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Energy efficient path planning for a marine surface vehicle considering heading angle

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ABSTRACT

Ocean environmental effects such as current, wind, water depth, and wave effects on a surface vehicle should be considered when planning the path of a marine surface vehicle, even though their complexity makes computation in a short time challenging. Moreover, the mechanical handling devices such as cranes installed on the deck floor of a surface vehicle can also severely confine a vehicle's heading angle at the goal point, especially in a docking or loading/unloading situation. This paper proposes the EEA* algorithm, a deterministic and energy-based 3-dimensional (3-D: x, y, and θ) path planning method for a marine surface vehicle on a 2-dimensional (2-D: x, y) surface plane that considers ocean environmental effects and the heading angle. The proposed path planner uses a realistic energy cost considering the loads on a vehicle due to tidal current and limited water-depth based on a given ship geometry. It also considers the vehicle's turning ability, thus generating more feasible way-points for real travel while satisfying heading angle constraints. By considering both effects in the path planning step, a more energy-efficient and maneuverable path can be found. Resultant paths and their costs are compared through various simulations in different environmental conditions with those of a classical distance-based A* algorithm, the DA* algorithm which is widely used in most applications.

1. Introduction

Many ideas from traditional robot navigation technology have been adopted to address ship navigation problems. In most cases, however, hydrodynamic effects in ocean environments and limited turning ability of a vehicle were not sufficiently taken into consideration or sometimes even ignored in path planning (Statheros et al., 2008; Tam et al., 2009). This could result in enormous waste of energy, or sometimes even potential collision risk to the obstacles if the effects are too strong to be controlled solely by the actuator of the vehicle itself.

Ocean environmental effects should be properly considered in path planning on the ocean surface; vehicle navigation in an ocean environment can be compared to navigation on terrain with various directional forces on the surface. Control on the fly is essential indeed to avoid unexpected collisions in a real-time cruise; however, it is possible to save energy and even reduce collision risks by considering environmental effects in advance in the path planning step. Considering external loads in the path planning step is very important, as in the path following step, because computational resources are much more limited during field operations in many cases. By considering the shallow water effect as well as the tidal current in the path planning step before real travel, way-points for a more economical and efficient path can be found.

Moreover, the mechanical handling devices such as cranes for loading or unloading the equipment or components for maintenance may also severely confine both the trajectory and the goal state. For example, some ships are required to berth on the port side only due to an asymmetric arrangement of docking or those devices. Unnecessary efforts of the given vehicle as well as the tug boats due to an undesirable final orientation can be significantly reduced if both the start and the goal orientation are considered during the path planning step.

1.1. Problem statement

General path planning on land finds the shortest path avoiding obstacles whereas other important elements should be considered for path planning in the ocean environment: environmental effects and

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the vehicle's heading angle. In this paper, we assume that a way-point based navigation system is used, since this method is preferred for the guidance system of a marine surface vehicle over a trajectory based approach due to its simplicity (Fossen, 2002). We also assume that the type of a vehicle is a large vessel with a single propulsion system without any bow thruster for simplification of the problem.

1.1.1. *Ocean environmental effects*

Various environmental effects exist in the ocean environment and exert considerable forces on surface vehicles. If the path generated ignores these effects, more fuel may be required or the path may be almost impossible to follow. With kinematics-based or distance-based approaches only, it is difficult to suggest an optimal path directly in terms of the expected energy consumption. Sometimes arbitrary coefficients or weight factors are employed for the cost function of the energy optimal path planning method. If these coefficients are not capable of describing each effect properly, logically sound comparisons between the path costs will be difficult, thus degrading the reliability of the path planning result. By considering environmental effects with respect to energy consumption using a realistic cost function, a more efficient path can be found. Fig. 1 describes an example of two paths generated by a classical distance-based path planning and a path planning method considering environmental effects.

Among the various environmental effects, tidal and water depth effects are mainly covered in this paper. The various environmental effects on a surface vehicle can be found in Lee et al. (2011a,b). To focus on the main subject of this paper, the effect of the current and angular constraints on the path planning, we ignored the wind load by assuming a high draft compared to the air projection area and there is not wind stronger than 10 m/s in a usual case. The wave effect is not negligible in terms of the magnitude of the forces, but the frequency range does not affect ship maneuvering, and the ocean wave mostly affects the floating body motions, which are more important for dynamic positioning than for path planning.

