Harmonic Potential Field Method for Autonomous Ship Navigation

Chaojian SHI, Mingming ZHANG and Jing PENG
cjshi@shmtu.edu.cn, mmzhang@online.sh.cn, jpeng@fudan.edu.cn
Merchant Marine College, Shanghai Maritime University
1550 Pudong Ave., Shanghai, P.R. China, 200135

Key Words: autonomous ship navigation, potential field, harmonic function, motion planning
Submission area: Special section - Maritime ITS technologies

Extended Abstract

Ship navigation is in a very complicated environment. Approximately 90% of international trade is carried by ship and there are more than 120,000 vessels in the global maritime fleet. More than 1.2 million mariners on board ships are calling more than 2,800 ports in the world. Accidents seem inevitable in such an environment. According to IMO statistics on total losses of ships of 100 GT and above and losses of lives as a consequence to the total losses, in the year of 2002, 148 vessels suffered total losses and 1274 people lost their lives. Statistics also shows that more than 80% of the accidents happened due to human factors. Autonomous ship navigation technology is a promising approach to improve the situation by reducing human errors and thereby to reduce navigational accidents.

Potential Field (PF) method has been successfully employed for autonomous mobile robot path planning in the past decade because of its elegant mathematical analysis and simplicity. Since the first work of PF presented by Khatib in 1980s, substantial refining and improvement has been implemented to the method. It is extensively applied to robot path planning in both static and dynamic environments. PF navigation for wheeled robots on natural terrain has also been explored. In general, PF method is suitable for the path planning and control of low-speed systems in two-dimensional space. In this paper, a potential field method is proposed for autonomous navigation of ships in diverse environments. A harmonic potential field is defined on the navigation region and the ship’s route is generated to avoid collision with obstacles or border lines of the waterway. Navigational rules and general practice of seaman have been incorporated in the system, which is necessary in ship navigation environments.

Harmonic functions are used in defining the potential field. A fluid dynamic analogy is used to solve the motion planning problem. The properties of the potential flow are taken as inviscid, incompressible and irrotational. By this assumption the potential field must satisfy the Laplace’s equation,

\[ \nabla^2 p = \sum_{i=1}^{n} \frac{\partial^2 p}{\partial x_i^2} = 0, \]

where \( n \) represents the dimensionality. Solution to this equation is in the form of harmonic functions and can be used to express the potential field. Harmonic functions can be used to generate collision-free streamlines without local minima problems. Potential flow is employed to generate the streamlines between the initial and goal configurations considered as source and sink, respectively. The environment is bounded and the boundary of obstacles is impenetrable by the flow. Gradient of this potential field constitutes the velocity field and is used to plan and control ship’s motion. Numerical method is employed to solve Laplace’s equation. A mesh of grid points is imposed on the navigation region and the Laplace’s equation at each grid point is then approximated using finite difference equations. The boundary conditions have to be satisfied on the obstacle’s boundaries, on the boundary of the environment, and at the source and the sink of the flow. To this end, Robin boundary condition is employed, which is a linear combination of Dirichlet and Neumann boundary conditions (BC). In the fluid dynamic paradigm, the source and the sink are fixed at high and low constant potential values, i.e. Dirichlet BC, respectively. The boundary of the environment and the obstacles inside the environment are considered impenetrable, i.e. Neumann BC. The Gauss-Seidel is a relaxation method generally used to calculate these values for all of the grid points of the cells without obstacles or targets.

When the ship is controlled by a vector field produced by harmonic functions, it will always tend to follow a path that minimizes the collision probability with the obstacles. In channel navigation environment, for instance, the ship will tend to follow an equidistant path to the boundaries of the channel.
This sometimes may not fit into general practice of seaman or navigation regulations. This problem is dealt with by solution of Sturm-Liouville problem. Laplace’s equation can be extended to a family of equations that generates functions without local minima. This family is defined by

\[ \nabla^2 p + F(\nabla p) = 0, \]

where \( F(\nabla p) \) satisfies two conditions: it is continue and \( F(0) = 0 \). In this paper, \( F(\nabla p) = \alpha \nabla p \cdot v \) is used to define the Sturm-Liouville problem, which is given by,

\[ \nabla^2 p + \alpha \nabla p \cdot v = 0, \]

where \( v \) is a bias vector and \( \alpha \) is a scalar. The numeric solution can be obtained in the same way as that of Laplace’s equation, that is, through the discretization of this equation and applying the Gauss Seidel relaxation method to calculate the values of the grid points. By adequate adjustment of the parameters, \( v \) and \( \alpha \), different paths can be produced for the ship to follow. The adjustment of the vector \( v \) allows a closer path to the one side of the channel to be obtained, which may be need in narrow channel navigation as the regulations for preventing collisions requires that ships navigate on starboard side of the channel. The vector \( v \), called behaviour vector, can be seen as an external force field that inhibits the natural tendency of ship to move away from the obstacles, and such that navigational rules can be incorporated in the potential fields. The parameter \( \alpha \) can be understood as the strength or influence rate induced by the \( v \) vector on the potential field.

Computer experiments are performed with typical water areas, such as narrow channel, traffic separation scheme region and coastal areas, in which different navigational practice or regulations may apply. With harmonic potential field and solution of Sturm-Liouville problem, ship navigation route can be generated avoiding collisions with obstacles, and following the navigational regulations for the specific region as well.