being compatible with the ArduSub system.

The sensors required for autonomous operation are listed in Table 11.

Table 11 Sensors for autonomous operation

Sensor	**Description**	**Status**	**Comment**
IMU	Provides linear acceleration data	Installed (Pixhawk)	
Gyroscope	Provides angular velocity data	Installed (Pixhawk)	
Compass	Provides heading angle	Installed (Pixhawk)	
Depth sensor	Provides depth	Installed (Pixhawk and additional sensor)	
Position sensor	Provides net-relative position	Not installed/Under development	Estimated from depth and heading or provided by dedicated positioning system (acoustics based or vision based).
Velocity sensor	Provides net-relative velocity	Not installed	Estimated by Kalman filter. Calculated based on rpm of motors.
Camera	Provides images for computer vision algorithms	Installed	Need computer vision algorithms to determine position.
Battery monitoring	Provides status on battery capacity	Installed	Part of ArduSub.

Table 12 List of requirements for obtaining high-quality images from the cameras

	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. Must be seen in relation to the motion of the robot. Exploit natural sunlight (likely best around 12:00 O'clock) and/or add artificial lighting.	TBD
Auto/manual focus	Manual and Auto focus should both be possible. Ideally, it should be possible to change the focus remotely.	TBD
Capturing distance from net/fish	Approx. 0.4 meters	TBD
Number of Required Cameras	One camera pointing forwards. May require additional camera pointing backwards. Stereo cameras can improve biofouling detection capabilities, but not positioning system as it is difficult to find a common reference point on a mesh.	TBD
Communication Bandwidth	Onboard image handling to detect holes/biofouling. Communication with docking station/control room must be fast and data storage on the robot must be sufficiently large.	TBD
Image Resolution	2.24 MP, 1900x1080p Raw data: 3*1900*1080 = 6 [Mb/frame] * 25 [frames/s] = 150 [Mb/s] which is too much if live feed from camera is required. H.264 compression reduces size. Max compression ratio: 2000:1 lossy compression. Images likely very bad at this ratio but can maybe be used to confirm a hole in the net. 500x500 pixels will be enough to use computer vision algorithms	Installed camera resolution: 2.24 MP will be OK
Etc. (which other parameters should be considered to make sure that the data obtained from the cameras are sufficient for the planned operations.	Generally, the signal to noise ratio should be good (large=> low noise). Color cameras for biofouling detection. Particles from the net will disturb the view. Always use raw images in the computer vision algorithms. This leads to huge amounts of data. H.264 is video compression that transmits the changes between two frames. Every now and then it transmits the full image.	TBD
Comments	Counting mesh openings might be difficult if a double net is used. This requires a powerful computer and may not be possible on a Raspberry Pi. May only be possible to analyze every second, not real time. Very low resolution image can be transmitted through acoustics under water. Human intervention necessary.	

Table 13 List of sensors that are available on the Remora vehicle

	Sensors installed on the Remora vehicle	To be installed
Depth sensor	Pixhawk	
Compass	Pixhawk	
Linear acceleration	Pixhawk	
Angular velocity (gyroscope)	Pixhawk	
Pitch / roll sensor	Pixhawk	
Camera/Cameras	Blue Robotics H.264 USB Camera	
LED lights	Lumen Subsea Light	
Battery monitoring	Power sense module	
Positioning system		Computer vision system
Oxygen sensor		Xylem Oxygen Optode
Water current sensor		Xylem ZPulse Doppler water current sensor
Temperature sensor		Part of other sensors
Salinity sensor		Xylem Conductivity Sensor
Turbidity sensor		Xylem Turbidity Sensor

