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Image processing for ice floe analyses in broken-ice model testing

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ABSTRACT

The ice floe shape and size distribution are important ice parameters in ice-structure analyses. Before performing an analysis at full scale, the dynamic positioning (DP) experiments in model ice at the Hamburg Ship Model Basin (HSVA) allow for the testing of relevant image processing algorithms. A complete overview image of the ice floe distribution in the ice tank was generated from the experiments. An image processing method based on a gradient vector flow (GVF) snake and a distance transform is proposed to identify individual ice floes. Ice floe characteristics such as position, area, and size distribution are obtained. A model of the managed ice field's configuration, including identification of overlapping floes, is also proposed for further studies in ice-force numerical simulations. Finally, the proposed algorithm is applied to an ice surveillance video to further illustrate its applicability to ice management.

1. Introduction

Operations in ice-covered regions are more technically and physically challenging than those in other accessible regions due to their low temperatures, remoteness, darkness, and to the presence of sea ice and icebergs. Because the behavior of ice forces is significantly different from other environmental forces, the development of temporally and spatially continuous field observations of sea ice conditions, such as ice concentration and ice floe size distributions is very important to mitigate the risks of such operations.

The use of cameras as sensors for offshore operations in ice-covered regions is explored to characterize the ice conditions. Camera sensors have the advantage of delivering spatially continuous measurements with high precision, which can be particularly important for providing detailed localized information about the ice to ensure safe operations in ice-covered regions. Image processing can reduce or suppress the ambiguities, incompleteness, uncertainties, and errors of an object and the environment and consequently produce more accurate and reliable information of the object and environment (Haugen et al., 2011). Various types of remote sensing technologies and corresponding image processing algorithms for analysis of sea-ice statistics and ice properties have been developed. Rothrock and Thorndike (1984) measured the sea ice floe size distribution by identifying the ice floes manually from aerial photographs. Ji et al. (2011) determined the ice thickness, ice velocity, and ice concentration in the Bohai Sea by using the sea ice digital image collection and processing system. In the model tests performed by Millan and Wang (2011), a machine vision system based on boundary detection and thresholding was used to analyze and record the ice conditions surrounding the vessel in real time.

For an actual ice image, the boundary hidden by an apparent connection between ice floes should be identified. Traditional boundary detection algorithms cannot easily detect this boundary, which seriously affects the floe size analysis. To mitigate this issue, Toyota et al. (2006, 2011) separated closely distributed ice floes by setting a threshold higher than the ice-water segmentation threshold. However, this threshold did not work well when the ice floes were connected. Consequently, they separated the connected ice floes manually. Zhang et al. (2012a, 2012b) applied and compared derivative and morphology boundary detection algorithms in both model ice and sea ice images. Traditional derivative boundary detection is sensitive to weak boundaries and noise, and it often produces non-closed boundaries. In contrast, morphology boundary detection results in a good description of the object shape and generates closed boundaries, but some boundary information is still lost. Blunt et al. (2012) adopted the Watershed transform, which has been widely used in connected object segmentation, to separate the connected sea ice floes into individual floes. They removed brash ice by using image opening and erosion operators literally, and then they used the Watershed transform to segment the connected ice floes. However, over- and under-segmentation of the ice floes are the major issues in watershed-based segmentation. Due to an ineluctable over-segmentation problem, Blunt et al. removed these over-segmented lines manually. Zhang et al. (2013) assumed that each ice floe had a convex boundary and that the junction line between two connected ice floes had at least one concave ending point. After the Watershed transform the convexity of each pair of ending points was checked, and two neighboring floes whose junction line ending points were both

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convex were merged to remove the over-segmentation automatically. Banfield (1991) and Banfield and Raftery (1992) introduced a mathematical morphology together with principal curve clustering to identify ice floes and their boundaries in a nearly fully automated manner. First, the image is binarized using the thresholding method. The erosion-propagation algorithm (EP) is then used to provide a preliminary clustering of the boundary pixels and to produce a collection of objects as floe candidates. To remove subdivisions caused by the EP algorithm, they developed a method based on an algorithm for clustering about closed principal curves to determine which floes should be merged. However, both Zhang et al. (2013) and Banfield and Raftery (1992) operated on the binary images, their methods focusing on the morphological characteristics of ice floes rather than on the real boundaries, and they were limited by crowded ice floe images where the mass of ice floes were connected to each other and no “hole” or concave regions could be found after binarization.

In this research, a gradient vector flow (GVF) snake algorithm is adopted to separate seemingly connected floes into individual ones. The GVF snake operates on the gray scale image in which the real boundary information, particularly “weak” boundaries, has been preserved. Moreover, the GVF snake will ensure that the detected boundary is a closed curve. To start the algorithm, an initial contour is required for the GVF snake. This initial contour should be close to the desired contour in the image. Otherwise, the snake may evolve incorrectly. Therefore, a manual initialization is required in some cases, particularly in connected and crowded floes segmentation. To solve this problem, an automatic contour initialization is proposed to avoid user interaction and to reduce the time required to run the GVF snake algorithm. Once individual ice floes have been extracted, the floe boundaries are obtained, and the floe size distribution and shape factor can be extracted from the images.

