Adaptation of R-Contiguous-Bits scheme borrowed from immune systems to identification of characteristic points of radar image

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Abstract: The problem of continuous position availability is one of the most important issues connected with human activity at sea. Since the availability of satellite navigational systems can be limited in some cases, for example during military operations, we should consider other methods of acquiring information about ship’s position. One of such methods is to apply information included in a radar image of a coast. The positioning system extracts characteristic points from the radar image, identifies them, i.e. assigns correct location to each of them, and finally fixes ship’s position using previously identified points as reference points. In this paper, a new method of identification of radar image characteristic points is presented which is an adaptation of r-contiguous-bits scheme borrowed from immune systems. The method proposed compares coastlines visible from radar image points with pattern coastlines generated from navigational chart.

Keywords: identification, immune systems, maritime navigation

1. Introduction

In recent years, positioning in navigation has been dominated by satellite systems, especially by GPS. These systems are used at sea (maritime navigation), in air (airplane navigation) as well as on the ground (land navigation). However, there are situations in which these systems can be turned off, destroyed or malfunctioning. Therefore, to ensure continuous access to information about vessel’s position required to conduct navigation it is necessary to equip every ship (it particularly concerns navy ships) in a spare positioning system which would be able to substitute the primary system in exceptional situations.

One of the methods making it possible to fix position in coastal areas is to apply information acquired from navigational radar. All bigger sea going vessels are equipped with such radar and its application in navigation is not a new idea. To fix position the traditional radar navigation uses characteristic points of a coast that are visible on the...
radar image. When we know accurate position of characteristic point visible on the 
radar image (we know its identity, i.e. its equivalent from a chart) and additionally 
bearing and distance to it we are able to fix position of our ship. Unfortunately, the 
identification of a point appearing in the image constitutes a frequent problem for 
navigators. For that reason, other methods are used. One of them is automation of 
traditional radar navigation [9]. In this case, all navigator activities performed in order 
to fix position are automatically executed by the system. At the beginning, the charac-
teristic points are extracted from the radar image. Then, they are identified, i.e. positions 
of equivalents from a chart are assigned to each of them. In the next phase, the 
system attempts to correct location of each point on the radar image, i.e. points are 
moved to more suitable positions. This is necessary because each characteristic point 
extracted from the radar image and identified in the next phase of calculations is 
merely an approximation of true characteristic point. This is not a tip of a peninsula 
but rather some close higher object, for example a building, which yields radar echo. 
An application of identified and shifted points as reference points and fixing position 
with relation to them based on information about bearing and distance to each of them 
is the last activity of the system. Bearing and distance can be fixed by means of radar.

![Diagram of the system](image)

**Fig. 1** The structure of the system

The extraction of characteristic points from the radar image is described in [7] and 
[9] and is restricted to the analysis of the second derivate of invariant representation 
[6] of the image. High value of the second derivate for some bearing indicates direc-
tion where potential characteristic point is situated.
The correction of point location on the radar image consists in moving the point towards the sea so as to adjust its representation, i.e. bearing and distance tree [8] or a coastline visible from the given point [10], to the representation of appropriate pattern characteristic point fixed from a chart. This method has not been examined so far and it requires further research.

The identification of the characteristic points was already considered in [8] and [9]. The methods proposed in the works mentioned compare representations of the characteristic points with representations of pattern points fixed from a chart. The more similar both representations, the more chance that they correspond to the same points. The key difference between two methods mentioned above is a form of the point representation. In [9] the identification method is presented which compares coastlines representing the pattern points with the coastlines representing the characteristic points extracted from the radar image. The coastlines representing the pattern points are generated from an electronic chart. The coastline visible from an image point \( p \), for bearing \( BRG \in (0^\circ, 360^\circ) \) is defined as follows [9]:

\[
g^p(BRG) = \begin{cases} 
A & \text{if } P^O_{BRG,p} = \emptyset \\
\min_{pq \in P^O_{BRG,p}} \|pq\| & \text{otherwise}
\end{cases}
\]  

where \( OX \) denotes \( OR \) or \( OM \), i.e. the radar image or an image generated from a chart, respectively, \( P^O_{BRG,p} \) is the set of “bright” pixels lying on the bearing \( BRG \) fixed from the point \( p \) and \( A \) is some value larger than the distance between any two points of the image. According to (1), each coastline includes information where we can see dry land ( \( g^p \neq A \) ) and where we cannot ( \( g^p = A \) ). During the identification, two factors are considered: a similarity between the coastlines and an identification risk. The similarity is expressed as the normalized Euclidean distance between the coastlines. In turn, the identification risk of a given radar image point depends on the total length of the mainland visible from that point. The longer the segment of the visible dry land, the lower identification risk. Radar image characteristic points that have appropriately similar counterparts among pattern points and their identification risk is suitably law are considered reference points in the position fixing process.

