A Novel Sea Farm Inspection Platform for Norwegian Aquaculture Application

Ottar L. Osen[†*], Per Martin Leinan[†], Martin Blom[†], Christer Bakken[†], Matias Heggen[†], and Houxiang Zhang[‡]
[†]Cyber-Physical Systems Laboratory
[†]Department of ICT and Natural Sciences (IIR)
[‡]Department of Ocean Operations and Civil Engineering (IHB)
Norwegian University of Science and Technology
Postboks 1517, NO-6025, Aalesund, Norway
{ottar.osen, hozh}@ntnu.no

***Abstract*—This paper presents the development of a novel floating mobile platform for inspection and monitoring of aquaculture installations at sea. The application is to provide first-hand information on the integrity of the fish cages, both the structures, the nets and the moorings. The whole system, called "Sea Farm Inspector", includes a low cost ROV and a USV. The USV is an active self-stabilising autonomous carrier. The low cost ROV will be carried by the USV to the operation location. A winch on the USV platform will lift the ROV down into the water column and follow the ROV during the operation. The winch will lift the ROV out of water automatically after operation is completed and the "Sea Farm Inspector" will relocate to the next operation site. In the order to make the operation stable and safe, the USV will provide dynamic position control function, autopilot and manual manoeuvring functions. The whole system design and realisations will be presented in detail. A serial of tests both in tank and at sea has been made to verify the concept.**

***Index Terms*—ROV, Concept design, dynamic position control, marine aquaculture applications.**

I. Introduction

Since the 1970s, the aquaculture industry has gradually become an industry of major importance in Norway. Fishery, marine aquaculture, and maritime industry are deeply rooted in Norwegian national economics and traditions, especially in the western coastal regions. Norway's long and jagged coastline is surrounded by cold, fresh seawater that provides excellent conditions for fishery and aquaculture. Currently, Norway is the world's second largest seafood exporter [1]. The industry includes traditional fishing as well as fish farming and processing of all kinds of seafood at onshore facilities. Due to various factors, such as new technology, restructuring, international competition, restricted quotas, etc., the traditional aquaculture has undergone a number of changes during the past few years [2], [3]. Even though the continued growth of Norwegian aquaculture production has also boosted the development of aquaculture equipment produced by industry, the aquaculture equipment market is highly competitive.

In order to remain leading producer of Atlantic salmon, Norway has been adopting and developing competitive equipment for improving its competence in aquaculture industry, which is mainly in monitoring, maintenance, circulation and feeding operations in modern fish farms. However, some concerns arise: these machines, which make mechanical movements and noises in the aquaculture environment, threaten the health of fish. The demand for aquaculture friendly equipment has already been acknowledged by the professionals in the fish farming industry. Even though significant progress has been made in this field, the technology of using automated equipment in aquaculture is still a very challenging topic when considering low noise, high efficiency, environmentally friendly usability, and no extra emphasis placed on fish, which should receive special attention. There is still a big knowledge gap between the aquaculture and automation, mechanics, and product design.

NTNU strives to equip the local aquaculture industry with advanced bionic technology, and also to utilise and improve technology to support environmental exploration and monitoring. As a part of this quest and based on input from the stakeholders this project has developed a prototype for sea farm inspection.

The aquaculture industry struggles with several challenges. Two of them are fish health inside the cage and environmental impact from the farm to the nature. Firstly the aquaculture industry has been hampered by diseases from pathogens. Careful monitoring of the water, currents, temperature, algae content etc. may give fish farmers ample time to take adequate actions to protect the farm and to prevent polluting the environment. Secondly fish farming must at all times minimise its footprint in nature. One

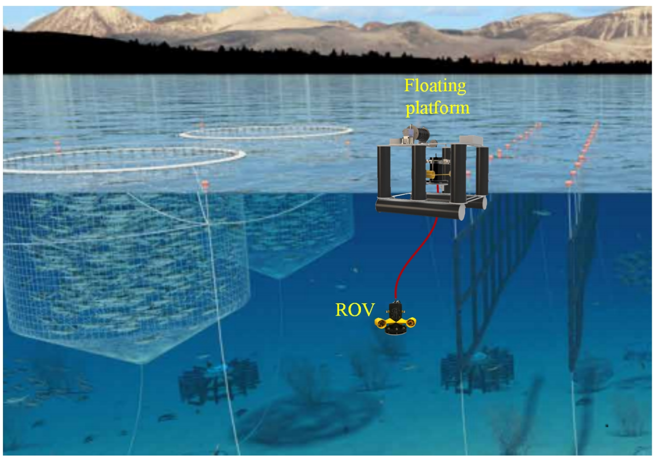


Fig. 1. "Sea Farm Inspector" project concept (modified from [4])

* As corresponding author. This project is supported by Mechatronics Lab at NTNU Ålesund

Authorized licensed use limited to: Norges Teknisk-Naturvitenskapelige Universitet. Downloaded on February 24,2022 at 19:59:05 UTC from IEEE Xplore. Restrictions apply.

important factor is escaped fish. Fish that escape from the sea farms is of course loss of revenue, but more importantly, the escaped fish can carry pathogens that may infect other fish. Finally escaped farmed fish may interbreed with the wild fish and thereby cause genetic introgression. This has proven to be a major concern for wild salmon [5]. Hence, frequent monitoring of the water-column and the structural integrity of the fish farm is an important measure in order to make fish farming sustainable. Our "Sea Farm Inspector" project is a contribution to ease and improve monitoring of sea farms and their environment.

