Development of an intelligent and distributed low-cost platform for marine observations

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***Abstract*— In this work a novel intelligent and distributed low-cost platform for marine observation is introduced. The observatory consists of an autonomous surface vehicle (ASV) and an autonomous underwater vehicle (AUV). This paper is focusing on potential search strategies for such an observatory. A novel search strategy based on Braitenberg search is introduced and the performance of this strategy is compared with the performance of inertia Levy-flight developed in recent work. Different settings of search algorithms are tested and their performance is evaluated using a computer simulation. It is shown that the combination of an ASV performing a pre-programmed search and an AUV performing inertia Levy-flight outperform a single AUV using inertia Levy flight for approximately 95 % of the chosen SGD positions. Both settings clearly outperform the introduced Braitenberg search.**

Keywords*— *Inertia Levy-flight, Braitenberg vehicle, Submarine Groundwater Discharge, Autonomous Systems

I. INTRODUCTION

The long-term goal of this research is to develop a flexible, low-cost and autonomous platform for submarine exploration. Such a platform could be used for locating submarine sources of interest, like dumped waste, lost harmful cargo or submarine groundwater discharges (SGD) [1]. Here, a medium size area, i.e. 400 m x 400 m, has to be examined by the platform during a mission [2]. SGD consist of a flow of freshwater from the sea floor to the coastal ocean (Fig. 1). The temperature of the inflow differs from the temperature of the coastal ocean [3]. Due to its lower density, the discharged groundwater rises to the surface. This enables the detection of SGD using aerial remote sensing or surface vehicles [3]. In this work, a new low-cost distributed sensor-system for the search for SGD and similar tasks is proposed. The system consists of an automated surface vehicle (ASV) and an autonomous underwater vehicle (AUV). The ASV can be used to obtain an overview of the whole search area to detect possible positions of SGD by following a pre-programed path on the surface [4, 5]. During this operation, the ASV measures the temperature of the surface, its speed over ground and its energy consumption. Speed and energy consumption are used to estimate the current profile of the search area. A low-cost ASV (Fig. 2) for marine observations is currently under development [6]. This ASV shares the information gained from its search with the AUV. The AUV uses the information to guide its own search towards the most promising regions of the search area. The path of the AUV is determined on-line during the mission. Therefore, an intelligent search strategy is needed, that guides the AUV through the search area. Previously, it was shown, that the inertia Levy-flight algorithm has the capability to guide a single AUV towards the source of interest [7]. This paper presents a novel search strategy for a tandem mission based on the recent work.

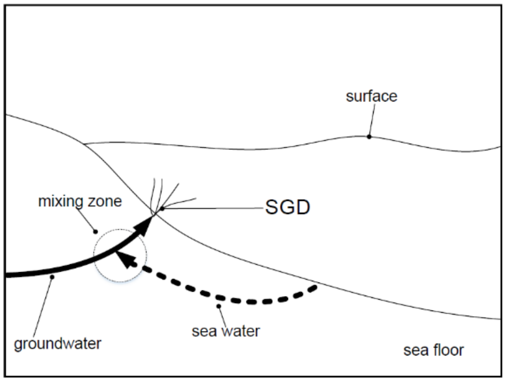

Fig. 1. Submarine Groundwater Discharge, adapted from [8]

Fig. 2. Autonomous Surface Vehicle during an autonomous mission

II. TEST ENVIRONMENT

The task of the AUV is to localize a point of interest such as SGDs. These provide a significant input of different substances, i.e. nutrients or fluorescent dissolved organic matter (FDOM) [1, 9, 10] to the marine environment. While substances are discharged to the ocean, the concentration of these substances is a function of the position and the time because of occurring mixing processes in the water column [11, 12]. Dynamic behavior could be simulated using numerical models [8] or models that are based on cellular automata [13]. However, for an unbiased comparison between the different algorithms, a static fitness function is used during this research. The conductivity in milli-Siemens per centimeter (mS/cm) and the water temperature were chosen as tracers to describe the distribution of the water mass inflow of a SGD seepage site. The values of conductivity and temperature used here are based on measurements at the Black Point SGD in Maunalua Bay Hawaii [14]. The concentration of both parameters in the search space are simulated as follows:

$$f(x)=\min\left(a\exp(bx)+c\exp(dx)\,,\,max\right) \qquad (1)$$

Where $f(x)$ denotes the value of the conductivity in mS/cm or the temperature in °C at distance x of the SGD source, x is the Euclidean distance between the position of the vehicle and the SGD, a and c represent scale parameters in mS/cm or °C respectively, b and d are gradient parameters with a unit of $1/m$ and max is the maximum value of the conductivity or the temperature. The values of the different parameters for the conductivity and the temperature are given in TABLE I.

