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COLREGS Based Path Planning and Bearing Only Obstacle Avoidance for Autonomous Unmanned Surface Vehicles

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Abstract

Obstacle avoidance for autonomous unmanned surface vehicles (USV) is a very critical issue and must be in accordance with international maritime rules such as Convention on the International Regulations for Preventing Collisions at Sea (COLREGS). Realtime obstacle avoidance for USV's can be achieved with distance and bearing information obtained by lidar (light detection and ranging), radar (radio detection and ranging) etc. sensors. But if these sensors fail while USV's are at sea, alternative strategies are needed to execute local obstacle avoidance for maintaining the safety of life and property at sea. In this paper, we present COLREGS based obstacle avoidance and path planning using Fast Marching Square algorithm for multiple USV's and effectiveness of visual guidance aided bearing only navigation in case of distance measuring sensor failure.

Keywords: unmanned surface vehicle; colregs; fast marching square; path planning; autonomous

1. Introduction

Since maneuverability of maritime vessels are lower than the land and air vehicles, USV's must *sense and avoid* the obstacles beforehand in order to prevent any collision at sea. As there is no article about USV's in existing international maritime regulations such as COLREGS [1], USV designs must comply with the existing rules [2].

It is imperative to develop alternative obstacle avoidance algorithms and strategies, since it is not possible to operate all electronic sensors mounted on unmanned vessels without any malfunction. Lidar or radar sensors can measure the distance of objects within range but there is no guarantee that these sensors will always work. Visual navigation for USV is starting to become widespread thanks to deep learning and other canonical image processing methods.

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With the development of artificial intelligence (AI) and robotic technology, it has become a necessity for unmanned vehicles to move in multiple and coordinated ways, to perform tasks together and to take the form of a "super organism" composed of multiple vehicles. Inspired by the fact that animals such as birds, insects, bees, fish, ants move in flocks, various studies are being carried out in order that unmanned vehicles can move in this way.

It has been shown for the first time that the Artificial Potential Field (APF) algorithm can be used in robotics to avoid obstacles [3]. According to this method, in an environment where obstacles exist, repulsive potential field changes depending on the distance to the obstacles in the environment and attractive potential fields are varying depending on the distance to the target point. Thus, the robots avoid the obstacles due to the artificial repulsive potential field emitted from the obstacles and move towards the target point due to the artificial attractive potential field emitted from the target point.

Although the APF method is developed for robots as a real-time obstacle avoidance and an algorithm that does not guarantee global safe path, it is used for robot planning with various optimizations and hybrid approaches made in the algorithm.

The virtual local minimum method and the genetic algorithms for parameter optimization are used by the AFP method for solving the local minimum problem [4] in the case that the repulsive and attractive potentials are equal and opposite to each other. In the virtual local minimum method; robot that has not yet reached the target point but cannot move -because the local minimum exists- has provided a virtual additional force within a certain radius circle. With this additional force, it is possible to get rid of that problem and the robot can move out of the local minimum field. Force angle (theta) and the effective range (R) are determined with the aid of canonical genetic algorithm.

The fast-marching square (FMS) algorithm in recent years has found use in path planning for USV's due to providing safe path without local minimum problem.

In this paper, real-time path planning and obstacle avoidance for USV formations in a practical maritime environment were simulated in accordance with the rules in COLGREGS when distance information cannot be obtained or may be obtained inaccurately by virtue of variety of reasons such as hardware or software failure, electronic attacks.

2. Global Path Planning

In this section, global safe path planning method for USV's is explained.

