Collection of Aquatic Biomass in Ports using Autonomous Marine Robots - Initial Findings

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***Abstract*— Large quantities of algae are an increasing global challenge caused by eutrophication and increasing temperatures. In this paper, we present the early results of a test using an autonomous marine robot which can collect the surplus of algae based biomass so it can be utilized for other purposes. There are many types of algae, but in this paper we focus on collecting macro-algae - also known as seaweed. Based on real-life testing, we were able to collect 2.7 kg of biomass per hour. However, the test showed that collection can be substantially improved by altering the platform and improving the navigation algorithms, which in this paper is illustrated on a number of emulations in a virtual environment.**

I. INTRODUCTION

Today, significant resources are spent on collecting and handling algae in public and private sectors. The primary reason for the cost is that the collection process is time-consuming, monotonous and carries a safety risk as the process is often performed manually supplemented by heavy machinery. However, algae in general has a number of extremely positive properties, and over the past several years there has been a significant increase in the interest in algae as a component in several product chains - including as an energy source. as a raw material and for consumption. Collecting macro algae in the water before it starts to decompose, will avoid emissions of gasses with high CO2 equivalent and remove excess nutrient (phosphorous and nitrogen) from the ecosystem up to 10 times more efficiently than when algae decays on the coastline. Removal of 10.000 tons fresh algae avoids methane emissions by an estimated 5.422 tons CO2, removes 400 tons nitrogen, five tons phosphorous and lead to additional CO2 reduction when using algae as a sustainable raw material [1].

In the past 30 years, more than half of synthetic fertilizer ever applied was used in the agriculture sector. More than 50 percent of this runs through the soil and ends up in the oceans making algae grow instead of being utilized by the plants on land. The number of coastal region dead zones have increased tenfold since 1950, and increasingly occur due to the use of fertilizers [2]. This leads to extensive eutrophication (the process of increasing bio-mass generation in a water-body caused by increasing concentrations of plant nutrients, most commonly phosphorus compounds and nitrate) and consequently so-called dead zones devoid of most life. [2].

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Fig. 1: The WasteShark ASV by RanMarine

University of South Florida has since 2006 used NASA satellites to observe seasonal algae blooms, and in 2018 documented one of the largest seasonal bloom of macro-algae in the world, dubbed the Great Atlantic Sargassum Belt. More than 20 million metric tons of it builds up from the west coast of Africa via northern Brazil, ending up as far as the Gulf of Mexico [3]. In Denmark, environmental consequences of collecting macro algae and the effect on emissions of greenhouse gases have been partially investigated in Skive Fjord [4]. However, there is a lack of an overall estimate for the extent of eutrophication-related mass occurrences of macro algae and for the temporal and spatial variation of these mass occurrences The rising incidence of algae blooms (both macro and micro) has increased the relevance of effective algae monitoring methodologies globally. Most research regarding algae bloom is based on monitoring of harmful micro-algae bloom using satellite or aircrafts [5] and little research exist concerning monitoring and collecting macro algae in ports.

Today, cleaning of beaches and coastlines is mainly done using conventional solutions, i.e. excavators or tractors, or by using manned beachrakes that comp the beach and remove leftover seaweed after an initial clean-up.

Autonomous Surface Vessels (ASVs) are increasingly being used for monitoring, surveillance and to some extend logistics at sea. The maritime domain is characterized by a large variety of obstacles, uncertain obstacle motion, complex interactions between vessels, and varying sea states (e.g. currents and waves), and autonomous collision avoidance [6]. Automated collection of debris while at sea is a new research area, which has so far not been done in any significant scale. Although several companies provide ASVs (e.g. Maritime Robotics, Sea Robotics, Kongsberg, DanaDynamics), existing platforms are designed for data collection and monitoring. To our knowledge, RanMarine is the only company who provides ASVs with the capability of collecting debris in the water while supporting autonomous navigation, see Fig. 1.

