Analysis of Filtration Process Influence on the Results of Thermal Imaging Control of the Subsurface Defect's Geometry in Solving Control Problems of Collaborative Robotic Systems

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Abstract. The paper proposes and experimentally verifies an approach for estimating the thermal imaging error depending from the method of the subsurface defect’s linear dimensions filtering for forming the appropriate commands of the control program in a collaborative robotic system. The results are presented for the absolute error estimation depending on the filtration method with a confidence probability $p=0.9972$.

1. Introduction
In modern robotics, there is an acute issue of accurate and prompt pattern recognition. At the same time, the processing of images obtained by various methods of visualization of space cannot always be carried out in the visible range of radiation. In this case, often, for example, when solving problems of flaw detection and detection of subsurface defects, it is the ranges invisible to the eye that are optimal for research tasks. However, thermal imaging systems have a set of specific sources of interference and measurement errors that can be reduced by filtering the final image. In this paper, a study is carried out to determine the optimal filtration mode, in the first approximation affecting only the comparative accuracy and speed of algorithms for averaging over time or over a region of space filtration from the standpoint of their applicability in collaborative robotics.

2. Background
As the functionality of robots grows, the number of possible applications grows and today many work processes need to be fully automated.

The expansion of the spheres and methods of using collaborative robotic systems (CRS) suggests the need to develop supervisory systems that control the interaction of people and robots and are responsible for the distribution of tasks in production. Safe movement of the robot and effective interaction with a human companion is possible due to the use of a multimodal representation of the surrounding space. [2, 4, 5, 6]

For the management of cattle, including for diagnostic medicine, it is necessary to solve a number of problems in the field of multimodal sensing [12]. Control programs created on the basis of information received from sensor systems allow one to take into account the surface parameters of objects processed by a robotic system [15]. However, this information is not enough to ensure the quality of a number of modern technological processes [13, 14]. This primarily concerns processes where it is necessary to take into account information on the presence, location and size of subsurface defects. Based on this information, the control program of the workover must form a command to
eliminate defects. The need for this arises, for example, when applying a protective coating to large structural elements of aircraft, primarily intended for the aerospace industry [11].

3. Formulation of the problem
Thermal imaging devices operating in the infrared range are successfully used to solve visualization problems and determine the location of subsurface defects [7, 19, 20].

Based on the results of research on the basis of the measuring and testing equipment of the Linear-Angle Measurement Laboratory of the Technological Test Site of the MSUT STANKIN, an approach was proposed to assess the error, depending on the method of filtering the results of measuring the linear dimensions of subsurface defects, using the thermal imaging method when solving workover control problems. [3]

An important aspect in obtaining measurement information is the elimination of noise from the measurement results. In the context of non-destructive testing with the use of the thermal imaging method, the role of noise can be both fluctuations of the thermal field and randomly scattered thermal radiation both on the measurement object itself and on the photosensitive element of the thermal imager [22]. The classical method for reducing random noise is the use of an averaging filter, however, in the case of real-time monitoring of the thermal field, two significantly different averaging methods can be used: averaging over time and over a region of space [8, 9, 10].

4. Materials and experiments
To check the degree of influence of each method, a thermogram was taken from a reference element. In the course of the experiment, in the climatic chamber MHU-255CLSA (accuracy of temperature maintenance ± 0.3 °C, uneven temperature distribution ± 2 °C), heating took place for 3 hours at a temperature of 40 °C. Subsequently, the chamber was cooled at room temperature (21 ... 22 °C). In the process of cooling, a gauge block (CMD) of room temperature with a nominal value of 20 mm was placed in the chamber for comparison with a radiating hot background (Fig. 1-3). The choice of an approach to control a "dark" object against a background of radiation is due to its great methodological similarity with measurements carried out by projection methods on instrumental microscope and measuring projectors [21]. Temperature fields were monitored using an IRTIS-2000 SV computer thermograph (measurement range from -40 to +300 °C, error at 30 °C - no more than 0.05 °C, resolution 640x480 pixels). The distance from the object to the thermal imager was 30 cm.
Figure 1. CMD with a nominal value of 20 mm against the background of a heated chamber.

Figure 2. Comparison of the pixel size of an exemplary CMD with a nominal value of 20 mm and a thermal background.
Figure 3. Thermal imager program window with a highlighted area for comparison of CMD radiation with a nominal value of 20 mm and background radiation.

5. Methods and results

The obtained thermograms in the form of a digital two-dimensional matrix were transferred to the MS Excel environment to implement the filtration process and compare the results [16, 17, 18]. Figure 3 shows the filtering area of 165 × 13 pixels. The analytical data collection area remained unchanged in all thermograms.