This project aims to develop a novel low-cost sea farm inspection platform consisting of an USV (Unmanned Surface Vessel) and a ROV (Remotely Operated Vehicle) that is suitable to inspect the sub-sea side of the sea cages, its moorings and the nets in an highly automated fashion.

The whole project concept is shown in figure 1. There are two main parts in the total "Sea Farm Inspector" system including a USV - mobile platform and a low cost ROV [6]. A winch on the USV platform will lower the ROV down into the water column. Then the ROV navigate in sway, surge and yaw, while heave is controlled by the umbilical which provides the power and transfer the control signals. The umbilical also carry a live video feed from the ROV which together with the other sensor signals and are transmitted wirelessly (Wi-Fi) to the operator/surveyor. After the operation, the winch on the platform will lift the ROV back out of the water, then relocate to the next location.

USV platform will work as a mobile station for various operations, which features dynamic position function, active heave compensation and flexible mobility. This paper will first present the novel concept of the low-cost USV with capacity to carry sensors and a small ROV for marine aquaculture applications. The design is inspired by a semi-submersible platform for its outstanding performance to withstand waves. The "Sea Farm Inspector" may perform a wide range of marine operations within sheltered waters and lakes, such as surveying, inspection of fish farms, collecting sensor data and hoisting.

This paper presents the development of the USV. The

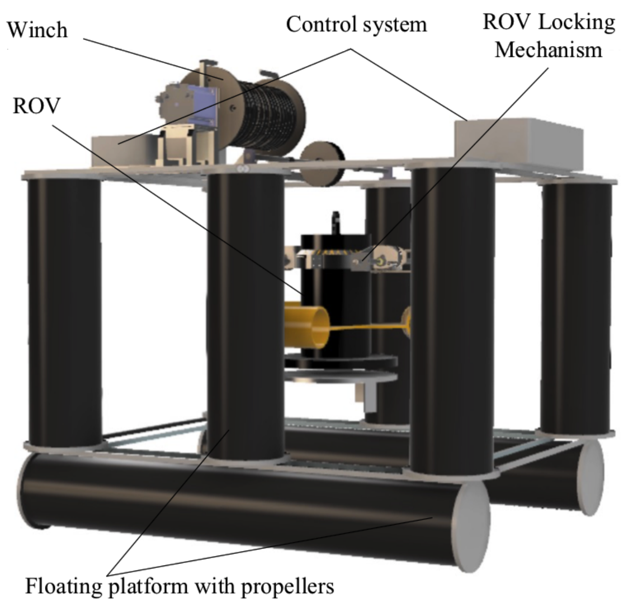


Fig. 2. "Sea Farm Inspector" project prototype.

ROV was presented in our paper [6] presented at OCEANS 2017 in Anchorage Alaska.

All related details in the system including design, stability control, navigation, obstacle avoidance and control realisation will be discussed. A serial of tests in the water tank and open sea environment were implemented to verify the concept and its performance. In the end, conclusions and future work are given.

II. Related work

The latest decade has witnessed an increasing interest in developing and employing modern machinery and robotic systems for aquaculture-related applications. In order to undertake a thorough and accurate investigation on the disturbance and stress introduced by present aquaculture equipment, surveys and studies must be carried out both on site and by gathering information from the fish farm. The investigation should include both the aquaculture and equipment suppliers. Therefore, a close cooperation with local aquaculture enterprises and research institutes should be carefully planned. In modern aquaculture facilities, automated machines and devices are installed for husbandry, monitoring and maintenance, all of which contribute to the stress of the fish. Investigations shall be made for recognising these factors and evaluating the underlying impact to the aquaculture environment.

High working efficiency, environmentally friendly work practices, high manoeuvrability and stability are always necessary for such systems. Underwater vehicles have been developed to undertake more and more work worldwide [7], [8]. Noise and disturbance to surrounding environments are two critical factors to consider when determining how to carry out successful and efficient work in practical environments. Therefore, the investigation will be undertaken in two fields. First, besides the traditional big remotely operated vehicles (ROVs) driven by electric motors and propellers, low cost simple ROVs will be considered as an alternative. Some prototypes including Blueye Pioneer, OpenROV are shown in the references [9], [10]. Devices and structures with unfriendly features, such as shapes, lights and noise, should be recognised and minimised. However, as a matter of fact, there are few ROV or underwater robots designed for aquaculture application so far [11], [12].

Furthermore, the mobility is also very crucial. Low manoeuvrability and low efficiency in limited working space are bottlenecks for ROVs in order to carry out successful and efficient work in practical aquaculture environments. From one fish net to another, moving in dynamic open environment is always challenging. If considering the current effects, dynamic position control is mandatory. However, for small ROV it is almost impossible to integrate all functions as a whole.

Therefore, a low cost ROV carried with an autonomous mobile platform may be a possible solution. On one hand, the ROV could implement the inspection and monitoring in an effective way; on the other hand, a flexible carrier could move from one location to the next efficiently, which also could provide power, signals and extra support to ROVs, shown in figure 1.

