BRNO UNIVERSITY OF TECHNOLOGY
Faculty of Mechanical Engineering
Institute of Machine and Industrial Design

Ing. Jakub Hurník

MEASUREMENT OF SHAPE AND DIMENSIONS OF FORGINGS

MĚŘENÍ TVARU A ROZMĚRU VÝKOVKŮ

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Supervisor: doc. Ing. Daniel Koutný, Ph.D.

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CONTENTS

1 INTRODUCTION

Forging is a manufacturing operation that is used to produce semi-finished products for high-strength mechanical parts. Heavy forgings are manufactured using open-die forging, due to their large dimensions and small-series production. These forgings are used in the energy, petrochemical and shipbuilding industry to manufacture various shafts. During open-die forging, significant deviations from the ideal forging dimensions and shape often appear. Shape deviations can be corrected directly after the forging operation. Although the costs of the production are very high, this is still often carried out based on primitive contact measurement techniques. Some geometric characteristics cannot be measured at all, including, e.g., forging axis straightness. Therefore, this important shape deviation can be corrected only based on forging press operator estimation. The evidence of low achievable accuracy is the large machining allowances, which must be applied. According to ČSN 42 9011, the allowances can exceed 20% of the total material used for forging manufacturing.

The problem is that due to the specific conditions in the environment of heavy industry, common available noncontact measurement systems cannot be used. The dimensions of heavy forgings are in meters, and their forging temperature varies between 1250 – 850 ° C. There are many physical effects, which can critically affect optical measurement systems, e.g., the radiance or contrasting scales on the forging surface, dimensionally and thermally unstable environment, or air lens around the forging. There are only a few systems in the world capable of forging measurement, including, e.g., the LaCam® Forge by Ferrotron. However, these are based on the laser scanning principle, which has many disadvantages. Therefore, the research continues to find an alternative. The literature suggests many advantages of passive, image-based measurement using forging silhouettes [1]. However, this approach showed limited accuracy during forging measurement and was never tested under industrial conditions. On the other hand, the measurement system in the literature used only basic optical measurement methods.

The aim of this thesis is to examine the possibilities of passive, image-based measurement of forgings in the process of their manufacturing, by using advanced methods of optical measurement. In this work, the measurement system, based on this principle, is proposed. The interfering effects of the industrial environment are discussed and many original methods, making this measurement method resistant to these effects, are proposed. The effectiveness of the methods was verified under both laboratory and industrial conditions and compared with the state-of-the-art. The knowledge obtained can be used to develop a professional measurement system, which would provide the feedback to the forging press operator, to accurately correct the forging shape and dimensions. This would lead to material savings on the machining allowances, and therefore energy and emissions savings. In the future, the measurement system can become a part of automated forging manufacturing line (e.g., like a concept presented in literature [2]), in accordance with industry 4.0 implementation.

2 STATE OF THE ART

Close-range photogrammetry is a branch of science that deals with the measurement of object shape, dimensions, or location, based on images. The result is normally its digital reconstruction (a set of points in a coordinate system). Close-range photogrammetry is used in many areas, including mechanical engineering, civil engineering, architecture, medicine, natural sciences, or crime investigation applications. Photogrammetry has a wide range of applications in the industry. The typical applications are mechanical parts, or assembly inspection, robot manipulator calibration, reverse engineering, or digitization of art creations [3]. To obtain the location or geometry of the object, the image formation process needs to be described from a geometric point of view. To describe the image formation process, modified central projection is normally used. The process of estimating these parameters is called camera calibration. The camera calibration can be carried out by imaging, for example, a planar calibration field with a regular pattern [4,5], a 3D calibration object with known geometry [6], or a 3D calibration field created of coded calibration targets with known location [7,8]. A special case is the self-calibration methods, which do not need any accurate calibration scene. Based on the parameters obtained, the object or the scene can be reconstructed. Research in close-range photogrammetry includes the spreading of optical image-based methods to new applications. This is possible thanks to the development of computational power, digital cameras, and computational methods, based e.g., on neural networks [9,10].

In this work, the challenge of forging measurement is resolved. During the open-die forging, shape deviations can appear and need to be measured. The products (heavy forgings) are mainly cylindrical, and their dimensions could be up to 20 m in length and 6 m in diameter. Forging temperatures range between 800 – 1250 ° C [1,11]**.** Measurement of these forgings is a challenge, as a result of the influence of interfering effects or the industry environment in general. Research can be divided into two basic approaches: active (the measurement system uses its light source, and the light emitted by the forging is suppressed) and passive (these systems utilize the light emitted by the forging).

2.1 CHALLENGES DURING IN-PROCESS FORGING MEASUREMENT

The first interfering effect, which negatively influences the in-process measurement of heavy forgings, is thermal radiation. Forging, which is heated to the forging temperature, emits radiation in the infrared, near-infrared, and visible spectrum. The mechanism differs in the case of active and passive methods. In the case of active methods, radiation influences the signal-to-noise ratio (SNR) of the signal projected on the forging surface (Fig. 2-1) [12]. In the case of passive methods, the problem is the contrast of the whole forging on the background [13,14] and the contrasting scales, making it difficult to find forging boundaries (Fig. 2-2) [15]. In both cases, the result can be inaccurately or false detected features (projected pattern, forging edges, surface structure) needed for the forging measurement.

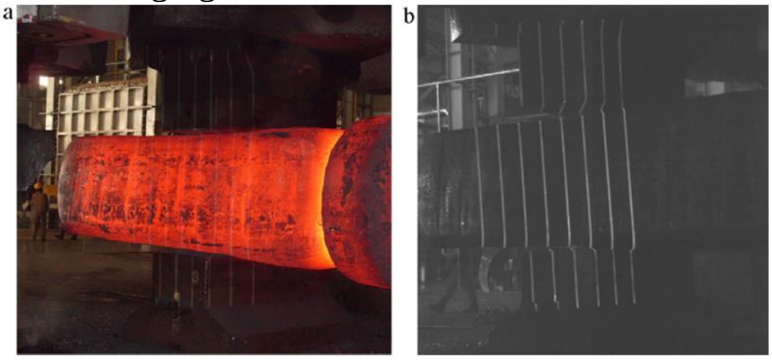

Fig. 2-1 Comparison of the measurement images without (a) and with (b) the usage of the spectral selective method [12].