This approach has two basic drawbacks. The least deformed element of the radar image of a coast is the coastline visible from the ship, i.e. from the center of the image. Fragments of the image located behind the coastline are most misshapen and making a decision based on them is very risky. The coastline visible from any point of the radar image other than the central point is not consistent with the coastline visible from the latter. The coastlines can partially include the same fragments of the land but they can also be segments indicating distinct areas of the radar image. Therefore, the representation of the characteristic point of the radar image may include only a part of all reliable information that we can obtain from the image, while omitting obscured
fragments of the coastline visible from the ship. What is more, it may also contain fragments that are rather detrimental for characteristic point identification process.

The second drawback of the point identification method proposed in [9] is the way of determining similarity between coastlines. Consider the following situation. We have one pattern point and the corresponding coastline generated from a chart. We also have two characteristic points extracted from a radar image together with their coastlines. The first point is noise-corrupted, whereas the second point corresponds in reality to our pattern point, but it has a strongly deformed coastline in some fragment of the image (for some range of bearings). Most of the coastline is very similar to the pattern coastline, but there is some continuous segment which significantly differs from the pattern. We can encounter such a situation, e.g. in winter, when some areas of the sea can be covered by ice. Consequently, the similarity between the pattern coastline and the coastlines representing both points extracted from the radar image may be comparable and the point which should be correctly identified will be rejected by the identification subsystem.

The identification method proposed in [8] applies bearing and distance trees to represent characteristic points. Each tree describes the location of the remaining characteristic points in relation to the point considered. This approach is devoid of all shortcomings of the previous method based on the coastlines. First of all, the only elements of the radar image taken into consideration during the identification are elements of the land visible from the ship. Fragments of the land that does not belong to the coastline visible from the ship are neglected. Moreover, the method is rather robust to local deformations of the image. Noisy points generated in deformed fragment of the image are recognized and eliminated by the identification system, thereby they are not considered in the identification of the remaining points. The only disadvantage of the method is that it can solely be applied in the case when at least two points corresponding to real characteristic points are visible on the radar image. Otherwise, the method is useless.

In the case, when only one true characteristic point is visible on the radar image, a modification of the method based on coastlines can help [9]. It assumes that the characteristic point of the radar image corresponds to the pattern point if their coastlines match each other for at least \( r \) contiguous bearings, where \( r \) is the parameter of the algorithm. The coastlines match each other for one bearing if the difference between their values is not greater than some assumed threshold (\( \delta \)). We can call this matching rule \( r-\delta \)-contiguous-values rule. Considering only the best matching fragments of the coastlines we lead to the situation in which the method is robust to local deformations of the radar image. To identify a point it suffices that the coastline representing the point resembles some pattern coastline only for \( r \) contiguous bearings. This concept of the identification has been borrowed from theoretical immunology and artificial immune systems [1,2,3,4,5]. The main difference between antigen detection in the immune systems and point identification is that antigens are usually represented as binary strings whereas the coastlines contain real values.
The paper is organized as follows. The next part of the article is devoted to a short presentation of the immune systems and $r$-contiguous-bits rule. Subsequently (section 3), the identification of characteristic points of the radar image by means of $r$-contiguous-bits matching rule is illustrated. Section 4 reports experiments conducted and conclusions are made at the end of the article.

### 2. $r$-contiguous-bits rule

$r$-contiguous-bits matching rule [3] compares two binary strings, i.e. the string imitating infectious, foreign molecule attacking our organism (pathogen) and the string imitating self cell or molecule constituting element of our immune system (detector). The task of our immune system is to protect us from large variety of viruses, bacteria and other infectious organisms collectively called antigens. In order to perform this mission the immune system must be able to distinguish self cells and molecules, which should be protected, from foreign antigens which should be eliminated. The pathogen is detected if it binds to receptor of some antibody (in fact, natural immune system consists of large variety of different class of cells and molecules e.g. B-cells, T-cells and antibodies). Binding is the chemical process that depends on the shape of antibody and pathogen receptors (receptors of the pathogen are called epitopes). The more similar both receptors the greater chance that their owners bind. Once pathogens are detected the immune system eliminates them in some manner. Artificial immune systems usually model both self and foreign molecules and cells as binary strings of some fixed length. The chemical binding between them is implemented as partial matching between the strings. There are many different matching rules that are used in various models of the immune systems, e.g. Hamming distance, edit distance, $n$-grams, $r$-chunks and $r$-contiguous-bits rule. In the case of the latter, that is the basis of the identification method proposed, two binary strings of equal size match each other if they agree on at least $r$ contiguous bits.

\[
\begin{array}{cccccc}
1 & 1 & 1 & 1 & 1 & 0 \ 0 & 1 & 0 & 0 & 1 \\
1 & 0 & 1 & 1 & 0 & 0 \ 1 & 0 & 0 & 1 & 1 \\
\end{array}
\]