The motivation of this project is to minimise the unwanted disturbance to farmed fish by adopting environmental friendly methods and equipment in fish farming for Norwe-

Authorized licensed use limited to: Norges Teknisk-Naturvitenskapelige Universitet. Downloaded on February 24,2022 at 19:59:05 UTC from IEEE Xplore. Restrictions apply.

gian aquaculture application. It is also important to allow for remote operation since weather and light conditions often are unfavourable for local operation. The ultimate goal is to find applicable solutions for upgrading present fish farming equipment to include bionic features, while respecting Norwegian aquaculture environments and traditions. The applicable solutions indicate adopting and domesticating present technologies and methods with regard to practical operations in the local aquaculture.

III. "Sea Farm Inspector" - design

A. Concept design

The whole project concept is shown in figure 1. There are two parts in the whole system including a USV as a mobile platform and a low cost ROV. The USV will carry the ROV to the operation location. A winch on the platform will lower the ROV down into the sea water and downwards into the water-column. Thereafter the ROV will work together with the USV. The USV provides an "anchor point" and the cable which provides the power and transfer the control signals also maintain the ROV, which is heavier than water, in a fixed vertical position. The ROV can move in the horizontal directions using its built in thrusters and adjust the ROV (and cameras) heading. After the operation, the winch on the USV platform will lift the ROV out of water, then move to the next location. For details on the ROV the reader should see [6].

The aim at this project is to create a novel and low cost autonomous platform that can serve as an USV, carry sensors and be "mothership" of an ROV. The USV need to have a robust design in order to withstand severe weather and it need to have dynamic position (DP) capabilities. Due to the design as a semi-submersible platform with small waterplane area the USV also need to be able to adjust its trim automatically.

The design and prototype is shown in figure 2. The USV is configured with 4 thrusters, one at each side and offset from center. This gives makes the USV fully actuated in the 3 DOF's, surge, sway and yaw. Hence, the USV has omnidirectional movement capability. Since it is over actuated (4 actuators and 3 DOFs) it also have redundancy.

The USV use Wi-Fi network to transmit sensor values and video feeds from both the USV and the attached ROV to the operators PC and to receive commands from operator to the USV and ROV.

The USV has the ability to store energy in its battery banks that are located in the bottom pontoons. These batteries supply power to the USV, the USV sensors (such as laser range detector, GPS, IMU and camera) and to the ROV. The batteries must be charged when the USV is in dock.

The ROV have camera, lights, and sensors for oxygen, pressure, depth, moisture, temperature and voltage in addition to gyroscope and compass. This makes it possible to monitor the environments both internally and externally.

The operator PC for the USV have a GUI for navigation, status and sending commands to the USV which can operate is autonomous mode in additional to manual mode. In addition it has a separate GUI for operating the ROV.

B. Vessel design

Table I show candidate structure layouts that was evaluated and based on evaluation of pros and cons the rectangular design was chosen.

The selected design is a six legged semi sub platform standing on two horizontal pontoons and measures approximately 1 m x 0.6m x 1 m. The top frame is made of aluminium profiles. On this frame the control system and electronics are placed in a waterproof box. Columns and pontoons are made of 160mm PVC plastic tubes. Four of the columns are used for pitch, roll and draft control by pumping ballast water in or out. Batteries are placed in the pontoons and also has the function of ballast. The four thrusters are placed on top of the pontoons facing outwards in all four directions. It is designed to carry minimum 15 kg of payload. The USV without the ROV weighs around 115 kg (see next section).

C. Buoyancy and stability

The design of the USV is heavily inspired by the semi-sub platforms used for offshore operations such as drilling. The prominent advantage of this design is the small water plane area. When a wave hits a classical vessel hull the increased buoyancy in the area where the wave interacts with the hull will result in heave, pitch and roll movements (in addition to any yaw, sway or surge displacements). These, in this case, unwanted movements are proportional to the area in the water plane. This is because the wave changes the submerged volume:

$$V_s = A_w(d + \delta d) \tag{1}$$

Where V_s is submerged/displaced volume (which is proportional to the buoyant force), A_w is the area in the surface, d is the draft and $\delta d)$ is the wave height.

Due to the slim columns in this design the effect of waves are minimised. The main part of the buoyancy is the pontoons at the lower part of the structure and hence, below the effect of waves. Furthermore the centre of gravity (COG) is low since the heavy batteries are also located in the pontoons. The result is a construction that has strongly reduced impact of waves and is very stable due to its low COG. For more details on stability see Kemp [13].

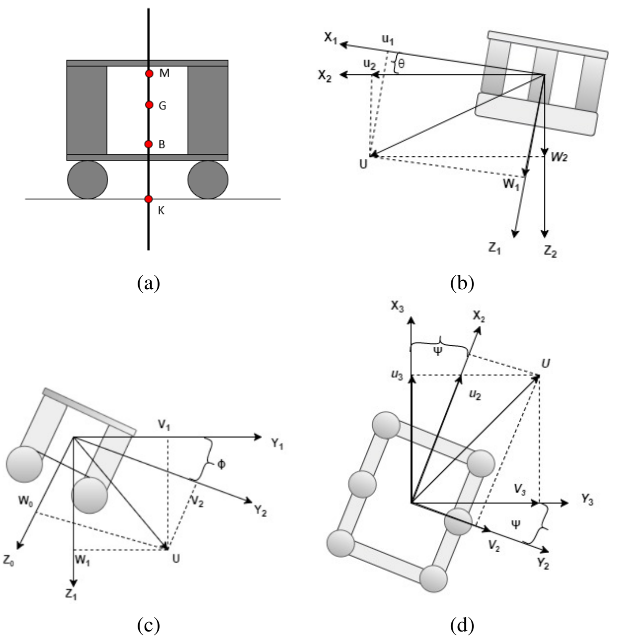


Fig. 3. (a) definitions; (b) pitch; (c) roll; and, (d) yaw.

