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A method of artificial potential fields for the determination of ship's safe trajectory

Sylwia Mielniczuk

Maritime University of Szczecin
Institute of Marine Technologies, Department of Mathematics
1–2 Wały Chrobrego St., 70-500 Szczecin, Poland
e-mail: s.mielniczuk@am.szczecin.pl

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Abstract

Various methods of trajectory determination are used for finding solutions to collision situations involving ships. This applies to avoiding collisions with other ships or stationary objects. In addition to the methods generally used, new or modified versions of methods derived from other modes of transport are proposed. One of the algorithms for route determination serving to avoid obstructions is the method of artificial potential fields, used for determining routes of mobile robots. The method is used in maritime transport, for instance for detecting anomalies in ship movement. The article presents the method of potential fields used for solving the problem of route selection avoiding navigational dangers and obstacles. This article presents an algorithm of route determination based on the said method, its implementation in the MATLAB program and examples of application for the ship's safe trajectory determination in some navigational situations.

Introduction

Collision situations involving other ships or stationary obstructions (shoals, islets, etc.) necessitate the selection of a new route. There are various methods for solving collision situations with another ship (Pietrzykowski, 2004; Pietrzykowski & Magaj, 2014; Hornauer et al., 2015; Lisowski, 2016; Lazarowska, 2016) or for passing stationary obstructions (Dramski & Mąka, 2012). These include graphs, artificial intelligence and heuristic algorithms. These methods are also used in other branches of transport. The similarities of the behaviour of a moving object in different branches of transport allow us to use the same methods. For instance, Dijkstra's algorithm is used in road transport to determine truck trajectories (Żochowska, 2011) or selecting a route of unmanned mobile robot (Wang, Yu & Yuan, 2011). Similarly, other methods are used, with some modifications due to the specification of the vehicle, such as dimensions and manoeuvring characteristics. This article proposes to use the method of artificial potential fields for avoiding navigational obstructions and dangers at sea.

The method of artificial potential fields

The method of artificial potential fields is one of the methods used for path planning for mobile robot motion (Garbacz & Zaczyk, 2011; Li et al., 2017). The principle of this method is based on the interaction of forces between charges that produce a potential field:

$$U_w = U_p + U_{o(i)} \tag{1}$$

where: U_w – resultant potential, U_p – attractive potential, $U_{o(i)}$ – potential of repulsion from *i*-th obstacle.

The potential from obstacles pushes the object away, while the potential from the goal attracts the object. The basic idea behind the method is the simultaneous attraction to the goal and repulsion from obstructions (Spong, Hutchinson & Vidyasagar, 2006). The interaction of the produced fields can be illustrated by forces. The attractive force comes from the goal, and the repulsive force comes from obstacles. A robot, regarded as a particle, moves in a field, and its movement is a result of forces acting on it, coming from obstacles (repulsive forces) and the goal (attractive force) (Figure 1). The position in each particular step depends on the determined direction of the resultant force.

Depending on whether the area in which the robot is moving is known, there are two methods: global and local search. Global search of the path is possible where the entire area of the object movement is known. Local search of a path takes place in the immediate surroundings of the object. In the case of mobile robot motion, sensors are placed on the robot and on obstacles. An example of the method of artificial potential fields application is described in Garbacz (Garbacz, 2006).

In maritime transport, potential fields are used for detecting abnormal vessel movement (different from classical behaviour) (Osekowska, Axelsson & Carlsson, 2013). It is possible to use global search of a path in marine navigation. The available charts and readouts from navigational devices, such as radar, make such a search possible.