Fig. 2 Illustration of 5-contiguous-bits rule

In the case of $r$-contiguous-bits rule, the matching result depends on value of $r$. If $r$ equals the length of all strings encountered in the system then any antibody string can solely recognize single antigen string. In turn, if $r=0$ then every detector string
matches every antigen string. In general, higher value of \( r \) causes the matching rule to be more specific whereas lower values make it more general. The value of \( r \) has influence on discrimination errors which the immune system could make during work. If self string is classified as foreign then we deal with false positive. In turn, if nonself string is classified as normal then we deal with false negative. Both errors are dangerous. In the first case the system attacks oneself, while in the second case it does nothing in order to defend oneself against outside threat.

3. Identification of characteristic points of radar image

The main task of the human immune system as well as the artificial immune system is to distinguish self and dangerous nonself. Our task is somewhat different. First, in our case we do not deal with negative detection, as in the immune system, but with positive detection. We do not have to recognize nonself, i.e. noisy point. Our task is to recognize self, i.e. characteristic point. Moreover, in addition to the detection of self the system has to identify it. Thus, the statement that we deal with the characteristic point is not sufficient in our case. We have to determine the identity of the characteristic point.

To compare the pattern and the radar image point and to use \( r\delta\)-contiguous-values rule for this purpose, transformation of the coastlines representing both points is necessary. The comparison process has to take into consideration three essential issues, i.e.:

1. orientation error of the radar image according to North-South direction;
2. restricted field of vision of radar;
3. presence of echoes of additional objects on the radar image.

Every ship is equipped with variety of navigational devices which serve to determine navigational parameters such as: distance, velocity, direction. One of such devices is gyrocompass whose task is to determine direction. The gyrocompass is used in all systems and devices of the ship, e.g. in radar, which require information about orientation of the ship according to North-South direction. Unfortunately, gyrocompass like radar is not a perfect tool. In the maritime navigation, it is assumed that the maximum error of the gyroscope amounts to ±3°. It is not a large angle, however, it can cause serious problems during identification of characteristic points and thereby it should be taken into consideration. Note, that the pattern coastline generated from a chart and its copy shifted at some angle may differ considerably. To take gyrocompass error into consideration, it is necessary to represent each point of the radar image not as the single coastline but rather as the set of coastlines. One of the coastlines from the set corresponds to the original radar image whereas the remaining coastlines are generated from a rotated copy of the original image. The size of the set depends on the accuracy of each coastline, i.e. on density of bearings for which the coastlines are fixed. We can define the set of representations of the radar image point in the following way:
where \( OR^i \) is the copy of the original image \( OR \) (\( OR^0 \) denotes the original image) rotated at \( i\Delta BRG \) degrees, \( p^{OR}_i \) is equivalent of \( p^{OR} \) coming from the rotated image \( OR^i \), \( g^{p^{OR}} \) denotes the coastline fixed from the point \( p^{OR} \) and \( \Delta BRG \) determines accuracy of the coastline (e.g. \( \Delta BRG = 1^\circ \)). Therefore, the identification of \( p^{OR} \) consists in comparing all pattern coastlines with all coastlines from \( G^{p^{OR}} \). To identify \( p^{OR} \) at least one coastline from \( G^{p^{OR}} \) has to match some pattern coastline, i.e. both coastlines have to be more or less the same for at least \( r \) contiguous bearings. The problem appears if the radar image point matches more than one pattern point or if one pattern point matches more than one radar image point. Such conflicts are rather unlikely but if they happen they are solved through comparing the size of matched fragments of the coastlines.

![Fig. 3 Illustration of maximum values of \( g^{p^{OR}} \) for sample radar image point (white dot in radar image)](image)

In order to make it possible to compare the coastline fixed for characteristic point of the radar image with a pattern coastline first it is necessary to reduce both coastlines to the “common denominator”. Note, that the chart and the radar image may possess different scales. To ensure compatibility of the coastlines it is necessary to fix them using real distances, e.g. in nautical miles, but not distances between pixels of the image. Next crucial issue is to take into consideration radar restricted field of vi-
sion. An area that we can observe by means of radar is limited by radar observation range. Let us denote $g_{\text{MAX}}^{\text{pOM}}(\text{BRG})$ as the maximum value of $g_{\text{pOM}}^{\text{pOM}}$ that we can obtain for the bearing $\text{BRG}$ and the radar image point $\text{pOM}$. In the case of pattern point $\text{pOM}$, values $g_{\text{pOM}}^{\text{pOM}}$ are only restricted by the size of the chart image that is usually larger than the range of radar observation. Therefore, it is necessary to cut values $g_{\text{pOM}}^{\text{pOM}}$ if they exceed maximum acceptable value. This value depends on the bearing $\text{BRG}$ and characteristic point of radar image compared with a given pattern point.