Virtual environments are becoming an increasingly important part of robotic application development and validating applications in simulation can shorten iteration time and reveal potential issues fast [7]. In this paper, a virtual environment representing a real test site has been programmed in Unity in order to benchmark different navigation algorithms of the ASV.

The paper is organized as follows; Firstly, an introduction to the problem is described in Section I. Section II, contains a brief overview of the types of biomass commonly found at Danish coastlines, which is followed by a description of how the test sites were selected. This section, also includes a description of the used ASV and the results in terms of technical issues identified and amount of biomass collected based on real world testing. Based on these findings, the last part of the paper in Section III, describes how navigation algorithms and collection of biomass can be improved. For technical reasons, this has not been possible to evaluate in real life, and is therefore based on simulation in a virtual environment. Section IV includes a comparison of the different navigation methods and the results are discussed. A summary and conclusion can be found in Section V.

II. Collection of aquatic biomass

Algae are found in countless varieties, all of which are photosynthetic organisms in aquatic ecosystems. They serve as natural filters of phosphates and nitrogenous wastes and release oxygen to the atmosphere by way of photosynthesis, like plants growing on land. It is useful to distinguish between micro-algae, or phytoplankton, and macro-algae. Micro-algae is a unicellular biomass on a microscopic level, whereas macro-algae are much larger, also commonly referred to as seaweed. The technical solutions for collecting the different types of algae differ substantially, as do the technical solutions for the commercial usage.

In this paper, we focus on macro-algae which are found in more than 10.000 species worldwide, categorized as green, red and brown, as well as in a variety of subspecies and therefore also different sizes and shapes, some growing tall from the bottom and upwards (e.g. Kelp) while other grow as mats on the surface (e.g. Sargasso or Sea Lettuce).

The types of biomass which are most commonly found in ports and beaches in Denmark are (also see Figure 2):

- Beach wrack. A term used to describe the accumulation of seaweed, seagrass and other specimens from the sea which collects near the shore and on beaches
- Bladder wrack (Fucus vesiculosus). Growing up to 35 inches (90 cm) tall, bladderwrack grows along the coastlines of the Atlantic and Pacific Oceans, the North and Baltic Seas, and various waters in Canada and the United States.
- Ectocarpus siliculosus which is filamentous brown alga often found at beaches.
- Eelgrass or seagrass (Zostera marina). Flowering plants (angiosperms) which grow in marine environments. There are about 60 species of marine seagrass. Seagrass are technically not counted as an algae but is considered equal to algae for the purpose of this project.
- Sea lettuce (Ulva lactuca). Ulva can grow to be more than 400 mm (16 in) in size, but this occurs only when the plants are growing in sheltered areas.
- Toothed wrack (Fucus serratus). This is a seaweed of the north Atlantic Ocean, known as toothed wrack or serrated wrack.

Fig. 2: Types of biomass typically found at Danish coastlines. Top line from left to right; Beachwrack (mix of algae), Bladderwrack (Fucus vesiculosus), Ectocarpus siliculosus. Buttom line from left to right; Seagrass (Zostera marina), Sea Lettuce (Ulva lactuca), Tooth wrack (Fucus serratus)

A. Selection of test sites

In order to find a suitable test site, a total of 20 potential sites in Denmark were inspected (See Table I). Where possible, an airborne drone was used to fly over the area to perform a visual inspection. However, for some locations, flying with drones were not possible due to regulation or weather conditions.

Beside visual inspection of each site, we used desktop research looking at the site's corresponding bathing water profile. The bathing water profile is a mandatory document for public beaches in Denmark, and is made by the municipalities. The document supports the municipality's management of the bathing water by gathering knowledge about the risk of reduced bathing water quality including the risk of macro algae [8]. An overview of the results can be found in Table I.