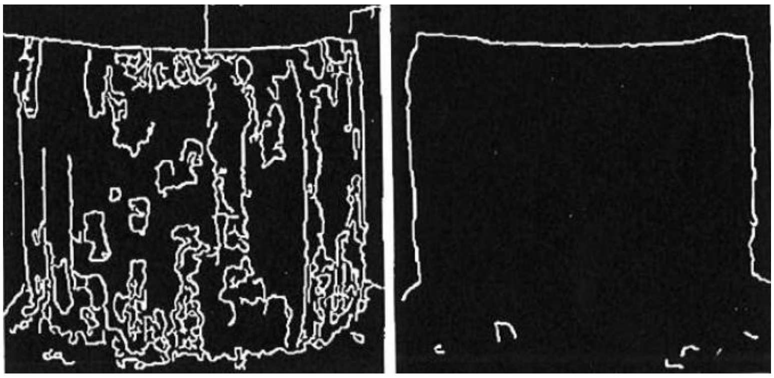

Fig. 2-2 Comparison of the forging image processed by Canny edge operator (left), and the proposed segmentation method (right) [15].

The heat haze and air lens surrounding the hot object can affect the accuracy of the measurement of the hot object due to light refraction (Fig. 2-3) [16–19]. All authors dealing with this effect admit that it is hard to obtain accurate boundary conditions for the computation (air temperature, pressure, humidity, airflow, and so on). The experiment presented by [17] also showed high deviations of the developed model. Therefore, the solution to reduce this effect can be a forced airflow system [19] or a suitable placement of the measurement device [18]. However, the works show a relatively small effect of this phenomenon, on the order of tenths of a percent [17] or on the order of tens of μm [18,20], depending on the situation. Therefore, in most works dealing with forging measurement, the effect of heat haze and air lens is not examined, even in the case of very accurate measurements, e.g., [21].

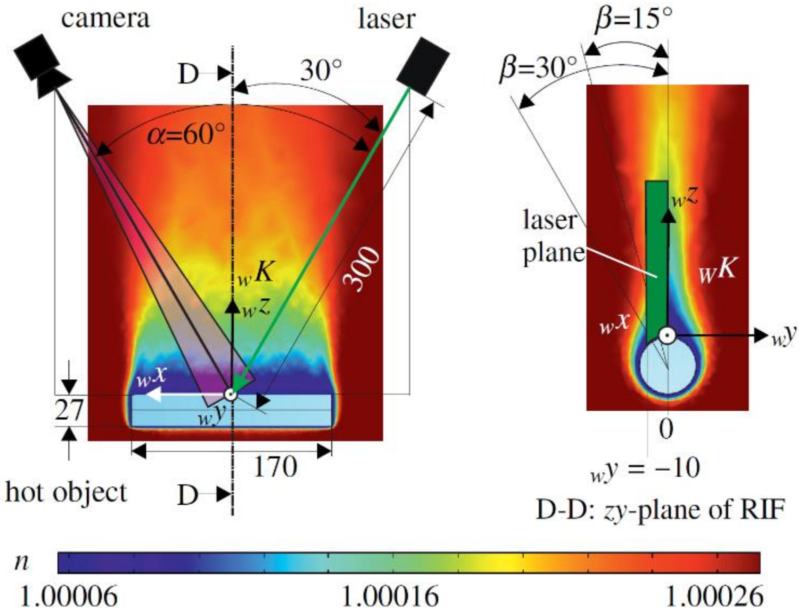

Fig. 2-3 Simulation layout (n is a local refractive index of air) [18].

The calibration methods of the forging measurement systems in the literature use a planar calibration field (e.g., [22–26]), a projected calibration field [27,28], or various manipulators [28,29]. These methods are difficult to use in large measurement volume, due to the large dimensions of calibration objects or for the industrial environment in general. Moreover, camera external parameters can change due to thermal dilations, causing significant error [20]. The solution can be a thermally controlled frame for mounting system components [20], or online calibration. For camera calibration in a large measurement volume, space resection can be used [7,8]. This method uses a field of coded calibration targets with known location and achieves high accuracies.

There are two main types of target coding, which can be distinguished – barcode type (Fig. 2-4 a, b, c) and coding based on unique element distribution [30,31] (Fig. 2-4 d, e). The barcode type can be distinguished to circular [6,32–37] or square designs [38–42]. The square target design is advantageous for machine vision or augmented reality applications, because one target codes four locations total (the target corners). On the other hand, the most common design of coded calibration targets in industrial photogrammetry, essential for calibrating the cameras, is the circular coded design (Fig. 2-4 a). This (or similar) design is used by many professional photogrammetric systems, including TRITOP (GOM), XJTUDP, Aicon Photogrammetry, and more. However, the circular coded calibration targets systems used for photogrammetric measurement can fail under demanding conditions [6,32–35,37], where the calibration targets could be damaged or occluded by scales falling from the forging surface. In various applications of machine vision, where the robustness of target recognition is essential, this problem is solved using error correction methods [40–42]. However, different target designs are used.

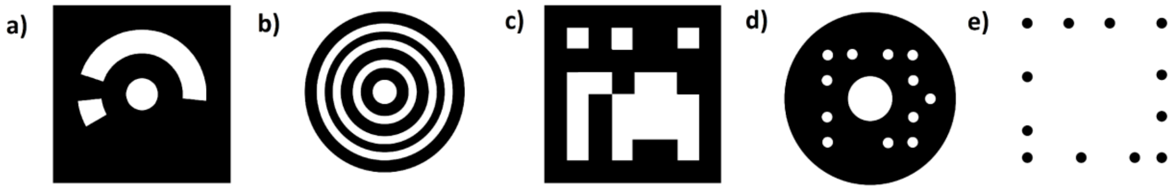

Fig. 2-4 Different designs of coded targets (schematic) – a) TRITOP (GOM); b) Calvet, 2016; c) Garrido-Jurado 2014; d) Ahn, 2001; e) Bergamasco, 2013.