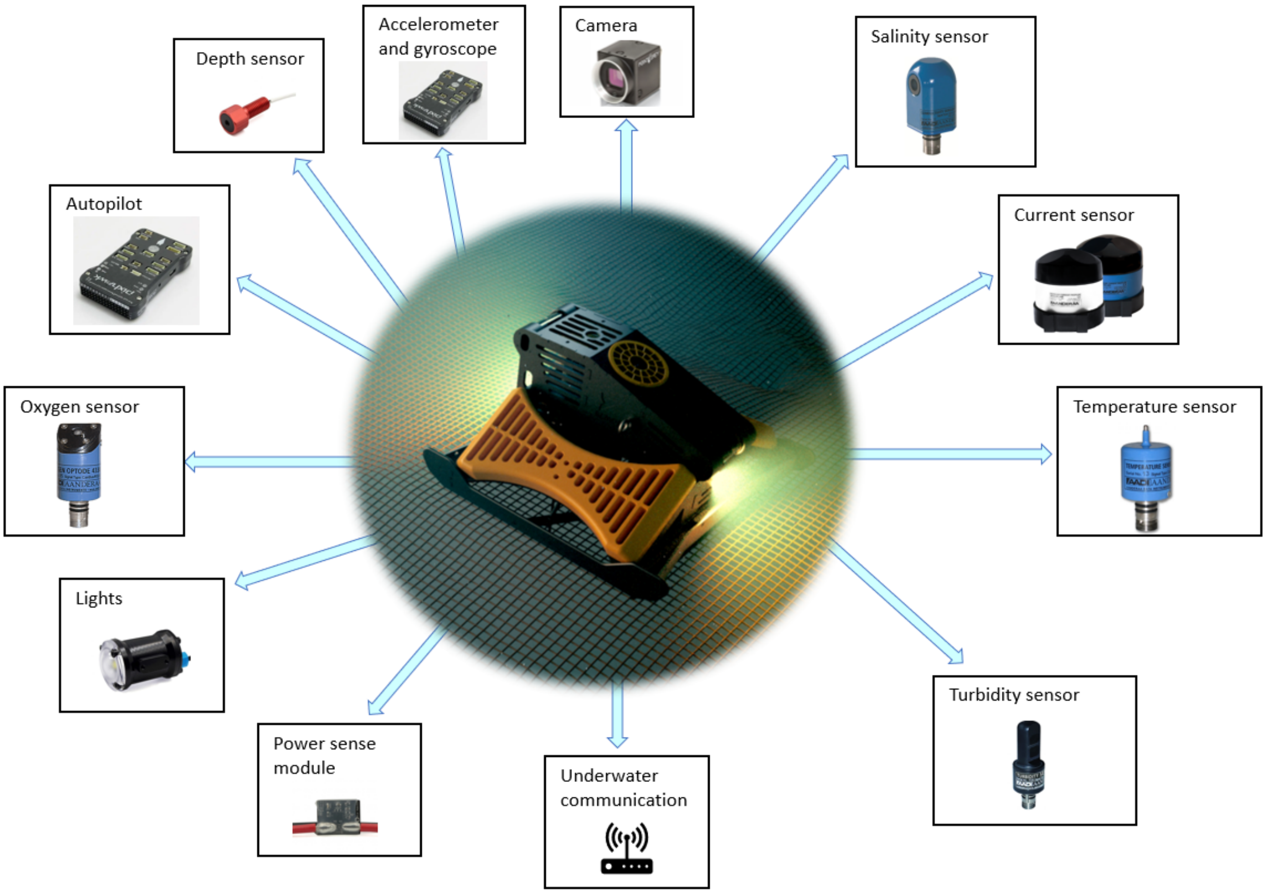

Figure 9 Illustration of the Remora vehicle with the desired integrated sensors

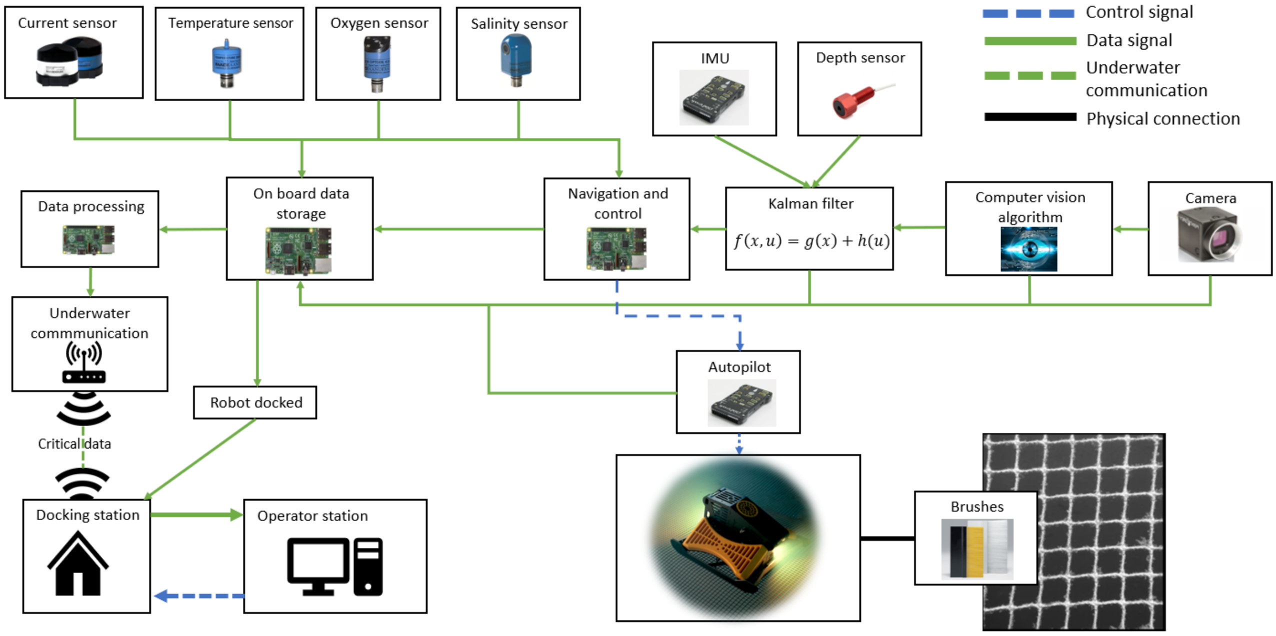

Figure 10 Illustration showing the signal flow in the Remora robot.

4.3 Control panel interface

For the operator to have a good understanding of the status of the vehicle, the vehicle surroundings, and the biofouling status it is important that the data is presented in an intuitive way. Therefore, the Remora net cleaning robot is dependent on a graphical user interface (GUI) software for presentation of gathered data. The supervising operators shall have the opportunity to plan missions or send manual instructions to the robot via the GUI.

Data transfer between the docking station and the robot can be divided into two modes: (1) data transfer via physical connections during docking and (2) wireless data transfer via acoustic communication during mission execution. The bandwidth capacity of wireless acoustic underwater communication is very limited compared to the bandwidth capacity of physical connections. Consequently, this affects how the GUI can communicate with the vehicle during and between missions. During mission executions, the vehicle should only transfer measurement data with low data rate requirements and the operators can only give simple instructions (for instance order the vehicle to stop or to dock). During docking, the vehicle is able to transfer measurements with higher data rate requirements, such as high-resolution images, while the operator can give more complex mission instructions to the robot.

Since data transfer is limited during mission executions, the most essential parameters (such as battery capacity, vehicle position and distress signals) will be prioritized when sending data to the docking station. Other low bandwidth demanding data such as environmental readings, vehicle state data and low-resolution images will be transferred if there's sufficient bandwidth capacity in the wireless communication.

During mission executions, the vehicle will store all relevant data on-board. During docking, this data should be transferred to the GUI, where it will be presented to the operator. This will include time-series graphs of environmental data and vehicle state data, as well as high quality images.

When docked, the operator shall be able to plan autonomous missions, either by choosing a pattern which describes how the robot will move across the net cage or by deciding waypoints by clicking on a 3D map of the net cage. The operator can also change settings, such as the desired velocity or the battery threshold for when the robot should return towards the docking station. When undocked, the operator can only send simple instructions, including commanding the vehicle to stop, continue or dock.

The GUI will be located on a top-side computer which should be connected to the docking station with high quality data transfer cables. From the underwater modem located by the docking station, the GUI and vehicle will be able to relay messages to one another. The GUI communicates with the vehicle using MavLink [22], a lightweight messaging protocol designed for controlling drones. Figure 11 shows the communication flow between the user, GUI, and vehicle.

The specific software solutions, graphical design and control capabilities to the GUI will be further investigated in Work Package 2.