The sites were evaluated in regard to the following parameters:

- Amount of aquatic biomass found in the water and at the beach
- Type of algae identified
- Accessibility for testing

Region	Location	Type of algae	Quantity on beach	Quantity in water	Date for inspection
Langeland	Spodsbjerg	Eelgrass	Low	Low	20.07.2020
Langeland	Rudkøbing/Bellevue	Eelgrass/beach wrack	Medium	High	20.07.2020
Møn	Hjelm bugt	Eelgrass/beach wrack	Low	Low	31.08.2020
Møn	Hårballe havn	Eelgrass	-	High	31.08.2020
Møn	Hårballe strand	Eelgrass/beach wrack	Medium	Low	31.08.2020
Møn	Uffshale Strand	Eelgrass	Medium	Medium	31.08.2020
South Zealand	Fakse Ladeplads	Eelgrass/beach wrack	High	Medium	31.08.2020
South Zealand	Kite Spot	Eelgrass/beach wrack	High	Low	31.08.2020
South Zealand	Enø Strand	Eelgrass/bladder wrack	Low	Low	01.09.2020
South Zealand	Vesterhave Strand	Eelgrass	High	Low	01.09.2020
South Zealand	Præstø Fjord	-	Low	Low	01.09.2020
South Zealand	Ore Strand	Eelgrass	High	Medium	01.09.2020
South Zealand	Masnedsund Habour	Eelgrass/beach wrack	N/A	High	6.11/25.11/10.12
Skive Fjord	Lyby Strand	Eelgrass/sea lettuce	Low	Low	13.10.2020
Skive Fjord	Grønning Strand	Eelgrass/bladder wrack	Medium	Medium	13.10.2020
Odsherred	Høve Hundeskov	Eelgrass/beach wrack	High	Medium	14.10.2020
Odsherred	Nordstrand	Eelgrass/beach wrack	Medium	Low	14.10.2020
Odsherred	Mogens Heringsvej	Eelgrass/beach wrack	High	Low	14.10.2020
Aarhus	Tangkrogen	Eelgrass/Ectocarpus/beach wrack	Low	Low	17.08.2020, 18.10.2020
Aarhus	Marselisborg	Eelgrass/beach wrack	High	Medium	17.08.2020

TABLE I: List of potential test sites

Based on this analysis, the sites at Fakse Ladeplads (Site 1) and Masnedsund Havn (Site 2) in South Zealand were identified as the most relevant for testing the technology.

B. Equipment

The ASV used in this paper, is a WasteShark provided by RanMarine which is an autonomous vessel designed to remove floating debris from the water surface in ports and harbors. Shaped like a catamaran, the electrically powered vessel is propelled forward using three thrusters and is able to go at a maximum speed of 3 km/hr = 1.62 knots. The vessel is 157 cm x 109 cm x 52 cm and weights 72 kg unloaded. It has a removable basket cartridge for disposal of collected debris with a volume capacity of 160 L and weight capacity of 60 kg. The maximum operating time on one charge is 8 hours, and charging time is around 5 hours. It is able to navigate autonomously based on GPS and RTK-GPS and has a LIDAR for obstacle avoidance. However, the unit can also be controlled using a standard RC Unit pre-programmed to interface RanMarine's software and firmware.

Observation of movements of the ASV and identification of algae in water was done using an aerial drone; more specifically a DJI Mavic Air 2 Fly More Combo.

The simulation environment was based on Unity, which is a cross-platform game engine developed by Unity Technologies.

C. Collection at Site 1: Fakse Ladeplads

The ASV was initially tested 28/10-2020. At the day of testing the wind was about 8 m/s with some current and waves in the harbor. Inside the harbor area at Fakse Ladeplads, we managed to collect different samples of macro algae using manual control of the ASV. The collection of

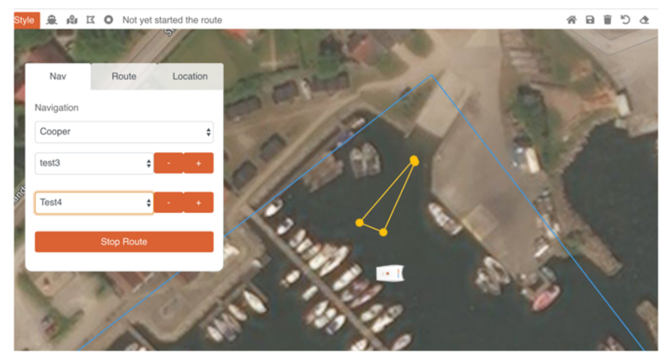

Fig. 3: The web dashboard for autonomous control of the ASV in Fakse Ladeplads

algae was based on three rounds of sailing in a limited area of the harbour. The types of algae we collected at the site were:

