TRANSNAV International Journal on Marine Navigation and Safety of Sea Transportation
Volume 5 Number 4 December 2011

A Simulation Environment for Modelling and Analysis of the Distribution of Shore Observatory Stations - Preliminary Results

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ABSTRACT: The paper has presented the usage of mathematical theory of evidence in evaluating of the possibility of object detection by monitoring radar stations. The level of object detection allows for effortless conversion to optimisation problem of monitored area coverage. Development of such task enables such distribution of observatory stations that maintains the detection rate higher than the assumed value. An appropriate rate level is achieved by covering the analysed set of points with sufficient number of radar stations. Combining evidence allows for calculating corresponding parameters for each set of observing equipment.

1 INTRODUCTION

A highly significant issue during the planning and construction of the shore observatory stations network is undoubtedly their proper location, as the success of the entire investment depends on the right positioning. The criterion for project evaluation may be adopted on the basis of the extent of coverage of the monitored area, the number of observatory stations used for this purpose and, hence, the degree of maritime transport safety. Restrictions imposed on such dilemma require a thorough analysis of the issue long before the realisation of the project. Problem analysis ought to focus on the placement of shore stations primarily. During the problem analysis various possible locations and observatory station types should be regarded. The results of completed analysis should answer the question which of the possible locations are the best for creating the sufficient network of the shore observatory stations.

Above all, the choice of location ought to fulfil marine shipping safety requirements, which are to a great extent related to the warranty for the monitored area coverage, as well as various technical and economic aspects. Provided the system constructed is a mere expansion of an already existing maritime traffic monitoring system, it ought to take into account existing observatory infrastructure.

2 FACILITY LOCATION AND LOCATION SCIENCE

Facility location problems investigate where to physically locate a set of facilities (resources, stations, etc.) so as to minimize the cost of satisfying some set of demands (customers) subject to some set of constraints. Location decisions are integral to a particular system's ability to satisfy its demands in an efficient manner. In addition, because these decisions can have lasting impacts, facility location decisions will also affect the system's flexibility to meet these demands as they evolve over time.

Facility location models are used in a wide variety of applications. These include, but are not limited to, locating warehouses within a supply chain to minimize the average time to market, locating hazardous material sites to minimize exposure to the public, locating railroad stations to minimize the variability of delivery schedules, locating automatic teller machines to best serve the bank's customers, locating a coastal search and rescue station to minimize the maximum response time to maritime accidents, and locating a observatory stations to cover monitored area. These six problems fall under the realm of facility location research, yet they all have different objective functions. Indeed, facility location models can differ in their objective function, the distance metric applied, the number and size of the facilities to locate, and several other decision indices. Depending on the specific application, inclusion and consideration of these various indices in the problem formulation will lead to very different location models (Hale & Moberg, 2003).

There exists two predominant objective functions in location science: minisum and minimax. These are also known as the median and centre problems, respectively. The diametrics of these objective functions also exist (maxisum and maximin), although they are somewhat less studied. Other objective functions are also studied within the location science community, especially recently. The most notable of these are the set covering and maximal covering objective functions. The former of these two objectives attempts to locate the minimum number of new facilities such that a prescribed distance constraint to existing facilities is not violated. In contrast, the latter strives to locate a given number of facilities to best meet the (weighted) demands of the existing facilities subject to a maximum distance between new and existing facility. It should be noted that for the set covering formulation, because all of the demands must be met (covered) regardless, the relative weight of the demands generated by the existing facilities are inconsequential, whereas in the maximal covering objective some existing facility demands may be left unmet (uncovered).

Location problems are generally solved on one of three basic spaces: continuous spaces (spatial), discrete spaces, and network spaces. The first of these three deals with location problems on a continuous space (in one, two, or three dimensions) where any location within the realm is a feasible location for a new facility. The second looks at problems where locations must be chosen from a pre-defined set while the third looks at location problems that are confined to the arcs and nodes of an underlying network (Hale, Moberg, 2003).

