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Motion planning for Unmanned Surface Vehicle based on Trajectory Unit

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ABSTRACT

Aiming at fine motion control on a small scale area for unmanned surface vehicle (USV), an approach for motion planning based on Trajectory Unit has been proposed. By making use of USV's hydrodynamic model and combining corresponding rules, the method generates a Trajectory Unit set which contains different orbit segments. Through the location and direction that the set of tracks can reach, the route searching in research waters can be done. Finally, a practical motion route will be planned for an USV. The experimental results show that, the planning route can not only avoid obstacles, but also meet the movement characteristics of an USV. And the approach has realized the fine motion control for an USV in a small range of scenarios.

1. Introduction

With the development and application of artificial intelligence and machine learning, unmanned surface vehicles (USVs) have become an attractive alternative way in a wide variety of marine missions (Svec et al., 2012), such as ocean sampling (Steimle and Hall, 2006), search and rescue (Shafer et al., 2008), harbor patrolling (Simetti et al., 2009) and so on. To accomplish these tasks, it is important for an USV to plan out a safe route under certain circumstances. In this field three stages have been developed, namely, Path Planning, Trajectory Planning and Motion Planning.

Path Planning as the basic stage treats research object as a particle, which has no kinematic and dynamic performance. So the problems discussed in this phase are often under a large-scale scene, the typical one is determining the shortest path (Kohei, 2016). Dijkstra algorithm (Dijkstra, 1959) is the classical method to deal with this problem. The algorithm searches every direction of node to extend outward iteratively until the end point is reached. One drawback is that it costs too much time to search the path. To make it more efficient, Hart (Hart et al., 1968) created a heuristic function to estimate the cost from current point to the final point. Thus, the search direction can be guided as goal-oriented and the search time is reduced. This approach is now known as A* algorithm. Another problem is finding a collision free path and the representative method is Artificial Potential Field (APF) (Khatib, 1986). The algorithm simulate an attractive (the goal) and a repulsive (the obstacles) potential field in the planning space. Combining with the two potentials, the object can reach the goal without collision. In summary, the study of path planning has proposed plenty of algorithms, and some of them turn out to have good results. However, there are often differences between planned path and the real trajectory. To make the results more realistic, the next stage becomes necessary.

Trajectory Planning can see as an improvement for path planning. Instead of regarding research object as a particle, trajectory planning takes into account its kinematics parameters, such as dimension, speed, heading and curvatures. What this stage tries to do is to make the planned path continuous and smooth (Lekkas, 2014). For instance, Velocity Obstacle approach (Fiorini and Shiller, 1998) focuses on the speed and the dimension of research object. According to the dimension, the dynamic obstacles were expanded firstly. Then, by taking use of relative velocity between research object and obstacle, a collision free path can be found among those expanded obstacles. Dubins Path (Dougherty and Woolweaver, 1990) put emphasis on heading and curvatures. The main idea is that for a particle with unity speed, the shortest possible path which meets a maximum curvature bound between a starting pose (which contains position and orientation) and a finishing pose consists of three pieces, and each piece is either a straight line or an arc of a circle. Apart from the circular curve, some other special curves, like Fermat's spiral (Dahl, 2013), B-Spline curve (Hong Li et al., 2016), Clothoid curve (Yi Wang et al., 2012) and so on, were proposed to replace Dubins curves. Although these methods make planning path closer to the real trajectory, trajectory planning, in fact, is just the adjustment for path planning under part of dynamic constraints. It still neglects the interaction among the constraints.

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Motion Planning is concerned with the control aspect. Unlike the first two phases, it focuses on whether the planning route can be realized via control system. Thus, the mathematical model of the research object will be studied intensively in this stage. The research of this field started from unmanned ground vehicles (UGV) or wheeled mobile robots, and the common approach is generally divided into two steps. First, by making use of traditional path planning algorithm, one plans out a collision-free path from the start point to the end point. Then, based on the path, a controller is designed, which contains kinematics and dynamics constraint to drive the robot safely and quickly to the target (Liang, 2010). The key point of this approach is motion control that uses control strategy to reconstruct or approximate the "ideal path". With different goals, the motion control can be classified into point stabilization, path tracking and path following (Hao, 2014). Another approach is improving traditional path planning method by taking advantage of the robot's mathematical model. The most common method is combining non-holonomic constraints of mobile robot with rapidly-exploring random tree (RRT) (Na et al., 2011; Mingbo et al., 2015; Jinze et al., 2010). Because the state transition in RRT algorithm can be improved by kinetic model, and new node generation can be constrained by kinetic equations (Na et al., 2011). Apart from making use of RRT, some researches combine the mathematical model with state lattice. The state lattice (Pivtoraiko and Kelly, 2005) is a discretization of the configuration space into a set of states, representing configurations, and connections between these states, where every connection represents a feasible path. Thus, it turns motion planning problems into graph searches (Bischofberger, 2009).

