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STOCHASTIC MODEL FOR IMAGE MATCHING BASED ON STATISTICAL ANALYSIS OF DESCRIPTORS

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Abstract—*The paper considers the problem of establishing correspondences between images based on the analysis of local structural features. A stochastic model for establishing correspondences between images is proposed in this study. The model is based on the statistical representation of keypoint descriptors and the use of probabilistic criteria for evaluating their similarity. Within the proposed approach, descriptors are considered as random feature vectors characterized by specific statistical parameters. Descriptor comparison is performed using a statistical similarity measure that accounts for the variability and distribution of features. To describe the geometric relationship between corresponding points of the images, a spatial transformation model is introduced. The parameters of this transformation are estimated using a likelihood-based approach. Within the stochastic framework, the alignment errors between corresponding points are treated as random variables, which allows the parameter estimation process to be formulated as a statistical optimization problem. The developed mathematical framework provides a formal representation of the image correspondence estimation process and enables parameter estimation using maximum likelihood or maximum a posteriori criteria. The modeling results demonstrate that the use of a stochastic approach improves the robustness of the correspondence estimation procedure under noise and other destabilizing factors. The obtained results confirm the feasibility of applying stochastic models to image analysis tasks and can be used in computer vision systems, automated video analysis, and other applied information systems.*

Keywords—Computer vision, stochastic model, keypoints, image descriptors, feature matching, statistic analysis.

I. INTRODUCTION

In modern image processing information systems, one of the key tasks is establishing correspondence between structural elements of different images of a scene. This problem arises in a wide range of application areas, including image registration, scene change analysis, three-dimensional model reconstruction, machine vision systems, and automated video data analysis. Most existing methods are based on identifying correspondences between keypoints or local features that characterise the structure of an image.

However, the process of establishing correspondences in real-world conditions is complicated by the presence of noise, illumination variations, geometric distortions, scale changes, and partial occlusions of the scene. Under such conditions, descriptors of local features may vary significantly, which reduces the effectiveness of deterministic comparison methods. Therefore, there is a need for approaches that take into account the stochastic nature of feature formation and the uncertainty involved in the comparison process.

One promising direction for solving this problem is the use of probabilistic models that describe image descriptors as random variables and evaluate their correspondence by considering statistical characteristics. Such an approach improves the robustness of correspondence estimation algorithms to noise and other destabilising factors.

Despite the large number of existing methods for comparing local features, the problem of formalising the correspondence estimation process within a unified stochastic framework remains relevant. In particular, it is important to develop a mathematical apparatus that allows the statistical properties of descriptors, geometric transformations between images, and matching errors to be taken into account.

In this regard, the aim of this study is to develop a stochastic model for establishing correspondence between images based on the statistical representation of keypoint descriptors and the estimation of spatial transformation parameters between images.

II. LITERATURE ANALYSIS

The rapid development of intelligent information systems, computer vision methods, cybersecurity technologies, and stochastic data processing approaches has led to the emergence of a wide range of studies devoted to mathematical support for decision-making, recognition, classification, and secure data transmission. At the same time, the problem of constructing formalized models capable of ensuring robust correspondence estimation under uncertainty remains relevant.

The general mathematical foundation for the development of decision-support and intelligent analysis systems is presented in the monograph [1], where considerable attention is paid to mathematical support, formalization principles, and model-based decision-making in complex systems. This work forms the conceptual basis for further development of probabilistic and stochastic approaches to data analysis.

A significant contribution to the assessment of complex organizational and technical systems was made in [2], [3], where a methodological approach to condition assessment was developed. These studies demonstrate the feasibility of combining formalized indicators, multi-parameter evaluation, and structured analysis in conditions of uncertainty. In a related direction, global optimization and population-based search procedures were studied in [4], where a solution search method using a population algorithm was proposed. Such approaches are important when considering parameter estimation problems in complex multidimensional models.

A separate group of studies is devoted to the reliability and security of critical information infrastructures. In article [5], an FMECA-based assessment of aviation critical information infrastructure importance was carried out, which confirmed the effectiveness of structured risk-based analysis. Threat management for critical information infrastructure facilities was further developed in [6], while a method for determining the cybersecurity level of state critical information infrastructure was proposed in [7]. These works emphasize the importance of formal models for the analysis of complex systems operating under destabilizing influences.