The main focus of this paper is on model ice images. The algorithm has been tested on different sub-images and on an overall ice tank image. This results in an identified set of broken ice floes, which can be used in several ways:

- To quantify the efficiency of ice management for Arctic offshore drilling operations and automatically detect hazardous conditions, for example, by identifying large floes that escape the icebreakers operating upstream of the stationary drilling vessel. The size and shape of those floes, as identified by the image processing system, can be compared with the maximal allowed values, and a warning signal can be sent to the risk management system. Eventually, a decision to disconnect the floater might be taken, based on the identified operational ice conditions.
- The managed ice concentration and ice floe sizes are essential parameters in the empirical formulas that estimate the ice loads on stationary Arctic offshore structures (Keinonen and Robbins, 1998; Palmer and Croasdale, 2012). One of the largest concerns of ice management modeling is accurately predicting not just the mean floe size resulting from an ice management system, but the floe size distribution (Brown et al., 2012).
- Individual ice floes identified by the image processing system, can be used to initialize high-fidelity numerical models, such as those in Daley et al. (2012), Vachon et al. (2012), Sayed et al. (2012a, 2012b), Gürtner et al. (2012) and Metrikin et al. (2013). Individual snapshots of identified ice floes can be used to validate the numerical models at various moments in time by matching the simulated ice fields with the actual ones.
- The ice floe size and shape distribution, calculated from an identified ice field, can be used in synthetic ice field generators. These generators draw polygons from the distribution and use packing algorithms to place the polygons on a 2D plane. Such synthetic ice fields may be used to study various packing configurations with the same ice concentrations and floe size distributions as well as the variability of the resulting ice loads on an offshore structure.
- The identification of the ice field may provide an early warning of an ice compaction event, which can be dangerous if the ice-structure interaction mode changes from a “slurry flow”-type to a “pressured ice”-type, as defined by Wright et al. (1999) and discussed in Palmer and Croasdale (2012).
- Finally, the ice-drift speed and direction (velocity) can be estimated by applying an image analysis to sequential frames. The ice-drift velocity is an important parameter for ice management because it poses requirements on the speed of icebreaking vessels and may indicate an approaching ice drift reversal scenario (which usually happens when the ice drift tends to zero velocity).

In addition to the above application areas, the ice floe identification algorithm may potentially help to illuminate the momentum exchange from atmosphere to ice discussed in (Steele et al., 1989), the melting rate of ice floes discussed in (Steele, 1992), and possibly providing a clue to the understanding of ice-floe formation processes as discussed in (Toyota and Enomoto, 2002).

2. Snake models

Snakes, or active contours as introduced in (Kass et al., 1988), correspond to a powerful method used to locate object boundaries. The initial curves can move under the influence of internal forces from the curve itself and external forces computed from the image data. The algorithm stops when the internal and external forces reach equilibrium. The internal and external forces are defined such that the snake will conform to an object boundary or other desired features within an image. There are two types of active contour models: parametric active contours and geometric active contours. This study considered the parametric active contours due to its superior detection capability of “weak”-boundaries.

2.1. Parametric snake model

A typical snake is a curve $\mathbf{C}(s) = (x(s), y(s))$, $s \in [0, 1]$ that moves through the spatial domain of an image to minimize the sum of the internal and external energy. This energy is given by

$$\mathbf{E} = \int_0^1 (\mathbf{E}_{int}(\mathbf{C}(s)) + \mathbf{E}_{ext}(\mathbf{C}(s)))\mathrm{d}s, \tag{1}$$

where $\mathbf{E}_{int}$ is the internal energy

$$\mathbf{E}_{int} = \frac{1}{2}(\alpha|\mathbf{C}'(s)|^2 + \beta|\mathbf{C}''(s)|^2), \tag{2}$$

where α and β are weight parameters that control the snake's tension and rigidity, respectively. $\mathbf{C}'(s)$ denotes the first derivatives of $\mathbf{C}(s)$ with respect to s, making the snake act as a membrane, and $\mathbf{C}''(s)$ denotes the second derivatives, making the snake act as a thin plate.

$\mathbf{E}_{ext}$ is the external energy defined in the image domain. It attracts snakes to salient features in the image, such as boundaries. To find boundaries in a gray scale image, the image gradient is typically chosen as the external energy (Kass et al., 1988)

$$\mathbf{E}_{ext} = -|\nabla \mathbf{I}(x, y)|^2, \tag{3}$$

where $\nabla \mathbf{I}(x, y) = \left(\frac{\partial \mathbf{I}}{\partial x}, \frac{\partial \mathbf{I}}{\partial y}\right)$ is the image gradient that represents a directional change in the brightness of the image with the gradient angle $\theta = \arctan\left(\frac{\partial \mathbf{I}}{\partial y} / \frac{\partial \mathbf{I}}{\partial x}\right)$. When also considering the image noise, the external energy is defined as (Kass et al., 1988)

$$\mathbf{E}_{ext} = -|\nabla \mathbf{G}_\sigma(x, y) * \mathbf{I}(x, y)|^2, \tag{4}$$