2.2 APPLICABLE APPROACHES

2.2.1 Active measurement systems

The only measurement method that is not significantly affected by the specific environment is laser scanning [11,43–45]. Therefore, no special countermeasures to interference effects were introduced in the literature. The best accuracy reported in the literature is 0.5 mm for the measurement of the concentricity of cylindrical objects with up to 900 mm in diameter [43] or ± 1 mm for the measurement of the forging diameter of 2800 mm [45]. In this case, however, the scanned points were validated based on forging passive silhouettes measurement method. The laser scanning method is also commercially applied (e.g., LaCam Forge for the measurement of forgings up to 28 m long, Fig. 2-5) [46]. The disadvantages of this approach are the high price of the sensor, the poorer accuracy in the case of measuring the length characteristics of the object, and relatively long scanning times (on the order of tens of seconds [46]), during which the forging must be held still.

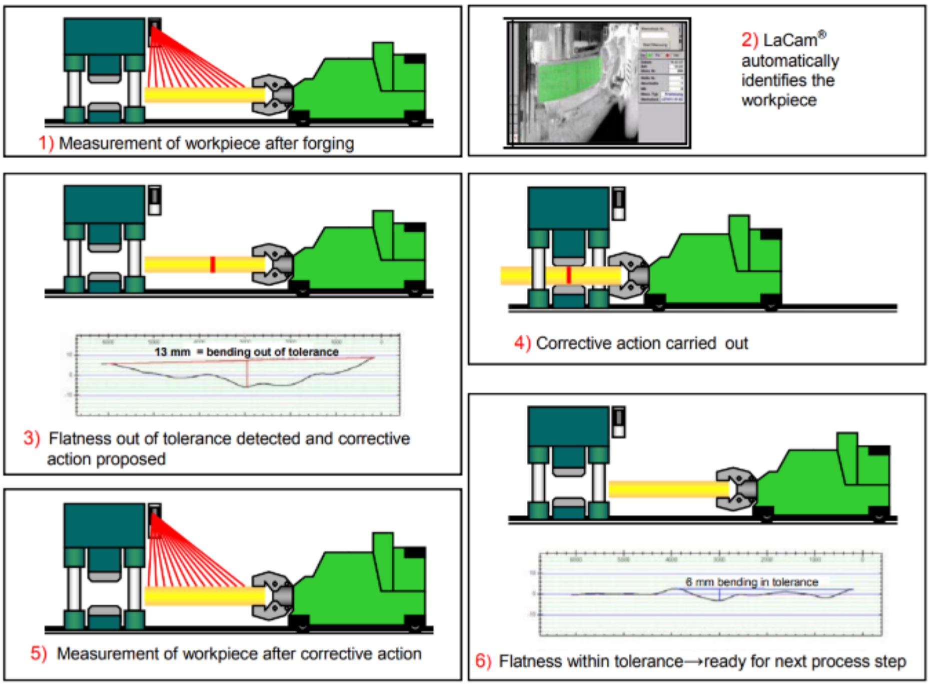

Fig. 2-5 Correction of axis straightness using LaCam® Forge by Ferrotron [46].

The remaining active methods are based on active, close-range photogrammetry. All of the mentioned methods are affected by the thermal radiation of the forging, which resulted in the need for a spectral-selective method (used in all cases in the literature). For fringe projection, many methods have been developed, which make this approach perform better during the measurement of hot objects. This includes the filtering method to suppress high-frequency noise [24], quality metric [47], adapted fringe projection sequences [21,48] and the prediction method to suppress unstable thermal radiation during image acquisition [48]. In case of active stereo vision, an evaluation method using subpixel detection of the projected feature lines based on the modified Gaussian [22] or Weibull distribution [23] function, or a specialized camera calibration method were developed [28]. In the case of the laser triangulation technique, the difference imaging method was developed to improve SNR [29]. Both the fringe projection [21] and laser triangulation [20,49] methods achieved implementation on forging lines. In these cases, the reported accuracy was 0.11 mm on a 1.9 m dimension in case of fringe projection system [21] and, in different case, 9 μm in case of 800 mm wide measurement volume (in case of calibrated ceramic plates measurement) [20]. However, these principles have relatively small measurement volume, or are able to measure dimensions only in cross section [29,50], and therefore specimen manipulators or a robot system to move the sensor are needed (e.g., Fig. 2-6). This increases measurement time and decreases the potential for implementation of these systems in certain applications in an industrial environment, including on-site heavy forging measurement.

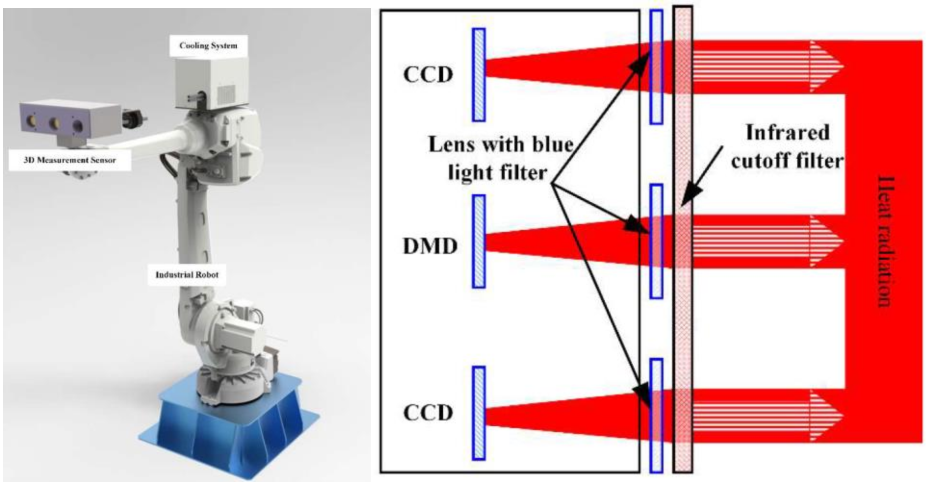

Fig. 2-6 Left - robot-driven fringe projection measurement system, right – sensor setup with a projector, 2 CCD cameras and dual optical filter [21].

Another active method, which could be used to measure the dimensions of heavy forgings, is based on active stereo vision [22,23,27,51,52]. A concept of active stereo vision with 8.6 m wide measurement volume was introduced (Fig. 2-7) [27], however, the accuracy of this system in these conditions was not verified. The system needed high-powerful light sources (1000 mW line lasers) and only a sparse point cloud was obtained. The best accuracy achieved by this method was 0.3% during the measurement of a hot object with dimensions of approx. 100 mm and a temperature of 1250 ° C under laboratory conditions [51].