Modern studies also actively investigate machine learning and neural-network-based approaches. In article [8], machine learning algorithms for intrusion detection in 5G and beyond mobile networks were analyzed, confirming the practical value of adaptive data-driven models. One of the classical foundations for sequence modeling is the work of Sutskever, Vinyals, and Le [9], where sequence learning with neural networks was presented. These results illustrate the potential of probabilistic and neural methods for extracting informative dependencies from complex data.

A number of studies address information protection and cryptographic methods. In article [10], ECC and RSA algorithms combined with DNA encoding were compared for IoT security applications. Integrated photonic technologies for QKD and QRNG were investigated in [11], and neural cryptography based on complex-valued neural networks was proposed in [12]. In turn, [13] analyzed the transition from continuous-time chaotic systems to pseudorandom number generators. These works confirm the growing role of stochastic and probabilistic mechanisms in secure information processing.

The application of intelligent analysis methods to classification problems was considered in [14], where a scalar metric for choosing a classification algorithm in machine learning tasks was proposed. In the context of UAV-related data protection, [15] analyzed methods for ensuring the confidentiality of data transmitted from unmanned aerial vehicles. This study is particularly important because it highlights the need to combine data processing efficiency with robustness and reliability under real transmission conditions.

Thus, the analysis of the literature shows that the existing studies mainly focus either on mathematical support for decision-making in complex systems, or on optimization, cybersecurity, and machine learning methods. However, the issue of constructing a unified stochastic model for robust correspondence estimation based on statistical representation of descriptors and probabilistic evaluation of matching quality remains insufficiently studied. This determines the relevance of further research aimed at developing a mathematical apparatus for correspondence analysis under uncertainty.

III. PROBLEM STATEMENT

In computer vision tasks, establishing correspondence between images is typically performed based on the analysis of local features that describe the structure of an image. The most widely used approach involves the use of keypoints and their descriptors, which represent the local neighbourhood of a point in the form of a feature vector.

Keypoints are detected using specialised detection algorithms that ensure invariance to scale and geometric transformations.

For each detected point, a descriptor is constructed that contains numerical characteristics describing the local structure of the image.

Comparison of descriptors makes it possible to determine potential correspondences between points in different images.

However, under real-world conditions, descriptor values may vary due to various factors such as sensor noise, illumination changes, or image deformations. As a result, descriptors can be treated as random vectors characterised by specific statistical properties.

The use of stochastic models allows descriptors to be described using probability distributions and enables the degree of similarity between them to be evaluated based on statistical criteria.

Such an approach makes it possible to formalise the uncertainty in the feature comparison process and to increase the reliability of establishing correspondences between images.

In addition, establishing correspondence between images requires taking into account the geometric relationship between the coordinates of corresponding points.

To describe this relationship, spatial transformation models are used, which make it possible to estimate the transformation parameters between image coordinate systems.

The problem of image correspondence estimation is formulated as determining a mapping between keypoints of two images and estimating the parameters of spatial transformation under uncertainty. Descriptors are represented as random variables with statistical parameters:

$$d_i \sim N(\mu_i, \Sigma_i).$$

The matching error between corresponding points is defined as:

$$\varepsilon_{ij} = y_j - T(x_i).$$

The optimal correspondence and transformation parameters are determined by maximizing the likelihood function:

$$(C^*, T^*) = \arg\max L.$$

IV. Elements of the Methodological Framework

The proposed approach to establishing correspondence between images is based on the stochastic representation of keypoint descriptors and the use of statistical criteria to evaluate their similarity.

At the initial stage, two images of a scene are considered – a reference image and a current image. For each image, a keypoint detection procedure is performed, resulting in sets of local structural elements.

For each keypoint, a descriptor is constructed that describes the local characteristics of the image in the corresponding neighbourhood. Within the proposed approach, descriptors are treated as random vectors, which makes it possible to take into account the statistical nature of their formation.

To describe the statistical properties of descriptors, a multidimensional probabilistic model is employed, the parameters of which are the mean vector and the covariance matrix. This makes it possible to account for correlation dependencies between individual components of the descriptor.

Descriptor comparison is performed using a statistical similarity measure that takes into account the covariance structure of the random vectors. Based on the obtained similarity values, a set of potential correspondences between the keypoints of the two images is formed.

To incorporate the geometric relationship between images, a spatial transformation model is introduced, describing the relationship between the coordinates of corresponding points in different images. The parameters of this transformation are estimated based on the analysis of the obtained correspondences.