TABLE I. PARAMETER VALUES FOR FITNESS FUNCTIONS

Parameter	**Parameter Values**	
	Conductivity	***Temperature***
a	45.62 mS/cm	27.5 °C
b	7.9e-4 1/m	-1.85e-7 1/m
c	-36.88 mS/cm	-2.801 °C
d	-0.3896 1/m	-0.1119 1/m
max	53.42 mS/cm	27.5 °C

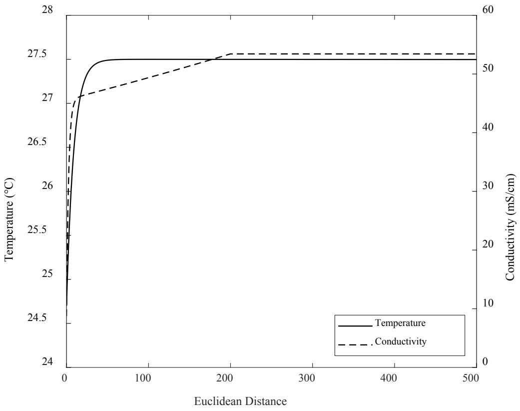

Fig. 3. Conductivity and Temperature values over Euclidean distance

The shape of conductivity and temperature over the Euclidean distance to the SGD is shown in Fig. 3. It can be seen from the figure that temperature gradients, caused by the shape of the temperature function, can only be determined up to a distance of approximately 20 m, while for conductivity an influence of the source can still be determined at a distance of 200 m. However, in a practical application the distance in which the gradient information can be used might be much shorter due to limited sensor accuracy and noise. The search area has the dimension of 400 m x 400 m. This makes it a difficult test environment for search algorithms, due to the absence of gradient information in large parts of the search area.

During the search, the vehicle moves through the search space following its specific search strategy described below and measures the conductivity respectively the temperature after each second. To make the simulation more realistic, noise was added to the fitness function (Eq. 1). For the conductivity a uniformly distributed noise with a maximum value of 0.5 mS/cm was used, while a normal distributed noise with a standard deviation of 0.3 °C was used for the temperature fitness function because temperature is more prone to environmental influence, e.g. by solar radiation. Furthermore, the measurement accuracy of the conductivity sensors is limited to 0.01 mS/cm and the accuracy of the temperature sensors is limited to 0.1 °C.

III. SEARCH STRATEGY

The ASV developed can be used to investigate medium size areas following a full coverage path autonomously [4, 5]. In the actual state of the research, the vehicle is equipped with a temperature sensor. During the travel the ASV will measure the temperature.

The search of the AUV must be guided by an appropriate search strategy. Such a strategy should be able to make use of the information gained from the environment to guide the AUV towards the point of interest within the limited search time caused by the limited energy capacity of the AUV. The search strategy has to be adapted to the information available, the swarm size and the physical capabilities of the vehicle used. In the past different search strategies were proposed and tested [7, 15].

A. *Inertia Levy-flight*

Biologists have observed that animals, like sharks, bony fish, sea turtles and penguins, often move in patterns that can be approximated by Levy-flights [16] following the Levy-flight foraging hypotheses. This hypotheses states that natural selection should have led to adaptations for Levy-flight foraging, because Levy-flights can optimize search efficiencies [17]. Since there is experimental evidence for inherent Levy search behavior in foraging animals [18], Levy-flight has been selected as a search strategy for a single AUV. While using Levy-flight, the AUV has to choose a random direction as well as a random step length for each iteration. The direction is chosen from a uniformly distribution in a range of 0 to 360 degree. However, the chosen step length is based on a power law cumulative distribution function:

$$s=r^\wedge(-1/\alpha) \tag{2}$$

Where r is a random number from the range [0,1] and α is a scaling parameter from the range of [1,2]. When using Levy-flight as a search algorithm, the value of α has to be chosen off-line by the user before the search. The value of α has direct impact on the step length s calculate in each iteration. Therefore, the search behaviour of the AUV depends heavily on the chosen value of α. Instead of manually tuning of α, a self-adaptive scheme to tune this parameter α is used. The AUV in each step calculates a value of α, based on the information gained from the environment [7] as follows:

$$\alpha=(g_c-g_w)/(g_b-g_w)+1 \tag{3}$$

Where g_c denotes the current fitness value, g_w the worst score fitness found so far and g_b the best score fitness found so far by the AUV.