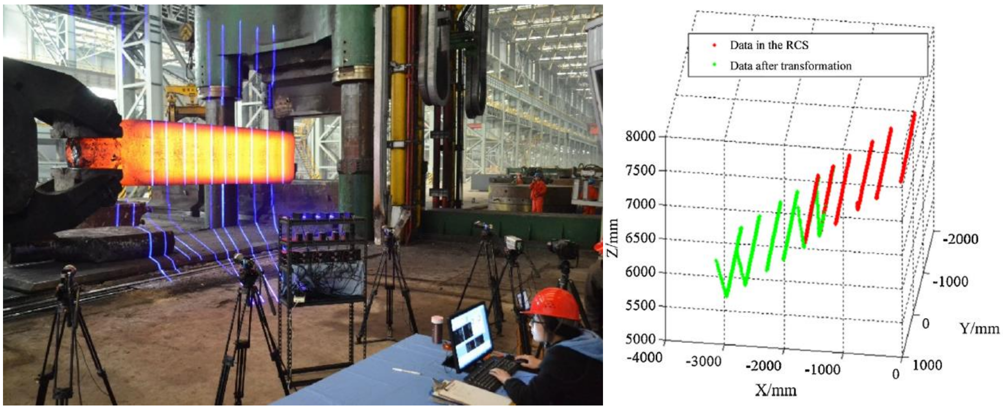

Fig. 2-7 Left – measurement system based on two stereo pairs, right – sample measurement result [27].

2.2.2 Passive measurement systems

Passive measurement methods for forging measurement include passive stereo vision and measurement based on forging silhouettes. Both methods can be used for accurate measurement of objects with contrasting surface structures or boundaries. For stereo vision, the object was illuminated by an external light source and a spectral selective method was used [53,54]. Standard methods of detection of feature points (Harris corner detector or SIFT) were used. For forging measurements based on their silhouettes, the 2D [25,55] and 3D [1,26,56,57] systems were used. In all cases, edge detection was reported as a challenge (resulting in corrupted edges as in Fig. 2-8). These methods in the literature were based on edge detectors with certain modifications [15], voting principle using the Hough transform [26], weighted variance to reveal measurement with low level of trust [25] or gradient in the image, and edge validation principles by using the surroundings or connectivity of edge points [1]. The cameras were calibrated using Zhang’s method [26] or basic space resection [1]. The 3D reconstruction method was based on the triangulation of feature lines (able to measure straight lines only) [26], or the transformation of the silhouette geometry into the object planes bounded to the positions of V-prisms (Fig. 2-9) [1]. The stereovision method was demonstrated in an industrial environment (Fig. 2-10). However, the accuracy was not studied [53]; different study examines the accuracy of stereo vision in a simulated environment, achieving a relative accuracy of 0.5% [54]. Moreover, 3D reconstruction could be sparse and depends on the forging surface texture. The accuracy of the measurement of 3D silhouettes varied from 0.8 (line triangulation) [26] to 2% (approach presented in [1]). In case of line triangulation, the experiment was carried out in industrial environment, however, in the other case, the experiment was carried out only in laboratory conditions.

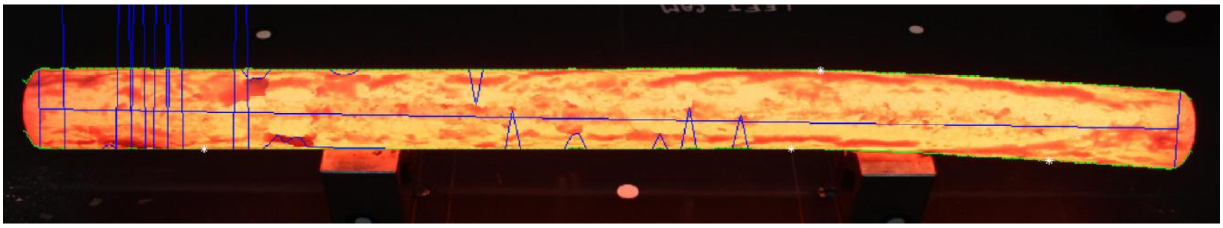

Fig. 2-8 The section of the measurement image with the edges; edges before and after the validation are marked blue and green, respectively [58].

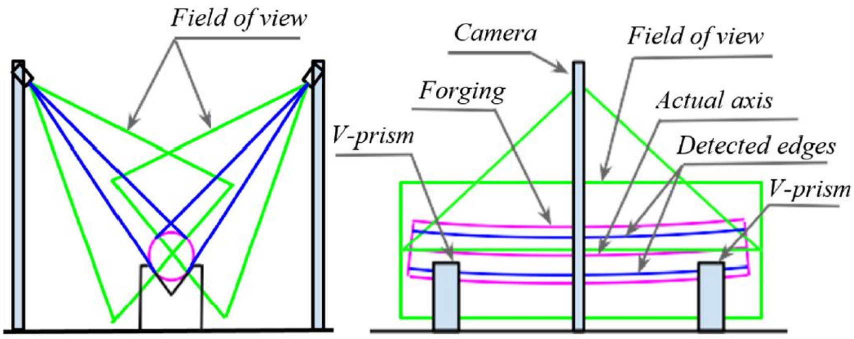

Fig. 2-9 The concept of a two-camera system for the measurement of heavy forgings [1].

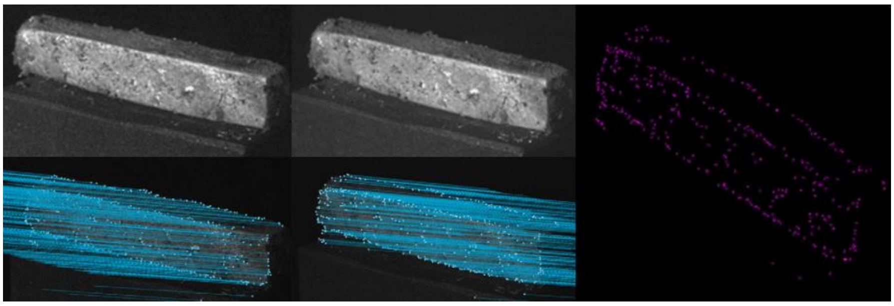

Fig. 2-10 Left – stereo images with corresponding feature points (marked blue); right – resulting 3D reconstruction of the object [53].