For an USV, the researches in first two stages usually apply the above mentioned approaches. However, because of the hydrodynamic force, the inertia, resistance and response time on waters are larger than those on ground, the motion control for USV is more complex and difficult than UGV or wheeled mobile robots, and the method of motion planning above can hardly be used for USVs. Some scholars take advantage of minimax game-tree search to select the smallest collision probability trajectory from the possible trajectories pool (Svec et al., 2012). But it is still unclear that how these possible trajectories are generated (or what the special properties they are) and how to control an USV (the specific instruction) to achieve the planned path. Moreover, with the increasing density of water traffic, the scope of sailing area is decreasing gradually. In some special navigation environment, small range of autonomous control and fine operation become necessary, such as the task of self-avoidance and self-berthing in harbor areas. Thus, to adapt water environment and achieve fine control, this paper presents a method based on trajectory unit. As trajectories contain all the dynamic constraints of USV, the method first, discretizes these trajectories through certain rules, and then extracts the position and heading that those discretized trajectories can reach, and finally, proceeds with route searching under the position and heading constraints.

2. Hydrodynamic model for USVs

Trajectories are generated according to the dynamic model of a research object. This paper takes advantage of the Maneuvering Mathematical Group (MMG) method (Ogawa, 1977) to build a hydrodynamic model for an USV. The main idea of a MMG model is decomposing fluid forces and moment into several parts which affect hull, propeller and rudder (shown in Fig. 1). The external effects on hull are characterized by inertia and viscidity (Kijima et al., 1990). Therefore, a MMG model consists of an inertia model, a viscidity model, a propeller model and a rudder model.

In order to simplify the problem, three assumptions are made as follows.

Assumption 1. Only planar motions are considered, neglecting heaving, rolling and pitching for an USV.

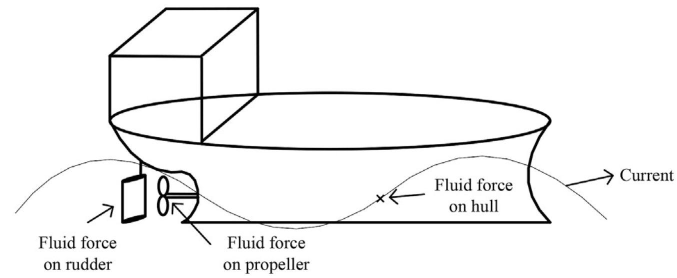

Fig. 1. The fluid force affecting on different parts of a vessel.

Assumption 2. No account of the influence of wind, current and waves.

Assumption 3. The rotation direction of the engine is only positive. When the USV is steady steaming, the rotation speed is considered not change.

Aiming at Assumption 3, it is necessary to explain. When a ship is sailing on the waters there will be the resistance, and the load of propeller will increase, which result in the rotation speed (n) declining. At the moment, the speed controller will raise the main engine power to offset the increased load of propeller and maintain the rotation speed. In the whole process the main engine is working in the closed-loop system of the automatic rotation speed control. The main engine control model is shown below (Jia et al., 1989).

$$T_D I_E \ddot{n} + I_E \dot{n} + k_p K n / 2\pi = k_p K n_r / 2\pi + \frac{1}{2\pi}\left[T_D \dot{Q}_P + Q_P\right] \tag{1}$$

where T_D is the time constant, I_E is the moment of inertia of the whole system, k_p is the gain of speed controller, n_r is command rotation speed, K is the gain from main driving lever to torque output, Q_P is absorption torque of propeller.

Thus, the model is based on three degrees of freedom: yawing, swaying and surging:

$$\begin{cases} X = X_I + X_H + X_P + X_R \\ Y = Y_I + Y_H + Y_P + Y_R \\ N = N_I + N_H + N_P + N_R \end{cases} \tag{2}$$

where I, H, P, R denote the forces (or moment) of inertia, viscidity, propeller and rudder respectively.

2.1. Inertia model

In the water, the motion of a ship can cause disturbance of surrounding flow field, forming fluid medium momentum (moment) or additional momentum (moment). Calculating differential in the corresponding direction can get the fluid inertia force and moment:

$$\begin{cases} X_I = -\left(m_x \dot{u} - m_y v r - m_y \alpha_x r^2\right) \\ Y_I = -\left(m_y \dot{v} + m_x u r + m_y \alpha_x \dot{r}\right) \\ N_I = -\left[J_{zz}\dot{r} + m_y \alpha_x (\dot{v} + ur) + \left(m_y - m_x\right) uv\right] \end{cases} \tag{3}$$

where m_x and m_y are additional mass along x-axis and y-axis respectively, α_x is the coordinate along x-axis which the point of action of m_y, J_{zz} is the additional moment of inertia to z-axis; u and v are the velocity along x-axis and y-axis respectively, and r is the angular velocity of yawing.

2.2. Viscidity model

The viscidity force and moment that ship effect is related to the geometric features of hull, the physical properties of fluid and the motion state of the ship. When the first two factors are invariant, the viscidity force and moment can be determined by the motion states, in particular,