- Eelgrass
- Bladder Wrack
- Sea lettuce
- Ectocarpus siliculosus

We were only able to collect algae in limited amounts based on manual control (less than 500 grams per hour) as algae did not easily collect in the basket. Some of issues that we identified based on this initial test were the following:

- The ASV is sensitive to current and wind, making manual navigation difficult in some areas of the port.
- If biomass is too dense, the vessel has problems gaining enough thrust to navigate through the biomass
- Eelgrass has a tendency to be tangled into each other in heavy bundles. This makes it difficult for the vessel to collect the biomass as it escapes the collection basket of the ASV.
- Biomass at this specific test site was often found on shallow ground or near stones, were the ASV could not operate

In order to test autonomy, a simple test was performed in the port. The vessel was set to follow a predefined route which was specified using the WasteShark web page dashboard (see Figure 3). Initially, a location had to be defined which works as a boundary box of where the robot can navigate. Afterwards a route had to be defined. In this case, the bounding box was defined around the harbor base, while a route was based on three locations in a triangle without any obstacles.

To validate the route, the WasteShark was observed using an airborne drone. Although it was not possible to document the entire path in this setup, the initial finding is that the ASV was following the designed path but deviated to some extent due to wind and current.

In order to validate the obstacle avoidance functionality, a new route was designed where the vessel deliberately should navigate between 3 poles placed in the harbor. The ASV managed to navigate through pole 1 and 2, and through pole 2 and 3 without any collisions. However, between the final

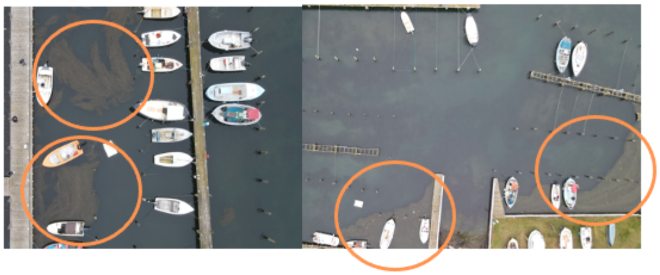

Fig. 4: Drone photo of Masnedsund havn. Orange circles marks identified eelgrass

Date	Amount gram	Time in minutes	Average gram/minutes
25.11.2020	1.342	30	45
25.11.2020	2.000	30	67
25.11.2020	2.500	60	42
06.11.2020	2.000	30	67
10.12.2020	250	30	8
Total	8.092	180	45

TABLE II: Measurement of collected biomass

points of the route, the vessel did collide with a pole on its way back to the starting point and had to be returned using manual control.

D. Collection at Site 2: Masnedsund Havn

The second test site was selected to be Masnedsund Havn. This selection was mainly due to the fact the harbor has big problems with biomass of accumulating eelgrass (See Figure 4). Additionally, the location is well-protected from wind and waves and provides easy access for off-loading and onloading the ASV. Acceptance to perform the test was granted by the local harbor master.

As can be seen from the Figure 4, the harbor is troubled by massive amounts of biomass (marked with orange circles) – especially eelgrass. The biomass is mostly located along the piers of the harbor, especially in the corner sections of the inner most part (the northern part). Talking to the local fishermen revealed that biomass sometimes made it impossible to sail in the harbor, which was occasionally being cleaned out using an industrial digger.