3 SUMMARY AND CONCLUSION OF STATE OF THE ART

- Active forging measurement methods showed a high level of development, but also disadvantages such as limited measurement volume or relatively long scanning times. The 3D forging measurement, based on its silhouettes, was chosen as a subject of this study. This approach showed both the potential to overcome the disadvantages of active methods and a low level of development in this area.
- The passive measurement method achieved limited accuracy in the literature. It is not clear whether the reason is the implementation of basic methods in studies dealing with this problem or the effect of the interfering effect of the environment. Moreover, this approach was not verified in large-scale industrial conditions, where the character of the scene (scales size and contrast, background complexity, etc.) could be radically different.
- The main challenge of passive forging measurement is edge detection, which is different due to scales. It is not clear whether more advanced edge detection methods, with subpixel accuracy, would help achieve a lower measurement error or whether the potentially higher accuracy will be dominated by the negative effect of contrasting scales or forging background.
- Heat haze and air lens can have a negative effect on measurement accuracy. However, this effect is complicated to compensate for or suppress in a large measurement volume. This effect is also neglected in most works, including those in which high accuracies were achieved. However, it is not clear how this effect would affect the passive measurement method on a large scale.
- Space resection appears to be the suitable camera calibration method for a large measurement volume. This method can also be carried out online to compensate for the unstable environment. However, this method usually works with circular coded targets in photogrammetry applications, which recognition can fail in demanding conditions. It is not clear how to enhance their recognition robustness. A possible solution could be the method of error correction method used for target recognition in machine vision applications.
- The verification of the accuracy of the measurement system in an industrial environment is a challenge, which is not considered in many studies. Possible solutions to examine the accuracy of the system used in the literature can be the analysis of the accuracy indicators of the system (reprojection error [8], variance of redundant measurement results [47]), objects with known dimensions [20], evaluation of the repeatability of the measurement [21], or comparison with an individual measurement method [29,50]. This can be, for example, laser scanning, which is not significantly affected by the interfering effects of the environment. However, based on the literature, it does not achieve sufficient accuracy to measure the reference dimensions.

4 AIM OF THESIS

During open-die forging, the shape and dimensional inaccuracies of heavy forgings need to be measured for their subsequent correction. This includes the measurement of length, diameter, and most importantly, the axis straightness. A review of the literature suggests the potential of a measurement method based on imaging of forging silhouettes in this application. However, this method showed a low level of development in this area. Therefore, the method achieved limited accuracy during the experiments. **The main goal of this thesis is to examine the properties and limits of the measurement approach based on object silhouettes in the industrial environment, during the measurement of heavy forgings. It is clear that original methods must be implemented to achieve high accuracy and reliability of the measurement system. These methods distinguish the proposed system from similar measurement systems based on the same principle. These methods and the study of their behavior represent the main novelty of the work.**

The goal is therefore achieved through the research, development, and systematic evaluation of the original or existing methods of optical measurement. The evaluation is carried out based on experimental data from both laboratory and industrial conditions. The interfering effects of the industrial environment are examined and resolved. The global contribution of this work is the original knowledge that brings the passive forging measurement method closer to implementation in the industrial environment. The work is a combination of applied research and experimental development. The specific subobjectives of research and development, based on the result of the literature review, are as follows:

- Objective 1: Research on the application of error correction method for circular coded targets used for camera calibration of the measurement system, to achieve reliable camera calibration in industrial environment.
- Objective 2: Development of calibration method for the cameras of the measurement system based on space resection, allowing on-line camera calibration to prevent the influence of dimensionally unstable environment.
- Objective 3: Research on the accurate edge detection method for the measurement of forging silhouettes, which can be corrupted by contrasting scales or background.
- Objective 4: Development of the forging silhouette measurement system, study of its precision in the industrial environment, and its comparison with independent comparative measurement method to demonstrate its feasibility.

4.1 SCIENTIFIC QUESTION AND HYPOTHESES

As mentioned above, the thesis is a combination of applied research and experimental development. There are two research objectives (Objective 1 and Objective 3 in this order), which can be expressed using the following scientific questions and hypotheses:

- Question 1: How to implement error correction method in cyclic codes decoding of circular coded targets, used for camera calibration?
    - Hypothesis 1: The error correction method could use optimized target code library and a rotation-invariant distance between the scanned code and a code in the lookup table.
    - Reason: This error correction approach is implemented in a target system ArUco [40]. This system is used for augmented reality or machine vision applications and works with a square target design. The optimization of the target library and the error correction method during target recognition help the target system achieve high robustness, although without increasing the target confusion rate.
- Question 2: How to suppress corrupted edges during silhouette measurement?
    - Hypothesis 2: The weights, expressing the level of edge corruption, could be based on complementary information from the image, such as edge gradient magnitude and direction.
    - Reason: Based on forging images, published e.g., in [1], it can be assumed that the most correct forging edges have a strong magnitude and gradient direction perpendicular to the forging axis. On the other hand, corrupted edges have a weaker magnitude and random direction. The corrupted edges could then be suppressed using weighted edge filtering.

4.2 THESIS LAYOUT

The thesis is composed of three articles in journals with impact factor (Paper A, C, and D), and, in addition, one conference paper indexed in Web of Science database (Paper B). The conference paper is not a primary part of the thesis. However, it covers one of the important experimental parts and connects the individual topics covered in this thesis. The papers cover the Objectives of research and development identified in Section 4.1 via bullets. These topics are essential to resolve to achieve the main goal. In paper A, an original circular coded target system, for accurate camera calibration in demanding conditions, is proposed. The scientific Question 1, which deals with the error correction method of cyclic codes, is solved in this article. In Paper B, the camera calibration method is developed for the calibration of cameras of the system. The method uses the mentioned calibration targets and is verified under industrial conditions, including the examination of the effect of the air lens. In paper C, the subpixel edge detection with weighted filtering is proposed, and the scientific Question 2 is answered. The Paper D deals with the development and verification of the multi-camera and multi-view measurement method, which is based on the acquired knowledge and fulfills the main goal of the thesis.