The method of artificial potential fields of maritime transport

The use of the method on board a ship comes down to the search for a path and simultaneous avoidance of obstacles such as navigational obstructions or dangers like shoals. There is a similarity to the determination of a path for a robot passing obstructions. The charges in these considerations are the object (vessel), the goal that the object is moving to, and obstructions that the object has to pass. The object is moving towards the goal, passing obstructions in order to avoid a collision. We can assume, therefore, that the object and the goal are unlike charges – they attract. On the other hand, the object and the obstacles are like charges and they repel. The ship, the goal and obstacles regarded as charges produce the potential field. The direction of motion is determined by the resultant force, calculated from the resultant potential expressed by formula (1). The potentials of attraction and repulsion are given by the formulas (Khatib, 1986):

– attractive potential:

$$U_p = \frac{1}{2} k_p d^2(\text{goal, ship}) \tag{2}$$

– potential of repulsion from obstacles:

$$U_{o(i)} = \begin{cases} 0, & d(\text{ship, obstacle}) > d \\ \frac{1}{2} k_o \left(\frac{1}{d(\text{ship, obstacle})} - \frac{1}{d} \right)^2 \\ & d(\text{ship, obstacle}) \leq d \end{cases} \tag{3}$$

where: k_p – attractive coefficient, k_o – repulsive coefficient, d – distance of obstacle detection as a threat, d(goal, ship), d(ship, obstacle) – Euclidean distances.

Thus, force of attraction and force of repulsion are described as derivatives of the corresponding potential:

– force of attraction:

$$F_p = \nabla U_p = k_p d(\text{goal, ship}) \tag{4}$$

– force of repulsion from obstacles:

$$F_{o(i)} = -\nabla U_{o(i)} =$$
$$= \begin{cases} 0, & d(\text{ship, obstacle}) > d \\ -k_o \left(\frac{1}{d(\text{ship, obstacle})} - \frac{1}{d} \right) \frac{1}{d^2(\text{ship, obstacle})} \\ & d(\text{ship, obstacle}) \leq d \end{cases} \tag{5}$$

The coefficients k_p and k_o are chosen experimentally. If k_p is a high value and k_o is a low value, the vessel will collide with the obstacle. On the other hand, low k_p and high k_o cause the ship repulsion from the goal instead of getting closer to it. The distance of safe passage from the obstacle is set at 1 Nm.

Figure 1 illustrates how the direction of ship movement is determined to pass an obstruction.

In order to use the method of artificial potential fields in maritime shipping it has been assumed that:

– the ship's initial position (x, y), course and speed are known;
– the locations of obstacles are known;
– the coordinates of the ship's destination (goal) are known;
– a distance below which an obstacle is considered as a threat is defined as d = 1.5 Nm;
– the maximum distance that a ship may cover in time dt is specified.

In addition, it is assumed that the ship is moving at a constant speed and the distance has been identified below which the goal is considered to have been reached (d_1). Other ship's positions are determined for an adopted time step dt and depend on the algorithm-determined course of the ship – the algorithm works iteratively.