$$g_{\text{pOM}}^{\text{pOM}}(\text{BRG}) = \begin{cases} A \text{ if } g_{\text{pOM}}^{\text{pOM}}(\text{BRG}) > g_{\text{MAX}}^{\text{pOM}}(\text{BRG}) \\ g_{\text{pOM}}^{\text{pOM}}(\text{BRG}) \text{ otherwise} \end{cases}$$ (2)

The set of pattern coastlines representing the pattern point $\text{pOM}$ can be denoted as follows: $G_{\text{pOM}}^{\text{pOM}} = \{ g_{\text{pOM}}^{\text{pOM}} ; i = -K..K, K\Delta \text{BRG} \leq 3 \}$. The next problem associated with application of $r$$\delta$-contiguous-values rule to the identification of characteristic points of radar image are differences between the radar image and the chart image (i.e. the image generated from a chart) involving single echoes of such objects as e.g. ships. The problem particularly concerns echoes of standing still objects since echoes of moving ones are straightforward to eliminate. To compare the coastlines generated from the radar image and the chart image it is necessary to remove from the former coastline all echoes of unnecessary objects. To this end, the rule (3) is used. It is run three times; first, for single-bearing echoes, next for double-bearing echoes and the last time for echoes covering three adjacent bearings. The rule mentioned is presented below:

$$\forall j=1,\ldots,1+w \text{ if } \begin{cases} g_{\text{pOM}}^{\text{pOM}}(j\Delta \text{BRG}) - \overline{\text{m}}_{\text{OBR}}(j+1,w) > \alpha \\ g_{\text{pOM}}^{\text{pOM}}((j+w+1)\Delta \text{BRG}) - \overline{\text{m}}_{\text{OBR}}(j+1,w) > \alpha \\ g_{\text{pOM}}^{\text{pOM}}((j\Delta \text{BRG}) - \overline{\text{m}}_{\text{OM}}(j+1,w) \leq \alpha \\ g_{\text{pOM}}^{\text{pOM}}((j+w+1)\Delta \text{BRG}) - \overline{\text{m}}_{\text{OM}}(j+1,w) \leq \alpha \end{cases} \quad (3)$$

$$g_{\text{pOM}}^{\text{pOM}}(j\Delta \text{BRG}) +$$

$$\forall k=j+1,\ldots,1+w \text{ then } g_{\text{pOM}}^{\text{pOM}}((k\Delta \text{BRG}) := \frac{g_{\text{pOM}}^{\text{pOM}}((j+w+1)\Delta \text{BRG})}{2}$$

$$\forall k=j+1,\ldots,1+w \text{ else } g_{\text{pOM}}^{\text{pOM}}((k\Delta \text{BRG}) := g_{\text{pOM}}^{\text{pOM}}(k\Delta \text{BRG})$$
\[ \bar{m}_{ox}(t, q) = \frac{\sum_{i=1}^{t+q-1} g^{ox}(i\Delta NR)}{q} \]  

(4)

where \( OX \) denotes \( OR \) or \( OM \), i.e. the radar image or the image generated from a chart, \( \bar{m}_{ox}(t, q) \) denotes the average value of the coastline in a window starting from the point \( t \) and including \( q \) consecutive values (one, two or maximally three), \( W \) determines length of the coastline, i.e. \( W\Delta BRG = 360^\circ \), \( g^{OR:OM} \) is a new representation of the radar image point \( p^{OR} \) adjusted to the coastline of the pattern point \( p^{OM} \), \( \alpha \) is a threshold.

Given that every radar image point \( p^{OR} \) has many representations belonging to \( G^{OR} \), the procedure of eliminating additional echoes has to be carried out regarding all of them. The set of final representations of the point \( p^{OR} \) is presented below.

\[ G^{p^{OR}:p^{OM}} = \left\{ g^{p^{OR}:p^{OM}} ; i = -K..K, K\Delta BRG \leq 3^\circ \right\} \]

Ultimately, having the set \( G^{p^{OR}:p^{OM}} \) of the coastlines filtered and corresponding to it the set \( G^{p^{OR}:p^{OM}} \) of the pattern coastlines, we can start comparison process. However, let us begin with two definitions.

**Definition 1.** Two real valued vectors \( x, y \in R^n \) match each other according to \( r, \delta \)-contiguous-values rule if the window of length \( r \) exists in which values of both vectors differ at most of \( \delta \). We can write it in the following way:

\[ xM^\delta_r y \iff \exists i \quad \forall j \in [i-r, i+r] \quad |x_j - y_j| \leq \delta \]  

(5)

We will write \( xM^\delta_r y \) if \( x \) does not match \( y \).