A. J. HURNÍK, A. ZATOČILOVÁ and D. PALOUŠEK. Circular coded target system for industrial applications. *Machine Vision and Applications*. 2021, **32**(1), 1–14. ISSN 14321769. Available at: doi:10.1007/s00138-020-01159-1

Journal impact factor: 2.983 (2021, WoS), *Author's contribution 75%.*

B. J. HURNÍK, A. ZATOČILOVÁ and D. PALOUŠEK. Camera calibration method of optical system for large field measurement of hot forgings in heavy industry. In: *Opt. Meas. Syst. Ind. Inspect. XI, Proc. SPIE*. 2019, p. 11056. Available at: doi:10.1117/12.2527693

Journal impact factor: -, *Author's contribution 65%.*

C. J. HURNÍK, A. ZATOČILOVÁ, D. KOUTNÝ and D. PALOUŠEK. Enhancing the accuracy of forging measurement using silhouettes in images. *Measurement*. 2022, **194**(September 2021), 111059. ISSN 02632241. Available at: doi:10.1016/j.measurement.2022.111059

Journal impact factor: 5.131 (2021, WoS), *Author's contribution 60%.*

D. J. HURNÍK, A. ZATOČILOVÁ, T. KONEČNÁ and P. ŠTARHA. Multi-view camera system for measurement of heavy forgings. The International Journal of Advanced Manufacturing Technology. 2022, ISSN 02683768. Available at: doi: 10.1007/s00170-022-09809-6

Journal impact factor: 3.563 (2021, WoS), *Author's contribution 50%.*

5 MATERIALS AND METHODS

5.1 MEASUREMENT SYSTEM PRINCIPLE

The principle of forging measurement, utilized and developed in this work, was its 3D passive measurement, based on its silhouettes. The system worked with two or more cameras facing the center of gravity of the forging. The basic principle of such a system is depicted in Fig. 5-1. Based on calibrated camera projection model, the principle uses the projection rays of silhouette points from the image to space. Using 2 or more cameras, a circular object cross section can be determined. Objects with different cross sections can also be measured. However, the precondition is the convex cross section of the object.

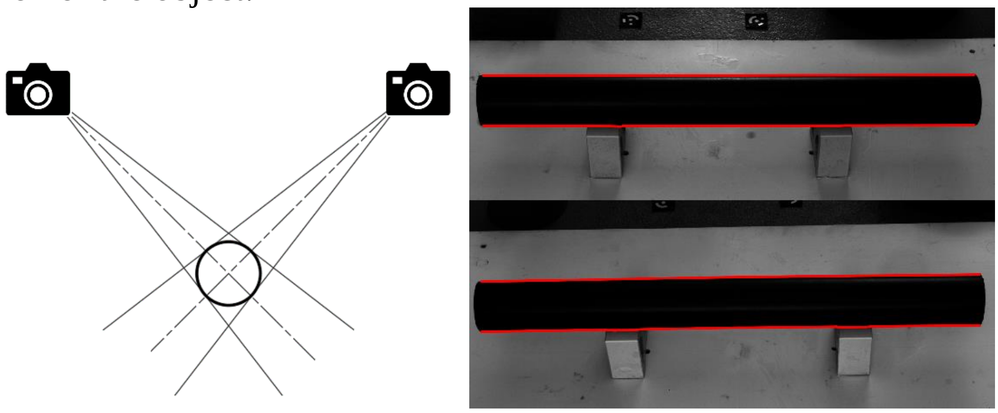

Fig. 5-1 Left - basic principle of a camera measurement system; right – example measurement images from the cameras of the system.

The measurement system workflow is provided in Fig. 5-2. The main input was the measurement images. There were two main parallel branches of the algorithm. The first was camera calibration. The first step was the coded target location in the image and their identification. Based on the target identification codes, the target coordinates in the space were associated with the target coordinates in the image. These data, together with the interior camera parameters, were the inputs to the exterior camera parameters calibration process. Both coded target coordinates in space and interior camera parameters were obtained during or before the installation of the system on-site. The other branch dealt with the silhouette extraction and object measurement itself. At first, the object was roughly segmented in the image and expected edge locations were obtained. The edges were then located using the zero-crossing subpixel edge detection method. To remove the influence of corrupted edges, the axis imprint and the edges were filtered. Based on the filtered edges and the camera parameters, the object geometry was calculated using the triangulation principle. The geometry was then aligned using two short regions on the forging ends. The geometrical characteristics of the forging, including forging length, diameter, circularity, axis straightness, maximum deflection, and its position, were then determined.

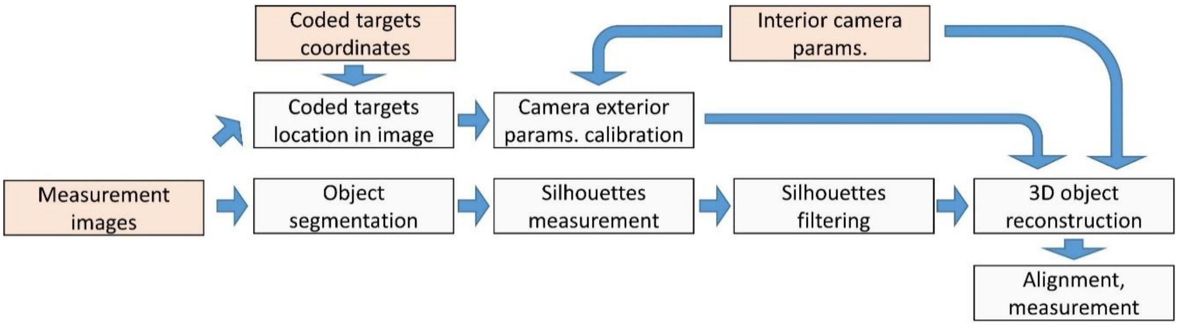

Fig. 5-2 Measurement system workflow (inputs marked red).

5.2 PROPOSED METHODS TO ENHANCE SYSTEM ROBUSTNESS

To ensure the robustness of the system, the interfering effect of the industrial environment was identified, and the original countermeasures are introduced. These proposed features distinguish the proposed measurement system from the usual measurement systems based on silhouette measurement and represent the novelty in this thesis.

