

Obstacle Avoidance for an Autonomous Marine Robot - A Vector Field Approach

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Abstract. A marine robot, especially a sailing boat robot, is exposed to a dynamic environment. This paper presents a simple and efficient obstacle avoidance control algorithm. The presented control method uses vector fields to regulate the marine robot.

Keywords: obstacle avoidance, marine robots, vector fields

1 Introduction

There is a growing interest in autonomous marine robots, for example they can be used for measurements on the sea or harbour monitoring [9] [4]. An autonomous marine robot has several advantages over oceanographic boats (with a crew) and buoys; these are explained in paper [4]. For missions of autonomous marine robots it is important to have an efficient and reliable control algorithm, especially when thinking of long term missions [10]. The detection of moving obstacles is possible using a number of technologies such as radar, camera and an automatic identification system (AIS). The algorithm should not just consider the desired path of the robot but should also detect other obstacles and avoid them. Moreover a general approach is desired, which cannot just be applied on one special type of marine robot but can be adapted to any kind of marine robot.

A control method that uses vector fields fulfills these requirements. The construction and application of a vector field to regulate a marine robot is presented in this paper. This approach of a potential field method is not very common on marine robots yet but is very appealing due to its simplicity. Assuming that a marine robot usually has a very limited processing power and sensing, it is important to consider the complexity of the control algorithm. The obstacle avoidance control algorithm was simulated with sailboat robots. The functionality of the obstacle avoidance control algorithm has been validated during WRSC 2013 where the algorithm was applied on the autonomous motorboat of the Team ENSTA Bretagne - Ifremer.

2 Basis of the control method: Vector Fields

In a vector field [1] there is an assignment of a vector to each point. In the case of this application a point (x,y) is mapped to a vector $\mathbf{f}(x,y)$. This is a function \mathbf{f} of the form $\mathbf{f}: \mathbb{R}^2 \rightarrow \mathbb{R}^2$ [2]. For the control method these vectors are considered as forces. The boat robot (represented as a point) moves in this vector field along the vector gradient, so the vector field describes the behaviour of the marine robot.

In order to be able to follow different trajectories, there has to be the possibility of constructing a complex vector field. This is why the vector field is constructed as a binary tree. On the basis of simple atomic vector fields (e.g. a vector field where all vectors point towards one line) which can be combined, it is possible to get a more complex vector field. Merging vector fields is always done in building a binary tree, where the top node (thus the entire tree) is the desired complex vector field.

2.1 Atomic Vector Fields

Two types of atomic vector fields can be distinguished. The first is an attractive field, where the vectors of the field point towards a desired trajectory. The second type is a repulsive vector field, in which the vectors point away from a particular area.

The vectors are normalized to the same limit values in their magnitude (when not going to infinity which is pointed out when explaining the specific vector field); like this they will have the same impact when they are combined by an operation.

As attractive vector field have been implemented:

- a field for an attraction to a circle (Fig. 1a)
- a circular vector field (Fig. 1b)
- an attraction towards a line (Fig. 1c)
- a vector field with vectors into one direction (Fig. 1d)
- a vector field for an attractive point in a long distance version (Fig. 1e)
- a vector field for an attractive point in a short distance version (Fig. 1f)

These fields are presented in the following with an explanation, an equation and a figure.

[6] provides an equation for a circle following (a vector field where every vector points towards the desired path of a circle). In fact this is a composition of two basic vector fields, an attraction towards a circle with a radius r_0 and a parameter $\rho \in]0, 1]$ that defines how fast the final state (circle) is approached and a circular vector field. To have a set of combinable atomic vector fields, the two vector fields are implemented separately. Equation (1) is the function for an attraction towards a circle and equation (2) is a circular vector field.

$$\mathbf{f}(x,y) = \begin{pmatrix} x \arctan(\rho(r_0 - \sqrt{x^2 + y^2})) \\ y \arctan(\rho(r_0 - \sqrt{x^2 + y^2})) \end{pmatrix} \quad (1)$$

$$\mathbf{f}(x,y) = \begin{pmatrix} y \\ -x \end{pmatrix} \quad (2)$$

A line following is a similar combination of two atomic vector fields. [7] presents a function to regulate the boat along a line from point A to B (infinite line). Here the two separate parts are implemented independently. Equation (3) shows the attraction towards a line on the x-axis and equation (4) is a constant vector field to the east.

$$\mathbf{f}(x,y) = \begin{pmatrix} 0.0 \\ \frac{1}{y} \cdot (10 * y * \arctan(-\frac{y}{50})) \end{pmatrix} \quad (3)$$

$$\mathbf{f}(x,y) = \begin{pmatrix} 10.0 \\ 0.0 \end{pmatrix} \quad (4)$$

Without loss of generality the direction of these two fields can be chosen to be fixed; the position and orientation may be changed by methods (rotation and shift) which can be applied to these atomic vector fields. For a line following task these two vector fields are added; the vector orientation is parallel to the line, when the boat position is on the line. Otherwise the angle is inclined towards the line; the greater the distance to the line, the higher the inclination. There is a maximum inclination of 45° (far away from the line where the vectors of both atomic fields have the same magnitude), so that the boat still keeps going ahead in the direction of the line.

