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EVALUATION OF THE METROLOGICAL CHARACTERISTICS OF AI-BASED OPTICAL INSPECTION SYSTEMS AND DEVELOPMENT OF THEIR MEASUREMENT UNCERTAINTY BUDGET

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Abstract. The paper addresses the metrological assurance of AI-based optical inspection systems that detect surface defects of knitted fabric in real time, treating them as measuring and control instruments. Analytical relationships between the measurement range, spatial resolution, exposure time and frame rate are derived, and their nominal values are formalised as a metrological passport. Following the GUM principles, an uncertainty budget comprising type A and type B sources was compiled; the expanded uncertainty was found to be U = ±0.031 (on the F1 scale, k = 2) A procedure for initial validation and periodic calibration of the system is proposed.

Keywords: metrological assurance, optical inspection system, artificial intelligence, measurement uncertainty, validation, calibration, knitted fabric, metrological passport

Introduction

In knitwear production, failure to detect defects (dropped stitches, stripes, holes, uneven density, etc.) in time leads to higher reject rates and wasted raw materials and energy. In recent years, systems that inspect the fabric surface in real time using computer vision and deep learning have become widespread [4–7]. In Uzbekistan, the strategy for the comprehensive development of the light industry [1] and the documents on supporting textile enterprises [2] set the tasks of ensuring product quality at the level of international requirements and of enhancing quality management and metrological assurance systems with digital tools.

In practice, however, such intelligent systems are often treated as a "black box": the procedures for confirming their detection accuracy (validation) and for periodic checks (calibration), as well as their metrological characteristics, are not standardised. Yet, according to clause 7.1.5 of O'z DSt ISO 9001, an organisation must ensure that the monitoring and measuring resources used to verify product conformity are fit for purpose, check them at specified intervals and document the traceability of results [8]. International studies [4, 5] focus mainly on improving detection accuracy, and the results are not reported together with a formal estimate of metrological uncertainty.

The aim of this paper is to substantiate quantitatively the metrological characteristics of an AI-based optical inspection system, to develop its measurement uncertainty budget, and to establish a procedure for its validation and calibration.

Object and Methods of the Study

The object of the study is an optical inspection system mounted on a circular knitting machine that monitors the fabric surface with a camera and classifies defects into five classes using a convolutional neural network. The study employed the theory of metrological assurance, the GUM

guide to the expression of measurement uncertainty [9], probability theory and methods of mathematical statistics.

According to the theory of metrological assurance, every measuring and control instrument must be linked to a calibration chain that ensures the traceability of the unit of measurement: working instrument – secondary standard – primary standard – national standard (Fig. 1). In an optical inspection system, the measured quantity (defect size and type) is determined indirectly through an image processing algorithm. Therefore, for such a system the role of the "secondary standard" is played by a set of reference samples with artificial defects of known type and size.