- Thermally and dimensionally unstable industrial environment, large measurement volume:
  - To ensure the high robustness of the target system, used for camera calibration in an industrial environment, the error correction method was introduced. The code library generator was implemented to create a code library with optimized properties. This included the rotation invariant distance between the targets in the library, to lower the target confusion rate, and the number of bit transitions, to lower the confusion rate between the targets and the objects in the environment. The error correction method then took advantage of the large distance between the codes in the library to recognize damaged codes. This was carried out based on the rotation invariant distance threshold, which was based on the distance between the codes in the code library. On the other hand, by using the target code recognition threshold, a higher confusion rate of the targets with random objects in the environment could be expected. Therefore, the similarity condition was introduced, which processed the scanned target code, based on the expected normal distribution of black and white target segments. In addition, robust target segmentation, code scanning, and accurate target location methods were implemented. These methods are described in detail in **Publication A.**
  - Camera calibration was based on the space resection method, which worked with a 3D calibration field of robust circular coded targets. Target coordinates are accurately measured using the TRITOP (GOM) professional photogrammetric system. The method consisted of single-

image, on-line camera exterior and multi-image, off-line camera interior parameters calibration. Online calibration was implemented to compensate for the dimensionally unstable environment. Moreover, to ensure stable intrinsic parameters of the camera, the cameras were placed in thermoregulated covers. The camera calibration method was described in detail in **Publication B**.

- Potentially low forging contrast in the image:
  - Based on the literature, forging contrast can be enhanced by using color filters. Red color filters were empirically chosen to enhance the forging contrast.
- Air lens and heat haze:
  - According to the literature review, the effect of air lens and heat haze cannot be easily compensated both physically (by using forced air flow, which is problematic in large measurement volume) and based on simulation (problem with boundary conditions). Therefore, in this work, the influence was minimized by suitable placement of the cameras (outside the hot air area) and by using red spectrum, to minimize the refraction.
- Forging segmentation in a complex environment:
  - Forging edges can be corrupted by contrast scales on the forging surface. Moreover, contrasting objects can appear near the forging in the scene. Major differences in brightness on the forging surface can be expected. Therefore, standard segmentation methods based on edge operators or thresholding fail. A specialized segmentation method was proposed. This segmentation method was based on the assumption that the approximate forging orientation and diameter are known. Therefore, the method worked as a filter sensitive to horizontal objects of a certain size. The method used the Sobel edge operator, morphological operations, dual threshold, and voting principle (Hough transform) to find the most probable forging axis and silhouettes in the image. The details of this method were described in **Publication C**. In the future, this method can be replaced by a more robust segmentation method based on neural networks.
- Corrupted edge points by scales on the forging surface or background:
  - According to the cylindrical forging images presented in the literature, it can be assumed that a correct edge has a strong gradient oriented perpendicular to forging axis. On the other hand, it can be assumed that the corrupted edge has a weaker gradient and an arbitrary orientation. Corrupt edges can have a major influence on measurement precision, mainly in the case of subpixel edge detection accuracy. Therefore, weighted edge filtering was implemented, based on these quality measures. Various combinations of these quality measures were

experimentally compared. The details of this method were described in **Publication C**.

- Effect of insufficient forging circularity:
    - In case of insufficient forging circularity and measurement with two cameras, major errors of the forging axis or diameter can appear. Normally, this problem is solved by using a large number of cameras; however, it is not possible in the industrial environment, where the possibilities of camera placement are limited. Therefore, a three-camera and multi-view measurement (utilizing an accurate forging press manipulator, used to accurately rotate the forging around its axis) was proposed. Details of these methods are presented in **Publication D**.

5.3 MEASUREMENT SYSTEM HARDWARE

The hardware of the measurement system consisted of a set-up of 2 or 3 cameras. To achieve high precision, high-resolution monochromatic cameras ZWO ASI 1600MM (Pro) were used. These cameras are equipped with a 4/3 ” CMOS Panasonic MN34230 sensor. The resolution is 4656 × 3520 px (16 Mpx), and the pixel size is therefore 3.8 μm. The cameras were equipped with industrial grade Zeiss Interlock Compact objectives. Different focal lengths were used in the industrial environment to compensate for the different camera distances from the object (due to the plant layout). No special experimental stand was needed; the cameras were directly mounted on supporting constructions of the forge, or, in the laboratory, they were placed on tripods. In the laboratory, the objectives were equipped with Haida UV+IR cut filters (390 – 750 nm). In the industrial environment, the cameras were protected by specialized thermos-regulated camera covers (Fig. 5-3). The temperature in the camera covers was controlled using a Ranque-Hilsch vortex tube. Bandpass filters Schneider-Kreuznach BP 680–100 HT were chosen based on empirical findings. The camera layout in both industrial and laboratory environments (initial experiments) is provided in Fig. 5-4 and Tab. 1. The final laboratory experiment simulated the camera layout in the industrial environment; however, the dimensions were scaled (decreased) approximately 7 ×. The measurement volumes were designed for 0.5 and 4 m long objects in the laboratory and industrial environment, respectively.

Fig. 5-3 Thermoregulated camera cover.

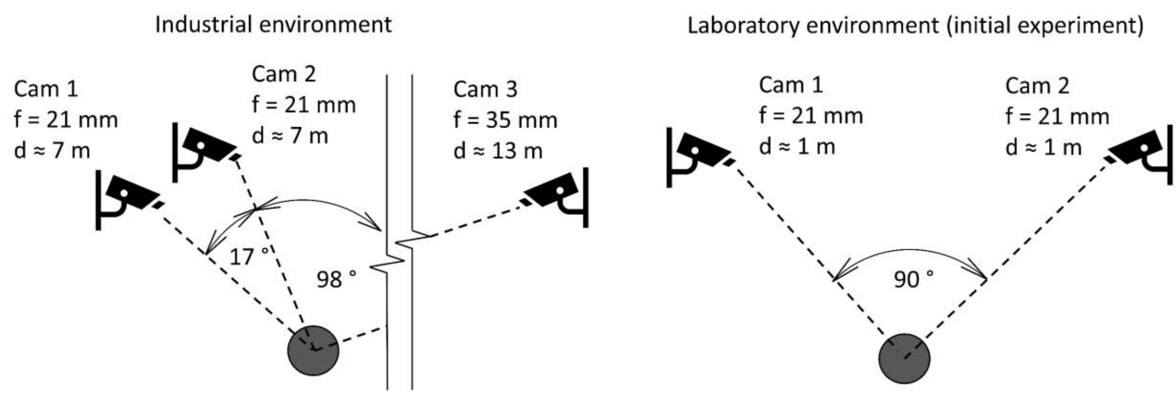

Fig. 5-4 Layout of the camera system in laboratory and industrial conditions.