A vector field towards one point, a long-range attractive point, is useful to have one goal position which is approached no matter where the boat is located. The function $f(x,y)$ to calculate the vector magnitude has to fulfill the requirements of having a constant limit value for $x \rightarrow \infty$ and $y \rightarrow \infty$ as well as going through the point $f(0,0) = 0$. The vector magnitude is nearly constant. At the attractive point there is a null vector and nearby that point the magnitude decreases. The function (5) fulfills all of these requirements and is used to calculate the vector magnitude in the vector field for a long-range attractive point.

$$f(x,y) = e^{-\frac{1}{\sqrt{x^2+y^2}}} \quad (5)$$

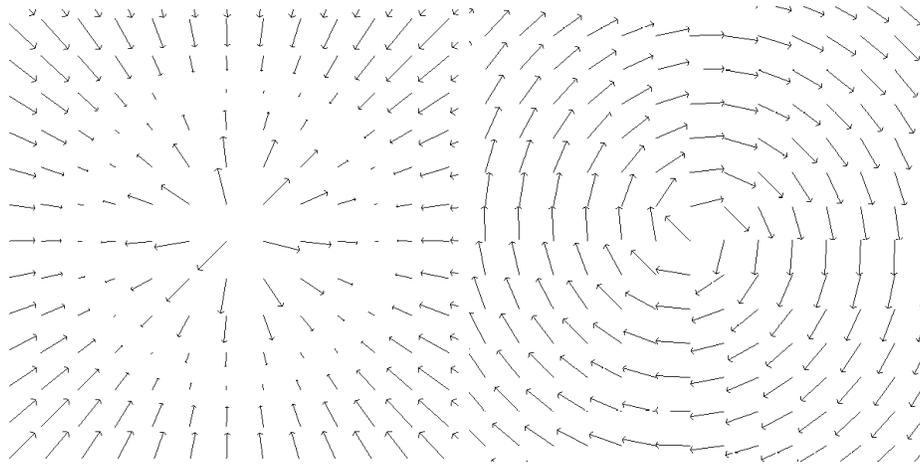
The last attractive vector field is the short-range attractive point, which can be explained as a classical electrical force. The shorter the distance to the attractive point, the higher is the magnitude of the vector. Equation (6) presents the calculation of this vector field.

$$\mathbf{f}(x,y) = \frac{1}{x^2+y^2} \cdot \begin{pmatrix} -x \\ -y \end{pmatrix} \quad (6)$$

These attractive vector fields are illustrated in Fig. 1. There are no axes with a scale in these figures, because they show the general vector fields which can be changed in position and size but the form stays always the same.

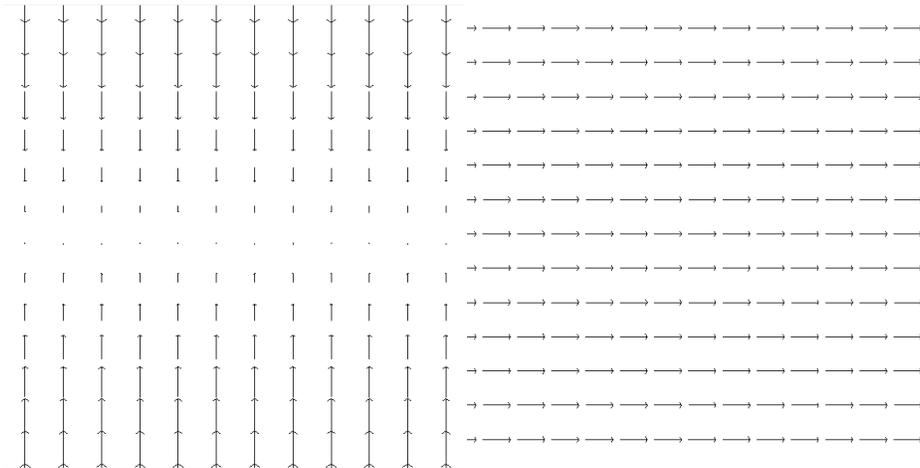
To realize obstacle avoidance there are two repulsive vector fields, a repulsive line and a repulsive point. The repulsive point vector field is calculated with function (7); at the repulsive point the magnitude tends towards infinity and at a greater distance the magnitude decreases to zero.

