Matching suitable feature construction for SAR images based on evolutionary synthesis strategy

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Abstract In the paper, a set of algorithms to construct synthetic aperture radar (SAR) matching suitable features are firstly proposed based on the evolutionary synthesis strategy. During the process, on the one hand, the indexes of primary matching suitable features (PMSFs) are designed based on the characteristics of SAR image, SAR imaging and SAR matching algorithm, which is a process involving expertise; on the other hand, by designing a synthesized operation expression tree based on PMSFs, a much more flexible expression form of synthesized features is built, which greatly expands the construction space. Then, the genetic algorithm-based optimized searching process is employed to search the synthesized matching suitable feature (SMSF) with the highest efficiency, largely improving the optimized searching efficiency. In addition, the experimental results of the airborne synthetic aperture radar ortho-images of C-band and P-band show that the SMSFs gained via the algorithms can reflect the matching suitability of SAR images accurately and the matching probabilities of selected matching suitable areas of ortho-images could reach 99 ± 0.5%.

1. Introduction

In order to get high-precision locating results, the synthetic aperture radar (SAR) image matching aided navigation requires not only a good performance of the matching algorithm, but also the matching suitability of matching areas, which, measured by matching suitable features, aims to guarantee the successful matching of observed images acquired by the SAR imaging sensor on the platform during flight and the SAR reference images stored in a database in advance. Therefore, what features shall be adopted to measure the matching suitability of image areas and how to extract these matching suitable features from given image areas become core problems in the study of SAR image matching suitability. To find out a good solution, this paper studies the construction method of efficient matching suitable features of SAR images.

Whether an SAR image area is suitable to match or not is influenced by many factors, therefore, stable matching suitable features should be a synthesis of many primary matching suitable features (PMSFs). Synthesized matching suitable features (SMSFs) reflect the matching suitability of the image area in an all-round way, while the primary ones, just partly.

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2. Algorithmic flow

The SMSF synthesis process is divided into five steps, which respectively are the construction of PMSFs, the construction of synthesized features, the design of EFOF, the design of optimized searching plan, and the result verification. The following is the description of main SMSF synthesis steps.

(1) PMSFs. In order to make primary features reflect the matching suitability accurately and concisely from various aspects, four basic construction principles of PMSFs are put forward according to the characteristics of SAR images and matching: (i) PMSFs should reflect the obvious characteristics of an image; (ii) they should reflect the abundance of the information contained in the image; (iii) they should reflect the stable characteristics of the image; and (iv), they should reflect the uniqueness of the surface features in the image.

(2) SMSFs. As a synthesis of PMSFs, the SMSF reflects the matching suitability of a SAR image in an all-around way. Being not a simple weighted array of primary features, in this work, the SMSF is obtained as follows: firstly, the binary tree-based operation expression of PMSFs is constructed as the primary synthesized structure of the SMSF, then effective PMSFs are selected from the PMSF set, and then, through the evolution algorithm, the individual of expression tree with the highest efficiency evaluation value is taken as the final SMSF.

(3) The EFOF. The EFOF is used to guide the evolution direction of synthesized features. Where the EFOF is reasonable defined, an obvious monotonous variation relationship is formed between the calculated synthesized feature finally serving as the SMSF and the matching probability of the corresponding image.

(4) The optimization algorithm. In order to find the SMSF with the highest efficiency evaluation value in the huge feature space, a high-powered optimized searching strategy should be adopted. In this paper, by reasonably defining the selection, crossover and mutation operators of the binary expression tree, the fast searching for the optimal combination mode of the synthesized feature is realized via the genetic evolution algorithm.

(5) Result tests. The process of getting the SMSF includes a training process and a test process corresponding respectively to a training image tank and a test image tank with known real matching probabilities. After being obtained by applying the feature synthesis algorithm to the training image tank, the SMSF is then checked via the test image tank. Fig. 1 shows the primary synthesized algorithmic flow of an SMSF based on evolutionary expression.