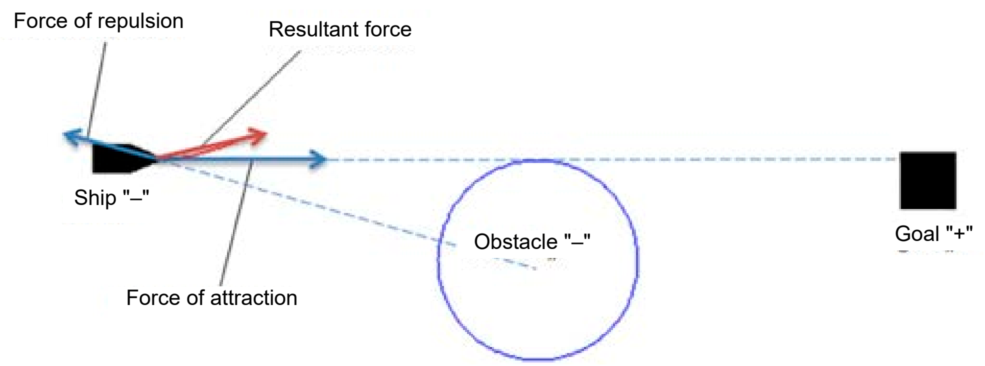

Figure 1. The method of ship direction determination for passing an obstacle

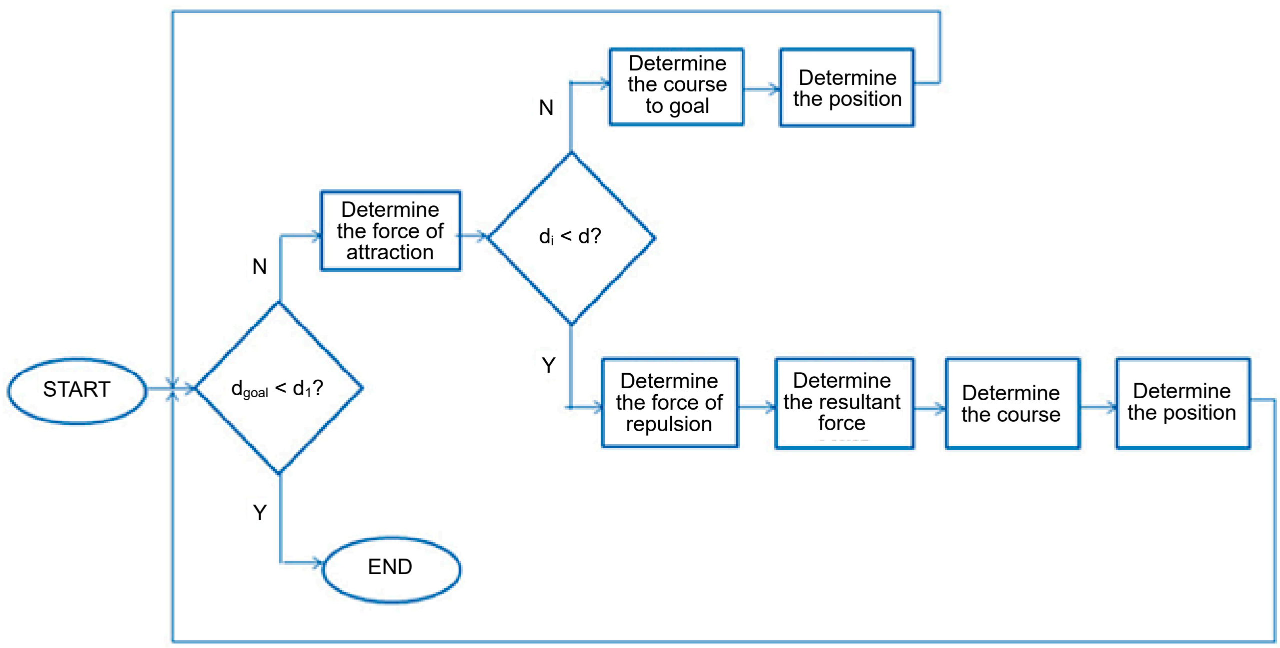

Figure 2. The algorithm of ship movement trajectory determination by the method of artificial potential fields

An algorithm for route determination by the method of artificial potential fields in the situation of obstacle avoidance is shown in Figure 2.

Notations:

d – obstacle detection range (distance);

d_1 – distance below which the goal is regarded to be reached;

d_i – distance from the ship to i-th obstacle, $i = 1..n$, n – number of obstacles;

d_{goal} – distance from the ship to the goal.

First, the algorithm checks the distance from the ship to the goal. If the distance is greater than the permissible range, the algorithm performs the following actions:

1) determines the force of attraction to the goal, using the formula: $F = k_p \cdot d_{goal}$;
2) checks whether the obstacle is at a dangerous distance, i.e. less than d;
3) if so, on this basis a force of repulsion from a given obstacle is determined,
4) then the resultant force is determined, derived from all the obstacles located in the immediate surroundings of the object;
5) the resultant force of attraction and repulsion is determined, indicating the ship's movement direction – course ψ;
6) a new position of the ship is determined:

$$x_{j+1} = x_j + V \cdot \mathrm{d}t \cdot \cos\psi$$
$$y_{j+1} = y_j + V \cdot \mathrm{d}t \cdot \cos\psi \tag{6}$$

If no obstacle is found within distance d at a given step of the algorithm, the movement direction is conforming with the direction of the force attracting the ship to the goal. The algorithm completes its operation when the distance from the ship to the goal d_{goal} is less than the initially set d.