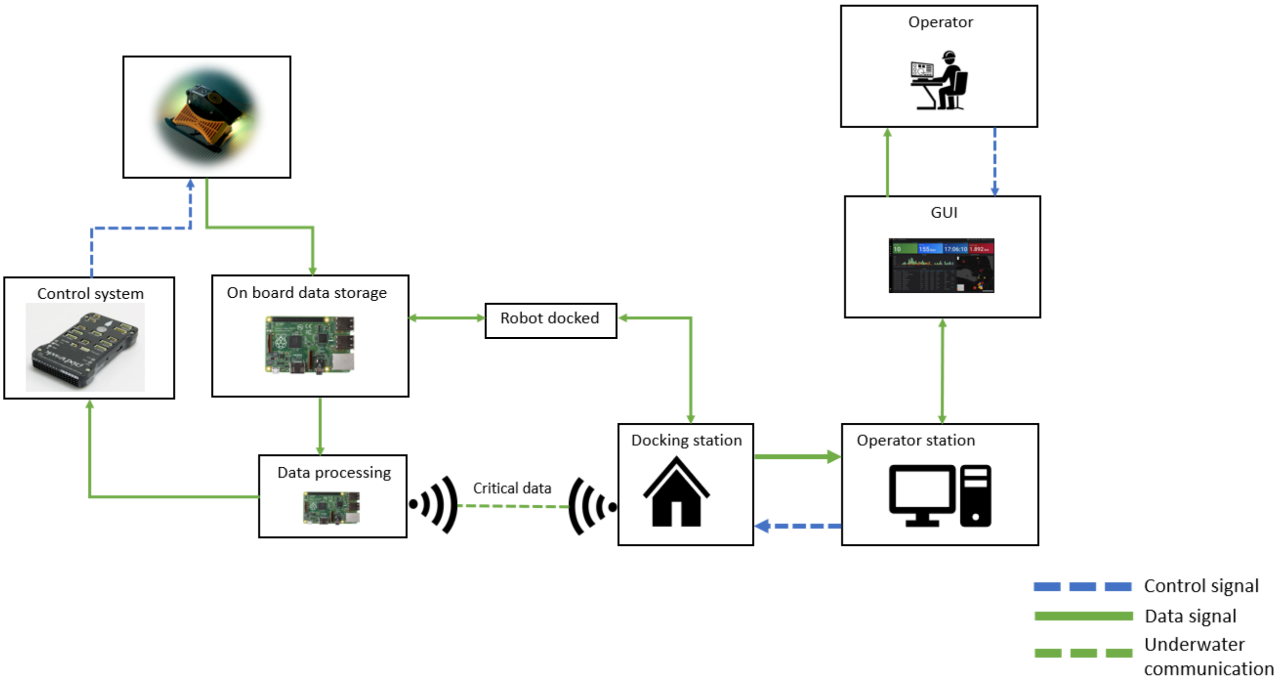

Figure 11 Diagram showing the signal flow between the operator and the Remora robot.

5 Summary

This report has presented an analysis of the autonomous cleaning operations handled in the NetClean 24/7 project. The analysis was conducted using the Autonomous Job Analysis (AJA) concept introduced in the Seatonomy method. Four operations were identified through the AJA, i.e., O1 Environmental condition monitoring, O2 Net and biofouling inspection, O3 Cleaning/prevention and O4 Docking. Each operation consists of a main goal and several sub-goals that have all been analysed. A requirement matrix has been developed for each operation. Furthermore, all necessary hardware and software required to perform the operations are identified and listed in this report.

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7 Appendices

A ArduSub system

ArduSub is an open-source autopilot system used to control the position and tilt of the robot, functionalities such as lights, and various sensors associated with the functionality of the robot. In this section a summary of the information related to the ArduSub open-source solutions adapted from Remora Robotics for the development of Remora vehicle is presented. In particular, the current version of the Remora robot is developed using the open source ArduSub solution for remotely operated underwater vehicles. ArduSub has extensive capabilities out of the box including feedback stability control, depth and heading hold and autonomous navigation. It is designed to be safe, feature-rich, open-ended, and easy to use. ArduSub works seamlessly with the QGroundControl software that can monitor vehicle telemetry and perform mission planning activities. It also benefits from other parts of the ArduPilot platform, including simulators, log analysis tools and higher-level APIs for vehicle management and control.

The ArduSub platform includes a motor library used to implement several supported frame configurations. Figure A.1 shows a motor configuration which fits that of the Remora robot. The configuration is already included in ArduSub.

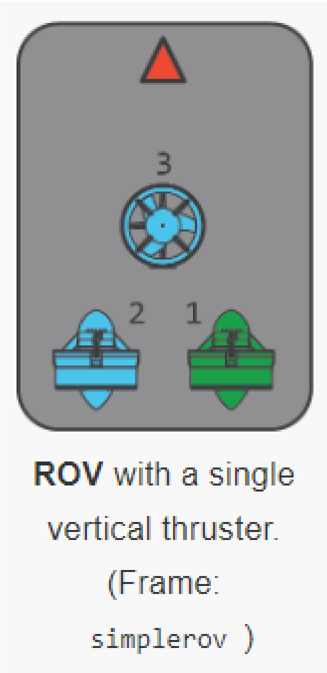


Figure A.1 Motor configuration fitting with Remora

A.1 Supported hardware

The ArduPilot project has support for a great variety of hardware platforms. ArduSub firmware is provided for many of these platforms, but only the Pixhawk 1 is fully tested and supported. The following platforms are reported to work with ArduSub:

- Pixhawk
- Pixhawk 2
- Pixhawk Mini

A.2 Capabilities

ArduSub includes:

- **Feedback control and stability:** Based on a multicopter autopilot system, the ArduSub controller has accurate feedback control to actively maintain orientation

- **Depth hold:** Using pressure-based depth sensors, the ArduSub controller can maintain depth within a few centimeters
- **Heading hold:** By default, the ArduSub automatically maintains its heading when not commanded to turn
- **Camera tilt:** Camera tilt control with servo or gimbal motors through the joystick or gamepad controller
- **Light control:** Control of subsea lighting through the joystick or gamepad controller.

A.3 Extensibility

In addition to the standard onboard sensors (IMU, compass), the ArduSub controller directly supports a number of external sensors including pressure/depth sensors for measurement and auto depth-hold. Other sensors, and in particular high-bandwidth and specialized sensors, are integrated as *Companion* sensors, attached to the companion computer and running alongside ArduSub and sharing communication pathways. This allows rapid integration of new and unique payloads and allows using the manufacturer's user interface to control the sensor. Sensors integration via companion includes sensors such as:

- Depth sounders
- UDP Input of external GPS data from underwater localization systems (such as Water Linked [20] and Sonardyne [21])
- Scanning sonars

A.4 Hardware components

The hardware required to run ArduSub can be divided into three categories:

- **Topside components**: A joystick and a computer are required.
- **ROV components**: An autopilot and (typically) a companion computer are required.
- **Tether components**: A suitable tether is required for operation. RC and WiFi connections will not penetrate water.

A.4.1 Topside Components

The following operating systems are supported to use with the topside software (QGroundControl):

- Windows 10
- macOS 10.10 or later
- Ubuntu 16.04 or later

The following joysticks are supported for use with the topside software (QGroundControl):

- Logitech F310
- Logitech F710
- Microsoft Xbox controllers
- Wired PlayStation 4 controllers

A.4.2 ROV Components

Below is a typical diagram of hardware components on the ROV and their connections. Note that many of the components in this diagram are optional and this is not the only possible hardware configuration.