3. Evolutionary synthesis of SMSFs

3.1. Construction of the set of PMSFs

When constructing various elements of the set of PMSFs, the characteristics of SAR images and the multi-source matching algorithm must be considered. Since speckles, the unique characteristic of SAR images sets difficulties in selecting typical image features, and at the same time, matching suitable features should reflect the characteristics of the whole image, the PMSFs constructed based on statistic and texture features would be more effective. Mutual information can measure the similarity between two images from the angle of statistic independence. In Ref. 20, a mutual information-based PMSF set consisting of 12 independent PMSFs has been established according to the construction principles. They are the information entropy of the reference image \( F_1 \), mean density of zero-cross points \( F_2 \), complexity of the reference image \( F_3 \), global standard deviation \( F_4 \), absolute value roughness \( F_5 \), mean fractional brownian motion \( F_6 \) fractal dimension \( F_7 \), mean noise threshold when mismatching \( F_8 \), mean sharpness of the highest mutual information \( MI \) peaks \( F_9 \), standard deviation of the edge density \( F_{10} \), MI-based self-matching coefficient \( F_{11} \), repeatability of mutual information \( F_{12} \), and ratio of MI peak and MI sub-peak \( F_{13} \). Among them, \( F_1, F_2 \) and \( F_3 \) are rich features, \( F_4, F_5 \) and \( F_6 \), salient features, \( F_7, F_8 \) and \( F_9 \), stable features and \( F_{10}, F_{11} \) and \( F_{12} \), unique features. These PMSFs are adopted in the paper and additionally, the gray mean \( F_{13} \) reflecting the basic information of the image is put into the PMSF set.

3.2. Construction of SMSFs

By taking the idea of machine learning for reference, the basic idea of constructing the expression of SMSFs is to...
build the structural model of binary expression tree based on PMSFs, and to train the corresponding synthesized feature expression of the highest efficiency evaluation value under given principles of feature generation to be SMSFs. Therefore, the synthesis of SMSFs includes three basic factors: a structural model of synthesized features, a set of principles of feature generation and an EFOF for synthesized features.

3.2.1. Binary tree structural model of synthesized feature expressions

Synthesized features, the nature of which is the function of various feature variables in the set of PMSFs, are expressed as the operation expressions of these primary features. Operation expressions have a strongpoint that they can realize a flexible combination of these primary feature variables. In order to make a variety of forms of the synthesized feature function, making reference to primary operators used in target recognition in Ref. 16, 14 unary and binary primary operators are set up, as Table 1 shows.

In order to prevent the expression from nested loop and to conveniently implement, the operation expression is described through an incomplete binary tree with its internal nodes representing unary or binary basic operators and leaf nodes representing PMSF variables. Since the basic operators and features can be randomly selected from the set of basic operators and that of primary features, the expression tree, reasonably constructed, can realize very complicated combination of functions.

3.2.2. Principles of synthesized feature expression generation

An expression tree is the realization of feature synthesis. Contents of nodes of the tree can randomly be changed and the total number of nodes is uncertain as well. The generation of synthesized feature expression tree is a recursive process. The generation principles are as follows.

(1) The node number of the left and right sub trees of each internal binary node should meet the equipartition principle as far as possible.
(2) When strict equipartition is impossible, the left sub tree takes the priority.
(3) For internal nodes connecting with leaf nodes, the left leaf node takes the priority.

3.2.3. Design of the EFOF for synthesized features

The efficiency evaluation value presents the ability of a synthesized feature to reflect the image matching probability. For an EFOF, its independent variable is a particular synthesized feature and its dependent variable is the evaluation of its effi-
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3.3. Evolutionary synthesis strategy of SMSFs

3.3.1. Operator design

From the structure of the expression binary tree, it can be seen that the form of the synthesized feature expression can be changed in various ways for the basic operators represented by internal nodes and primary features represented by leaf nodes are changeable and the number of internal nodes itself is also uncertain. All these lead to a huge space of searching for the synthesized features with high efficiency. It is an effective way to adopt the fast algorithm in searching for optimal features in such a huge space, or the huge processing time will not be accepted in the application of the matching suitability evaluation of images. With the help of genetic revolutionary mechanism and the efficiency evaluation value of the EFOF as measure criterion, the synthesized feature with the highest efficiency can be gotten in the huge space through selection, crossover and mutation of many randomly generated synthesized feature trees. The designs of selection, crossover and mutation operators are as follows.

(1) Operator selection

It aims to select some expression binary trees with the highest efficiency evaluation values in the current population.