Authorized licensed use limited to: Norges Teknisk-Naturvitenskapelige Universitet. Downloaded on February 24,2022 at 19:59:05 UTC from IEEE Xplore. Restrictions apply.

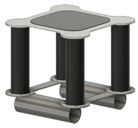
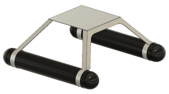
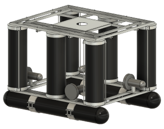
Design	Advantage	Disadvantage
Four legged version 	Simple design	Pipes has to be scaled up to a point where the model is larger then the other models to provide the same buoyancy. It is preferred to increase the number of columns instead of the diameter of them.
Hexagon and Octagon versions 	The design provides extra stability by having several arms reaching out in more than four directions.	While the design provides extra stability, the arms also prevents some waterflow in the front and rear part of the platform. Also, the design is found to be more complex than necessary.
Catamaran version 	Lightweight design, for a small scale use this could be a plausible design	The model would not be semi-submersible which means, the waves would influence the vessel more than the other models.
Rectangular version 	The model provides both buoyancy and stability. It has a natural front and rear, considering the placement of the vertical columns. Since the model has six legs, the pipes doesn't have to be as big as in the four legged one. Only two columns are visible in front and rear, so the water would easily flow through the vessel.	None significant.

TABLE I
MODEL COMPARISON

One significant drawback from such a design is that changes in weight load will result in significant changes in draft. This is seen from equation 1. Since A_w is constant and small (in our case) the only way to increase the submerged volume V_s is to increase the draft (d). Hence, in order to fulfil Archimedes law, the draft much change significantly. If load increases too much the upper part of the USV, the deck, comes to close to the water and can be flooded by waves (and slamming forces can affect stability). Furthermore if the load is decreased to much the pontoons get close to the surface and will be affected by waves and the new COG will result in lower stability. Hence, only small changes in load can be handled by changing the draft of the USV, larger changes in pay-load must be handled by adjusting the amount of ballast water in the columns. The capacity of the ballast pumps limits the rate of load change and the capacity of the ballast tanks limits the maximum pay-load changes.

Description	Weight
Bottom frame, with battery pontoons, end caps and s.s. rods, W/O batteries	24.2 kg
Top frame	8.8 Kg
Six vertical pontoons, with s.s. rods @ 5.14 kg	30.84 kg
Four thrusters @ 1.25 kg	5 kg
Two packs of five batteries	16.78 kg
Eight water pumps	2.4 Kg
Two boxes for electrical installation	4.3 kg
Cables, lights, valves, electronics	22.07 kg
Total	114.39 kg

TABLE II
WEIGHTS

Table II shows the weight of the individual parts of the platform.

D. ROV integration

A self-designed ROV is suspended in the middle of the USV via a locking mechanism. The basic concept of this ROV is low-cost, built with off-shelf and easily manufactured components. As shown in figure 2, there are three wings on the body part. One thruster is embedded into each wing to provide the propulsion. Based on the cooperation of three thrusters, the ROV has omnidirectional movement capability. A series of tests in the water tank were implemented including motion comparison, speed and turning tests to verify the concept and its propulsion mechanisms. The ROV details can be found in [6].

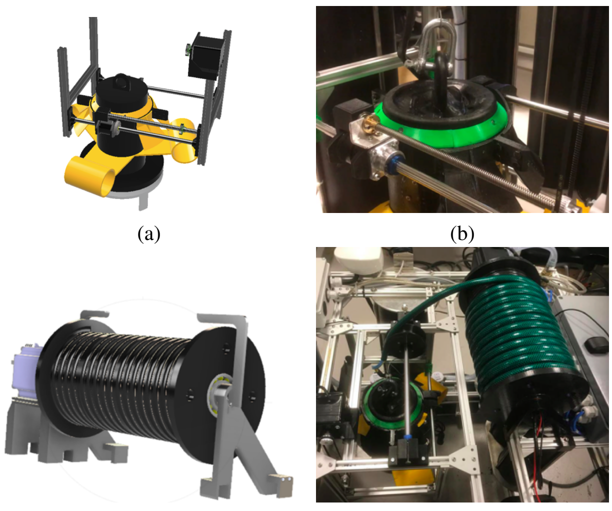


Fig. 4. ROV and winch: (a) and (b) ROV locking mechanism; (c) and (d) winch with spooling

When the ROV is in standby mode, it will be locked and secured inside the platform for further transportation. This requires a more stable and aligned connection between

Authorized licensed use limited to: Norges Teknisk-Naturvitenskapelige Universitet. Downloaded on February 24,2022 at 19:59:05 UTC from IEEE Xplore. Restrictions apply.

the platform and the ROV, stronger than just via umbilical. Placing the ROV inside of the platform will protect the ROV, and it also brings the ROV closer to the centre of gravity for the platform. In case of power outage on the platform the locking house should keep the ROV aligned and secured to the platform due to mechanical holding forces. Since the ROV has a circular shape, the shape of locking house is also circular to give a good connection of the ROV with the rest of the platform, see figure 4(a) and (b) . The design of the lock keeps the ROV in holding position both in horizontal and vertical direction. Hence, there is no need for further breaking systems to be installed to hold the weight of the ROV when the winch is in standby. As shown on figure 2, the locking house is placed more to the left side of the complete structure. When the hoisting operation of the ROV is complete, the cable will be positioned at the left side of the drum.

