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Method for Finding the Optimal Ship Route in Ice Based on Vector Geo-algorithms

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Optimization of the ship route in ice-covered waters improves the efficiency and safety of navigation in the Arctic. This article describes a new wave-based approach for ice routing of a ship. Unlike grid-based approaches, which use a predefined grid to describe possible ship movements, the proposed algorithm is cell-free and extends the method of isochrones. All calculations of isochrone propagation are done using geo-algorithms and operations with geo-polygons. This allows us to use a standard vector ice data in its initial form, as well as to consider such special features as the discontinuities in ice cover, ice leads, and fractures.

INTRODUCTION

Path optimization is a key challenge for safe and cost-efficient ship navigation in ice-covered waters. Recent technology developments make it possible to solve such a routing task in an automatic mode. At the same time, there are several requirements for implementing this idea. First, the formal statement of the routing problem should provide the possibility of considering the maximum number of factors and ice parameters that influence ship speed and route selection. Second, any software-based automatic routing method should serve as an additional tool, which a shipmaster or ice expert will use along with the other instruments to build the recommended route.

There are numerous studies, where routing techniques were applied to develop the methods of path optimization of ships, as well as to explore the alternative navigation lines in terms of metocean conditions. In most studies devoted to ship route optimization in open water conditions, the metocean data are represented in a gridded format, i.e., at the nodes of a regular grid. Due to this reason, the researchers prefer to use the graph-based routing methods that suit the grid concept the best. Various interpolation techniques are frequently used to calculate the metocean data in all possible locations of simulated ship routes, based on the initial grid nodes of wind and wave data information. Such an approach allows for the building of an arbitrary grid for path optimization, using the same gridded metocean data. The gridded format of the wind and wave data is so widespread in routing applications because the results of atmospheric and ocean circulation models are presented and distributed in this format. However, in the case of ice data, things are quite different.

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Ice data representation standards are based on the concept of an ice zone. The ice zone is an area with uniform ice characteristics that may have an arbitrary geometry. In 2004, the World Meteorological Organization (WMO) approved the vector format to store and distribute the ice data, known as SIGRID-3 (WMO, 2004). This format is based on the shapefile vector format. Each ice chart in SIGRID-3 format is a combination of linked SHP and DBF files. An SHP file specifies the uniform ice zone as polygons defined by the sets of boundary coordinates. The linked DBF file contains the attributes of each polygon that describe the total ice concentration, partial ice concentrations, floe shapes of the first, second, and third thickest ice, as well as the other commonly used parameters describing the ice cover (see Fig. 1).

Representation of ice data in a vector format leads to certain requirements on the processing of such data in terms of polygon handling. Indeed, the use of standard routing methods requires transferring the data from polygons into regular grid nodes. Therefore, we suggest performing all routing calculations by means of operations with vector polygons. This forms the main idea of the proposed method to optimize the ship route in ice-covered waters.

ISOCHRONE AS A VECTOR OBJECT

Among the numerous routing approaches, the "method of isochrones" suits our purposes best, since it does not require any grid or graph representation and may be implemented using only vector operations. The method to optimize ship path, taking into account metocean conditions, was originally developed by James (1957). The isochrone is a curve formed by a set of points that model the maximum ship advance from its initial location during a given period. There are numerous variations of this method for specific cases (Klompstra, 1992; Szłapczyńska and Śmierzchalski, 2007; Topaj et al., 2019). There are several isochrone-based approaches. However, they all describe isochrone by a set of points, but not as a vector curve.

There is an evident analogy between the raster graphics and the approach to represent geo-information in grid nodes. Grid data