$$\mathbf{f}(x,y) = \frac{1}{x^2+y^2} \cdot \begin{pmatrix} x \\ y \end{pmatrix} \quad (7)$$



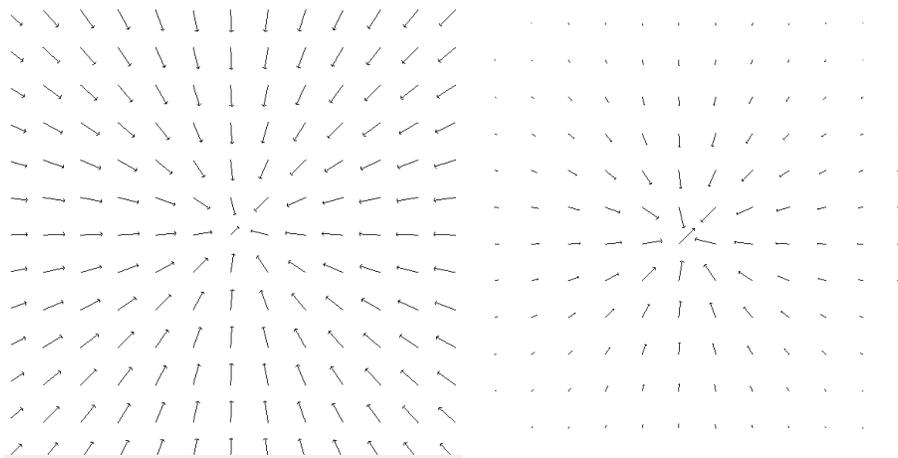
(a) Attractive Circle

(b) Circular Vector Field



(c) Attractive Line

(d) GoX Vector Field



(e) Attractive Point - Long Range

(f) Attractive Point - Short Range

Fig. 1: Attractive vector fields

The equation for the vector field of the repulsive line is similar to the repulsive point vector field and is shown in equation (8). The x-axis is defined to be the repulsive line, so just the distance towards the x-axis has influence on the magnitude of the vector.

$$\mathbf{f}(x,y) = \frac{1}{x \cdot \sqrt{x^2 + y^2}} \cdot \begin{pmatrix} x \\ 0.0 \end{pmatrix} \quad (8)$$

The magnitude of the repulsive vector fields guarantees collision avoidance, because near the point/line the repulsive vector dominates. These two repulsive vector fields are shown in Fig. 2.

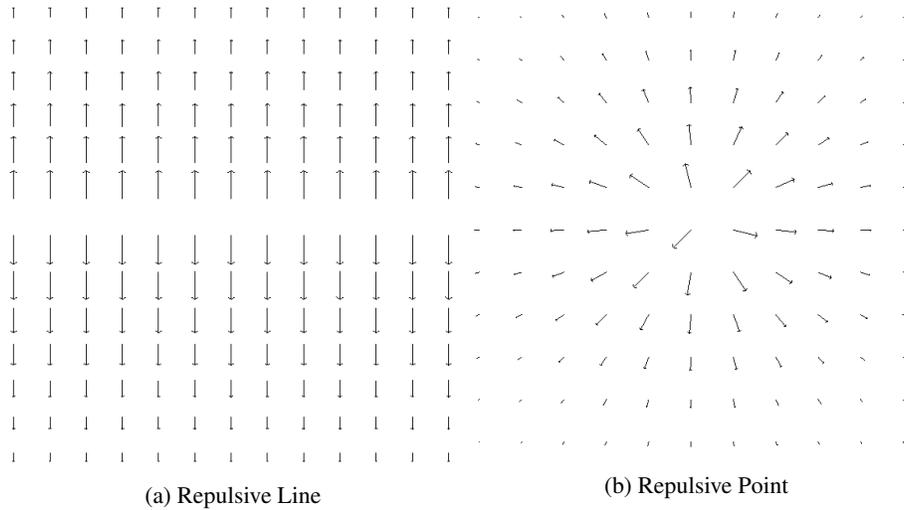


Fig. 2: Repulsive vector fields

2.2 Operations on Vector Fields

In order to build a complex vector field the atomic vector fields can be combined using the following set of operations:

- Addition
- Rotation
- Scalar
- Shift along x-axis
- Shift along y-axis
- Projection

Two vector fields can be added, for this simply the two vectors of both vector fields for one point are added. Next, a vector field can be rotated. The line following is not just possible in the default direction. The vector field for a line following can be rotated to have a line towards any direction. The scalar method is an enlargement of the vector field by a certain factor. With this method e.g. the attractive circle vector field (see Fig. 1) can be scaled up to have a bigger radius or the vector field for the repulsive point could be enlarged to have a bigger influence radius. The latter could be necessary if the obstacle to avoid is quite large.