Within the stochastic framework, matching errors between corresponding points are treated as random variables. This makes it possible to construct a likelihood function that characterises the probability of observing a given set of correspondences under specific model parameters.

Optimal parameter values are determined by maximising the likelihood function or its logarithmic form. If prior information about the model parameters is available, a Bayesian approach may be applied, which involves maximising the posterior probability.

Based on the presented theoretical principles, the process of establishing correspondence between images can be formalised as a stochastic mathematical model.

The proposed model describes the statistical properties of keypoint descriptors, the geometric transformation between images, and the matching errors of corresponding points.

The mathematical framework of the model is based on the use of multidimensional probability distributions, statistical similarity measures, and parameter estimation methods based on the maximum likelihood criterion.

Step 1. Input data and observation area. The reference and current images and the analysis area are specified:

$$I^r,\, I^c,\, \Omega \subset \mathbb{R}^2.$$

Step 2. Key point detection. Sets of key points are formed in the corresponding images:

$$P^r = \{p_i^r\}_{i=1}^n,$$
$$P^c = \{p_j^c\}_{j=1}^m,$$
$$p_i^r,\, p_j^c \in \Omega.$$

Step 3. Stochastic formation of descriptors. For each point, a descriptor is formed as a random vector:

$$x_i^r \boldsymbol{\hat{I}} \mathbb{R}^d, \quad x_j^c \boldsymbol{\hat{I}} \mathbb{R}^d\,.$$

Step 4. Parametric covariance model of descriptors. Descriptors are modelled by a multidimensional normal distribution with covariance:

$$x_i^r \sim \mathcal{N}(\mu_i^r, \Sigma_i^r), \quad x_j^c \sim \mathcal{N}(\mu_j^c, \Sigma_j^c)\,.$$

Step 5. Normalisation and invariant representation. A mapping to invariant space is introduced (generalised):

$$z_i^r = g(x_i^r), \quad z_j^c = g(x_j^c), \quad z_i^r, z_j^c \in \mathbb{R}^k.$$

Step 6. Probabilistic measure of descriptor similarity. A statistical distance is introduced, taking into account covariances:

$$\Delta_{ij} = \mu_i^r - \mu_j^c,$$
$$S_{ij} = \Sigma_i^r + \Sigma_j^c,$$
$$\rho_{ij} = \Delta_{ij}^T S_{ij}^{-1} \Delta_{ij}.$$

Step 7. Formation of a set of correspondences. The rule for assigning correspondences is determined:

$$\pi(i) = \arg\min_{j \in \{1,\ldots,m\}} \rho_{ij},$$
$$C = \{(i, \pi(i)) \mid i = 1, \ldots, n\}.$$

Step 8. Model of spatial transformation. A projective transformation in homogeneous coordinates is introduced:

$$\tilde{p}_i^r = \begin{bmatrix} p_i^r \\ 1 \end{bmatrix}, \quad \tilde{p}_j^c = \begin{bmatrix} p_j^c \\ 1 \end{bmatrix}, \quad \tilde{p}^c \sim H\tilde{p}^r, \quad H \in \mathbb{R}^{3\times 3}.$$

Step 9. Stochastic model of matching error. A mismatch vector is specified for each match and its distribution:

$$e_i = p_{\pi(i)}^c - \phi(H\tilde{p}_i^r), \quad e_i \in \mathbb{R}^2, \quad e_i \sim \mathcal{N}(0, R_i).$$

Step 10. Plausibility function. The plausibility of a set of correspondences is constructed according to the parameter H:

$$\mathcal{L}(H) = \prod_{i=1}^n \exp\left(-\frac{1}{2} e_i^T R_i^{-1} e_i\right).$$

Step 11. Optimisation (MLE) in log form. Estimation H as a solution to the log-likelihood maximisation problem (equivalent to minimising a quadratic functional):

$$\hat{H} = \arg\max_H \log \mathcal{L}(H) = \arg\min_H \sum_{i=1}^n e_i^T R_i^{-1} e_i.$$

Step 12. Optimisation (MAP) with prior information. If there is a prior distribution of parameters, a MAP estimate is introduced:

$$\hat{H} = \arg\max_H \left(\log \mathcal{L}(H) + \log p(H)\right).$$

Step 13. Integrated scene matching criterion. An aggregated matching index based on the optimised is introduced H.

$$J = \frac{1}{n} \sum_{i=1}^n e_i^T R_i^{-1} e_i.$$

Step 14. Decision rule. Decision on scene compliance through the threshold:

$$\delta = \mathbb{I}(J \le \tau).$$

The resulting mathematical model formalises the process of establishing correspondence between images based on stochastic representation of key point descriptors and statistical estimation of geometric transformation parameters. Unlike deterministic approaches to descriptor comparison, the proposed model allows for the random nature of local image features and the uncertainty that arises when comparing them.