For the problem of averaging over time, 20 consecutive frames were taken, the total recording time of which was 46.9 seconds (it is obvious that this type of averaging cannot be used in the analysis of dynamically changing processes). In this case, the temperature of pixels with the same row and column numbers was sequentially summed up at each frame, and then the resulting sum was divided by the number of frames:

\[ Tt(j; k) = \frac{\sum_{i=0}^{19} T(j; k)_i}{20}, \]

where \( Tt(j; k) \) is the average pixel temperature over all frames, \( T(j; k)_i \) is the pixel temperature on the frame with the number \( i = 0 \ldots 19 \), \( j \) and \( k \) are the row and column numbers for a particular image pixel.

The average temperature in the control area, equal to 29.667 °C, was taken as a threshold filter for separating the CMD image from the background.

For the problem of averaging over the area in the first frame, a 3 × 3 pixel image section was sequentially taken. The temperature value in each pixel was summed up with the rest, and then the resulting sum was divided by the number of pixels:

\[ Tp(j; k) = \frac{\sum_{i=0}^{2} \sum_{m=0}^{2} T(j + i; k + m)}{9}, \]
where $T_p(j; k)$ is the average temperature, $T(j + i; k + m)$ is the pixel temperature in the averaging zone, $j$ and $k$ are the row and column numbers for a particular image pixel, $i$ and $j$ are the position of the averaged pixel in the zone averaging.

As a threshold filter for separating the CMD image from the background, the average temperature in the control area was also taken, for the first frame equal to 29.66 °C. The outermost two columns and the outermost two rows were excluded from the analysis, so the total control area was reduced to a size of $163 \times 11$ pixels. In this regard, edge pixels were also excluded from the averaged thermogram and the thermogram of the first frame during the analysis. For a separate frame, the threshold filtering temperature was chosen similarly to the two previous methods and amounted to 29.83 °C. The results of a comparative analysis of the obtained values are presented in table 1.

| Line number | Pixel width of CMD with a nominal value of 20 mm per line in the first frame | Pixel width of CMD with a nominal value of 20 mm per line after averaging over time | Pixel width of CMD with a nominal value of 20 mm in a line after averaging over an area of $3 \times 3$ pixels |
|------------|--------------------------------------------------------------------------|-----------------------------------------------------------------|----------------------------------------------------------|
| 1          | 31                                                                       | 30                                                             | 30                                                       |
| 2          | 31                                                                       | 30                                                             | 30                                                       |
| 3          | 31                                                                       | 30                                                             | 30                                                       |
| 4          | 31                                                                       | 31                                                             | 31                                                       |
| 5          | 32                                                                       | 31                                                             | 32                                                       |
| 6          | 32                                                                       | 32                                                             | 32                                                       |
| 7          | 33                                                                       | 33                                                             | 33                                                       |
| 8          | 33                                                                       | 34                                                             | 33                                                       |
| 9          | 33                                                                       | 34                                                             | 33                                                       |
| 10         | 33                                                                       | 34                                                             | 33                                                       |
| 11         | 33                                                                       | 34                                                             | 33                                                       |
| Mean       | 32.09                                                                    | 32.09                                                          | 31.82                                                    |
| The sum of image pixels, interpreted as an area on the CMD | 342                                                                      | 342                                                            | 339                                                      |

It can be seen from the table that all key statistical values for the unfiltered image and for the temporally filtered image are the same. It is important to note that the resulting pixel values have not been interpreted in linear terms. However, since the CMD error is incomparably lower than any possible error of the thermal imaging geometry estimation method, it can be calculated that for an average value of 32.09 pixels, the linear resolution of the thermal imager was:

$$\frac{20}{32.09} \approx 0.623 \text{ [mm/pixel]}$$

Then the value of the CMD width after spatial filtering will be $0.623 \times 31.82 = 19.83$ mm.

Thus, the absolute error depending on the filtration method was 0.17 mm. The standard deviation of the error was 0.05 mm. Thus, the final estimate of the error, depending on the choice of the filtration method, is $(0.17 \pm 0.16)$ mm with a confidence level of $p = 0.9972$.

6. Conclusions
Based on the results of experimental studies and calculations, it can be concluded that the use of a certain type of image filtering in the implementation of automated control in the context of the
implementation of group interaction of robotic systems can play a decisive role in the accuracy and speed in determining the position of defects or in the process of pattern recognition. In this case, the key parameters for evaluating the effectiveness of a particular method can be considered the running time of the algorithm, which largely depends on the rate of collection of the required number of frames, and the accuracy of transmission of undistorted information on the distribution of temperature fields. At the same time, due to the significant inertness of thermal processes, the procedure for monitoring subsurface defects should be implemented by automated systems at reduced operating speeds of scanning the environment. Nevertheless, the obtained maximum value of the error associated with the choice of the filtering method allows us to consider it comparable with the image sampling error. At the same time, the time taken by the system to take one frame, which is about 2.4 seconds for the used installation, makes it difficult to use temporary filtering algorithms for stream monitoring of defects in a mode close to real time.