**Definition 2.** \( r \) is the maximum matching \( Q^\delta(x, y) \) between two real valued vectors \( x, y \in R^n \) according to \( r, \delta \)-contiguous-values rule if \( x \) matches \( y \) for window of length \( r \) and \( x \) does not match \( y \) for window of length \( r+1 \). We can also write it in the following way:

\[ r = Q^\delta(x, y) \iff xM^\delta_r y \wedge xM^{\delta}_{r+1} y \]  

(6)

The matching rule (5) assumes the same value of \( \delta \) for all components of compared vectors. Thus, the difference between all components of matched vectors should be more or less the same. However, let us imagine the situation in which we are interested in different treatment of components located at various positions in vectors. The coastlines are distances to objects visible on the radar image. The location of every
object on the radar image is fixed by means of radar. However, radar is not a perfect tool. It only serves to determine rough distance and bearing to an object. The radar error in fixing the distance to an object depends on the real distance to this object. The distance to further objects is fixed with greater approximation than the distance to closer objects. Thus, in order to raise awareness of the system of radar errors, differences between the coastlines related to further regions of the sea (further from our ship, i.e. from the center of the radar image) should be treated with greater indulgence than differences corresponding to closer areas. Let us define the modification of matching rule (5) which differently treats various components of compared vectors.

\[
x^i_t \equiv M^j_{x_t} \iff \exists \alpha \in \alpha_i \quad \forall \mu \in \mu_i : |x_j - y_j| \leq \delta(j)
\]

(7)

In the case of comparing coastlines, the function of maximum acceptable difference between vector components, i.e. \( \delta(j) \), may take the following form:

\[
\delta(j) = \begin{cases} 
\delta_{\max} & \text{if } d^{\rho OR}(j \Delta BRG) = A \\
\left(\frac{\delta_{\max} - \delta_{\min}}{R_{\max}}\right) d^{\rho OR}(j \Delta BRG) + \delta_{\min} & \text{otherwise}
\end{cases}
\]

(8)

d^{\rho OR}(BRG) = \begin{cases} 
A & \text{if } g^{\rho OR}(BRG) = A \\
\left\{ \begin{array}{ll}
\text{BRG} & \text{otherwise}
\end{array} \right\} & \text{otherwise}
\end{cases}
\]

(9)

where \( q^{\rho OR}(BRG), g^{\rho OR}(BRG), p^{\rho OR} \) is the radar image point which can be seen on bearing \( BRG \) and in distance \( g^{\rho OR}(BRG) \) from the point \( p^{\rho OR} \), \( d \) is the distance between two points, \( p^{\rho OR} \) is the central point of the radar image, \( \delta_{\max}, \delta_{\min} \) denote maximum acceptable differences between the coastlines when the distance from \( q^{\rho OR} \) to the central point of the radar image equals \( R_{\max} \) (maximum radar observation range, \( R_{\max} < A \)) or 0 respectively.

The next feature of the matching rule (5) which may hinder its use to compare the coastlines, is that matching between components located at different positions in vectors is equally important. However, let us imagine a situation in which matching between some components is more important than matching between other components. Namely, the coastlines contain two kinds of components. First of them inform about dry land visible for some bearings. These components are unequal to \( A \) (see (1)). The second group of components indicates bearings for which we cannot see any land. We do not know where we can expect dry land for these bearings. We only know that it is
too far to see it. These components of the coastlines are equal to A. Generally, we can state that components of the coastlines different from A carry “stronger” information than components equal A. To make use of this feature of the coastlines we can introduce into the matching rule proposed a principle according to which matching vectors should contain in matching windows definite proportions of both groups of components. The elements that are more informative should constitute, for example, at least a quarter of all elements in the window. In the more general case, i.e. when we deal with greater number of component categories, a next modification of the matching rule (5) may look as follows.

\[
x M_{\text{t}(2)} \ y \ Leftrightarrow x M_{\text{t}(0)} \ y \land \\
\forall k \in [1..|\text{t}|] \quad \land \quad P(r \leq c_k) \leq p_r \land P(r \leq c_k) \leq p_r
\]

where \( \rho_x, \rho_y \) denote categories of components from matched windows of vectors \( x, y \), \( C \) is the set of the categories, \( c_k \) is \( k \)th category, \( p_k \) is assumed probability of element to be at most \( k \)th category and \( p \) is probability vector.

In the rule (10) probabilities \( p_k \) determine our preferences regarding a distribution of categories in the windows compared. The vectors match each other if they match according to the rule (7) and if we deal with definite distribution of categories in the windows matched.