Furthermore, the AUV stores the fitness value of the previous iteration g_{c-1} and compare this value with the fitness value in the actual time step g_c. If there is an improvement, the AUV will keep its direction. Otherwise, it will choose a new direction randomly.

B. *Braitenberg Vehicle 2B*

In 1986 Valentino Braitenberg published his book “Vehicles” [19]. In this work, various simple vehicles that mimic complex behavior based on simple wiring of sensors and drives are proposed. Neither real implementations nor practical applications are given in this work. However, due to the simple implementation, the concept of Braitenberg vehicles was used in the field of robotics in recent years, for example [20, 21]. In this research the concept of Braitenberg vehicle 2B is used. This concept is also known as “Aggression-behavior” [19]. The vehicle is equipped with two sensors and two drives. Each sensor is connected to the drive on the opposite site of the vehicle. The speed of the drives depends on the sensor reading (Fig. 4). If a sensor is next to a source, the output of the sensor is high and hence the speed of the drive. Due to this circumstance, the vehicle will get closer to the source. The Braitenberg vehicle 2B can be seen as an implementation of the biological principal of tropotaxis [21].

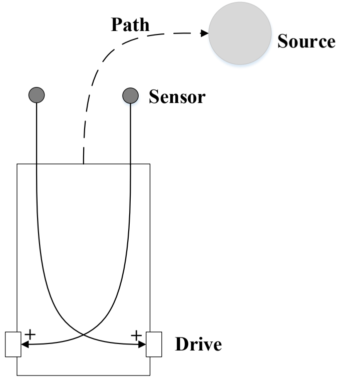

Fig. 4. *Sketch of Braitenberg vehicle 2B*

The vehicles described in [19] are living in a two-dimensional world. However, in the real world the search for SGD will take place in three-dimensions. To solve this problem, the BlueROV 2 used in this research as an AUV is equipped with four sensors instead of two (Fig. 5). This allows the vehicle to search in three-dimensions. In this paper a two-dimensional fitness function was used. Therefore, only two sensors, i.e. the left and right one, are used during the search.

The real BlueROV 2 used in this research utilizes more drives than the theoretical Braitenberg vehicle 2B. Furthermore, the maximum search time of an AUV is limited due to energy constrains [7]. For that reason, the idea of Braitenberg vehicle 2B was adapted. During the Braitenberg search, the speed of the AUV is set to a fixed value and the rudder-throw-angle will be changed with respect to the sensor readings. The fixed speed avoids the AUV getting stuck in areas without gradient information. However, a transfer function is needed to calculate the rudder-throw-angle theta from the sensor readings. In this work a transfer function based on the sigmoid function is used. In the first step the sensor readings are normalized. Subsequently the norm value n is calculated as follows:

$$n = I_{right} - I_{left} \tag{4}$$

Where n denotes the norm value, I_{left} the normalized sensor on the left site and I_{right} the normalized sensor reading on the right site. Due to the normalization the value of n will be in the interval of $-1 \leq n \leq 1$.