2.1. Fast Marching Method (FMM)

The fast-marching method (FMM) was first propounded by Sethian [5] to solve the Eikonal equation which defines simulation of interface propagation. The eikonal equation has the form of:

$$|\nabla T(x)|V(x) = 1 \tag{1}$$

where T(x) is the interface arrival time at point x and V(x) is the interface propagating speed. The method of fast marching solves the eikonal equation that has by solution the fastest path that in optics represents the principle of Fermat: "Light travels the path which takes the least time" [10]. The FMM algorithm is described as follows:

Algorithm 1 Fast Marching Method [6]

1. assign all the grid points with cost of *Infinity*.
2. T (startPoint) ← 0
3. *Far* ← all grid points
4. *Known* ← all grid points with known cost
5. **for** each adjacent a of Known point **do**
6. Trial ← a
7. T(a) = costUpdate(a)
8. end for

```
while Trial is not empty do
 sort Trial
 p ← point with lowest cost in Trial
 remove p point from Trial
 Known ← p
 for each neighbor point a of p do
         T(a) = costUpdate(a)
         if a ∈ Far then
                 remove a from Far
                 Trial ← a
         end if
 end for
end while
return T
```

2.2. Path Planning with FMM

The path from start point to end point can be generated by applying the gradient descent algorithm conveniently to the map calculated by FM algorithm which is described in *Algorithm 1*. Reading a binary map (M) where points in collision free space have values 1 and points in obstacle areas have values 0 and calculating its speed matrix (V) is the first part of the FMM based path planning algorithm which is described in *Algorithm 2*. Dimension of speed matrix (V) is equal to binary map (M) but it contains propagation speeds of each point in the binary map (M). After that, arrival time matrix (T) is calculated using speed matrix (V). If a constant speed matrix is used, speed matrix (T) can be thought as potential map where all potential values represent local arrival time of propagating interface. Lastly, path is generated by applying gradient descent algorithm. The FMM based path planning is described as follows:

Algorithm 2 FMM Path Planning Algorithm [8]

Inputs: map (M), start point (p_{start}), end point (p_{end})

```
Calculate speed matrix V from M
Arrival time matrix (T) ← FMM (V, p_start, p_end)
path ← gradientDescent(T, p_start, p_end)
return path
```

The FMM algorithm is more advantageous than the AFP algorithm when the global path planning of USV is taken into consideration. FMM avoid falling into local minimum trap because it has only one local minimum point.

2.3. Fast Marching Square (FMS) Method

Safety is a top priority for unmanned surface vehicles. Using FMM method for USV path planning can cause problems such as getting so close to both moving and static obstacles as can be seen in the Fig. 1.a [9]

To get rid of that safety problem, Fast Marching Square algorithm which was proposed by Garrido [10] can be used. The basic idea behind the FMS algorithm is applying conventional FMM algorithm twice. It is clear that path generated by FMS in Fig.1.b is safer than the path generated by FMM in Fig 1.a.

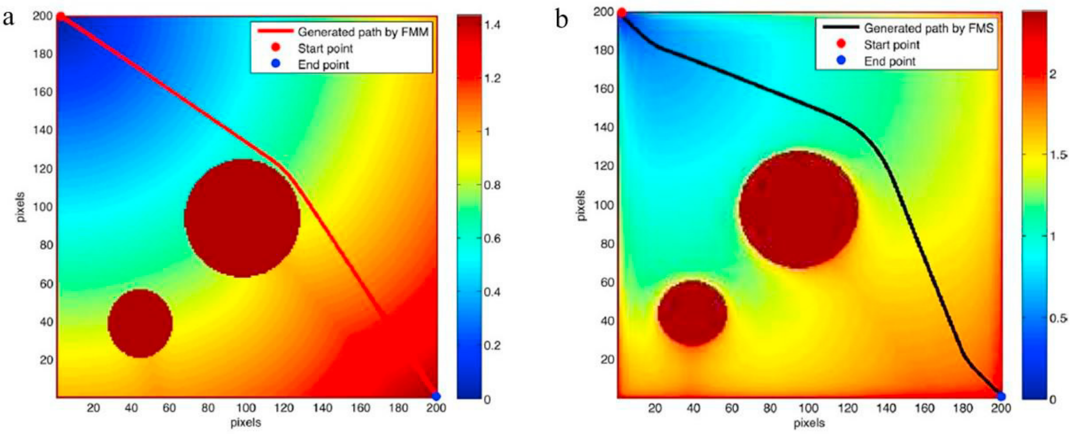

Fig. 1. (a) Path generated by FMM; (b) Path generated by FMS [9]

FMS algorithm is described as follows:

Algorithm 3 Fast Marching Square Algorithm [9]

Inputs: map (M), start point (p_{start}), end point (p_{end})

for each point a in obstacle area in M **do**
  obstaclePoints ← obstaclePoints+a
end for
M_s, ← FMM (***M**, obstaclePoints*)
T_{FMS}, ← FMM (M_s, p_{start})
path ← gradientDescent(T_FMS, p_{start}, p_{end})
return path

3. Experiments and Results

Since it is not possible to operate all electronic sensors mounted on unmanned vessels without any malfunction, it is imperative to develop alternative obstacle avoidance algorithms and strategies. Lidar or radar sensors can measure the distance of objects within range but there is no guarantee that these sensors will always work.