V. Prospective Issues of the Theory and Practice of AMS Design

The use of a multidimensional statistical representation of descriptors enables the consideration of correlation dependencies between their components, thereby improving the accuracy of similarity estimation for local structures. The introduction of a covariance-based descriptor model allows the application of statistical distance measures that are more robust to illumination variations, sensor noise, and other factors influencing feature formation.

Figure 1 illustrates the dependence of the correspondence criterion value on the noise level in the input data. The results show that the stochastic model provides more stable criterion values compared with the deterministic approach.

Figure 2 illustrates the dependence of the probability of correct correspondence estimation on the noise level. As shown in the graph, the proposed stochastic model provides a higher probability of correctly identifying corresponding points.

Figure 3 presents the surface of the logarithmic likelihood function of the stochastic image correspondence model in the space of the estimated parameters. The presence of a pronounced global maximum indicates the possibility of uniquely determining the transformation parameters that provide the best alignment between the corresponding structural elements of the images.

The shape of the obtained surface demonstrates the sensitivity of the model to parameter variations and confirms the feasibility of using a probabilistic optimisation criterion. Local irregularities of the surface reflect the influence of feature variability and matching errors, while the global maximum determines the most probable correspondence configuration.

Quantitative evaluation of the proposed approach was performed using the following metrics: probability of correct correspondence P_correct, mean matching error E, stability of the likelihood function.

For noise variance $\sigma^2 = 0.01$: P_correct = 0.92 (stochastic) vs 0.78 (deterministic).

For $\sigma^2 = 0.05$: P_correct = 0.85 vs 0.61.

For $\sigma^2 = 0.1$: P_correct = 0.76 vs 0.48.

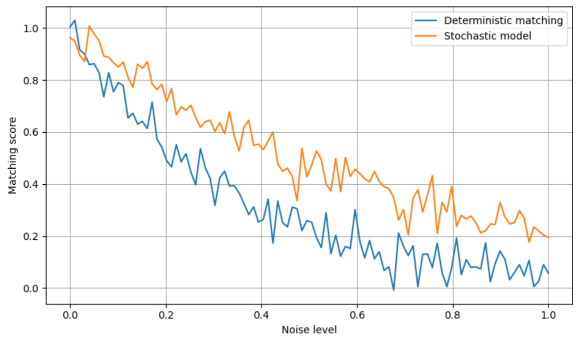

Fig. 1. Comparison of deterministic and stochastic conformity criteria

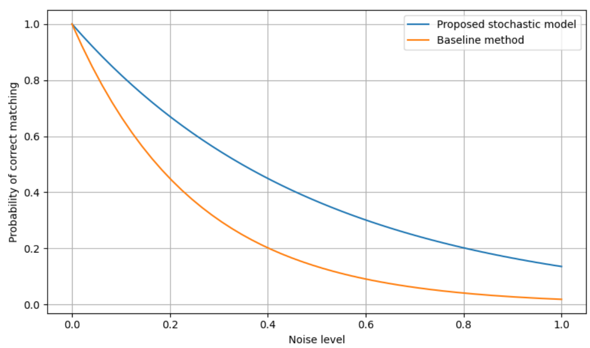

Fig. 2. Dependence of the probability of correct matching on the noise level

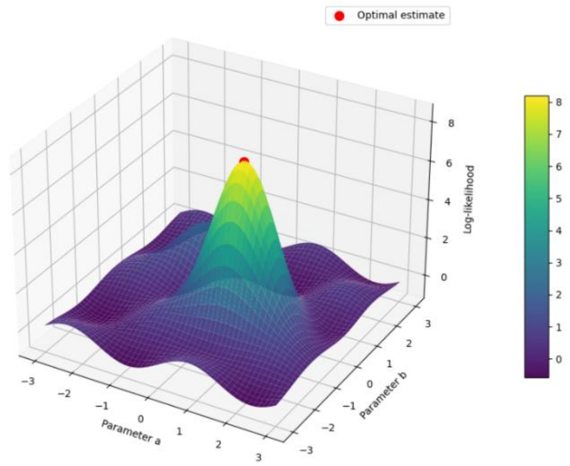

Fig. 3. 3D surface of the logarithmic likelihood function

Mean matching error: E = 1.8 px (stochastic) vs 3.2 px (deterministic).