The winch is designed to lift up and low the ROV and provide power and control signals via the umbilical. The main diameter of the winch drum is 150mm, which would be sufficient with the estimated length of the umbilical. The length of the drum is 297mm to have an effective drum length of approx. 273mm. The main reason for the increased length is the slip ring fitted inside the drum. When the ROV is moving underwater, the winch will follow the motion according to the drag force, see figure 4(c) and (d). Hence, the umbilical will also provide safety and security for ROV operation. All parts are 3D printed.

E. USV control system

The USV has two separate control systems, one for horizontal movement and one for pich, roll and draft. In other words, one for navigation and dynamic positioning and one for ballast control.

The flowchart (figure 5) shows where the equipment is located. The equipment inside the dotted lines are on board the USV and the equipment outside the lines and connected with Wi-Fi are onshore alongside the operator. The Oderoid on the USV works like a master while the Arduino acts as a slave.

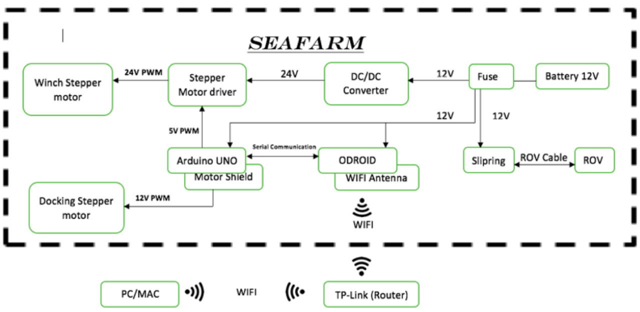


Fig. 5. Control system

To make the control system as safe as possible, the stability system is designed as a stand-alone system. Therefore, the decision was made to use a method called cyber-physical systems, where software and hardware are closely linked, and computing are decentralised. In this way, the stability system is not dependent on the server to operate and a failure in any other system would not affect the stability of the platform.

All components of the stability system is connected to a microcontroller which controls the system and sends the required information to the server. The Arduino Mega is chosen for this task because it has an easy setup, and for its number of I/Os. Another advantage of using Arduino is the simple operating system with fewer component that could fail.

IMUs and pressure sensors are used for stability control. Four IMUs provide more stable and accurate measurement. They are mounted on each corner of the platform, and the average value of all four IMUs are calculated. IMUs are prone to noise and this is compensated by averaging the 4 IMUs in a Kalman filter. The pressure sensors are used to measure the draft of the platform and the height of the water inside the pipes. The sensors are calibrated to show the depth in cm.

IV. Motion ralisation and DP control

A. Thruster allocation

The thruster allocation- and configuration is based on the same algorithms used in the previous bachelor thesis [14], [15], but modified in therms to fit the design and thruster configuration of the platform. For marine craft with n DOF it is necessary to distribute generalised control forces $\tau \in \mathbb{R}^n$ to the thrusters in X and Y direction in a 2 dimensional plane. The wanted forces are generated in the manual mode of the control system or in the autopilot/DP system on the server.

B. Thruster configuration

A force vector $\tau_{ref} = \begin{bmatrix} X & Y & N \end{bmatrix}^T$ is used as the input to the thruster allocation. X is the desired thrust in x-direction, Y is the desired thrust in y-direction and N is desired thrust about the z-axis. A positive momentum about the z-axis in a right-handed coordinate system will act clockwise, see figure(6). The control thrust from a single thruster is $F = u$. The thrust generated by each thruster can

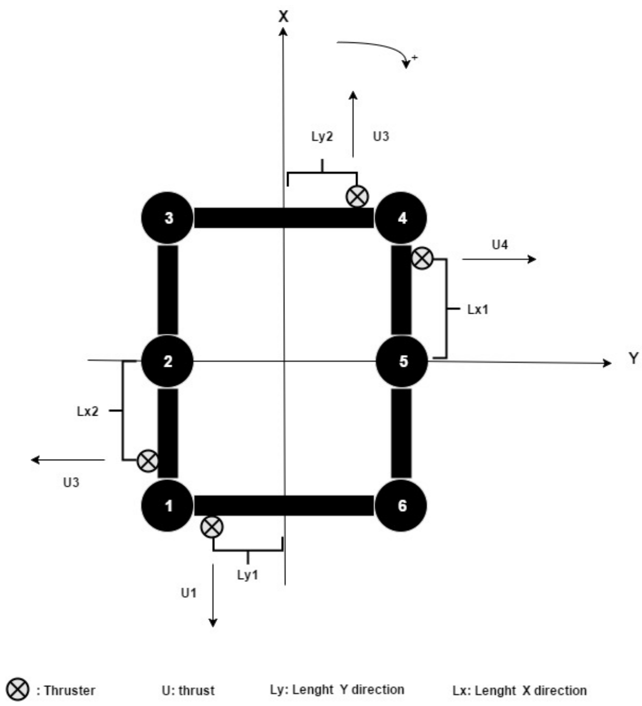


Fig. 6. Thruster configuration

Authorized licensed use limited to: Norges Teknisk-Naturvitenskapelige Universitet. Downloaded on February 24,2022 at 19:59:05 UTC from IEEE Xplore. Restrictions apply.