Consider the scenario that the USV faces the following conditions while moving at sea:

- LIDAR does not work,
- RADAR does not work.

In this case, local obstacle avoidance can only be achieved by visual guidance. It should also be decided what to do if the fault of these sensors take too long or if the global path which was generated by FMS algorithm is lost.

Absolute bearing refers to the angle between the magnetic North (magnetic bearing) or true North (true bearing) and an object. [12] It is possible to calculate the bearing of an object using only the camera and the compass with the help of image processing techniques. [11]

The following expressions regarding the change of bearing can be said:

- If the bearing of an obstacle does not change over time, it can be said that risk of collision will occur.
- If the bearing of an obstacle changes slowly over time, it can be said that obstacle will pass close to the our USV.
- If the bearing of an obstacle changes quickly over time, it can be said that obstacle will pass far from the our USV.

As stated in the introduction, USV’s movement and existing international maritime rules must coincide. In the next section, we will explain the local obstacle avoidance method using only bearing information of USV’s in accordance with two of the rules in COLGREGS.

3.1. Map Preparation and Global Path Planning

Original map of Turkish Prince Islands which was taken from Google Maps has been used in this work (Fig 2.a). But nautical charts provided by official institution such as Office of Navigation, Hydrography and Oceanography [14] can be also used.

Then we converted original RGB map to binary map (see Fig 2.b) to use FMS algorithm. During this process, the texts on the map are cleaned manually.

Fig. 2. (a) Original map of Turkish Prince Islands in Istanbul / Turkey; (b) Binary map of Turkish Prince Islands

We applied FMS algorithm to the map with start and end points. As shown in *Fig. 3.a*, FMS algorithm only has one local minimum.

Also, as shown in Fig 3.b, FMS algorithm is able to create a safe path for USV’s successfully.

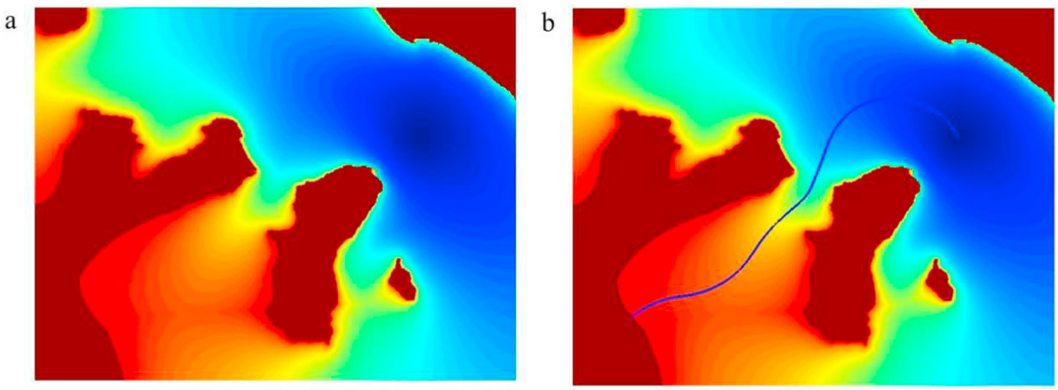

Fig. 3. (a) FMS algorithm applied to binary map; (b) example path generated by FMS algorithm

3.2. Head-on Situation

COLREGS Rule 14.a [1] states head-on situation as:

"When two power-driven vessels are meeting on reciprocal or nearly reciprocal courses so as to involve risk of collision each shall alter her course to starboard so that each shall pass on the port side of the other."