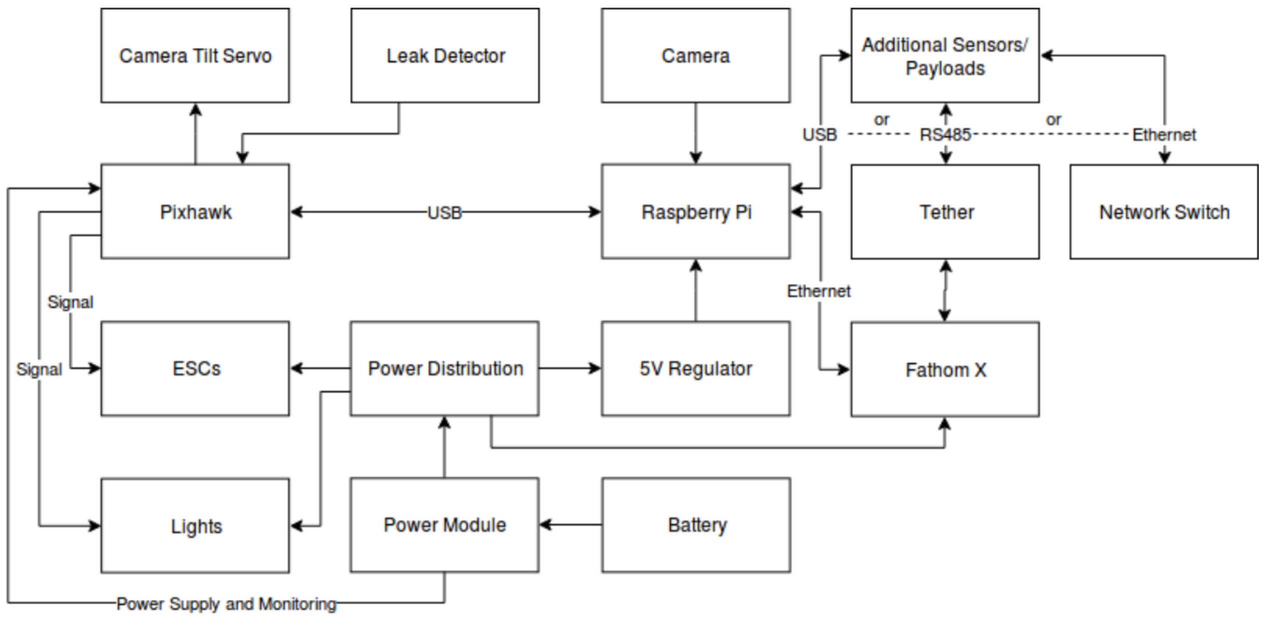


Figure A.2 ROV hardware components

Autopilot
The autopilot is responsible for controlling the ROV. The autopilot will typically have multiple on-board sensors like gyroscopes, accelerometers, and a compass to determine the vehicle's attitude. The autopilot processes the pilot input and sensor data, and controls the motors, lights, servos and relays on the vehicle.

Depth sensor
ArduSub supports the use of the MS5837 as an external water pressure and depth sensor. A depth sensor will need to be connected to the autopilot in order to used *depth hold* mode.

Leak sensor
ArduSub can be configured to read leak sensors and perform a failsafe action when a leak is detected. The SOS leak sensor is recommended.

Battery
It is recommended to design the vehicle to operate on battery power. Powering an ROV through the tether is not a trivial task and is outside the scope of the documentation presented online. Battery selection can be intimidating due to the overwhelming number of options, but there are a few important considerations:

- **Voltage:** Batteries often specify their voltage as well as a corresponding 'S' rating indicating the number of 3.7V cells in wired **S**eries inside the battery. The voltage of the battery needs to be matched to the ratings of the ESCs. As an example: The Blue Robotics ESCs supports 3S (11.1V) and 4S (14.8V).
- **Capacity:** Batteries usually specify their capacity in units of mAh. The larger this number, the more energy the battery will store, and the longer the ROV can run.
- **Electric current rating:** Batteries usually specify a 'C' rating for **C**urrent. In order to calculate the rated electric current in Amps, multiply the capacity of the battery in Ah (mAh/1000) times the **C** rating. For example, a 10000 mAh (10 Ah) battery with a 10C rating is rated for 100 Amps. As a general rule of thumb, the battery should be rated for a continuous current draw of 15 Amps times the number of thrusters. For Remora this equals 45 Amps.

Companion computer
The Companion Computer has two major functions on the ROV:
- Streaming HD video to the surface computer.
- Relaying communications between the autopilot and the surface computer via ethernet communications.

The companion computer must be running the Companion Computer Software to function correctly with ArduSub. Currently, only the Raspberry Pi 3 Model B (not B+) is supported for use with the Companion Computer Software.

Camera
The Companion Computer will stream HD video to the Ground Control Station at the surface. The Raspberry Pi camera and USB webcams with H.264 output are supported. The Blue Robotics H.264 USB Camera has been tested to work with the Companion Computer Software.

Motors and ESCs
ArduSub is designed to work with brushless motors. Brushless motors require Electronic Speed Controllers (ESCs) to operate. ArduSub requires all of the motors to operate in forward and reverse, so the ESC must support this functionality. Most ESCs for UAVs and Drones only operate in one direction! The Blue Robotics Basic ESC is supported for the use with ArduSub.

A.5 Software

There are three major software components involved in the operation of ArduSub:
- ArduSub: This is the autopilot software responsible for processing pilot input and controlling the ROV. ArduSub is the 'brains' of the ROV
- QGroundControl: This is the user interface for setting up the ROV. Can also be used for control, but is probably not suited for planning movements in a fish cage.
- Companion: The Raspberry Pi Companion Computer runs software that relays communications between the autopilog and QGroundControl via Ethernet communications. The Companion software also streams HD video to QGroundControl (this requires a cabled connection).

Figure 13 shows a typical diagram of the software components and their interactions.