(2) Operator crossover

Crossover occurs between two expression trees. At first, an internal node is randomly selected from each tree, then the sub trees taking these two internal nodes as root nodes are switched and then two new expression trees are formed. If the number of internal nodes in the new trees exceeds the upper bound of that of internal nodes established in advance happens, the crossover occurs again.

(3) Operator mutation

Occurring in one expression tree, mutation randomly changes the structure of some expression binary trees, so as to guarantee the diversity of the group in the evolutionary process. Trees are randomly selected to be mutated, and the following four mutation methods should be selected with equal probability.

- (i) Sub tree substitution. Taking the randomly selected internal node in some tree as the root node, a sub tree, with the same node scale, is regenerated so as to substitute for the old one to form the new tree.
- (ii) Internal node mutation. The operator of the randomly selected internal node in some tree is replaced by an operator with same property.
- (iii) Sub tree crossover. The two randomly selected sub trees in some tree, which do not subordinate to each other, are switched.
- (iv) Feature mutation. The PMSFs of the far left leaf node are randomly changed.

3.3.2. Description of the evolutionary process

With the reasonable construction of the synthesized feature expression tree and of the EFOF, the individual of expression tree with the optimal efficiency gained via the genetic evolutionary process is taken as the SMSF. If crossover probability

<table>
<thead>
<tr>
<th>Step</th>
<th>Description of the step</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Calculate the real matching probability of each image in the training image library</td>
</tr>
<tr>
<td>2</td>
<td>Calculate the value of the synthesized feature expression of each image in the training image library</td>
</tr>
<tr>
<td>3</td>
<td>Sort the images in the training image library according to the corresponding expression value</td>
</tr>
<tr>
<td>4</td>
<td>Calculate the average matching probability of the prior N images with the biggest expression value</td>
</tr>
<tr>
<td>5</td>
<td>Take the average matching probability as the EFOF of this synthesized feature</td>
</tr>
</tbody>
</table>
is represented by rate\textsubscript{Crossover}, mutation probability, rate\textsubscript{Mutation}, the biggest evolution time, \(T_{\text{generation}}\), and the threshold of efficiency evaluation value when the evolutionary process stops, \(\text{Threshold}_{\text{eff}}\), the genetic evolutionary process can be described as Table 3.

The following two points should be noticed in the evolutionary synthesis process of SMSFs:

(1) The number of the internal nodes \(n\) of the early generated individual of expression tree is given randomly with suitable scale. If \(n\) is too big, the mutation effect will not be obvious because many mutation opportunities will be taken by sub trees in unimportant positions; if \(n\) is too small, the reduced scale of searching space for expressions is not beneficial to getting the synthesized features with high efficiency.

(2) Selection, crossover and mutation are operated directly focusing on the structure of individuals in groups, and do not demand decoding of individuals. This is quite beneficial to the realization of the flexible change in the structure of expression trees.

4. Efficiency evaluation experiment and analysis

4.1. Experiment environment construction

In order to accurately and objectively verify the validity of SMSFs got via the method above, real AIRSAR data is used to construct the test environment. First, get 832 pairs of SAR images in the matched image area corresponding to the image source of C and P wavebands that are precisely rectified, and each image should have the size of 300 pixel \(\times\) 300 pixel and pixel resolution of 5 m. In the test, SAR images of C band serve as reference images for the mutual information matching with real-time SAR images of P band to calculate the matching probability of each reference image. Select 624 reference images randomly to form a training image library to train the expression binary tree of the synthetic features with high efficiency, and then use the left 208 reference images to form a test image library to detect the environmental adaption of the obtained SMSFs.

4.2. Basic performance of SMSFs

First, check the basic performance of SMSFs. Basic performance indexes include the components of the expression tree of SMSFs, the efficiency values respectively acting on the training library and test library, the training, test time, etc. The experiment uses 2.4 GB Intel Core2 CUP for the synthesized experiment of 10 groups of mutually independent SMSFs expressed as \(SF_i\) (\(i = 1, 2, \ldots, 10\)). The scale of the evolutionary population of each group is set as 200, the evolution operation for 600 generations is performed each time, the crossover factor is set as 0.8, the mutagenic factor, 0.15, and the upper limit of the internal node of the expression, 35. The first 18% of image matching probability is taken to perform the calculation of the matching suitable EFOF. Table 4 shows the performance index such as the EFOF of a SMSF, and the training time and test time obtained in each independent experiment. Table 5 gives a statistics of PMSFs included in the SMSFs.