The maximum matching for modification (10) can be defined as follows:

\[
[r, p] = Q^{(2)} (x, y) \ Leftrightarrow x M_{\text{t}(2)} \ y \land \\
\forall [z, v] x M_{\text{t}(2)} y \overset{(2)}{<} [r, p]
\]

The relation \( \overset{(2)}{<} \) determines our preferences regarding vectors \([r, p] \), i.e. whether we prefer longer matchings with elements of “worse” category or shorter matchings but solely with elements of “better” category. In our particular case, i.e. when we deal with two categories of coastline elements, the relation above may look as follows:

\[
[z, v_i] \overset{(2)}{<} [r, p_i] \Rightarrow (p_i < 0.75 \land v_i \geq 0.75) \lor \\
[[p_i < 0.75 \land v_i < 0.75] \land (r > z)] \lor \\
[[p_i < 0.75 \land v_i < 0.75] \land (r = z) \land (p_i < v_i)]
\]

where \( p_i \) and \( v_i \) are probabilities of window element being equal A.

In the rule (10) solely appropriate proportions of categories in compared vectors are crucial for the matching process. An order of the components belonging to the same category is insignificant. Below we present two proposals of modification to the
matching rule (5), which take into consideration different significance of vector components but also draw attention to the order of the components in the windows compared.

\[
x M_r^{\delta(3)} y \Leftrightarrow x M_r^{\delta(1)} y
\]

\[
\land \exists_{r_1} \forall \{ M_r^{\delta(1)} \}_{r_1} \exists_{[2,|C|]} \left[ x[r_1] M_r^{\delta(1)} y[r_1] \right] (12)
\]

\[
x M_r^{\delta(4)} y \Leftrightarrow \forall_{r_1} \left[ M_r^{\delta(1)} y \right] (13)
\]

\[
x M_r^{\delta,\ell(1)} y \Leftrightarrow \exists_{i \in [1,|C|]} \left[ \begin{array}{c}
x \land y \\
\geq \land \leq \land \geq \land \leq \end{array} \right] (14)
\]

\[
r_i \text{ is the length of window containing elements of at least } i \text{th category, } x[r], y[r] \text{ are windows of length } r \text{ in which vectors } x \text{ and } y \text{ match each other according to (7), and } \rho(i, x) \text{ is the category of } i \text{th element of vector } x \text{ (the category of the element can depend on: position of the element in vector, value of the element or both these factors; in the case of comparing the coastlines } \rho(i, x) \text{ takes the following form:}
\]

\[
\rho(i, g^\rho(i\Delta BRG)) = \begin{cases} 
1 & \text{if } g^\rho(i\Delta BRG) = A, \\
2 & \text{otherwise}
\end{cases}
\]

Two vectors match each other according to (12) if they match according to (7) and additionally if matched windows from both vectors match according to (14). The rule (14) requires matched vectors to include sub-windows of definite length containing elements of appropriate category. In the scheme (13) matching between vectors for different categories does not have to take place in a single, indivisible piece of both vectors. This time matching on one level may involve one fragment of vectors while matching on other level may occur somewhere else.

The definition of maximum matching for modifications (12) and (13) looks analogically as in the case of the rule (10):

\[
r = Q(r) (x, y) \Leftrightarrow x M_r^{\delta,\ell(1)} y \land \forall_{t \in [1,|M|]} t \prec r (15)
\]

where \(i=3,4\) and denotes the modification of the rule (5). The definition of maximum matching for scheme (13) can also be presented in the following form:
\[ r = Q^{(3,4)}(x, y) \leftrightarrow \bigwedge_{i=1}^{\infty} \left[ x M_{t_i}^{\delta_i(j)} y \wedge x \bar{M}_{t_i+1}^{\delta_{i+1}} y \right] \] (16)

Relations \( \prec \) serve to compare different matchings and in our case they may look as follows:

\[
\begin{align*}
(t < r &\iff (r_2 > a \wedge t_2 \leq a) \lor \left((r_2 > a \wedge t_2 > a) \wedge (r_1 > t_1)\right) \lor \\
&\left((r_2 > a \wedge t_2 > a) \wedge (r_1 = t_1) \wedge (r_2 > t_2)\right)
\end{align*}
\] (17)

where \( a \) determines required length of „better“ window, i.e. window including elements different from \( A \).

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**Fig. 4. Pseudocode of the algorithm proposed.**

Ultimately, we can define an algorithm of identification of characteristic points of radar image. In the algorithm presented further, we assume that every radar image
characteristic point from the set $P^{OR}$ and every pattern characteristic point from the set $P^{OM}$ has some unique index assigned. Input data to the algorithm are: radar image OR, the set of radar image characteristic points $P^{OR}$, the set of pattern coastlines $G^{OM}$ and parameters of $r$-$\delta$-(i)-contiguous-values matching rule ($i=2,3,4$ and denotes the variant of $r$-$\delta$-matching rule). The matrix $\Psi$, identifying radar image characteristic points, constitutes the output of the algorithm.