Masnedsund Havn was visited on three different occasions, 6/11-2020, 25/11-2020 and 10/12-2020. In order to test the potential for collecting biomass, the ASV was remote controlled in a random route in the harbor area in a fixed period of time (either 30 or 60 minutes). A total of 5 tests were made, which can be seen in the Table II. For each test, the collection bin of the ASV (See Figure 5b) was emptied before navigating the ASV around in the harbor using remote control. After the time had elapsed, the collected biomass was measured using a handheld weight and a plastic bucket (See Figure 5a).

Based on the testing in Masnedsund, it is estimated that the WasteShark is able to collect 45 g/minute based on a random path plan. This corresponds to 2.7 kg/hour or 65 kg/day (assuming a day is defined as 24 hours non-stop operation). According to the vendor, the ASV is able to run for about 8 hours before recharging, corresponding to 21,7 kg of biomass per charge. However, in practical use this figure will depend very much on the conditions on the site, i.e. density of biomass, wind, current etc.

(a) Measurement of collected biomass

(b) Collection of biomass using ASV

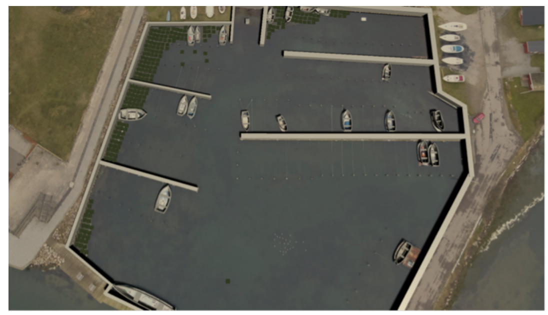

Fig. 6: The simulated environment of Masnedsund havn

III. Virtual Environment

In order to estimate how performance of biomass collection could be improved, a virtual replica of Masnedsund harbour was modelled in Unity 6. The model was based on a drone photo taken the 10/12-2020, which constituted the plane of the simulation environment, including location and dimension of piers, boats and observed biomass. The virtual model was based on a number of simplifications of the ASV including infinite storage, infinite battery, an efficient collection mechanism and limitless thrust. Also the model did not consider wind nor current.

The model additionally consisted of the following objects:

- A 3D model of the ASV
- 2D models of static and dynamic biomass
- 3D models of boats, piers surrounding the harbor and boat walks
- Virtual waypoints for navigation planning

The ASV was modelled using a 3D CAD-model of the WasteShark-platform provided by RanMarine. The steering behavior was modelled to resemble the real platform, making it able to move forwards and backwards while rotating around its own axis. Catching algae was simulated using Unity's built-in collision detection algorithm. When collision with biomass and ASV was detected, this was counted as catching the biomass which was then removed. The size of the ASV was scaled to represent the corresponding size in the harbor based on the drone-photo. The speed of the vessel however was arbitrary, as only comparison between different navigation methods (not the absolute values) are of primary interest here. Although the virtual environment allows for several instances of the vessel, only one instance has been used in this paper.

Static Biomass are representations of biomass which is not moving, and were modelled as square tiles in two dimensions (in Unity labeled a Sprite). A total of 245 instances were manually placed in the map, representing real stationary biomass, i.e. biomass which did not move. The location of static biomass was based on the drone photo, i.e. the objects were placed manually based on visual inspection of the drone photo. Catching biomass was modelled by simple 2D collision-detection between the ASV and a sprite representing the biomass. Catching only happened when the ASV was moving forward. For each tile which caught, a counter was increased by one.

Dynamic biomass was also modelled like square 2D tiles (Sprites). However, dynamic biomass represented the biomass which was constantly flowing into the harbor from the sea. The biomass moved from the entrance of the harbor based on random generated positions and angle, but always moving towards the northern most piers, thereby emulating the common movement of biomass. A constant defined the frequency of which new biomass was entering the harbor. When a moving biomass objects collides with a pier or a boat, the object's movement stops. When biomass collides with other biomass, it slows down its movement with 80 percent.

Boats were modelled using an Open Source 3D model. A total of 19 instances were placed in the harbor representing real boats with the corresponding location, direction and size. In the model, boats are static objects, meaning they do not move. Boats were modeled as physical obstacles, meaning that the ASV would change direction before colliding with the object.