be denoted in a vector $\mathbf{u} = [u1, u2, u3, u4]$, while the thrust and momentum generated can be related to the control thrust τ_{ref} by the equation

$$\tau_{ref} = \mathbf{Tu} \tag{2}$$

Where **T** is a matrix that describe the thruster configuration on the craft. [14]

For u_1 we have

$$\tau = \begin{bmatrix} 1 \\ 0 \\ L_{y1} \end{bmatrix} u_1 \tag{3}$$

For u_2 we have

$$\tau = \begin{bmatrix} 1 \\ 0 \\ -L_{y2} \end{bmatrix} u_2 \tag{4}$$

For u_3 we have

$$\tau = \begin{bmatrix} 1 \\ 0 \\ -L_{x1} \end{bmatrix} u_3 \tag{5}$$

For u_4 we have

$$\tau = \begin{bmatrix} 1 \\ 0 \\ L_{x2} \end{bmatrix} u_4 \tag{6}$$

which gives the following thruster configuration system

$$\tau_{ref} = \begin{bmatrix} X \\ Y \\ N \end{bmatrix} = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ L_{y1} & -L_{y2} & -L_{x1} & L_{x2} \end{bmatrix} = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} \tag{7}$$

The thruster allocating consist of finding values that satisfy eq.(7). Measured distances perpendicular on the axis to the thrusters are as follows: $L_{x1} = L_{x2} = 0.45$ metres, and $L_{y1} = L_{y2} = 0.19$ metres, see fig(6). The theoretical centre of mass is retrieved from the cad drawing of the prototype without taking in account the weight of the pumps, thrusters and the electric system. CO is located where the X and Y axis cross, see fig(6).

C. Actuator Models

The control force due to a propeller, a rudder or a fin can be written (assuming linearity)

$$F = ku \tag{8}$$

where k is the force coefficient and u is the control input depending on the actuator considered; The linear model $F = ku$ can also be used to describe nonlinear monotonic control forces.

D. Solution by quadratic programming and JOptimizer

Taking the thrusters limitations in consideration, the optimisation problem has to be reformulated. The problem formulation used to solve the thruster allocation problem is based on the presented solution in section IV([16]), *Linear Quadratic Constrained Control Allocation*. The notation is from, [14] to match the values and variables used, and is as follows:

Actuator	u (control input)	α (control input)	$f^{\top}$ (force vector)
Main propellers (longitudinal)	Pitch and rpm	–	$[F, 0, 0]$
Tunnel thrusters (transverse)	Pitch and rpm	–	$[0, F, 0]$
Azimuth (rotatable) thruster	Pitch and rpm	Angle	$[F\cos(\alpha), F\sin(\alpha), 0]$
Aft rudders	Angle	–	$[0, F, 0]$
Stabilizing fins	Angle	–	$[0, 0, F]$

Fig. 7. Definition of actuators and variables

$$\begin{aligned} \underset{u,s}{\text{minimise}} \quad & u^T W u + s^T Q s \\ \text{subject to} \quad & Tu = \tau_{ref} + s \\ & u_{min} \leq u \leq u_{max} \end{aligned} \tag{9}$$

where s is a vector of slack variables that takes in consideration incidents of where τ_{ref} can't be reached by **Tu**. The condition $u_{min} \leq u \leq u_{max}$ ensures that the thrusters don't exceed their minimum(u_{min}) and maximum (u_{max}) values. By choosing the weighting matrix $\mathbf{Q} \gg \mathbf{W} > 0$, the slack variable should be close to zero, and an accurate generalised force **Tu** can be archived. [16]

The following explanation of the ThrustAllocator class is from(page 77-78, [14]) By defining

$$\begin{aligned} p &= \begin{bmatrix} \tau_{ref}^T & u_{min}^T & u_{max}^T \end{bmatrix} \\ \text{and } z &= \begin{bmatrix} u_{max}^T & s^T \end{bmatrix} \end{aligned} \tag{10}$$

then the problem can be reformulated to the form

$$\begin{aligned} \underset{z}{\text{minimise}} \quad & z^T \Phi z \\ \text{subject to} \quad & A_1 z = C_1 p \\ & A_2 z \leq C_2 p \end{aligned} \tag{11}$$

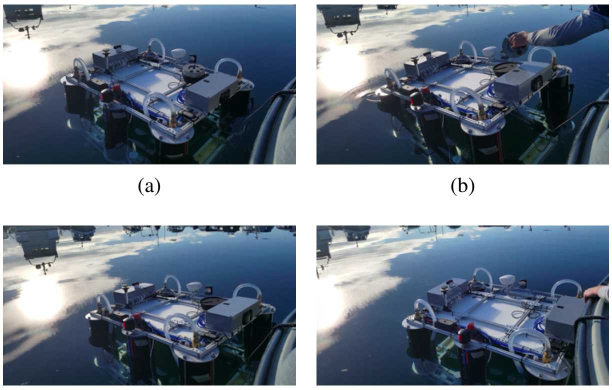
where

$$\begin{aligned} \Phi &= \begin{bmatrix} W & 0_{4\times3} \\ 0_{3\times4} & Q \end{bmatrix} \\ A_1 &= \begin{bmatrix} T & -I_{3\times3} \end{bmatrix} \\ C_1 &= \begin{bmatrix} I_{3\times3} & 0_{3\times8} \end{bmatrix} \\ A_2 &= \begin{bmatrix} -I_{4\times4} & 0_{4\times3} \\ I_{4\times4} & 0_{4\times3} \end{bmatrix} \\ C_2 &= \begin{bmatrix} 0_{4\times3} & -I_{4\times4} & 0_{4\times4} \\ 0_{4\times3} & 0_{4\times4} & I_{4\times4} \end{bmatrix} \end{aligned} \tag{12}$$