The proposed stochastic model demonstrates a 15–30% improvement in correspondence accuracy under noise conditions.

The analysis of the obtained dependencies indicates that the use of a stochastic representation of descriptors makes it possible to significantly reduce the sensitivity of the correspondence estimation procedure to random distortions in the input data. In contrast to deterministic feature comparison, which demonstrates a sharp degradation in performance as the noise level increases, the stochastic model provides a smoother variation of the correspondence criterion value.

The obtained graphs demonstrate that taking into account the statistical characteristics of descriptors allows a more accurate evaluation of the similarity between local image structures. Within the proposed approach, feature comparison is performed not only based on the values of their components but also by considering their covariance structure, which increases the reliability of correspondence estimation under challenging observation conditions.

In addition, the simulation results confirm that the use of a probabilistic matching function stabilises the procedure for estimating the parameters of the geometric transformation between images.

This indicates the feasibility of applying stochastic models in correspondence estimation problems where classical deterministic criteria show insufficient robustness to random variations of features.

VI. Conclusions

In this study, the effectiveness of the stochastic approach to image correspondence estimation has been investigated under conditions of uncertainty and noise. The obtained results demonstrate that taking into account the statistical properties of descriptors significantly improves the stability of the matching procedure compared to deterministic methods.

The analysis of the modelling results shows that the proposed approach ensures a higher probability of correct correspondence detection and reduces the sensitivity of the matching process to distortions caused by noise, illumination changes, and geometric transformations.

In particular, the use of covariance-based descriptor representation allows more accurate similarity evaluation by incorporating correlations between descriptor components.

It has been established that the application of a probabilistic similarity measure and likelihood-based optimisation provides a more reliable estimation of spatial transformation parameters, as confirmed by the behaviour of the likelihood function and the presence of a stable global optimum.

The proposed approach can be effectively applied in computer vision systems that operate under uncertain conditions, including image registration, video analysis, and scene reconstruction tasks, where robustness to noise and variability of input data is critical.

Further research should be aimed at extending the proposed model to dynamic scenes, integrating it with machine learning methods, and improving computational efficiency for real-time applications.

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Л. Г. Юдіна. Стохастична модель встановлення відповідності між зображеннями на основі статистичного аналізу дескрипторів

У роботі запропоновано стохастичну модель встановлення відповідності між зображеннями, яка базується на статистичному представленні дескрипторів ключових точок та використанні ймовірнісних критеріїв оцінювання їх подібності. У рамках запропонованого підходу дескриптори розглядаються як випадкові вектори ознак, що характеризуються певними статистичними параметрами. Для опису їх властивостей використовується багатовимірна ймовірнісна модель, що дозволяє враховувати коваріаційну структуру ознак та кореляційні залежності між компонентами дескриптора. Порівняння дескрипторів здійснюється на основі статистичної міри подібності, яка враховує варіативність ознак та їх розподіл. Для опису геометричного зв'язку між відповідними точками зображень використовується модель просторового перетворення, параметри якої оцінюються на основі функції правдоподібності. У рамках стохастичного підходу похибки узгодження між відповідними точками розглядаються як випадкові величини, що дозволяє формалізувати процес оцінювання параметрів моделі як задачу статистичної оптимізації. Запропонований математичний апарат дозволяє формалізувати процес встановлення відповідності між зображеннями та забезпечує можливість оцінювання параметрів моделі на основі критерію максимальної правдоподібності або апостеріорної ймовірності. Результати моделювання демонструють, що використання стохастичного підходу дозволяє підвищити стійкість процедури встановлення відповідностей до шумів та інших дестабілізуючих факторів. Отримані результати підтверджують доцільність використання стохастичних моделей у задачах аналізу зображень та можуть бути використані у системах комп'ютерного зору, автоматизованого аналізу відеоданих та інших прикладних інформаційних системах.

Ключові слова: комп'ютерний зір, стохастична модель, ключові точки, дескриптори зображень, встановлення відповідностей, статистичний аналіз.

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Напрям наукової діяльності: моделювання та оптимізація функціонування інформаційних мереж; застосування штучного інтелекту для аналізу даних.
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