The possibility of collision can be calculated with continuous control of the change of bearing. If the bearing of an obstacle does not change over time, it can be said that risk of collision will occur. We assume distance measuring sensors does not work and we have only bearing information which is obtained by the camera. Bearing of the obstacle can be maintained by visual guidance. In this case, a certain amount of change of the course is necessary to avoid obstacle. Our algorithm simply consists of these steps:

- Check the bearing of the obstacle in every time steps
- Calculate the change of bearing
- If the bearing of the obstacle does not change over the time and obstacle is coming from the opposite direction, set a virtual temporary target point on the (θ degrees) starboard side of the obstacle in order to change course to the starboard side.

According to the scenario we created, three autonomous USV's (blue) and one mobile obstacle (red) are navigating around Turkish Prince Islands. USV. We present simulation results for *head-on situation* in *Fig 4*.

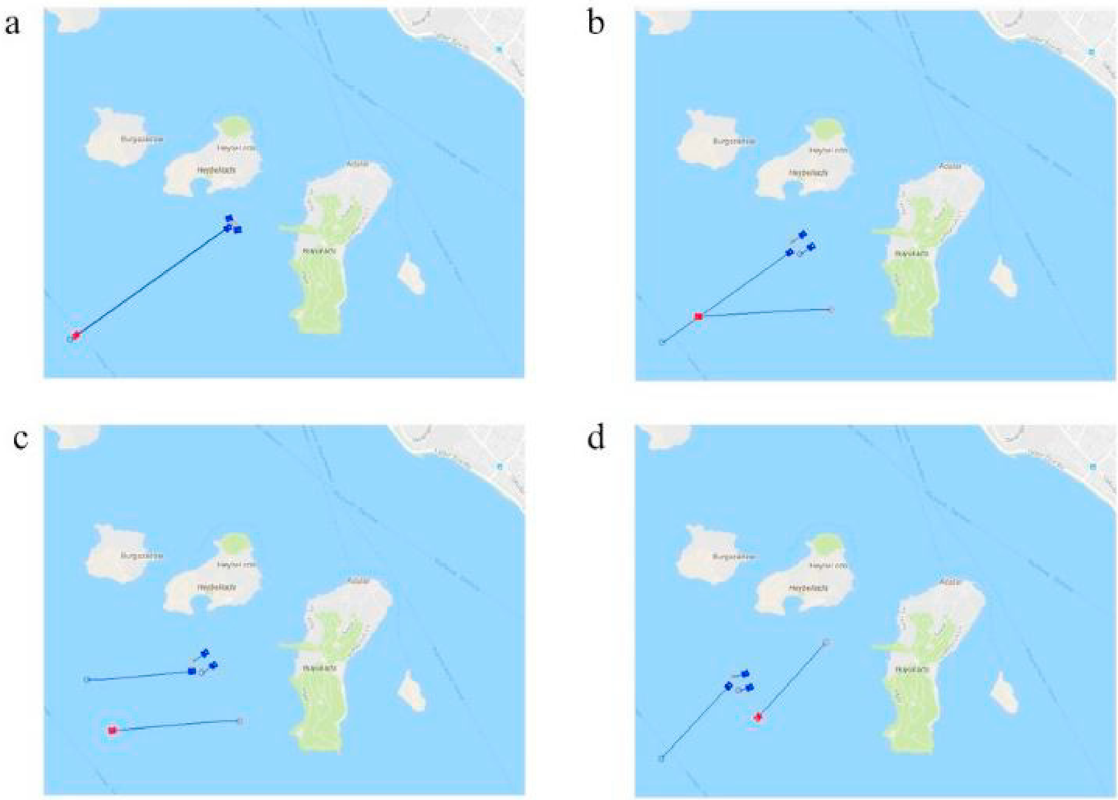

Fig 4. Head-on situation
(a) Three autonomous USV's in formation (blue) and one mobile obstacle (red) start to navigate;
(b) Mobile obstacle alters her course to starboard via setting virtual local target;
(c) Formation leader USV alters her course to starboard via setting virtual local target;
(d) After collision avoidance formation and mobile obstacle set their targets to main targets

3.3. Crossing Situation

COLREGS Rule 15 [1] states crossing situation as:

"When two power-driven vessels are crossing so as to involve risk of collision, the vessel which has the other on her own starboard side shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel."