Implementation of the method of artificial potential fields

Depicted below are the results of the artificial potential fields method applied in various configurations of obstacles found on the ship's route. The ship is heading for the goal located straight ahead. There are obstacles in the way, graphically displayed as circles. The route of the ship was presented as a continuous curve. It is assumed that the ship passes the obstacles at a safe distance. The method of artificial potential fields was implemented for four different situations.

In Situation 1, there are two obstacles on the route of the ship. The result is presented in Figure 3. The vessel avoids the obstacles on the left side.

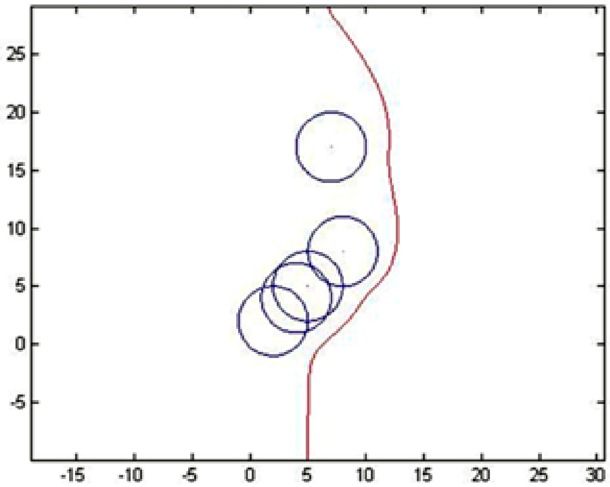

Figure 3. A trajectory determined for obstacles distributed in Situation 1

In Situation 2, one of the obstacles has been shifted to the right. Figure 4 shows the result.

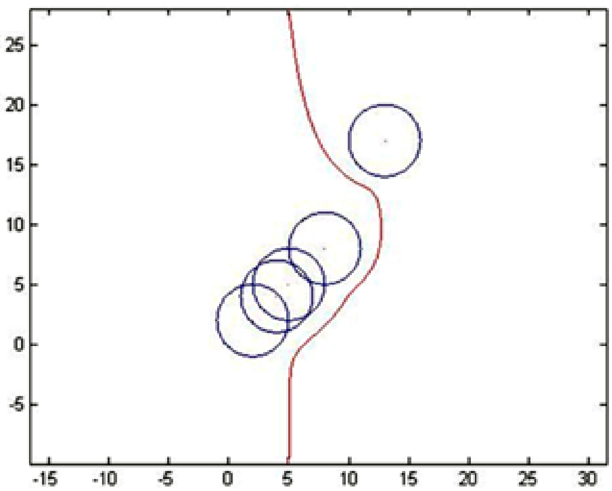

Figure 4. A trajectory determined for obstacles distributed in Situation 2

Figure 5 presents the solution of Situation 3, including three obstacles safely passed by the vessel. It proceeds between the obstacles.