3 MATHEMATICAL THEORY OF EVIDENCE IN MARINE TRAFFIC ENGINEERING

3.1 *The classical approach*

The mathematical theory of evidence, one of various tools employed in the application, will be used for evaluating the possibility of objects detection by, e.g., radio stations monitoring specified area. Approximate reasoning, the other significant element used in the application, provides extrapolation and interpolation of the incomplete knowledge of monitoring stations characteristics. The solution to the problem of detection, namely assessing the possibility of detection by each station, allows for moving on to the optimisation problem of supervised area coverage. Such task can be solved by locating observatory stations in a manner enabling detection level indicators to be higher than the assumed value. An adequate level of indicator values is achieved by covering a set of analyzed points with the relevant number of suitably located stations. Detection levels are estimated for a specific discrete search area with regard to records consisting of observing equipment data. Submission of records allows for calculating appropriate parameters for each point of the analyzed area. Solving this problem is possible through the mathematical theory of evidence.

The characteristics of each observatory station are the starting point in the computational process. Sufficient technical parameters provided by the equipment manufacturers are incomplete values, calculated for a certain meteorological conditions at sea (e.g., calm sea) and for typical naval units. Approximate inference mechanisms as well as additional knowledge of experts are needed, the latter being a major source of output data due to the subjective expert assessment, affected by a degree of uncertainty. This subjectivism requires the use of appropriate mathematical apparatus. The mathema-tical theory of evidence in its flexibility allows the use of fuzzy and approximate figures. Calculation of masses of the particular framework of discourse hypotheses with use of membership function creates a structure of beliefs enabling extensive use of the mathematical theory of evidence.

Water areas monitoring is conducted with the use of radar (among others), characterized, as any other technical equipment, by certain limited level of functioning and of reliability in the sense of realisation of basic tasks. The possibility of detecting object is vital parameter of any device of this kind. Modern monitoring stations are able to detect floating objects in considerable distances. One may venture to say that their range is horizontal in fine hydrometeorological conditions. Obviously, the ability to detect depends on the so-called Radar Cross Section (RCS), a feature which is associated primarily with the size of a given unit. Another significant parameter is a draft of a vessel, which in turn reduces the above-water body, affecting directly the size of the reflecting surface. Detection of smaller units at rough sea may pose problems. Whether a specific type unit will be detected in particular conditions depends on the distance to the observatory station, the sea state and the observing equipment characteristics. In some areas the heavy maritime traffic calls for an appropriate location of observatory stations ensuring sufficiently high level of unit detection.

The Dempster–Shafer theory (DST) is a mathematical theory of evidence. In Dempster-Shafer (DS) theory, there is a fixed set of n mutually exclusive and exhaustive elements, called the frame of discernment, which is symbolized by:

$$\Omega = \{A_1, A_2, ..., A_n\} \tag{1}$$

The representation scheme Ω describes the working space for the desired application since it consists of all propositions for which the information sources can provide evidence. Information sources can distribute mass values on subsets of the frame of discernment, $A_i \in 2^{\Omega}$. An information source assign mass values only to those hypotheses, for which it has direct evidence.

$$0 \leq m(A_i) \leq 1 \tag{2}$$

Basic Probability Assignment (BPA) has to fulfil the conditions as follows:

$$m(\phi) = 0 \tag{3}$$

$$\sum_{A_i \in 2^{\Omega}} m(A_i) = 1 \tag{4}$$

If an information source cannot distinguish between two propositions, A_i and A_j, it assigns a mass value to their union $(A_i \cup A_j)$. Mass distribution from different information sources, are combined with Dempster's rule of combination (5). The result is a new distribution, which incorporates the joint information provided by the sources.

$$m(A_k) = \frac{\sum_{A_1 \cap A_2 \cap ... \cap A_d = A_k} \left(\prod_{1 \leq j \leq d} m_j(A_j) \right)}{1 - K} \tag{5}$$

$$K = \sum_{A_1 \cap A_2 \cap ... \cap A_d = \phi} \left(\prod_{1 \leq j \leq d} m_j(A_j) \right) \tag{6}$$

A factor K is often interpreted as a measure of conflict between the different sources (6) and is introduced as a normalization factor (5). The larger K is when the more the sources are conflicting and the less sense has their combination.

If factor K = 0, this shows a consensus of opinions, and if 0 < K < 1, it shows partial compatibility.

Finally, the Dempster's rule of combination does not exist when K = 1. In this case, the sources are totally contradictory, and it is no longer possible to combine them. In the cases of sources highly conflicting, the normalisation used in the Dempster's combination rule can be mistaking.