The matrix $\Psi$ determines assignment of the radar image characteristic points to the pattern points. If $k^{th}$ radar image point is identified as $l^{th}$ pattern point then $\psi_{kl} = 1$. The remaining elements of $\Psi$ are set to 0. In order to create the matrix $\Psi$ function EliminateConflicts() searches the matrix $\Omega$ for the best maximum matchings, located in distinct columns and rows and then sets their counterparts in $\Psi$ to 1.

4. Experimental results

The experiments were carried out on the Gdańsk Bay stretch. Data to the experiments came from a navigational bridge simulator. Particularly, it concerns radar images which were not original radar images but simulated ones. All images were registered in 10 test positions evenly deployed on the experimental area. During the registration we used radar observation range equal 12 Nm (nautical miles). Pattern points applied during the experiments were chosen arbitrary. Characteristic points of land such as for example, tips of peninsulas, piers as well as artificially generated virtual points constituted a set of these points. Totally, we used 20 pattern points, i.e. 10 virtual points and 10 true characteristic points belonging to the land. The additional virtual pattern points were generated at open sea more or less in the center of the research area. The artificial pattern points were not the only objects visible on the stretch considered. In addition to them, standing still ships were also introduced to the research scenario. The location of the ships was random. Their number was also random but it did not exceed 20 ships.

To take into consideration radar error in fixing a distance to observed object, in the experiments, the virtual pattern points were moved in relation to their original positions. A direction of the displacement overlapped a line connecting the virtual pattern point and a test point, i.e. the point in which the test radar image was recorded. The quantity of movement was random but it did not exceed a maximum value. In the experiments the following maximum quantities of movement were used: $(\pm 0.02 \times \text{exact_value}) \text{Nm}$, $(\pm 0.02 \times \text{exact_value} \pm 0.05) \text{Nm}$ and $(\pm 0.02 \times \text{exact_value} \pm 0.2) \text{Nm}$. Exact_value is the distance between the test point and the virtual pattern point.

In order to simulate possible deformations of the radar image that can appear during work at sea, all the test radar images were gradually noised. The deformations were introduced manually so that they occupied larger and larger parts of the radar images. Elements of the radar images that particularly underwent deformations were coastlines. During the research, the following image deformations were applied: deformations in-
cluding about 0%, 20% and 50% of the coastline. An additional category of images constituted images with the coastline deformed in fifty percent and with only one pattern characteristic point visible on the research stretch.

![Fig. 5 Examples of radar images used in the experiments](image)

Throughout the research, the matching rule (13) was used. The rule requires four parameters, i.e. $r_1, r_2, \delta_{\text{min}}, \delta_{\text{max}}$. $r_1$ denotes the minimal acceptable length of the window
including elements of any category. \( r_2 \) specifies required length of the window with elements different from \( A \). The following values of these parameters were tested in the experiments: \([r_1, r_2]\) - (0.4W, 0.1W), (0.2W, 0.05W), (0.1W, 0.025W). With regard to \( \delta_{\min}, \delta_{\max} \) we assumed the following values of these parameters: \( \delta_{\min} = 0.1Nm \), \( \delta_{\max} = 0.34Nm \). Both values are adjusted to the radar observation range applied in the experiments (12Nm).

![Graph showing detection of pattern points](attachment:image.png)

Fig. 6 Detection of pattern points (method 1, 2, 3 – \( r-\delta \)-matching rule for \([r_1, r_2]\) = (0.4W, 0.1W), \([r_1, r_2]\) = (0.2W, 0.05W) and \([r_1, r_2]\) = (0.1W, 0.025W) respectively), method 4 – using Euclidean distance to compare coastlines [9], method 5 - comparing bearing and distance trees [8])

The research consisted in identifying points visible on the test radar images. 36 radar images were registered for every test position. Every registration corresponded to a different displacement of virtual pattern points, a different location and number of ships on the stretch, a different degree of noise introduced to the image and different values of algorithm’s parameters. The coastlines representing every pattern point as well as radar image point were generated every 1° (\( \Delta BRG = 1^\circ \)). Therefore, every coastline contained 360 elements (\( W = 360 \)). The pattern coastlines were generated from specially prepared electronic chart whereas the coastlines representing characteristic points of radar image were generated from the test radar images.

There are three possible results of the identification, i.e. correct identification, wrong identification and “I do not know” answer. The latter situation takes place when no point among the pattern points match the radar image point considered on the level determined by parameters of the algorithm. We deal with the correct identification or the wrong identification when at least one point of the pattern points matches the radar image point considered.
The correct identification occurs when the pattern point chosen is the nearest point among all pattern points, to the radar image point, in terms of the real distance between these points. The wrong identification takes place when the choice of the system concerns the pattern point, which is not the nearest point to the radar image point considered. Simply, we can find at least one point among the pattern points, which is closer to the radar image point, than the pattern point selected.