Piers and boat walks were modelled as simple 3D cubes which are standard objects in Unity. Like boats, they are static objects and do not allow the ASV to continue its path but has to change direction before collision. Piers stop dynamic biomass from moving, however this is not the case for boat walks, because biomass is able to move under, which is also the case in real life.

In order to emulate navigation with obstacle avoidance, we implemented a navigation mesh which is an abstract data structure to aid agents in path-finding through complicated spaces [9]. Navigation Meshes are a built-in feature in Unity and allows the ASV to navigate to any random waypoint in the harbor, without colliding with boats, boat walks or piers.

A number of constants were set for each simulation, and a number of variables are dynamically set and updated during simulation. An overview can be seen in Table III.

Name	Description	Value
Navigation Method	A constant which defines the navigation method of the ASV during a simulation.	0 = Dynamic Collision, 1 = Fixed plan, 2 = Random plan, 3 = Nearest neighbor
Max Number of Iterations	Integer value defining the maximum number of iterations per simulation. This represents the total time of simulation.	10.000
SPEED	Float value representing the simulated speed of the ASV per iteration	0.3
Xspeed	A random float value representing the speed of biomass in x-axis. This random value is generated for each new biomass tile.	Range (-0.1 - 0.15)
Yspeed	A random float value representing the speed of biomass in y-axis. This random value is generated for each new biomass tile.	Range (0.01 - 0.05)
algae modulo	Representing how frequent biomass is floating into the harbor from the outside. New biomass is generated as a modulo of the iteration number (0-10.000) and this constant.	300
max load	The maximum load of biomass before the ASV has to return to the habour to get offloaded. In navigation mode 1-3, the ASV automatically return to harbor for offloading.	9999 (infinite)
totalCatch	Variable representing how much biomass has been caught by the ASV. This is increased with the value of 1 for each collection of biomass tile	Updated continuously
maxUpdates	In navigation method 2, this random value is used to define for how long time the ASV moves backwards after collision. This random value is generated for each collision.	Range (0.5 - 1.0)
myAngle	In navigation method 2, this random value is used to define how much the ASV should rotate while moving backwards after collision. This random value is generated for each collision.	Range (40 - 80)

TABLE III: Overview of constants and variables in the simulated environment. Speed values are unit-less, as the simulation represent relative performance and not absolute values.

IV. Comparison of navigation methods

Based on these figures, we have run a number of emulations of biomass collection in Masnedsund Havn. Note that the emulations do not show what an instance of a biomass objects corresponds to in real-life (the exact amount in mass or volume), and do not take into account that the ASV has to be recharged and off-loaded. However, the emulation can be used to show relative difference, i.e., compare efficiency of different navigation methods.

A. Navigation method 1: Waypoint Navigation based on Fixed Plan

The simplest way of navigating is to let the ASV follow a path of predefined waypoints, which corresponds to the way the platform navigates using the web control dashboard. These waypoints have to be defined manually. The first emulation is based on a simple path plan defined using 6 waypoints starting and ending in the area of the launch pad (the location where the ASV is put into the water).

As can be seen from Table IV, the average number of biomass collected using this emulation is 3 with a standard deviation of 2. Based on this method, the robot will collect only dynamic biomass moving with current in the harbor but not the static biomass which located at fixed positions. Biomass which is already stuck near the piers will not be collected, as the ASV will not approach it based on its predefined path.

This approach can be optimized, by defining a path plan which also includes static biomass. This is done by increasing the number of waypoints, and manually defining a route making the ASV pass by all identified static biomass. The number of waypoints is now increased to 27. As can be seen in Table IV this significantly increases the collection of biomasses, removing almost all biomass in the harbor.

Although this a very efficient approach in theory, our real-life tests show there will be a number of practical implications. First of all, the collection system of the ASV is currently not able to handle dense biomass, which will not be collected as expected or even block the movement of the vessel. Additionally, this approach requires manual definition of the specific plan, which will differ from site to site and maybe also from day to day.