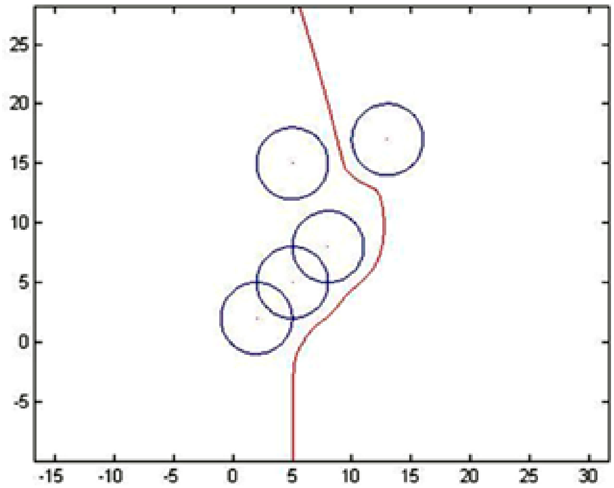

Figure 5. A trajectory determined for obstacles distributed in Situation 3

The above routes have been generated with the method of artificial potential fields using the algorithm presented above. None of the trajectories crosses the area bounded by the circles – the vessel has no collisions with any of the obstacles. In Situations 2 and 3, despite the changed position of one of the obstacles, the determined routes do not differ significantly because of the interaction of the other obstacles remaining within the range of obstacles treated as a threat.

The obstacles deployed for Situation 4 roughly form a "U" shape positioned at an angle. In general (Figure 6), U-shaped obstacles surrounding an approaching ship cause a problem in determining subsequent ship positions. This constitutes the problem of local minima of the artificial potential field (Spong, Hutchinson & Vidyasagar, 2006). The resultant vector of forces is equal to zero outside the point of destination.

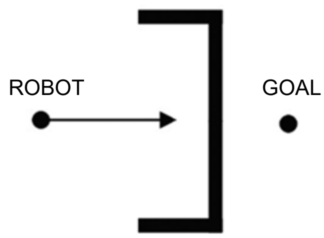

Figure 6. The local minimum problem

In order to avoid the problem of a local minimum, the following approaches are used (Spong, Hutchinson & Vidyasagar, 2006; Huang, 2009):

- obstacles are of simple, convex shapes;
- the object is withdrawn to a position that excludes the entry into the area of obstacles;
- random movement of the object;
- the object proceeds along the edge of obstacle area;
- exclusion of the attractive force and/or increase of repulsive forces.

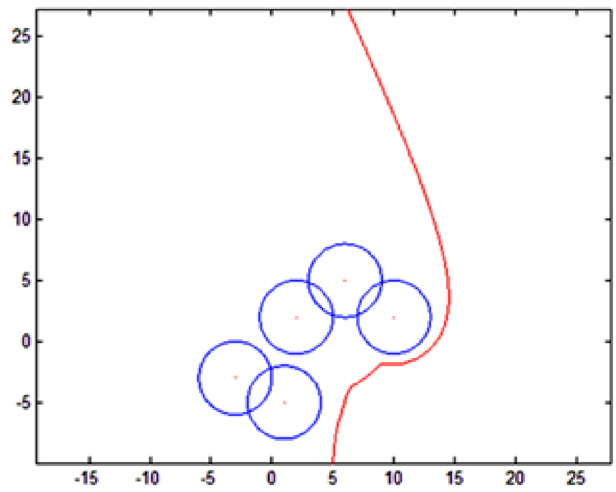

Figure 7. A trajectory determined for obstacles in Situation 4

The algorithm described above solves the local minimum problem. Figure 7 presents the route of the ship circumnavigating the obstacle that creates this problem. The ship does not proceed into the obstacle, but passes it and proceeds towards the goal.

Conclusions

The method of artificial potential fields is used for determining motion routes of a mobile robot. The article presents a modified algorithm for determining the route of a ship in situations of avoiding static obstacles. The results of the simulations show the possibility of using the artificial fields method in maritime transport. Generated routes are safe in that the distance to the obstacle is equal to or larger than the pre-set value. The distance travelled in subsequent iterations of the algorithm allows the route to be determined continuously. The designated position is checked for the possibility of switching on/off the potential of repulsion from an obstacle to prevent large course alterations within successive sections of the trajectory. Various local minimums were also considered. The research will be continued to take into account dynamic obstacles, such as other proceeding ships.

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