In the experiments, no case of wrong identification was noticed. Points were either correctly identified or remained unidentified. Below, the results of the experiments are presented. For comparison purposes, all diagrams also include outcomes of competing methods which are reported in [8] and [9].

Figure no. 6 presents average outcomes obtained for all situations tested during the experiments, i.e. for insignificant and large deformations of radar images and for slight and considerable differences between positions of the pattern points and their counterparts from radar images. The experiments showed that \( r-\delta-(4) \)-matching rule with less demanding values of parameters (method 2 and 3) is the best identification method out of all methods tested. However, it is necessary to remember that above averages also include the case with only one pattern point visible on the stretch, what is the main reason of so poor results of method 5. It is necessary to stress that in the remaining cases, i.e. when more than one pattern point was apparent on the stretch, method 5 demonstrated similar performance as method 2 and 3.

With regard to deformations of radar images, they had the greatest negative influence on performance of method 4. Methods 2 and 5 seem to be rather robust to them. As to be expected, the only case in which method 5 was unable to detect any pattern point was the situation with only one pattern point visible on the stretch (last column in Fig. 7).
During the experiments, it turned out that only maximal displacements of pattern points on radar images had any influence on point detection. Fewer displacements did not cause greater difficulties in point detection. As before, outcomes of method 5 are averaged over all tested situations, i.e. also for the case with only one pattern point visible on the radar screen, what considerably deteriorates the results of the method presented in Fig 8.

To fix ship’s position by means of radar it is necessary to perform the following activities: to distinguish a number of characteristic points (e.g. tips of piers, peninsulas etc.) from the radar image, to identify them, and finally, to fix bearing and distance to each point identified. The article presents one aspect of the problem of the positioning at sea, namely the problem of point identification. In the paper, the identification method is described which compares pattern coastlines generated from a chart and coastlines generated from the radar image. The pattern coastlines represent pattern characteristic points whereas coastlines created based on the radar image represent characteristic points from this image. To compare the coastlines adaptation of r-contiguous-bits matching rule, known from artificial immune systems, was applied. To identify the radar image point the coastlines (the pattern coastline and the radar image point coastline) have to be similar but only on r contiguous bearings (positions in coastline vectors), where r can be relatively small in relation to the overall length of every coastline. Appropriate selection of r is a key factor deciding about success in using the method proposed. The value of this parameter on the one hand should make it possible to identify the possibly largest set of radar image points but on the other hand, it should rule out possibility of making a mistake during the identification.

The tests conducted with simulated radar images showed that the method proposed can successfully be used to identify characteristic points of radar image. During the experiments, it turned out that the solution proposed is robust to major distortions of
radar images. Even considerable noise introduced into images appeared not to be an obstacle in correct identification of points.

References


Test Pattern Generator for Delay Faults

Streszczenie

Jednym z urządzeń wykorzystywanym w nawigacji morskiej do wyznaczenia przybliżonej pozycji okrętu jest radar nawigacyjny. Aby wyznaczyć pozycję przy pomocy radaru należy wykonać następujące czynności: wyznaczyć na obrazie radarowym zbiór punktów charakterystycznych (koniec półwyspów, mola itp.), dokonać identyfikacji tych punktów (przyporządkować każdemu z nich dokładną pozycję odpowiednika z mapy), wyznaczyć namiar i odległość do każdego ze zidentyfikowanych punktów, użyć klasycznej nawigacji radarowej oraz całej zdobytej informacji do określenia pozycji jednostki.

W artykule przedstawiono metodę identyfikacji punktów charakterystycznych obrazu radarowego opartą o regułę r-contiguous-bits (rcb). Reguła rcb używana jest w sztucznych systemach immunologicznych do porównania ciągów binarnych imitujących antyciała i antygeny. Zgodnie z regułą rcb dwa ciągi binarne odpowiadają sobie wzajemnie, jeśli występują w nich podobne fragmenty o określonej długości.

Proponowana w artykule metoda identyfikacji zakłada, że punkty charakterystyczne reprezentowane są w postaci wektorów rzeczywistoliczbowych. Składowe wektorów są odległościami od obiektów widzianych dookoła punktu charakterystycznego. Wektory reprezentujące punkty charakterystyczne obrazu radarowego porównywane są z wektorami reprezentującymi wzorcowe punkty charakterystyczne wyznaczone z mapy nawigacyjnej. Dwa wektory reprezentują ten sam punkt, jeśli występują w nich podobne fragmenty o określonej długości.


Metoda identyfikacji zaproponowana w artykule została sprawdzona eksperymentalnie. Testom poddana została głównie odporność metody na lokalne zakłócenia obrazu radarowego. Wyniki eksperymentów zaprezentowane zostały w ostatniej części artykułu.