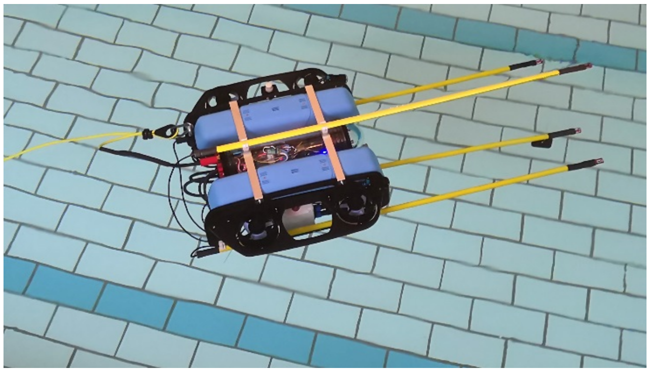

Fig. 5. *Braitenberg-vehicle based on a BlueROV 2 during a test dive*

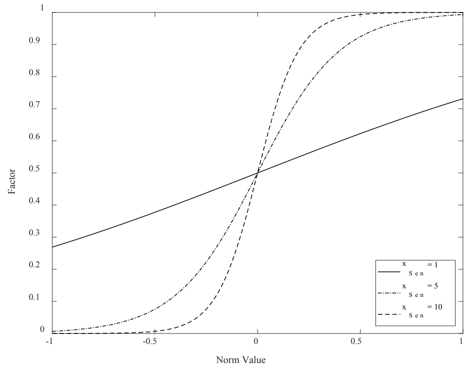

Fig. 6. Influence of the sensitivity on the output of the sigmoid function

In the next step the rudder throw angle is calculated, using the norm value. To fine tune the behavior of the Braitenberg search two control parameters, i.e. the maximum rudder throw angle x_{Amp} and the sensitivity x_{Sen} are introduced. The first one limits the maximum angle through a specific value, while the second defines how strong the vehicle reacts to a detected difference between the sensor readings. The rudder throw angle is calculated as follows:

$$t=-x_{Amp}+(2*x_{Amp}*(1/(1+\exp(-x_{Sen}*n)))) \qquad (5)$$

Where t denotes the rudder throw angle, x_{Amp} the maximum rudder throw angle, x_{Sen} the sensitivity and n the norm value. The influence of the sensitivity is shown in Fig. 6. It can be depicted from the figure, that x_{Sen} has a huge impact on the factor. For smaller values of x_{Sen} the same measured difference results in a smaller rudder throw angle t.

C. Combination of Inertia Levy flight and Braitenberg search

The proposed Braitenberg search requires gradient information to be successful. However, due to the test environment the absence of useful gradient information is most likely. In that case the Braitenberg search is not able to guide the AUV towards the source.

To deal with the absence of gradient information, a combination of inertia Levy flight and Braitenberg search is introduced. In this case, the vehicle starts its search performing an inertia Levy flight. If it manages to find a gradient, the AUV switch the search strategy to Braitenberg search. In the case that the AUV loses track of the gradient, it switchs back to inertia Levy flight to explore other parts of the search space.

For both switching decisions an additional control parameter is needed. The threshold for the change from inertia Levy-flight to Braitenberg search $x_{T,L-B}$ and the threshold for the change from the Braitenberg search back to inertia Levy-flight $x_{T,B-L}$. The measured difference between the two mounted sensors is used for the threshold $x_{T,L-B}$. However, for the reverse decision process, the actual value of an additional temperature sensor mounted on the centered line of the vehicle is compared with a previous reading of this sensor. The optimal values of these thresholds depend on the fitness function.

IV. EXPERIMENTS

To evaluate the performance of the proposed search strategy, computer simulations were carried out using different vehicle and algorithm settings.

In the first set of experiments the ASV performed a pre-programmed search measuring the temperature, while the AUV performed the inertia Levy-flight measuring the temperature and the conductivity. The AUV used the conductivity information for the inertia Levy-flight. If the ASV detected a promising region, it shared this information with the AUV. If the temperature value found by the ASV was better than the actual temperature value measured by the AUV, it started moving to the region detected by the ASV. Otherwise it ignored the information sent by the ASV.

The second set of experiments consisted of the same vehicles as the first one. However, in this setting the AUV was allowed to use the Braitenberg search. The threshold for changing into Braitenberg search was set empirically to a value of 0.2 mS/cm, the sensitivity was set to a value of 9 and the maximum rudder throw angle was set to 45 °.

In addition, a single AUV performing an inertia Levy-flight was used. In this setting the AUV only used the conductivity information for the search.

During all experiments the ASV started its search at position (0 m | 0 m) and the AUV started at position (200 m | 200 m) respectively. In order to exclude an influence of the selected position of the SGD on the search performance, 500 different positions were randomly selected for the SGD. For each of the selected positions, 1,000 test runs were performed because the AUV used pseudo-random numbers within its search strategies.