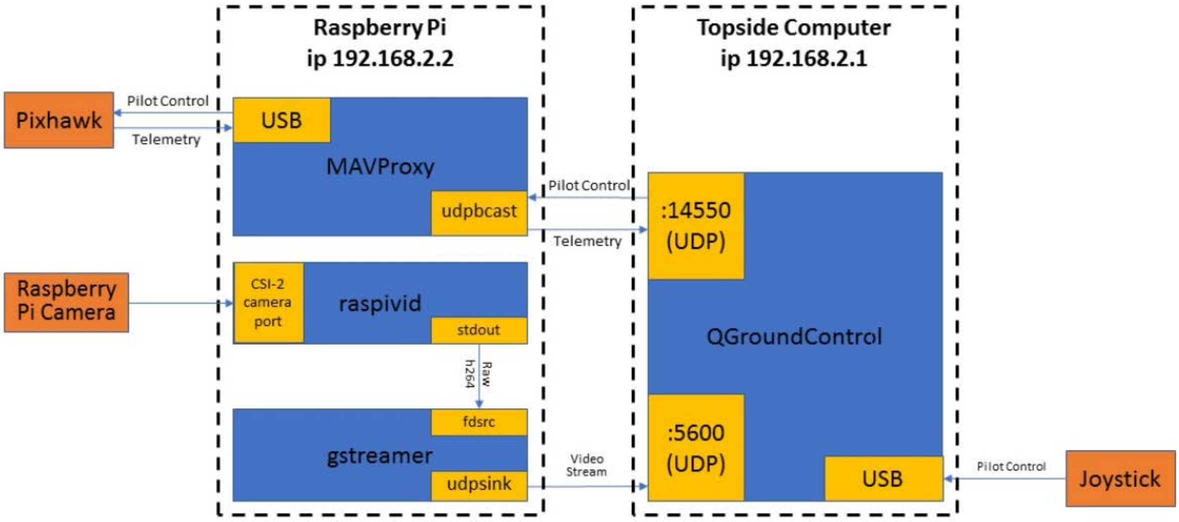


Figure A.3 Software components and their interactions

B Component specifications

This appendix presents tables of all equipment and software used in the current model of Remora with a short description.

Table B.14: Electronics, sensors and motors used in the current model

Specifications for current model				
	Name	Producer	Description	Link
Electronics	Advanced ROV Electronics Package for ArduSUB	BlueRobotics		Click
Advanced ROV Electronics Package for ArduSub				
	Pixhawk Autopilot	PX4	Advanced autopilot system.	Click
	Power sense module	BlueRobotics	Analog electric current and voltage sensing to Pixhawk	Click
	Fathom-X tether interface board set	BlueRobotics	Long-distance ethernet connection. Enables HD video. CAT5 cable. 8Mbps.	Click
	Low-Ligh HD USB Camera	BlueRobotics	Onboard compression. 2MP, 1080p	Click
	16GB SD Card	SanDisk	Preloaded with Raspbian for ArduSub and BlueRov 2	Click
	6" Left-Angle Micro USB cable for Raspberry Pi to Pixhawk			
	5V 6A power supply for Raspberry Pi and Pixhawk servo rail	BlueRov	Converts 7-26V to steady 5V at up to 6A	Click
	Pixhawk shelf and mounting hardware			
	Raspberry Pi Model B	Raspberry Pi	Companion Computer. Supported by ArduSub	Click
	Electronic Speed Control	ThrustMe	ArduSub recommends BlueRobotics ESC	
	Lumen Subsea Light	BlueRobotics		
Sensors	Bar02 Ultra High Resolution 10m	BlueRobotics	NOT COMPATIBLE WITH ARDUSUB!!	Click
	Power sense module	BlueRobotics	See above	
Motors		ThrustMe	Permanent magnet BLDC. Max thrust >= 15kg, Max Torque 1,5. ArduSub does not support these by default?	

Table B.215 Pixhawk Flight Controller. Advanced autopilot system key features

Description	Value
Main system on chip	STM32F427
CPU	180 MHz ARM Cortex M4
RAM	26 KB SRAM
Failsafe system on chip	STM32F100

CPU	24 MHz ARM Cortex M3
RAM	8 KB SRAM
Wifi	ESP8266 external
GPS	U-Blox 7/8 Hobbyking / U-Blox 6 (3D robotics)
Optical flow	PX4 flow unit
Connectivity	1x I2C 1x CAN (2x optional) 1x ADC 4x UART (2x with flow control) 1x Console 8x PWM with manual override 6x PWM/GPIO/PWM input S.BUS/PPM/Spektrum input S.BUS output
Other	Redundant power supply External safety switch Multicolor LED main display High-power multi-tone piezo audio connector microSD card for high rate logging

Table B.3 Power sense module. Provides analog electric current and voltage sensing to the pixhawk autopilot.

Description	**Value**	
Electrical		
Max Voltage Input	25.2V(6S)	
Max Current Sensing	100A(non-continuous)	
Output Connector	Non-insulated Spades(S5-3.5SNB)	
Input Connector	3.5mm Bullet Connector	
Physical (Board Dimensions)		
Length	24mm	
Width	19mm	
Height (without header pins)	7mm	
Power Pin Out		
Pin	Signal	Volt
1 (red)	NOT CONNECTED	
2 (blk)	NOT CONNECTED	
3 (blk)	CURRENT	+3.3V
4 (blk)	VOLTAGE	+3.3V
5 (blk)	GND	GND
6 (blk)	GND	GND

Table B.4 Tether interface. High speed, long-range ethernet connection. Enables HD video and high bandwidth data.

Description	**Value**

Electrical	
Supply voltage (terminal block)	7-28 volts
Supply voltage (USB port)	5 volts
Max power draw	2.5 W
Performance	
Max Practical Bandwidth	80 Mbps
Physical Layer Bandwidth	200 Mbps
Working Frequency	2-30 MHz
Max tether length (Published)	2000 m
Max tether length (tested)	300 m
Physical	
Operating temperature	-20 to +85 C
Storage temperature	-40 to +85 C
USB Connector type	USB Mini B Female
Tether wire gauge	12-30 AWG
Power Wire Gauge	16-26 AWG
Screw hole diameter	3.3 mm

Table B.5 Raspberry pi companion computer specifications

Description	**Value**
CPU	A 1.2 GHz 64-bit quad core ARMv8
Wifi	802.11n wireless LAN
Bluetooth	4.1 low energy
RAM	1GB
USB	4 ports
GPIO pins	40
HDMI	Full HDMI port
Ethernet	1 port
Audio	3.5mm jack and composite video
Camera interface	CSI
Display interface	DSI
SD Card	MicroSD card slot
Graphics	VideoCore IV 3D graphics core

Table B.6 Low-light HD USB camera

Description	**Value**
Physical	
Camera PCB Dimensions	32mm x 32mm
Mounting hole spacing	28mm x 28mm
Connector	JST-PH to USB
Performance	
Field of view (Horizontal)	80 degrees
Field of view (Vertical)	64 degrees
Focal length	2.97 mm
Format	1/2.9"
Distortion	1%
Resolution	2.24 MP
Standard	1080p