From a mass distribution, numerical values can be calculated that characterize the uncertainty and the support of certain hypotheses. Belief (7) measures the minimum or necessary support whereas plausibility (8) reflects the maximum or potential support for that hypothesis.

$$Bel(A_i) = \sum_{A_j \subseteq A_i} m(A_j) \tag{7}$$

$$Pl(A_i) = \sum_{A_j \cap A_i \neq \phi} m(A_j) \tag{8}$$

3.2 *Mathematical theory of evidence and fuzzy values*

When the assessment of the situation undergoes solely a subjective expert rating, the results are only to be obtained in form of linguistic variables. Theories presented show (Zadeh, 1975) possibility of transforming such values into figures with use of the fuzzy sets theory, a concept created by L.A. Zadeh in the sixties of the 20th century and developed ever since (mainly by its author), which increasingly intercedes in various economic issues. According to Zadeh, the aforementioned theory has not been sufficiently employed for the purpose of detection analysis of marine units. A more extensive use of possibilities offered by the fuzzy sets theory appears as a necessity for rational construction of new maritime traffic monitoring systems.

The mathematical theory of evidence deals with function combining information contained in two sets of assignments, subjective expert ratings. This process may be interpreted as a knowledge update. Combining sets results in forming of new subsets of possible hypotheses with new values characterising probability of specific options occurrence. The aforementioned process may continue as long as provided with new propositions. This function is known as Dempster's rule of combination.

A fuzzy nature can be attributed to events which may be interpreted in fuzzy manner, for instance, inaccurate evaluations of precisely specified distances to any point. Subjective evaluations in categories: near, far, very far may be expressed with fuzzy sets defined by expert opinions. Such understanding of fuzzy events is natural and common. Introduction of events described by fuzzy sets moderates the manner in which the results of processing are used, expands the versatility of such approach, as well as changes the mode of perceiving the overall combining procedure. Deduction of specific events involved in the process of combining pales into insignificance, as obtaining information on related hypotheses is of greater interest. Combining evidence of fuzzy values brings new quality into knowledge acquisition due to the usage of combination results as a data base capable of answering various questions. After combing many fuzzy distances, the results allow to set the support level for the veracity of statement claiming a distance between a vessel and a barrier is very close, safe or yet another. Other possibilities of the mathematical theory of evidence in problems of navigation can be found in Filipowicz, 2010.

As to the problem of monitored area coverage, phrases used for assessing the distance of units will be linguistically interpreted. The determination of distance at which an object is located is possible with use of linguistic values: very close, close, far, very far. Particular linguistic expressions and corresponding exemplary range of values are presented in the Figure 1. More on this subject can be found in Neumann, 2009.

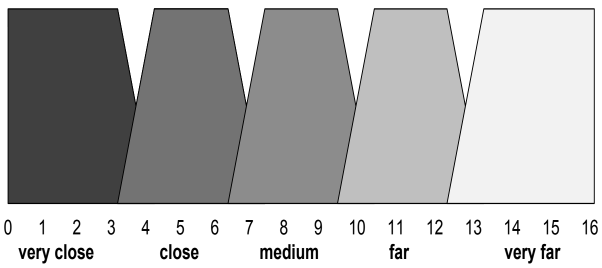

Figure 1. Diagram of linguistic relations

3.3 *The optimisation problem of observatory stations distribution*

Optimisation is determining the finest solution, therefore finding the extremum of given function in terms of specified criterion (e.g., cost, time, distance, efficiency).

The optimisation of observatory stations distribution is achieved by such location of stations that makes the tracking surface of the monitored area nearest to the overall surface of study area. Obtaining equality in two aforementioned surfaces marks an ideal state of no occurrence of shaded area. The usage of a given sort of observatory stations affects the type and size of shaded areas resulting from environmental impact. In case of conventional radar stations tracking surface depends on:

- blind spots caused by port infrastructure, topography of the area,
- range and bearing discrimination.

Arrangement of shore stations seeks to maximise the tracking surface while minimising the number of newly built radar stations. Object-caused bind spots may be eliminated by installing higher number of observatory stations in various locations in a manner enabling their range to cover the entire tracking surface. This goal may be achieved by using a number of additional observatory stations. However, one of the regarded optimisation criteria are economic conditions, additionally: the characteristics of the terrain where stations are to be built, technical possibilities of connecting stations to the network. The presented approach has been implemented in the computer application allowing for analysing maritime areas, proposing a distribution of observatory stations, as well as for comparative assessment of existing area monitoring schemes.