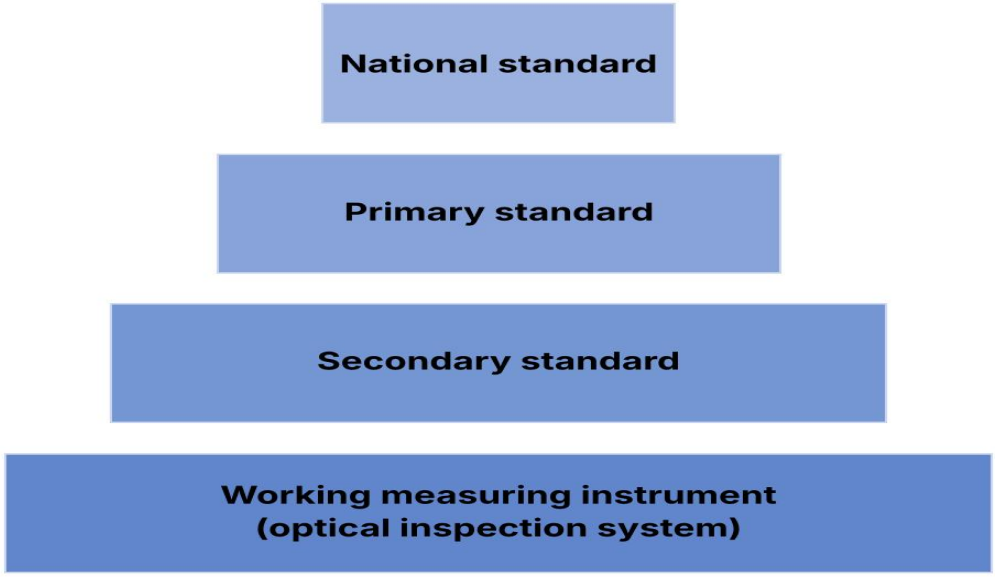


Fig. 1. Traceability chain of the unit of measurement

Results and Discussion

Analytical relationships between the metrological characteristics. The linear speed of the fabric surface relative to the system in the inspection zone is related to the kinematic parameters of the machine:

$$v = \pi \cdot D \cdot n / 60, \quad (1)$$

where v is the linear speed of the fabric surface, m/s; D is the working diameter of the machine, m; n is the rotational speed, rpm. For the values adopted in the industrial trials, D = 0.762 m and n = 25 rpm, v ≈ 1.0 m/s.

The spatial resolution of the system, i.e. the distance corresponding to one pixel, is determined as follows:

$$\delta = W / N_x, \quad (2)$$

where W is the width of the field of view, mm; N_x is the number of horizontal pixels of the sensor. For reliable detection, the image of a defect must occupy at least 3–4 pixels. When the smallest inspected size is set to d_{min} = 1.0 mm, the requirement $\delta \leq 0.25$ mm/pixel follows. With N_x = 1920 and W = 384 mm, δ = 0.2 mm/pixel, which meets the specified requirement with a margin.

To record the image of the moving fabric without motion blur, the exposure time must satisfy:

$$t_e \leq \delta / v. \quad (3)$$

At v = 1.0 m/s this gives $t_e \leq 200$ μs. The frame-rate requirement follows from the condition of continuous coverage of the inspection zone:

$$f_k \geq v / [W \cdot (1 - k_q)], \quad (4)$$

where k_q is the overlap coefficient of adjacent frames ($k_q = 0.2$). The calculated minimum rate is 3.3 fps; taking a reliability margin into account, f_k = 12 fps was included in the normative document.

The resulting nominal values were formalised as the metrological passport of the system (Table 1). They must be recalculated using expressions (1)–(4) for the conditions of each enterprise (machine diameter, rotational speed).

Table 1

Metrological passport of the optical inspection system (nominal mode)

Parameter	Symbol	Value	Requirement
Measurement range (minimum defect size)	d_{min}	1.0 mm	≤ 1.0 mm
Spatial resolution	δ	0.2 mm/pixel	≤ 0.25 mm/pixel
Exposure time	t_e	≤ 200 μs	≤ δ/v
Frame rate	f_k	12 fps	≥ 3.3 fps
Data stream intensity	Q	27.6 MB/s	calculated check

Measurement uncertainty budget. According to the GUM principles, uncertainty is divided into two types: type A, evaluated from the statistics of repeated measurements, and type B, evaluated from calibration certificates, manufacturer data and expert judgement [9]. For an optical inspection system, the main source of type A uncertainty is the statistical error of the classification model. We estimate it through the standard error of the F1 score:

$$u_A = s_F = \sqrt{[F1 \cdot (1 - F1) / n]}. \quad (5)$$

In the industrial trials, for F1 = 0.931 the half-width of the 95 % confidence interval was ±0.020, hence $u_A = 0.020 / 1.96 \approx 0.010$. The type B sources – geometric distortion of the camera, non-uniform illumination, thermal noise of the sensor and variation of the lens-to-fabric distance – were evaluated separately. The combined standard uncertainty is determined by the root-sum-of-squares rule:

$$u_c = \sqrt{(u_A^2 + \Sigma u_{Bi}^2)}, \quad U = k \cdot u_c, \quad (6)$$

where k = 2 is the coverage factor (confidence level ≈ 95 %).