Compression format	H.264/MJPEG/YUV2 (YUYV)
Working temperature	-20 to +85 C
Minimum illumination	0.01 lux
Sensitivity	5.0V/lux-sec@550nm
Electrical	
Supply voltage	5 volts
Max power Draw	220mA

Table B.7 Brush specification

Description	**Value**
Manufacturer	Mink Bursten
Body	Aluminium
Brush fabric	Polyester PBT
Length	1000.0 mm
Working length	992.5 mm
Brush height	40.0 mm
Total height	85.0 mm

Table B.8 AC/DC converter. Flatpack2 380V/3000W HE

Description	**Value**
Electrical	
Input (operating range)	85-305 VAC
Output voltage	300-400 VDC
Current	9 ADC
Max voltage	400 VDC
Max power	3000 W
Physical	
Dimensions WxHxD	109 x 41,5 x 327 mm
Weight	1.95 lbs (0.88 kg)

Table B.9 DC/DC converter. Used subsea on Remora

Description	**Value**
Electrical	
Input (operating range)	260-410 V
Output voltage	24 V
Output current (max)	62.5 A
Power	1600 Watts
Physical	
Dimensions	61,0 mm x 25,1 mm x 7,2 mm (L x W x H)

Table B.10 Depth/pressure sensor

Description	**Value**
Electrical	
Supply voltage	2.5-5.5 Volts
I2C Logic Voltage (SDA and SCL)	2.5 – 3.6 Volts

Peak current	1.25 mA
Mating connector	Hirose 4-pos DF13
Pressure	
Maximum mechanical pressure	10 bar
Standard operating pressure	0.3-1.2 bar
Standard operating pressure	0-2 bar
Operating depth	10m
Relative accuracy	+/- 4 mbar (4cm in freshwater)
Temperature	
Operating temperature	-20 to +85 C
Storage Temperature	-40 to +85 C
Absolute accuracy	+/- 2 C
Physical	
Recommended through hole size	10.2 mm

Table B.11 Voltage stabilizer

Description	**Value**
Item name	UBEC
Output	5V/3A or 6V/3A (selected via jumper)
Input	5.5-26V (2-6s lipo battery or 5-15s NiCd/NiMH battery)
Dimension	43mm x 17mm x 7mm
Weight	11g
Ripple wave	Less than 50mVp-p (@2A/12V)

Table B.12 Common power module (pixhawk)

Description	**Value**
Maximum input voltage	18V
Maximum current	9A
Output	5.37V and 2.5A power supply to autopilot

Table B.1316 Motors

No.	**Item**	**Specifications**	**Note**
1	Motor type	Permanent magnet BLDC motor with outer rotor	
2	Insulation level	H	
3	Ingress protection rating	IPX7	
4	Resistance (mOHM)	<= 51.5	Room temp. 20 C
5	Voltage endurance	500V@1s <= 1mA	
6	Motor case diameter	42.5 mm	
7	Motor length	53 mm +/- 0.2 mm	
8	Screw diameter	25 mm – 4*M3	
9	No-load current	<= 1.9 A	
10	No load KV	360 +/- 5%	Input Voltage 18.5 V
11	Rated Power	1000W	Input Voltage 18.5 V
12	Maximum Torque	1.5 Nm	Input Voltage 18.5 V

13	Maximum Thrust	>= 15 kg	Input Voltage 18.5 V
14	Maximum permissible Voltage	25.2	
15	Maximum continuous current	40 A	Water cooling
16	Maximum instantaneous current	60 A	Water cooling, no less than 10 seconds
17	Number of Pols (rotor)	14	
18	Number of slots (stator)	12	
19	Noise (at rated voltage)	<= 86 dB	No load. 0.3 m from dB meter
20	Vibration	Runs smoothly	No load
21	Start with low voltage	Starts smoothly	No load

Table B.14 Electronic Speed Control (ESC)

No.	**Item**	**Specifications**	**Note**
1	Input voltage	9-25, 2 V (3s – 6S)	LI-ion
2	Cont. Current	40A	Water cooling, heat sink condition
3	Peak current	60A	Water cooling, heat sink condition, no less than 10 seconds
4	Input capacitor	390 uF/35V 8*20mm, 2PCS	Rubycon
5	MOSFET power of MOSFET	Rds (on): 0.7 mR @ VGS=10V VDS: 40V QTY: 12 PCS Type: TPHR8504PL-L1Q	
6	Driving method	FOC	Motor and ESC must match to work well and the motor wiring is very important
7	Throttle range	1100 us~1900us, middle is 1500us	Forward (F): 1900 us Reverse (R): 1100 us
8	Protect function	Protect function	
9	Upgrade function	Software upgrade	
10	Standby power loss	<= 50 mA	
11	BEC Type	No	
12	Lifetime	More than 2000 hours	Voltage 3~6S average power 600W, water cooling heat sink
13	Waterproof level	IP68	Fully glued
14	Weight	200 grams	With wires
15	Dimensions	100 x 32 x 18 mm	Without wires
16	Safety certification	R0HS, CE, FCC	Third party detection institution

Table B.15 Software

Description	**Value**
Communications protocol	MAVlink
Microcontroller software	Pixhawk PX4
Programming language	C++, Qt, Python
Image processing	OpenCV
Computer vision	Remora Robotics' own algorithms
Control	QGroundControl

Autonomy	Currently: Simple pattern following
Biofouling detection	Detect abundance of biofouling. To be developed
Positioning	Count masks in net. Not implemented

C Environmental sensors

The robot shall be equipped with sensors capable of measuring e.g., temperature, oxygen levels and pressure at different locations. The gathered data will be provided to the operators, thus providing them with a good overview of the environmental conditions at other locations than that of the stationary sensors.

Currently, only a temperature sensor is installed. This is part of the pressure/depth sensor and may not be accurate enough. The following environmental sensors/measurements are desired:

- Temperature
- Salinity
- Oxygen
- Water current strength and direction
- Turbidity

C.1 Temperature

Almost all other sensors include a temperature measurement with sufficient accuracy. Hence a dedicated temperature sensor is not required as the temperature measurement of the other sensors can be combined.