It can be seen from Table 4 that the efficiency values of SMSFs obtained based on the training library can maintain above 0.95 and those obtained based on the test library are lower but still maintain above 0.94. Compared to the former,

<table>
<thead>
<tr>
<th>Step</th>
<th>Evolutionary process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Begin</td>
</tr>
<tr>
<td>2</td>
<td>Randomly generate Group\textsubscript{Initial}, the initial species group of expression binary tree with a scale of (N_{\text{Initial}})</td>
</tr>
<tr>
<td>3</td>
<td>Select the top (N_{\text{Evolution}}) trees in efficiency evaluation values in Group\textsubscript{Initial} and form the evolutionary set Group\textsubscript{Evolution} with them</td>
</tr>
<tr>
<td>4</td>
<td>for (i = 1) to (T_{\text{generation}})</td>
</tr>
<tr>
<td>5</td>
<td>Select the top (N_{\text{Evolution} \cdot \text{rateCrossover}}) trees in efficiency evaluation values to do crossover</td>
</tr>
<tr>
<td>6</td>
<td>Sort the new trees and the old ones in Group\textsubscript{Evolution} according to their efficiency evaluation values</td>
</tr>
<tr>
<td>7</td>
<td>Select the top (N_{\text{Evolution}}) trees in efficiency evaluation values and form a new evolutionary set with them to replace for Group\textsubscript{Evolution}</td>
</tr>
<tr>
<td>8</td>
<td>Select the top (N_{\text{Evolution} \cdot \text{rateMutation}}) trees in efficiency evaluation values to do mutation</td>
</tr>
<tr>
<td>9</td>
<td>Sort the new trees and the old ones in Group\textsubscript{Evolution} according to their efficiency evaluation values</td>
</tr>
<tr>
<td>10</td>
<td>Select the top (N_{\text{Evolution}}) trees in efficiency evaluation values and form a new evolutionary set with them to replace Group\textsubscript{Evolution}</td>
</tr>
<tr>
<td>11</td>
<td>If (\max_{x \in \text{GroupEvolution}} (V_{\text{eff}}(x)) &gt; \text{Threshold}_{\text{eff}})</td>
</tr>
<tr>
<td>12</td>
<td>Stop the loop and exit</td>
</tr>
<tr>
<td>13</td>
<td>End if</td>
</tr>
<tr>
<td>14</td>
<td>End for</td>
</tr>
<tr>
<td>15</td>
<td>Sort the trees in Group\textsubscript{Evolution} according to their efficiency evaluation values</td>
</tr>
<tr>
<td>16</td>
<td>Output the expression binary tree with the highest efficiency evaluation value</td>
</tr>
<tr>
<td>17</td>
<td>End</td>
</tr>
</tbody>
</table>
the reason why the later is lower is that SMSFs with high efficiency values are obtained based on the training library. Under the set evolution scale, without considering the time cost of calculating various PMSFs, the average training time for the synthesis of SMSFs is around 120 s and the average test time is around 370 ms. The number of the internal node of each SMSF individual is basically close to the set upper limit for the internal node, which means in the allowable scale, a complex feature synthesis situation is beneficial to forming SMSFs with high efficiencies. It can be seen from Table 5 that when the evolution ends, the component of different SMSFs differs from each other obviously: SF1 consists of F1, F3, F4, F5, F8, F9, F11 and F13; while SF2 consists of F6, F5, F9, F10 and F12. From the statistics about the PMSFs contained in SMSF individuals, it can be found that in 13 basic elements of the PMSF library, the occurrence frequency of F3, F4, F5 and F13 is much higher than that of F7, F10, and F12, which indicates that an SMSF has preference to its component.

Further, three synthesized features of SF3, SF4, and SF5 are randomly selected from Table 5, and the restored expressions are reverted as follows.

It can be seen from Table 5 and Eqs. (1)–(3) that the structure and efficiency value of each SMSF obtained are different. Actually, it is very hard and not necessary to pursue the absolute optimized synthesized features, since the randomness of the actual environment causes a great difficulty for the precise calculation of matching probability, and the results obtained in different environments differ from each other, therefore, diversified structures for SMSFs shall be allowed.