Our algorithm simply consists of these steps:

- Check the bearing of the obstacle in every time steps
- Calculate the change of bearing
- If the bearing of the obstacle does not change over the time and obstacle is on the starboard side, set a virtual target point on the (θ degrees) starboard side of the obstacle in order to change course to the starboard side and avoid from the obstacle.
- If the obstacle is on the port side, do nothing for a limited time. After certain amount of time, if the collision risk still exists, set a virtual temporary local target point on the port side of the obstacle in order to change course to the port side and avoid from the obstacle.

Note that COLREGS rule 2 [1] states "Nothing in these rules shall exonerate any vessel, or the owner, master or crew thereof, from the consequences of any neglect to comply with these Rules or of the neglect of any precaution which may be required by the ordinary practice of seamen, or by the special circumstances of the case." So it is crucial to remember that avoiding obstacles and the risk of collision is the main focus in every situation.

According to the scenario we created, three autonomous USV's (blue) and one mobile obstacle (red) are navigating around Turkish Prince Islands similar to head-on situation. USV. We present simulation results for crossing situation in Fig 5.

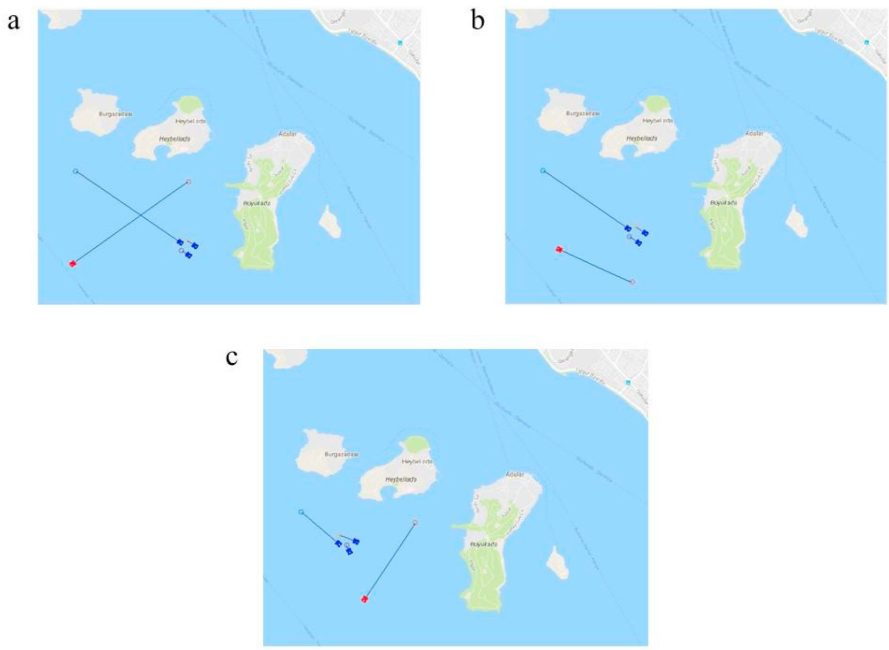

Fig 5. Crossing situation
(a) Three autonomous USV's in formation (blue) and one mobile obstacle (red) start to navigate;
(b) Mobile obstacle changes her course to starboard via setting virtual target;
(c) After collision avoidance mobile obstacle sets her target to main target

4 CONCLUSION

In this work, we have introduced practical safe navigation on genuine nautical chart for autonomous unmanned surface vehicles. All the simulations were performed under certain limitations such as failure of distance measuring sensor and obligation to comply with the COLREGS rules. We showed that our bearing only obstacle avoidance method can be used an alternative powerful *sense and avoid* strategy in the matter of failure of distance measuring sensors. Further work should include other COLGREGS rules, more robust visual guidance method for obtaining bearing information from only low-cost camera using Convolutional Neural Networks (CNN) and ensuring that USV's make judgements so as to selection good actions over bad ones using Reinforcement Learning.

Acknowledgements

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