4 THE FEATURES OF APPLICATION

The application was created for MS Windows operating system (Neumann, 2010). This software provides an uncomplicated system for management of stored shoreline patterns along with the suggested locations of shore stations. This very construction scheme for the aforementioned application was chosen due to its ability to design, analyze and assess practically all substantial parameters to be evaluated. Its functions include: creating new projects, browsing the list of existing projects, browsing the information on given project and editing information on given project. Transparent, clear and flexible application architecture makes expanding the system and implementing changes easier. This allows to avoid many mistakes that could have a significant impact on the quality of performed calculation.

The application was designed according to the design pattern Model-View-Controller, with the main purpose of separating the part of application responsible for realisation of data processing from the representative part displaying data. Such partition has numerous advantages, e.g., greater flexibility of the application, more readable code and increased degree of code reuse.

In such constructed architecture three main layers may be distinguished:

- the presentation layer – responsible for output data formatting and displaying the final result,
- the business logic layer - mechanisms employing the basic logic of the application with implemented methods of mathematical theory of evidence. Contain the entire application engine.
- the data layer – the database and the data stored in the system.

The main purpose of this application is such distribution of shore observatory stations that provides coverage of the entire desired area. Therefore, principal objectives of the observatory stations location test may be specified as follows:

- to ensure the greatest possible coverage of the monitored area, using the smallest possible number of observatory stations.
- to ensure the highest possible probability of floating unit detection in the medium weather conditions.

The greatest possible coverage is one of the input parameters of the application. While using the visual interface of the application, the user determines the maritime area of his or her interest, whose monitoring is to be ensured by the shore stations. The user determines also the set of localisation where shore stations may be constructed. A unit detection characteristics in inclement, medium and fair weather conditions may be entered for each station. The entered characteristic is converted to the corresponding values of detection possibility for the specified point. Calculated values can be changed at any moment of application's work, hence the determination of, e.g., permanent dead zones for observatory stations becomes possible.

One of the application elements is the module, which allows for defining detailed characteristics of an observatory station. By defining a station, the user determines its maximum range of floating unit detection. Characteristics for each station ought to be created with regard to all features affecting the quality of observation. The method for defining parameters is presented in the Figure 2. From the viewpoint of the brick defining individual intervals and the level of medium size floating unit detection in medium weather conditions are highly significant elements. The employment of linguistic operator will improve work with the application and emulate behaviour similar to human reasoning. Entering any directional characteristics for each station gives the opportunity to accurately reproduce the actual situation, increase range of the station in the direction of fine terrain parameters, while limiting the range where natural barriers preventing good observation occur.

The main algorithm for this application analyses each of the interesting points with use of the mathematical theory of evidence, searching for such distribution of observatory stations, that would ensure the specified coverage of the given area. Of all locations available the smallest number is chosen for observatory stations.

An entirely separate module is the comparative analysis of various observatory stations arrangements, allowing for choosing the location for an observatory station, providing its characteristics and, subsequently, calculating the detection level in specific points in the chosen area. The calculation results for each observatory stations distribution system are collected in detailed report specifying additionally the best of given shore stations distribution systems, as well.

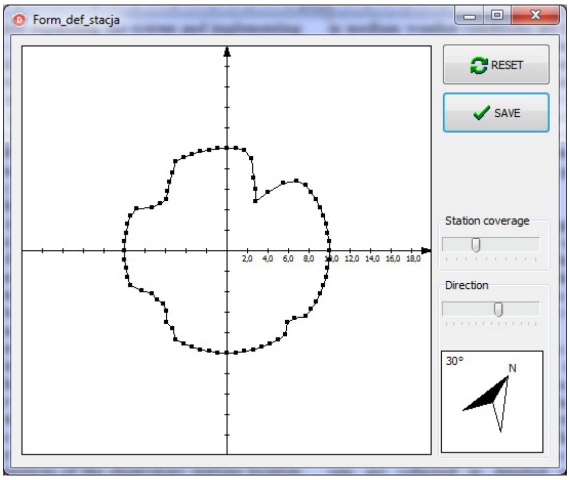

Figure 2. Module for defining detailed characteristics of an observatory station.