C.2 Salinity

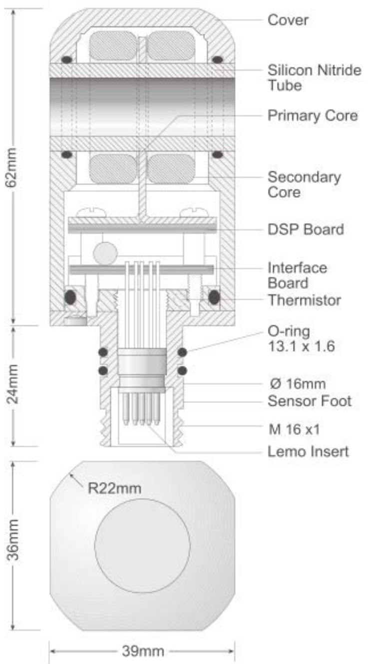
Xylem Conductivity Sensor 4319. Features:

- Direct readout of engineering data
- Unaffected by sea depth
- Output RS-232

Conductivity is a key parameter for in-situ determination of several fundamental physical properties of seawater. For seawater, the ability to conduct electrical current is mostly dependent on temperature and the amount of inorganic dissolved solids. This means that, together with temperature and depth information, a good estimate of the salinity may be determined. Salinity is defined as the concentration of dissolved solids. Other important properties of seawater are again dependent on salinity. Among these are the density and the speed of sound.

The Conductivity Sensor 4319 is based on an inductive principle. This provides for stable measurement without electrodes that are easily fouled and may wear out in the field.

Specifications:



Conductivity:	
Range:	0-7.5 S/m (0-75 mS/cm)
Resolution:	0.0002 S/m (0.002 mS/cm)
Accuracy: 4319A 4319B	 +/- 0.005 S/m (+/- 0.05 mS/cm) +/- 0.0018 S/m (+/- 0.018 mS/cm)
Response time (90%):	< 3s (dependant on flow through cell bore)
Temperature:	
Range:	-5 – 40 C
Resolution:	0.01 C
Accuracy:	+/- 0.05 C / 0.1 C (for interval < 30s)
Response time (63%):	<10 seconds
Output format:	AiCaP CANbus, RS-232
Output parameter:	
AiCaP:	Conductivity, temperature
RS-232:	Conductivity, temperature, salinity, density and speed of sound
Sampling interval:	2 sec – 255 min
Supply voltage:	5 to 14 VDC
Current drain:	
Average:	0.16 + 48 mA/S where S is sampling interval in seconds
Maximum:	100 mA
Quiescent:	0.16 mA
Operating depth:	
Shallow water (SW):	0-300 m
Intermediate water (IW):	0-3000 m
Deep water (DW):	0-6000 m
Electrical connection:	10-pin receptacle mating SP-plug
Dimension (WxDxH):	36 x 39 x 86 mm

Weight:	240 g
Materials:	Epoxy coated titanium

C.3 Oxygen

Xylem Oxygen Optode 4531. Features:

- Optical lifetime-based luminescence quenching
- Long time stability with red reference LED
- Stand-alone sensor
- RS-232 output

Since oxygen is involved in most of the biological and chemical processes in aquatic environments and in the process industry, it is one of the most important parameters to be measured. The fluorescent indicator is a special platinum porphyrin complex embedded in a gas permeable foil that is exposed to the surrounding water. A black optical isolation coating protects the complex from sunlight and fluorescent particles in the water. This sensing foul is mounted on a glass window providing optical sampling from inside a watertight housing. The sensing foul is excited by modulated blue light; the sensor measures the phase of the returned red light. For improved stability the optode also performs a reference phase reading by use of a red LED that do not produced fluorescence in the foil.

The sensor has an incorporated temperature thermistor which enables linearization and temperature compensation of the phase measurements to provide the absolute O2-concentration. The lifetime-based luminescence quenching principle offers the following advantages over electro-chemical sensors:

- Less affected by fouling
- Measures absolute oxygen concentration without repeated calibrations
- Better long-term stability
- Not affected by pressure

Specifications:

Oxygen:	O2 concentration	Air saturation
Foil:	Stable and rugged WTW foil	
Operation range:	0 – 1000 µM	0 – 300%
Calibration range:	0 – 500 µM	0 – 120%

Resolution:	< 0.1 µM	0.05%
Accuracy:	< 8 µM	< 5%
Response time (63%):	< 30 sec	
Typical field drift:	< 0.5% per year	
Temperature:		
Range:	-5 to +30 C	
Resolution:	0.01 C	
Accuracy:	+/- 0.03 C	
Response time (63%)	2 sec	
Output format:	4531A: 0-5V, RS-232 4531B: 0-10V, RS-232 4531C: 4-20mA, RS-232 4531D: RS-232	
Output Parameters:		
RS-232:	O2 Concentration in µM, Air saturation in %, Temperature in C, Oxygen raw data and Temperature raw data	
Analog channel 1:	O2 Concentration in µM, or Air Saturation in %	
Analog channel 2:	Temperature in C	
Sampling interval:	2 sec – 255 min	
Supply voltage:		
RS-232:	5 to 30VDC	
Analog:	7 to 30VDC, 12 to 30 VDC for 0-10V	
Current drain:		
RS-232		
Average:	0.16 + 48mA/S where S is sampling interval in seconds	
Maximum:	100mA	
Quiescent:	0.16mA	
Analog:	20mA + RS-232 drain	
Operating depth:	0-100 meters	
Elec. Connection:	Amphenol 16C or Subconn 8M	
Dimensions:	Ø38.2 x 193/273mm	
Weight:	Sensor: 160g, 5m cable 500g	
Materials:	PA	
Cable:		
Outer diameter:	9.9 +/- 0.4mm	
Min. bending radius:	155mm	