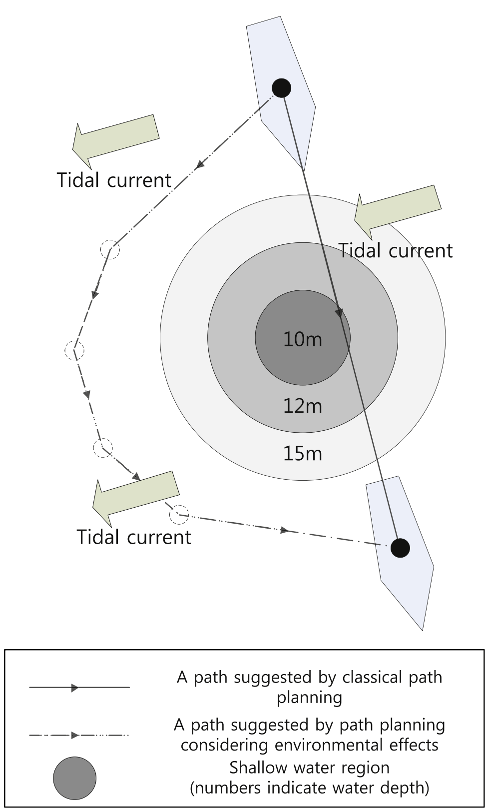

Fig. 1. An example that shows the comparison between a path by a general distance-based path planning and a path by an energy-based path planning method considering environmental effects such as tidal current and limited water depth.

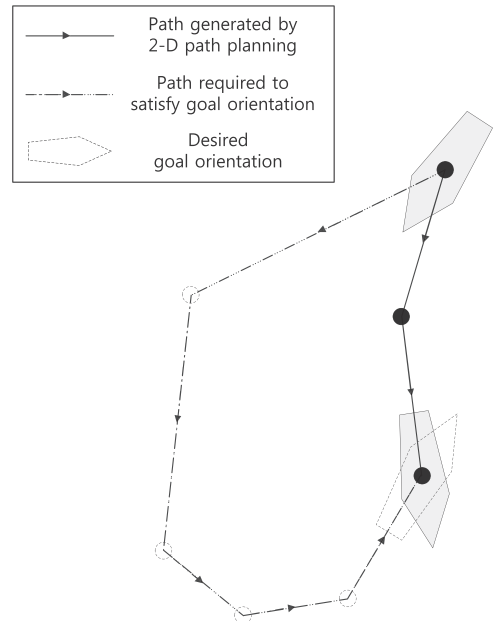

Fig. 2. An example that shows the limitation of a general 2-D path planning method. The condition of a goal orientation cannot be satisfied by the typical 2-D path planning method.

1.1.2. *Vehicle heading angle*

The orientation of a marine surface vehicle is very important in path planning, not only because the forces exerted on the vehicle may differ depending on the orientation, but also because it may affect the path itself. Marine surface vehicles have turning ability that can confine the angle changes between the via points generated by the path planning system. They also carry various instruments on the main deck, and several of these instruments such as gantry cranes or berthing devices have directional constraints at start or goal points that depend on the vehicle orientation.

Since most surface vehicles are highly under-actuated, it is challenging or sometimes impossible to make enough turns in a confined space. Typical 2-dimensional (2-D) path planning thus puts the vehicle in a difficult situation at a goal state if the heading angle is not considered, as in Fig. 2. For example, the general 2-D path planning method cannot satisfy the goal orientation condition in Fig. 2.

1.2. *Previous works*

Many researchers have tried to solve the path planning problem from various perspectives: collision avoidance, kinematic feasibility, environmental disturbances, or energy consumption.

Benjamin et al. (2006), Szlapczynski (2006), and Xue et al. (2011) focused on a collision avoidance in path planning of multiple surface vehicles. Benjamin et al. (2006) employed an interval programming technique for a behavior-based architecture for collision avoidance. This technique suggests a safe path by combining the COLREGs (The International Regulations for Avoiding Collisions at Sea[1]) rules and CPA (Closest Point of Approach) concept. Smierzchalski (1999) used an evolutionary method to generate a trajectory of a given vehicle by

[1] http://www.imo.org/ourwork/safety/navigation/pages/preventing-collisions.aspx