For comparison the average of the best conductivity value found by the AUV over the 1,000 test runs is used. The distribution of the average values for the 500 different SGD locations are shown as a cumulative probability plot in Fig. 7.

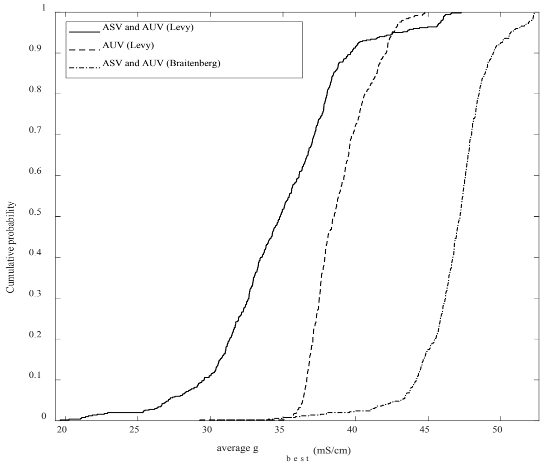

Fig. 7. Cumulative probability functions of the different search strategy settings for 500 different locations of the SGD and 1,000 experiments per location

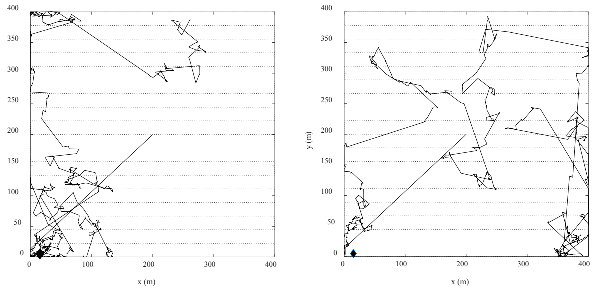

Fig. 8. Trajectory of the AUV and the ASV (dotted line) during a succesfull search (left) and an unsuccesfull search (right), guided by the ASV (Diamond indicates the position of the SGD)

In Fig. 8 two typical search runs of the guided search (setting 1) are depicted. It can be observed, that the ASV guided the AUV towards the most promising region of the search space. After arriving the AUV started exploiting this area. In most cases the AUV was able to locate the SGD using the inertia Levy-flight algorithm. However, in some runs the AUV was not able to locate the SGD even if it was nearby. Afterwards the AUV started exploring other regions of the search space in order to search for a better solution. During this test run, the SGD was located at (15.1 m | 5.0 m). Therefore, the minimum distance during the search between the ASV and the SGD was 5.0 m.

V. DISCUSSION

The experiments illustrated clearly that in general the ASV is able to improve the search performance of the AUV, by scanning the whole area and guiding the AUV towards the most promising region. However, in some cases the AUV was not able to locate the SGD even it was close to it. This may be caused by the added noise and the limited sensor accuracy.

Furthermore, it can be observed that the combination of ASV and AUV using inertia Levy-flight outperform the single AUV using the inertia Levy-flight. However, the performance of the ASV and the AUV using Braitenberg search is worse compared with the other search algorithms (Fig. 7).

There are different possibilities for the poor performance of the Braitenberg search. Possibly the limited sensor accuracy in combination with the noisy environment prevented the stable detection of gradient information. Another possible reason for the poor performance could be the chosen implementation of the algorithm using the sigmoid function.

VI. CONCLUSION AND FUTURE WORK

In this work a novel intelligent and distributed low-cost platform for marine observation was introduced. This paper focused on possible search strategies for this platform. Therefore, different settings of search algorithms were tested and their performance was evaluated using a computer simulation. It was shown that the combination of an ASV performing a pre-programmed search and an AUV performing inertia Levy-flight outperform a single AUV using inertia Levy flight for approximately 95 % of the chosen SGD positions. Both settings clearly outperform the introduced Braitenberg search. A possible reason for the poor performance could be the chosen implementation of the algorithm using the sigmoid function. Still it is expected that, against the findings, the idea of Braitenberg search might have the capability to improve the search performance of the AUV. In future work other possible transfer functions, for example Jeffrey's model for locating sounds [22], will be incorporated into the Braitenberg search in order to study their capability of improving the search performance.

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