7. References

[1] Ermishin K V, Yushchenko A S 2016 Collaborative mobile robots are a new stage in the development of service robotics Robotic and technical cybernetics 3(12) pp 3-9
[2] Serebrenny V V, Sheruezhov M A 2018 The main issues of the development of collaborative robotic systems for industrial use Bulletin of the Kabardino-Balkarian Scientific Center of the Russian Academy of Sciences 6-3(86) pp 106-113
[3] Romash E V and Bushuev S V 2020 Estimation of the Linear Dimensions of Subsurface Defects Using the Thermal Imaging Method for Solving Control Problems in Multipurpose Robotic Systems 2020 International Multi-Conference on Industrial Engineering and Modern Technologies (FarEastCon) (Vladivostok) pp 1-4 doi: 10.1109/FarEastCon50210.2020.9271228
[4] Vorotnikov A, Bashevskaya O, Ilyukhin Y, Romash E, Isaev A, Poduraev V Y 2016 Geometrical Approach for Industrial Robot Axis Calibration Using Laser Tracker Proceedings of the 26th DAAAM International Symposium pp 0897-0904 B Katalinic (Ed.) Published by DAAAM International ISBN 978-3-902734-07-5 ISSN 1726-9679 (Vienna, Austria) DOI: 10.2507/26th.daaam.proceedings.125
[5] Vorotnikov A, Romash E, Isaev A, Bashevskaya O, Bianchi G, Poduraev Y 2016 Uncertainty estimation of axes direction determination of industrial robot using an ellipsoid concentration model Annals of DAAAM and Proceedings of the International DAAAM Symposium 27 pp 480-486
[6] Vorotnikov A A, Klimov D D, Romash E V 2017 Cutting velocity accuracy as a criterion for comparing robot trajectories and manual movements for medical industry Mechanics & Industry T 18 7 p 712
[7] Vavilov V P 2009 Infrared thermography and thermal control (M.: ID Spektr) p 544
[8] Jozef Živčák, Radovan Hudák, Ladislav Madarász, Imre J Rudas 2013 Methodology, Models and Algorithms in Thermographic Diagnostics Springer p 230
[9] 2012 Infrared Thermography Recent Advances and Future Trends Carosena Meola Bentham e-Books p 240
[10] Varaksin A Y, Protasov M V, Romash M E, Kopeitsev V N, Glubokov A V, Romash E V 2015 Display of free concentrated fire vortices by means of a thermograph Measurement Techniques T 58 5
[11] Bashhevskaya O S, Bushuev S V, Ilyukhin Y V, Mel’nichenko E A, Romash E V, Poduraev Y V, Kovalskiy M G 2015 Comparative analysis of thermal deformations in structural elements of measurement stands and supports Measurement Techniques T 58 5
[12] Vorotnikov A A, Poduraev Y V, Romash E V 2015 Estimation of error in determining the centers of rotation of links in a kinematic chain for industrial robot calibration techniques Measurement Techniques T 58 8 pp 864-871
[13] Bashevskaya O S, Bushuev S V, Nikitin A A, Romash E V, Poduraev Y V 2015 Selection of roughness parameters to assess the quality of an article surface after electroerosion machining Measurement Techniques T 58 8 pp 860-863
[14] Bashevskaya O S, Bushuev S V, Nikitin A A 2017 Assessment of Surface Roughness Using Curvature Parameters of Peaks and Valleys of the Profile Measurement Techniques T 60 2 pp 128-133
[15] Bushuev S V, Romash E V 2018 Tools for analyzing the relief and surface defects of machine parts Bulletin of MSUT Stankin 2(45) pp 57-62
[16] Bashevskaya O S, Bushuev S V, Poduraev Yu V, Kovalsky M G, Keiner G B, Romash E V, Melnichenko E A 2014 Development of an experimental-analytical technique for determining the temperature deformations of gage blocks in the nanometer range Measuring equipment 3 pp 8-11
[17] Bashevskaya O S, Gulieva R M, Romash E V, Melnichenko E A 2014 Investigation of temperature deformations of gauge blocks Vestnik MSUT Stankin 4(31) pp 36-40
[18] Bashevskaya O S, Bushuev S V, Poduraev Yu V, Kovalsky M G, Romash E V, Melnichenko E A, Ilyukhin Yu V 2015 Development of a method for determining the temperature coefficients of linear expansion of gauge blocks Izmeritel'naya tekhnika 6 pp 18-20
[19] Vavilov V P 2008 Thermal control of composite materials "In the world of non-destructive testing" 4 pp 32-36
[20] Antonio Rafael Ordóñez Müller 2018 Close range 3D thermography: real-time reconstruction of high fidelity 3D thermograms Kassel University press p 156
[21] Afonina I I, Bashevskaya O S, Bushuev S V, Romash E V, Melnichenko E A 2018 Non-destructive testing of subsurface defects using the thermal imaging method Vestnik MSUT Stankin 4(47) pp 122-125
[22] Waldemar Minkina, Sebastian Dudzik 2009 Infrared Thermography: Errors and Uncertainties Wiley p 200

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