In order to verify the result consistency of SMSFs with different structures in the application of matching suitable area selection, three groups of independent experiments are performed to compare the matching performance of reference images preferably selected from the test image library by SMSFs. Figs. 2 and 3 separately indicate the average matching probability and the repeat ratio curve of matching suitable SAR images selected by different SMSFs with different preferred threshold values. The preferred threshold value here denotes some given proportion of best image individuals selected by the SMSFs, which is expressed as a proportion of preferable data in figures.

It can be seen from Fig. 2 that generally, SAR images selected by SF3, SF4 and SF5 have a high matching probability. The SMSF calculated-value-based sequencing shows that the average matching probability of images ranking in Top 5% of test library reaches 98% above, which indicates that for the same SMSF, the higher the calculated value, the better the matching performance of corresponding images. It can be seen from Fig. 3 that the matching suitable SAR images preferably selected by SF3, SF4 and SF5 are not completely

Table 4 Statistics of basic performance indexes.

<table>
<thead>
<tr>
<th>SMSF id</th>
<th>SF1</th>
<th>SF2</th>
<th>SF3</th>
<th>SF4</th>
<th>SF5</th>
<th>SF6</th>
<th>SF7</th>
<th>SF8</th>
<th>SF9</th>
<th>SF10</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFOF</td>
<td>0.957</td>
<td>0.956</td>
<td>0.957</td>
<td>0.958</td>
<td>0.958</td>
<td>0.957</td>
<td>0.954</td>
<td>0.953</td>
<td>0.957</td>
<td>0.957</td>
</tr>
<tr>
<td>Training time (s)</td>
<td>0.943</td>
<td>0.953</td>
<td>0.947</td>
<td>0.958</td>
<td>0.952</td>
<td>0.951</td>
<td>0.947</td>
<td>0.947</td>
<td>0.953</td>
<td>0.952</td>
</tr>
<tr>
<td>Test time (ms)</td>
<td>125.9</td>
<td>124.8</td>
<td>134.0</td>
<td>130.4</td>
<td>122.7</td>
<td>131.9</td>
<td>121.9</td>
<td>107.7</td>
<td>154.6</td>
<td>112.9</td>
</tr>
<tr>
<td>Number of internal nodes</td>
<td>34</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>31</td>
</tr>
</tbody>
</table>

Table 5 Statistics for the basic components of the SMSFs.

<table>
<thead>
<tr>
<th>SMSF id</th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
<th>F4</th>
<th>F5</th>
<th>F6</th>
<th>F7</th>
<th>F8</th>
<th>F9</th>
<th>F10</th>
<th>F11</th>
<th>F12</th>
<th>F13</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>SF2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>SF3</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>SF4</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>SF5</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>SF6</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>SF7</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>SF8</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>SF9</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>SF10</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>4</td>
<td>5</td>
<td>13</td>
<td>15</td>
<td>24</td>
<td>8</td>
<td>3</td>
<td>4</td>
<td>10</td>
<td>2</td>
<td>8</td>
<td>3</td>
<td>15</td>
</tr>
</tbody>
</table>
the same: with different threshold values, there show different repeat ratios. The repeat ratio of images ranking in Top 5% is low, while that of images ranking in Top 30% reaches 92%, which indicates the preference of different SMSFs while selecting matching suitable images. Fig. 4(a) is a SAR image with good matching suitability evaluated by SF_3, SF_4 and SF_5 under the measure of normalized mutual information with test matching probability reaching 100%, while, Fig. 4(b) is one with poor matching suitability and test matching probability of below 20%. Obviously, pixel features in Fig. 4(a) are salient and abundant than those in Fig. 4(b).

4.3. Efficiency comparison of SMSFs

(1) Comparison with PMSFs

A comparison of matching suitability efficiency is conducted between the SMSFs based on the evolutionary expression tree and independent PMSFs. Fig. 5(a)–(c) are curves indicating the relationship between the indicator value of three typical PMSFs (F_4, F_5 and F_7) and the matching probability of all images in the training library; and Fig. 5(d)–(f) refer to curves indicating the relationship between the three SMSFs and matching probability. According to the process of constructing PMSFs and SMSFs, it is known that for different matching suitable features, the change trend of the relation curves is meaningful but not the feature values. That is to say, Y-coordinates under different matching suitable feature criteria in Fig. 5 cannot be used to compare with each other.