B. Navigation method 2: Waypoint Navigation on Random Plan

As an alternative to the first navigation method in which waypoints were predefined, we implemented a method which randomly defines the position of waypoints. This means that the ASV always starts at the launch pad but then follows different routes in the harbor. As the locations of the waypoints are random, the path will potentially make the ASV collect both static and dynamic biomass. Also, this approach will require advanced obstacle avoidance in order for the ASV not to collide with a boat or boat walk. However, by implementing the Navigation Mesh in the emulated environment, the ASV automatically avoids obstacles.

A total of 5 simulation runs have been performed with 10.000 iterations each. As can be in Table IV, this navigation approach gives a slightly higher average, but the standard deviation is also higher. In order to compare this method with the optimized fixed plan with 27 waypoints, a random plan with 27 waypoints have be evaluated for 10.000 iterations as can be seen in Table IV.

C. Navigation method 3: Nearest Neighbor

The nearest neighbor is an algorithm which automatically makes the ASV navigate to the biomass object which has the shortest Euclidian distance. The nearest neighbor algorithm was one of the first algorithms used to solve the travelling salesman problem approximately, i.e. optimizing a route plan for x number of locations to visit. The algorithm quickly yields a short tour, but usually not the optimal one. Based on the average number of collected biomass objects in the same period of time (10.000 iterations), this algorithm turns out to perform worse than the fixed optimized plan with 27 waypoints approach, but better than the other approaches. However, a requirement is that the ASV continuously knows, where the nearest biomass is. This requires an updated overview of the harbor at all times using (or at least frequently) for example run time drone footage or on board camera solution.

D. Navigation method 4: Dynamic Collision

The last navigation algorithm which has been emulated is a collision-based algorithm, which is similar to the way that simple robot vacuum cleaners operate. This algorithm does not use collision detection with physical objects using a navigation mesh as the three former algorithms. The ASV move forwards until it actually collides with an obstacle. This will make the ASV move backwards, while turning for a predefined period of time. After the time period has elapsed, the robot will start moving forwards again until it collides with another obstacle. The advantage of this algorithm is that it does not require knowledge about biomass or physical obstacles, but still performs relatively well. It should be noted that in the first run, the ASV did not catch anything. This is a drawback of this algorithm, i.e., the route is based on several random values meaning you run the risk that the ASV takes a very disadvantageous route - for example by navigating in circles not collecting anything.

Navigation Method	**1**	**2**	**3**	**4**	**5**	**Avg.**	**Std. Dev.**
Fixed Plan (6 way-points)	2	1	5	4	3	3	2
Optimized plan (27 waypoints)	581	589	506	507	342	505	99
Random Plan (6 waypoints)	7	6	7	1	3	5	3
Random Plan (27 waypoints)	46	63	92	97	60	72	22
Nearest Neighbor	431	495	429	111	117	317	187
Dynamic Collision	0	141	120	106	45	82	58

TABLE IV: Comparison of simulated navigation methods based on 10.000 iterations

E. Discussion of results

Table IV show the performance of the evaluated algorithms.

As can be seen from Table IV, the most efficient method is the fixed optimized plan with 27 waypoints with an average of 505 instances of biomass. In average, the Nearest Neighbor algorithm, performs approximately 106 times better than the worst performing navigation algorithm which is Fixed Plan algorithm with 6 way-points (317/3 = 106). Although this approach is not as efficient as the fixed optimized plan, the advantage of this approach is that no manual path planning is required. Interesting enough, does the Dynamic Collision (82) not perform much better than the Random Plan with 27 waypoints (72). This might be caused by the fact, that these strategies are both based on a high degree of randomness.