The methods to shift along the x-axis and y-axis are used to position the vector field at the right point; a repulsive point should always be shifted towards the position of the corresponding obstacle.

Projection is an important method for a sailing boat robot. Sailing boats cannot go in every direction directly; there is a no-go zone around the direction where the wind is coming from. Vectors that point into this no-go zone need to be projected towards the next possible direction (generally $\pm 45^\circ$ towards the direction into the wind); the vector field just has vectors pointing towards sailable directions. [5] also presents a potential field method, where the no-go zone of the wind is treated as a virtual obstacle. This repulsive field prevents the sailboat from going into the no-go zone. Yet it makes close hauled course manoeuvres unlikely. The projection method used in this approach is better for still being able to sail close hauled.

3 Control Architecture

The vector field needs to be constantly evaluated in order to regulate the marine robot direction. The robot embedded system above the plain vector field (low-level control) receives the vector after handing the current position of the boat to the vector field. It sets the actuators in order to steer to this direction. For sailboats this low-level controller corresponds to the controller described in [7]. High-level control needs to check conditions to be able to change to a next vector field respectively modify the vector field, when a waypoint is reached. This controlling strategy is illustrated in Fig. 3.

This control loop consists of four main steps. In *step 1* the sensors of the boat robot transmit the current values (e.g. GPS position and heading of the boat). This is the left block in Fig. 3. The high-level controller checks conditions in a *step 2* and potentially modifies the control vector field. *Step 3* is the computation of the vector field. The input is the position (x,y) of the boat robot. The corresponding vector is calculated, so that we get the desired direction as the output of this computation. In *step 4* the low-level controller sets the maximum sail angle and the rudder angle proportionally to the heading error (for the sailboat robot) respectively the motor thrust and angle (for the motorboat). This is the setting of the actuators of the boat (see arrow to the block on the right side of Fig. 3).

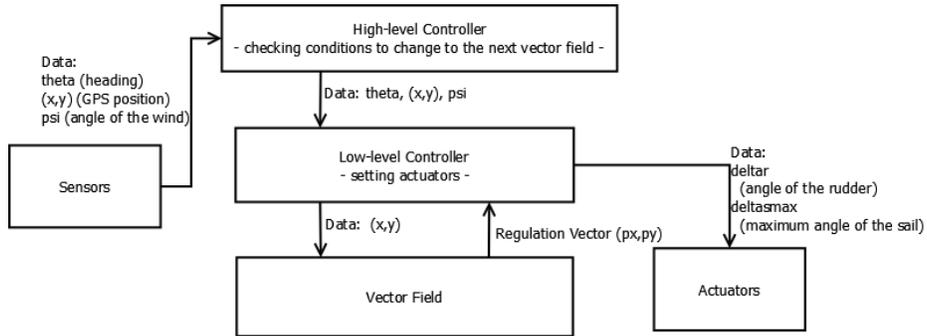


Fig. 3: Control Architecture

4 Experimental Validation

This control method has been simulated, subsequently implemented and tested at the World Robotic Sailing Championship and International Robotic Sailing Conference 2013 in Brest, France. The algorithm has been successfully applied on the motorboat of the team ENSTA Bretagne - Ifremer (Fig. 4).



Fig. 4: Motorboat Team ENSTA Bretagne - Ifremer

In a first test the motorboat was regulated with a simple circle following vector field. The path is shown in Fig. 5. After one circle the boat was brought off its trajectory (due to an encounter with another boat). It can be seen that it subsequently returned to the circle line again.

One of the tasks, which the motorboat performed successfully, is the “Mobile obstacle of known position avoidance task”. In this task the motorboat robot has to stay in a square DEFG (see Fig. 6) of 200 m. When an obstacle of known position (data transmission via XBee or Wifi) enters the square, the robot has to avoid a collision and



Fig. 5: Path Circle Test

leave the square ([3]).