In every simulation project adapting the general model to the specific problem situation plays essential role. Adapting particular model of simulation project realization does not equal the lack of possibility to introduce changes, contrary – it ought to be continuously modified to consider conditionings of specific projects.

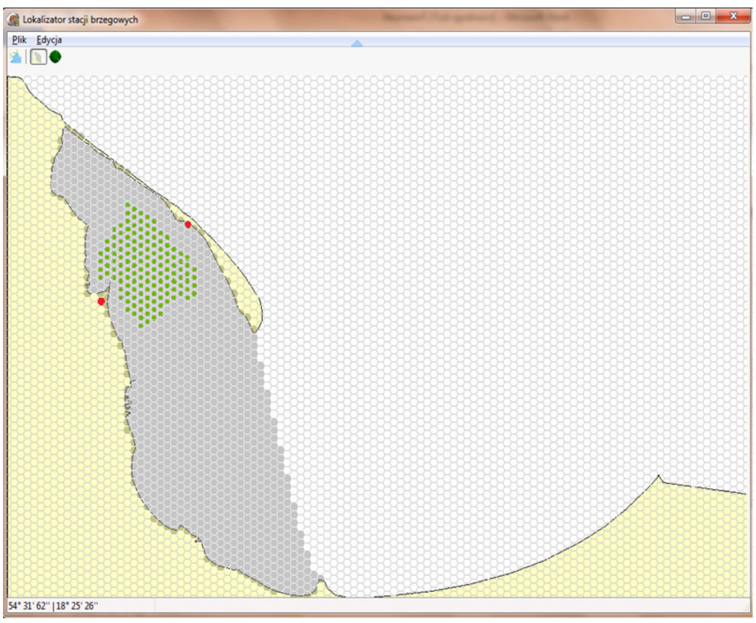

Figure 3. Results of analysis for the experimental area of the Gulf of Gdansk for the two observation stations

At the current stage of work on creating simulation environment, the completion of calculations depends on fulfilling weather condition for each of analysed points. The method suggested enabling assessment of observatory station emplacement searches in the solution set for the solution assuring unit detection at the level higher than the entered value. The number of solutions to the problem can be bigger, yet it is always a finite number. All of solutions obtained in this way may be compared. The solution in which the sum of all calculated values of specific points detection coefficients has the highest value may be indicated as the best one. As employing this method as the best point at the solution of extreme values, an alternative way for choosing the solution (based on assigning weights to possible results intervals and calculating the sum of coefficients with regard to aforementioned weights) was implemented.

The results analysis may suggest changes in shore observatory stations distribution. Other location of observatory stations can cause enlargement of the observation area in monitored maritime areas and a rise in the number of current situation data. More effective distribution of stations contributes to the navigation safety improvement and brings measureable benefits to the environment, as every failure to detect a floating unit may result in shipwreck and contamination of the environment.

The visualisation of the results is presented in the Figure 3. Degrees of colour saturation stand for values obtained in specific points of analysed problem.

The method for calculating coefficients characterizing the obtained solution depends in particular on the representation of the assessments of events occurring in the defined structures. The assessments may have form of exact or approximate values; it may be based on the interval values or fuzzy values. The type of used assessment requires employment of adequate mathematical apparatus when combining evidence.

5 SUMMARY

The paper has presented the usage of mathematical theory of evidence in evaluating of the possibility of object detection by monitoring radar stations. The level of object detection allows for effortless conversion to optimisation problem of monitored area coverage. Development of such task enables such distribution of observatory stations that maintains the detection rate higher than the assumed value. An appropriate rate level is achieved by covering the analysed set of points with sufficient number of radar stations. Combining evidence allows for calculating corresponding parameters for each set of observing equipment.

The usage of software engineering methods in simulation study on distribution of shore observatory stations is not limited solely to the possibility of realising a project of such type on the basis of model derived from this field. The growing importance of IT factor entails verification of models in a documented and structured manner – therefore techniques developed for software testing are also applicable. The main purpose of the application is to determine locations of shore observation points in order to ensure the control, management and maritime traffic control in areas of limited surface.

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