According to Fig. 5(a)–(c), the common feature of the PMSF curves lies in the fact that there exists serious shaking in the curves, which causes unobvious monotonocity between calculated values of features and matching probability. The SMSF curve in Fig. 5(d)–(f) shows an obvious monotonous ascending trend of the calculated value along with the change of the matching probability, and the calculated value shows the trend of convergence at a large matching probability. By comparing the curves, it can be seen that SMSFs have obvious advantage over PMSFs when selecting matching suitable images.

Meanwhile, combined with the statistics of the basic components of SMSFs in Table 5, it can be found that feature curves of PMSFs preferred by SMSFs show some certain monotonous relationship with the matching probability, such as F_5, F_4, F_3 and F_11; however, some of PMSFs (such as F_13 and F_9) still appear in the SMSF with a high frequency although they have poor feature curve performance when they independently appear, which shows that the PMSF with poor independent performance may represent a better feature after it is synthesized with other PMSFs.
(2) Comparison with weighted combined features

The weighted combination is a kind of typical feature synthesis method and is widely used in application. Based on the performance of each PMSF in matching suitable images in Fig. 5, $F_3$, $F_4$, $F_5$, $F_{10}$, $F_{11}$ and $F_{12}$ which own excellent performance are selected as independent variable to constitute different combined feature functions. For the convenience of setting the weight, it is required to firstly adjust the range of each independent variable in $[0, 1]$ via linear normalization conversion, and then uniformly adjust the feature curve of each independent variable as ascending trend. Due to the fact that the independent variables are mutually independent, the average weighting scheme can be adopted during the feature combination process. Fig. 6(a) refers to the feature curve obtained after combined feature $CF_1$, which is combined by $F_3$, $F_4$ and $F_5$, acts on the training library, and Fig. 6(b) refers to the statistic curve of matching probability of figures selected after the weighted combined feature $CF_1$, $CF_2$, combined by $F_3$, $F_5$ and $F_6$, and $CF_3$, combined by $F_3$, $F_4$ and $F_{10}$, and the SMSF $SF_3$, $SF_4$ and $SF_5$ respectively acting on the test library.

It can be seen from Fig. 6(a) that the weighted combined feature can establish an obvious monotonous relationship between the calculated value of features and the matching probability, and it even can represent a certain convergence trend. In addition, by comparing the curves in Figs. 6(a) and 5(a)–(c), it can be seen that the matching performance of images selected via weighted combined features is obviously better than that of an independent PMSF. However, it can be also found in Fig. 6(b) by comparison that there exists a certain difference between the weighted combined features at each assessment threshold and the corresponding evolutionary SMSF, and this phenomenon can be explained as below: both the selection of independent variable and setting of the weight in the weighted combined feature are based on human experience. Although it is able to improve the matching suitability of a selected matching area to a certain extent, due to limited experience, it is very difficult to obtain the best combination scheme in a wide searching space, and this is just the advantage of evolutionary SMSFs. This conclusion can further verify the efficiency of evolutionary SMSF in selecting matching areas.
5. Conclusions

In the paper, in order to select matching suitable areas in SAR image matching, a set of algorithms for constructing the SMSF of a SAR image are proposed based on the evolutionary strategy at first. Then, several PMSFs are synthesized via the binary expression tree structural model, and then the synthesized feature with the highest efficiency value is selected from the feature space as the SMSF. The following conclusions are obtained via researches and experiments:

(1) Under the condition that the sizes of the reference image and observation image are determined, it is able to obtain the SMSF changing monotonously with the change of the matching probability of a SAR image area via the evolutionary expression tree.

(2) With flexible forms, the SMSF expression tree fully synthesizes the advantages of various PMSFs in different aspects and effectively excavates the potential advantages of PMSFs with poor effect when existing independently.

(3) The method of seeking for the individual with the highest efficiency in the whole synthesized feature space spanned by PMSFs via evolution algorithm can fully adopt while not being limited by expertise, which is good for obtaining an objective and optimal SMSF.

According to the conclusions above, the matching suitability of any SAR image area in given image size can be estimated via the expression value of the SMSF. However, it shall be pointed out that SAR images employed in experiments in this paper are corrected in a geometric way; therefore, the unconsidered geometric distortion caused by terrain wave during the SMSF synthesis relying on image information is a problem to be further studied.

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References


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