This task has been implemented using two vector fields; the first one is built with repulsive lines as the borders of the square and the obstacle is added as a repulsive point. The second vector field is a line following with the other obstacle as a repulsive point. When the obstacle (which was a zodiac boat) entered the square the controller changed from the first to the second vector field, so that the robot there left the square. The angle of the line (rotation) has been calculated to not cross the path of the entering obstacle. The trajectory of the robot and of the zodiac (obstacle) are shown in Fig. 6. A black circle (number 1) shows the starting position. A short time before this point the program was started but the robot was still on the transporting boat. From this starting position the robot went to the middle of the square DEFG. The path of the zodiac is shown in red. When the zodiac enters the square between point D and G, the vector field of the motorboat robot changes to the line following (with the zodiac as a repulsive point) and the motorboat robot starts to leave the square. After the robot is 100 m away from the borders of the square, the robot automatically stops the motor, so that it is easier to pick up the motorboat robot. This completes the task.

5 Discussion

A simple and fast obstacle avoidance control method based on vector fields has been presented.

There are a few disadvantages of potential fields like local minima and oscillation in narrow corridors [11] that are known from experience on land-based robots. Yet these problems are unlikely to occur at an ocean environment.

An advantage is that vector fields as a control allow the robot to take the best way towards the desired path no matter where the position is (there can be calculated a vector for each point). The arbitrary combination of vector fields gives the possibility to build the best suitable control vector field for the particular mission. Furthermore, it is easier to combine vector fields in order to avoid obstacles (so that we have one vector

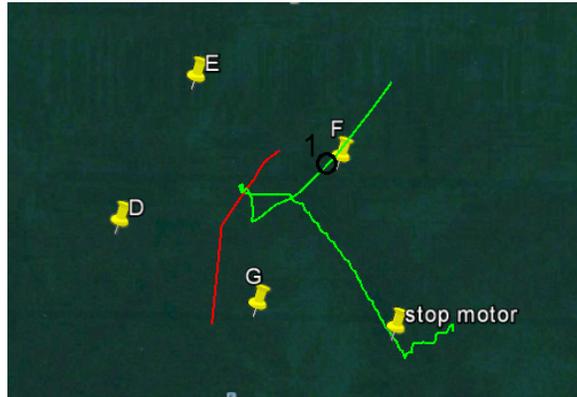


Fig. 6: Path Obstacle Avoidance Task

field for control) than to calculate multiple waypoints.

The algorithm can be also applied to sailboats. This was done in the simulation. Fig. 7 shows a screenshot of a sailboat simulation. The right side shows the simulated sailboats floating on the water. On the left side there is a top view of the control vector field (of one of these sailboats) with the two boats presented by triangles.

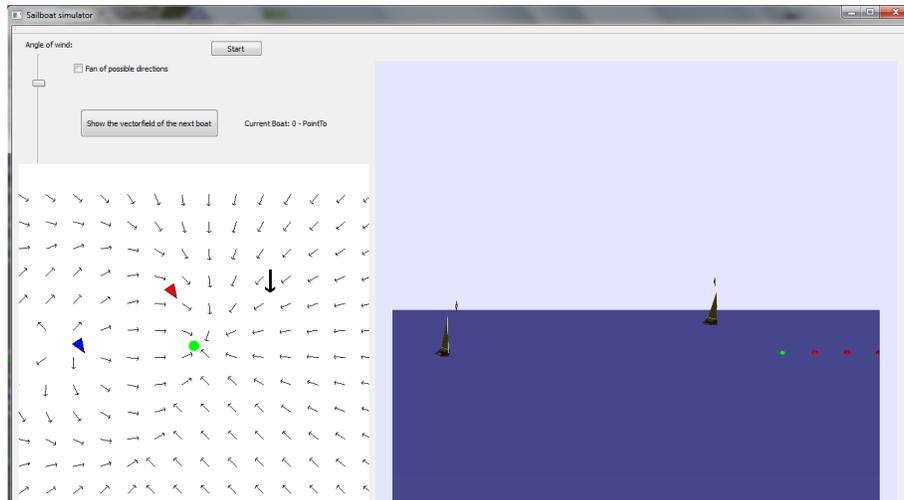


Fig. 7: Sailboat Simulation

The paper presents live tests conducted at the WRSC 2013 which has shown that the algorithm successfully implements obstacle avoidance. Compared to planning-based approaches, the vector field approach does consider the exact instantaneous position of

obstacles. Moreover control parameters for the low-level control are calculated live and therefore the storage space is less than with a planned-based approach.

The simulation has been carried out with sailboat robots. In future this obstacle control algorithm should also be tested on a real sailboat robot. An enhancement of this algorithm could be to take the speed of the marine robot into account, achieving a faster reaction to a change in direction.

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