C.4 Water current strenght and direction

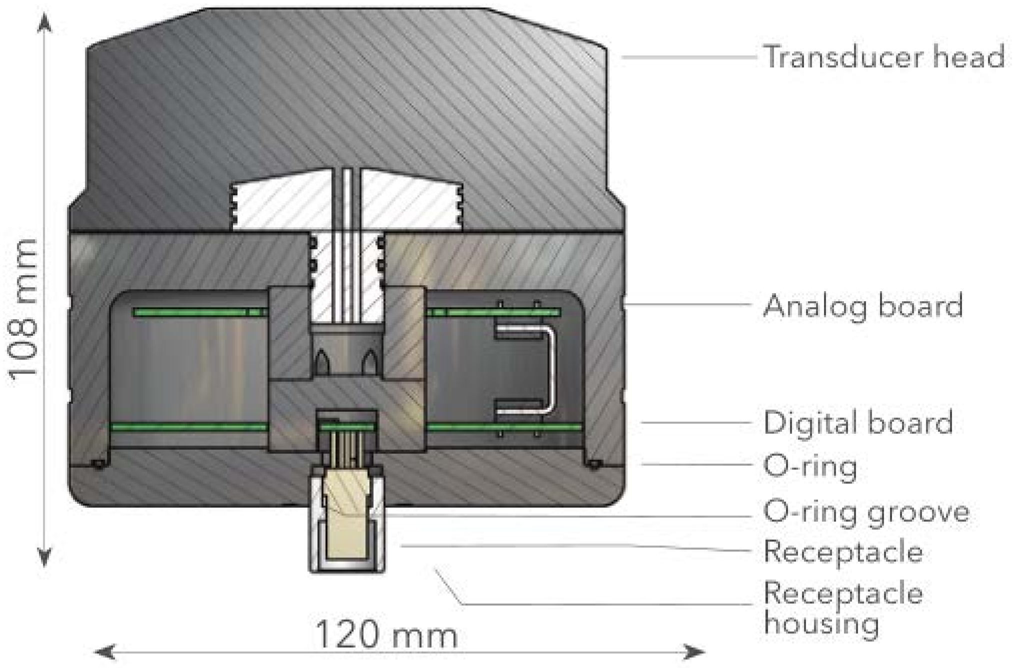
Xylem ZPulse Doppler Current Sensor. Features:

- Measure water current speed and direction
- Fast sampling rate
- Direct readout of engineering data
- Three axis tilt compensated compass
- Low power consumption
- RS-232 output
- Can include temperature

The sensor is based on the backscatter acoustic Doppler principle. The DCS has two orthogonal transducer axes with two transducers on each axis which is a great advantage. This makes it insensitive to disturbance

from vortex speeds around the sensor itself and the mooring line when the forward ping feature is enabled. One transducer on each axis transmits short ultrasonic pulses simultaneously. The same transducers receive backscattered signals from particles in the water. This gives an orthogonal x and y speed component which is tilt compensated to find the correct horizontal speed components.
The North and East speed components are calculated based on the x and y speed components and the heading from the built-in solid-state electronic compass. The sensor takes several of these two-component measurements and finally calculates the averaged north and east speed components and the vector averaged absolute speed and direction.

Specifications:



Water current speed: (Vector averaged)	
Range	0-300 cm/s
Resolution	0.1 mm/s
Mean accuracy	+/- 0.15 cm/s
Relative	+/- 1% of reading
Statistic precision (std)	0.3 cm/s (ZPulse mode), 0.45 cm/s
Water current direction:	
Range	0-360 degrees magnetic
Resolution	0.01 degree
Accuracy	+/- 5 degrees for 0-15 degree tilt +/- 7.5 degrees for 15-35 degree tilt
Temperature (selected models only)	
Range	-5 C to +40 C
Resolution	0.01 C
Accuracy	0.1 C
Settling time (63%)	30s
Tilt circuitry:	

Range	0-35 degrees
Resolution	0.01 degree
Accuracy	+/- 1.5 degrees
Compass circuitry:	
Resolution	0.01 Degree
Accuracy	+/- 3 degrees
Frequency	1.9 to 2.0 MHz
Power	25W in 1ms pulses
Beam angle (main lobe)	2 degrees
Interfaces:	
Model 4420/4520/4830/4930 Model 4420R/4520R/4830R/4930R RS-232/RS-422 Output	AiCaP protocol, RS-232 RS-422 9600 baud, 8 data bit, No parity, 1 stop bit, Xon/Xoff
Maximum cable length:	
RS-232	15m
RS-422	1500m
Installation distance	
From surface	0.75m
From bottom	0.5m
Supply voltage	6-14 Vdc
Operating temperature	-5 to +50 C
Depth capability:	
4420/4830	300m
4520IW/4930IW	3000m
4520DW/4930IW	6000m
Electrical connection	10-pin plug
Material and finish	
4420/4420R	Durotong, POM
4830/4830R	Durotong, POM, epoxy coated titanium
4520/4930/4520R/4930R	Durotong, epoxy coated titanium

C.5 Turbidity

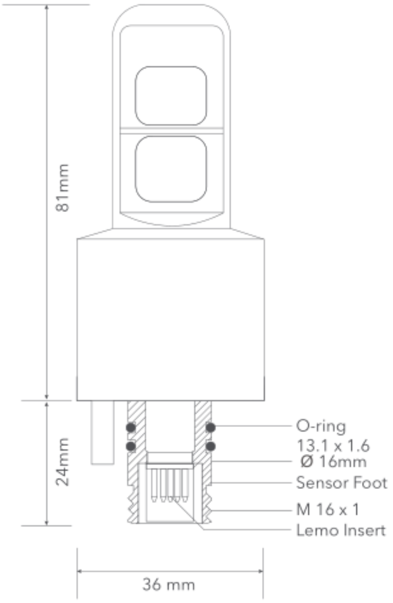
Xylem Turbidity Sensor 4112. Features:

- Optically confined sensing volume
- Insensitive to ambient light when under water
- 4 selectable ranges
- Optic feedback compensated for temperature drift and aging of optical components
- Very low power requirements

The turbidity sensor is based on the Seapoint Turbidity Meter. The sensor detects light scattered by particles suspended in water. This measurement is known to have good correlation to the amount of suspended matter in water and can be used to monitor e.g. sediment, algae or particle pollution. The sensor generates an output voltage proportional to the turbidity or suspended solids.

The low power consumption makes it ideal for applications where battery drain is a concern. The sensor offset voltage is within 1mV of zero and requires no adjustment across gains.

Specifications:



Operating temperature:	0C to 65 C
Output signal:	0-5.0 VDC
Output Time Constant:	0.1 sec
Power Requirements:	7-20 VDC
Current drain:	
Average: Peak:	3.5mA 6mA
RMS Noise:	< 1mV
Power-up Transient Period:	< 1 sec
Light Source Wave length:	880 nm
Sensing Distance:	< 5cm (approx.) from windows
Linearity:	< 2% deviation 0-750 FTU (the sensor is delivered adjusted for linearity in the range 0-750 FTU)
Temperature coefficients:	< 0.05% per degree Celsius
Depth Capability:	
Shallow water (SW): Intermediate water (IW): Deep water (DW):	0-300m 0-3000m 0-6000m
Weight (in air):	86g
Materials:	ABS Plastic, Titanium
Electrical Connection:	10-pin receptacle mating plug

C.6 Nitrate and phosphate

TBD

C.7 I/O and software requirements

All sensors from Xylem Aanderaa comes with an RS-232 interface. Hence the signals can be read by any software capable of receiving an RS-232 signal.