Table 2

Measurement uncertainty budget of the optical inspection system (F1 scale)

Source of uncertainty	Type	Standard uncertainty u_i	Contribution to variance, %
Statistical error of the classification model	A	0.0102	42
Geometric distortion of the camera	B	0.008	26
Non-uniform illumination	B	0.006	15
Thermal noise of the sensor	B	0.005	10
Variation of the lens-to-fabric distance	B	0.004	7
Combined standard uncertainty u_c	—	0.0157	100
Expanded uncertainty U (k = 2)	—	±0.031	—

Table 2 shows that the largest share of uncertainty (42 %) is due to the statistical error of the classification model, while among type B sources the geometric distortion of the camera dominates (26 %). This leads to a practical conclusion: the most effective way to reduce uncertainty is to enlarge the validation sample and to retrain the model on enterprise data, and on the hardware side, to calibrate lens distortion. The expanded uncertainty U = ±0.031 is entered in the metrological passport and serves as a baseline for comparing results when the system is introduced at other enterprises.

Validation and calibration procedure. Before the system is put into production, initial validation is carried out in the following stages: 1) preparation of a set of reference samples – at least 20 artificial defect samples for each defect class; 2) placement of the samples under controlled illumination and tension conditions; 3) testing the system on the samples and recording its response for each event; 4) calculation of precision, recall and the F1 score; 5) comparison of the results with the normative limits ($F1 \geq 0.90$; $U \leq \pm 0.04$) and issuing of a validation report.

During operation, dust accumulation, lens contamination and the decline of the luminous flux of the illuminator cause a “drift” of the system characteristics. Therefore, periodic calibration is mandatory once every three months or after maintenance. If the deviation of the F1 score on the reference samples from its nominal value exceeds 2–3 percentage points, the system is sent for readjustment or retraining (Table 3).

Table 3

Schedule of validation and calibration of the inspection system

Type of check	Frequency	Responsible service	Record form
Initial validation	Once, before commissioning	Metrology service	Validation report
Scheduled calibration	Once every 3 months	Metrology service	Calibration certificate / log
Post-maintenance check	After each repair or replacement	Maintenance department	Unscheduled inspection report
Retraining when the product range changes	When switching to a new fabric type	Quality control department	Retraining record

The result of each calibration is entered in the metrology log, and every defect record registered by the system is tagged with the calibration status at that moment (date and result of the last calibration). This makes it possible to meet the O‘z DSt ISO 9001 requirement for traceable monitoring of measuring resources and to confirm the metrological assurance of the measurement result in each specific case. Readings of a system whose calibration has expired are not used in official quality reports.

Conclusions

1) The need for metrological assurance of an AI-based optical inspection system as a measuring and control instrument has been substantiated, and it has been shown that in its calibration chain the set of reference samples acts as the secondary standard.

2) Analytical relationships (1)–(4) between the measurement range, spatial resolution, exposure time and frame rate of the system were obtained; the values $\delta = 0.2$ mm/pixel, $t_e \leq 200$ μs and $f_k = 12$ fps were substantiated for the nominal mode, and a metrological passport was compiled.

3) According to the uncertainty budget compiled on the basis of the GUM principles, the expanded uncertainty is U = ±0.031 (F1 scale, k = 2); 42 % of the uncertainty is due to the statistical error of the classification model.

4) A procedure for initial validation of the system and its periodic calibration every three months has been developed; it makes it possible to meet the requirements of clause 7.1.5 of O‘z DSt ISO 9001.

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