The open-source library JOptimizer for java is used to solve this optimalisation problem. In the class ThrustAllocator these matrices are initiated in the constructor. Then a **PDQuadraticMultivariateRealFunction**-object, which is the objective function that is being minimised. This object then take the matrix Φ as a parameter in the constructor. An array **ConvexMultivariateRealFunction**-objecs that set the constraint function is also initialised in the constructor. Finally an object of the class **JOptimizer** is instantiated. The JOptimizer object take care of the actual optimisation. This object use a primal-dual interior point algorithm to solve the quadratic programming problem [17]. A description of this algorithm can be found in [18]

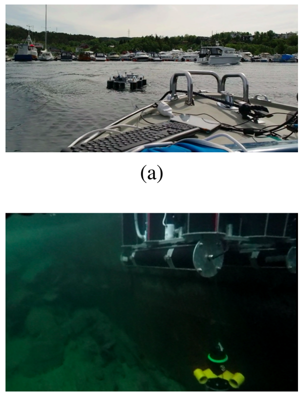
To calculate the vector **u** for a given τ_ref the method calculateOutput in the ThrustAllocator-class. This method returns an array of dimension 4 of the type double, where the elements in the array represent the thrust each thruster should generate.

Authorized licensed use limited to: Norges Teknisk-Naturvitenskapelige Universitet. Downloaded on February 24,2022 at 19:59:05 UTC from IEEE Xplore. Restrictions apply.



(a) (b) (c) (d)

Fig. 8. Stability test in the sea



(a) (b)

Fig. 10. Operation test in the sea

V. Experiments

In order to verify the system performance, a series of tests have been made in the water tank and in the open sea.

A. Stability control

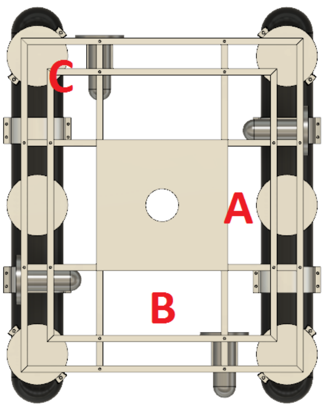


Fig. 9. Stability tests with different payload placement (A, B, C positions)

Pos/Kg	3 Kg	5Kg	10Kg
A	6.1s	8.7s	14.9s
B	7.8s	No Data	No Data
C	13.4s	19.7s	No Data

TABLE III
Stabilisation before draft compensation

Pos/Kg	3 Kg	5Kg	10Kg
A	6.1s	8.7s	14.9s
B	7.8s	No Data	No Data
C	20.4s	20.7s	No Data

TABLE IV
Stabilisation and draft compensation

Pos/3Kg	A=150mm T=4s	A=150mm T=3s	A=200mm T=4s
A stabilisation	6.0s	6.9s	5.3s
A draft correction	9.5s	6.9s	17.3s
B	No Data	No Data	No Data
C	No Data	No Data	No Data

TABLE V
Stabilisation with fixed payload in position A with changes in Amplitude A and period time T on the waves

We made a stability function test in the sea, as shown in figure 8. There is payload on the platform. When some payload was taken away, the Sea Farm begins to roll. From the signal from the IMU the stability control system learns that the platform is no longer level and pumps water in land out of different legs according to the sensor information and control strategy. Soon the new balance will be achieved. Some testing results are shown in tables III, IV and V.

B. Operation

An operation test was made in the sea. The sea state was in a good condition. When a boat passed by, the wave effected "Sea Farm Inspector" platform dynamically, see figure 10(a). However, the platform kept the position and realised stability in a good way.

Thereafter the ROV was unlocked from the USV and the ROV could move freely. The following function provided by the winch secures the ROV operation, as shown in figure 10(b).

VI. Conclusions

This paper presents a floating mobile platform for aquaculture application called "Sea Farm Inspector". The project concept, system design and integration are presented systematically. Especially, on-site testing in our water tank lab and in open sea confirm the effectiveness and robustness of the system.

The project is still in it's early stage. There are still a lot of work to be done. For example, how to improve the DP functions, how to realise a full autonomous pilot, upgrade the stability system with fuzzy logic or AI, multiple platforms team-work and cooperation are all challenging issues for the real application. We will work with Norwegian aquaculture industry to improve the system. A case study will be made in the near future.

Acknowledgement

The project is fully supported by the Mechatronics Lab at Department of Ocean Operations and Civil Engineering (IHB), NTNU in Aalesund.

Also the authors thank the great contributions from Mathias Tungevåg, Eivind Humberset, Simen Solbak, Fredrik Ryslett for their work on designing the winch and final system integration.

Authorized licensed use limited to: Norges Teknisk-Naturvitenskapelige Universitet. Downloaded on February 24,2022 at 19:59:05 UTC from IEEE Xplore. Restrictions apply.