Although these emulations are simple models of the real world, it is interesting to transfer the results to the real-world experiments. Our real-world experiments were based on a manual navigation pattern which is somewhat similar to the emulated Random Plan with 27 waypoints. According to the emulation, the Fixed Optimized Plan with 27 waypoints is the best performing approach in terms of collected biomass over time. In theory using this navigation approach would increase the amount collected 7 times (505/72 = 7). A drawback is that planning the route is a manual task which has to be done for each site – maybe even several times a day to reach the level of efficiency. The second-best method is Nearest Neighbor which is 4.4 times better (317/72 = 4.4). Although this does not perform as well as a manual plan for

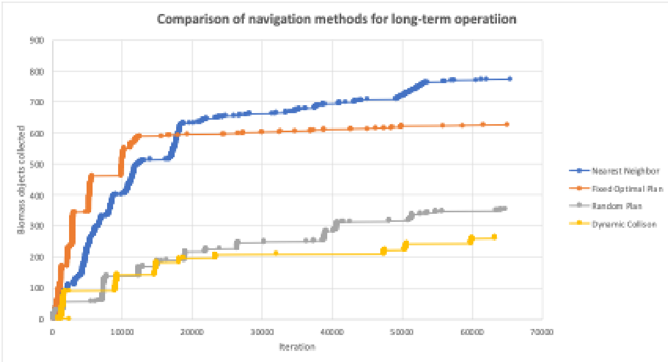

Fig. 7: Comparison of navigation methods for long term operation (65.000 iterations)

this specific site, the advantage of this approach is that is does not require any manual work, and dynamically adjusts its behavior at runtime. If biomass collecting is to be automated completely, the latter approach is worth investigating more.

It is worth comparing the navigation methods in a long-term scenario, which is done by increasing the number of iterations to 65.000. Figure 7 shows the number of biomass objects collected as a function of the iteration number.

The emulation shows, that although the Fixed Optimal is the most efficient method for short-term operations, it will get outperformed by the Nearest Neighbor method in the long run (after approximately 18.000 iterations). This is due to the fact that when all static biomass is collected, the fixed plan does not longer suffice, as the ASV keeps sailing in an area with little biomass left. Using the Nearest Neighbor algorithm, the ASV will constantly navigate to a location with biomass, so when new biomass enters the harbor, this algorithm will automatically find it. However, a prerequisite is an updated overview of the location of biomass which can be obtained using drone photos or an on-board camera. The figure additionally shows that a random plan outperforms the Dynamic Collision method in the long run. This is due to the fact, that Dynamic Collision method can cause the ASV to navigate in circles for periods of time - this can for example be seen from iteration 25.000-48.000. However, the risk of navigating in circles depends on the layout of the harbor.

V. Conclusion

The conducted work has led to several findings:

- By inspecting 20 different potential test sites in Denmark, we have identified at least 5 types of biomass (Eelgrass, Sea lettuce, Bladder wrack, Ectocarpus siliculosus and Toothed wrack). The different types are often found mixed together (known as beach wrack).
- Based on the quantity of biomass found and accessibility for testing, we have selected to test sites at Southern Zealand - Fakse Ladeplads (site 1) and Masnedsund Havn (site 2). At these sites, biomass (especially eelgrass) is occasionally removed using industrial diggers and we found almost only eelgrass which has been present in vast amounts in the test period from October 2020 to January 2021.
- Our tests at site 1, show that the basic technical functionality of the ASV works as expected, including remote control, autonomous sailing based on a predefined plan and obstacle avoidance. However, the platform is more sensitive to weather conditions than anticipated.
- At test site 2, we managed to collect 2,7 kg/hour of biomass based on random navigation. It has been observed, that the ASV had problems collecting the biomass efficiently as it is often too dense and entangled to enter the collection basket of the robot.The amount of biomass collected can be substantially improved by mechanical improvements of collection mechanism and increased thrust.
- Based on a virtual replica of site 2, we have compared different navigation methods. Emulations show that the efficiency of the navigation method depends on whether collecting is based on a short-term or long-term operation. For short term operations, manual planning is the most efficient but requires a priori knowledge of the location of biomass. For long term operation, the nearest neighbor algorithm outperforms the efficiency measured in amount collected over time - however this algorithm requires dynamic knowledge about the position of the biomass, which potentially can be obtained using different camera solutions.

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