References

[1] I. The Norwegian Ministry of Trade and Fisheries, "Aquaculture," web, 2017. [Online]. Available: http://www.fisheries.no/aquaculture/Aquaculture

[2] NAV, "Norwegian fishery," web, 2017. [Online]. Available: http://www.nav.no/82986.cms

[3] (2018) Salmon farming industry handbook. [Online]. Available: http://marineharvest.com/globalassets/investors/handbook/salmon-industry-handbook-2018.pdf

[4] (2018) Leroy, ngo launch multi-trophic farming project. [Online]. Available: https://www.undercurrentnews.com/2013/08/16/leroy-ngo-launch-multi-trophic-farming-project/

[5] S. Karlsson, O. H. Diserud, P. Fiske, and K. Hindar, "Widespread genetic introgression of escaped farmed atlantic salmon in wild salmon populations," *ICES Journal of Marine Science*, vol. 73, no. 10, pp. 2488–2498, 2016.

[6] O. Osen, R.-I. Sandvik, J. Berge Trygstad, V. Rogne, and H. Zhang, "A novel low cost rov for aquaculture application," *Proceedings of the IEEE OCEANS 2017*, 2017.

[7] M. Nagai, *Thinking fluid dynamics with dolphins*. Ohmsa, Ltd., Tokyo, Japan: IOS press, 2002.

[8] K. H. Low, C. W. Chong, and C. Zhou, "Performance study of a fish robot propelled by a flexible caudal fin," in *Robotics and Automation (ICRA), 2010 IEEE International Conference on*. IEEE, 2010, pp. 90–95.

[9] blueyerobotics, "Blueye robot," web, 2017. [Online]. Available: https://www.blueyerobotics.com/

[10] openrov, "openrov," web, 2017. [Online]. Available: https://www.openrov.com/products/openrov28/

[11] UTM, "Utm robot," web, 2017. [Online]. Available: http://www.jurnalteknologi.utm.my/index.php/jurnalteknologi/article/view/3262/2444

[12] V. N. Kuhn, P. L. J. Drews, S. C. P. Gomes, M. A. B. Cunha, and S. S. d. C. Botelho, "Automatic control of a rov for inspection of underwater structures using a low-cost sensing," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 37, no. 1, pp. 361–374, 2015. [Online]. Available: http://dx.doi.org/10.1007/s40430-014-0153-z

[13] J. F. Kemp, C. B. Barrass, and P. Young, *Ship Stability: Notes and Examples*. Butterworth-Heinemann, 2001, vol. 3rd ed. [Online]. Available: http://search.ebscohost.com/login.aspx?direct=true&db=nlebk&AN=104911&site=ehost-live

[14] . Kandidates: 807, 819, "Usv - unmanned surface vessel," *Bachelor thesis NTNU Aalesund*, vol. 368, no. 10, pp. 74–77, 26.05.2016.

[15] T. I. Fossen, *Handbook of Marine Craft Hydrodynamics and Motion Control*. John Wiley & Sons, Ltd, 2011.

[16] T. I. Fossen and T. A. Johansen, "A survey of control allocation methods for ships and underwater vehicles," *Mathematical Association of America*, vol. 6, no. 1, pp. 1–6, 2006 14th Mediterranean Conference on Control and Automation.

[17] joptimizer.com, "Primal-dual interior-point method." [Online]. Available: http://www.joptimizer.com/primalDualMethod.html

[18] S. B. andLieven Vandenberghe, *Convex Optimization*. The Edinburgh Building, Cambridge, CB2 8RU, UK: Cambridge University Press, 2004.

Author Biographies

OTTAR L. OSEN graduated with MSc in Engineering Cybernetics from the Norwegian Institute of Technology in 1991 (NTH, now the Norwegian University of Science and Technology (NTNU)). He is the head of R&D at ICD Software AS and an associate professor at NTNU in Ålesund. In addition to 13 years in academia he has worked for 15 years as an consultant in the maritime and offshore industry both in Norway and internationally. He has taken part in the engineering phase on several of the large offshore projects on the Norwegian continental shelf. He has broad experience in subsea control systems and SCADA systems in general. His research interests belong to the fields of artificial intelligence, cybernetics, instrumentation, real-time systems, industrial control systems, mechatronics, and modelling and simulation.

PER MARTIN LEINAN, **MARTIN BLOM**, **CHRISTER BAKKEN** and **MATIAS HEGGEN** are BSc students in automation engineering at NTNU in Ålesund.

HOUXIANG ZHANG (M'04–SM'12) received Ph.D. degree in Mechanical and Electronic Engineering in 2003. From 2004, he worked as Postdoctoral Fellow at the Institute of Technical Aspects of Multimodal Systems (TAMS), Department of Informatics, Faculty of Mathematics, Informatics and Natural Sciences, University of Hamburg, Germany. In February 2011, he finished the Habilitation at University of Hamburg. Dr. Zhang joined the Department of Ocean Operations and Civil Engineering (IHB), Norwegian University of Science and Technology, Norway in April 2011 where he is a full Professor on Robotics and Cybernetics. He also has a gift professorship on product and system design from Norwegian Centre of Expertise Maritime. The focus of his research lies on bio-inspired mobile robotics, modular robotics, and nonlinear control algorithms. In these areas, he has published over 100 journal and conference papers and book chapters as author and co-author. Recently, he has received the best paper award at the IEEE/AEME AIM2008 conference, and three finalist awards for best conference paper at IEEE Robotics and Automation conferences.

Authorized licensed use limited to: Norges Teknisk-Naturvitenskapelige Universitet. Downloaded on February 24,2022 at 19:59:05 UTC from IEEE Xplore. Restrictions apply.