Tab. 1 Detailed information about the camera system.

Industrial environment		
	Camera 1, 2	**Camera 3**
Focal length	21 mm	35 mm
Mutual FoV	Approx. 6 × 6 × 2 m	
Pixel equivalent	Approx. 1.29 mm	
Laboratory environment (initial experiment)		
	Camera 1, 2	
Focal length	21 mm	
Field of view	0.8 × 0.8 × 0.3 m	
Pixel equivalent	0.17 mm	

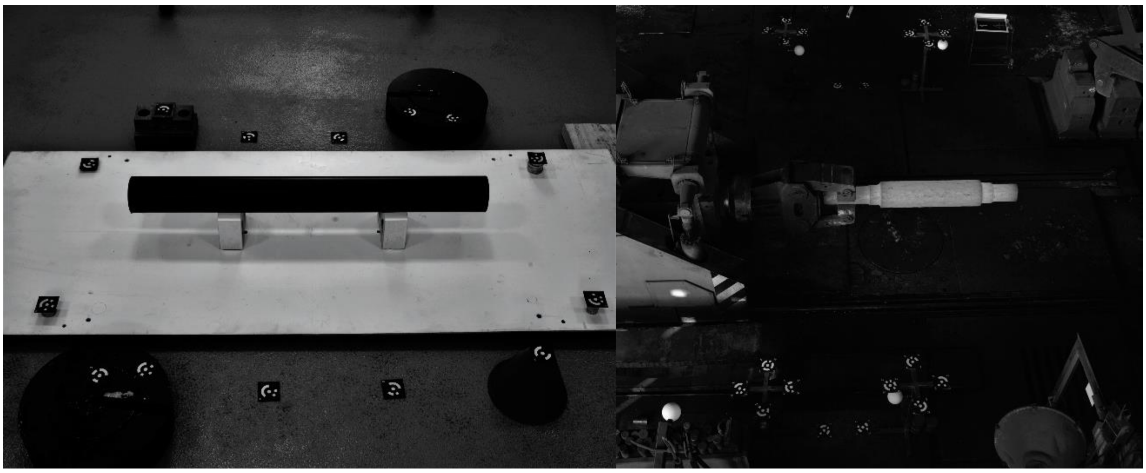

Fig. 5-5 Sample measurement image from the laboratory (left) and industrial environment (right); the images are adjusted and cropped.

The measured objects in the laboratory were steel pipes with 500 mm length, 50 mm diameter, and approx. 1 mm deflection (3 total). Repeated measurements of this object were carried out, with arbitrary object rotation around its axis. In case of measurement in an industrial environment, the measured objects were cylindrical forgings with fittings, a length of approx. 1.9 m, a maximum diameter of approx. 300 mm, and a surface temperature around 1000 ° C.

5.4 REFERENCE GEOMETRY AND COMPARATIVE MEASUREMENT

To estimate the accuracy of the measurement system, the reference geometry of the samples in the laboratory was obtained using a professional 3D scanner ATOS III TripleScan 8M (GOM). The scanner was used in the MV560 configuration. The scanner works on the principle of fringe projection. According to VDI/VDE 2634 the measurement accuracy is in the order of thousandths of millimeters. However, in the industrial environment, a reference cannot be obtained. Therefore, to demonstrate the feasibility of the proposed methods, a comparison with independent, comparative method was used. Based on the literature, laser scanning was chosen. FARO Focus 3D S 120 professional laser scanners were used. The object was measured from both sides simultaneously. The scans were registered based on sphere targets placed in the scene. The result of both measurement methods is 3D point clouds, which were processed and evaluated using GOM Inspect software.

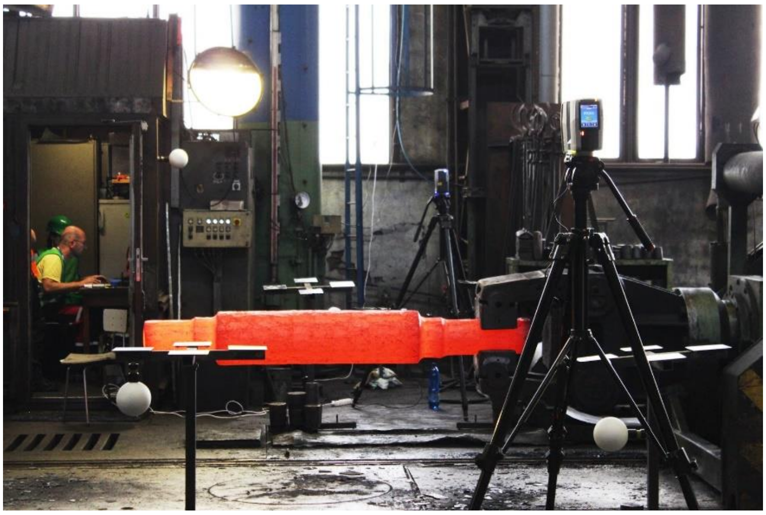

Fig. 5-6 Comparative forging measurement using laser scanners.

5.5 TARGET SYSTEM BENCHMARK

To verify the properties of the target system, a benchmark was introduced. Basic input target images were modified by image processing methods to simulate code damage and selected negative image effects, including image scale, observation angle, image noise, or image blur:

- Code damage: image scale 0.9, 0 – 7.5 bits occluded with a patch of random intensity.
- Image scale: 0.05 – 1.
- Image blur: image scale 0.9, convolution with Gaussian kernel with σ = 0 – 8.
- Image noise: image scale 0.9, additive noise with σ = 0 – 0.4.
- Observation angle: image scale 0.9, simulated angle extent 2 – 90°.

The sample cuts from the datasets are provided in Fig. 5-7. The mentioned intervals contained 100 samples. The effectiveness of the proposed methods was evaluated based on precision p, recall r, and their harmonic mean F:

$$F = 2\frac{p \cdot r}{p + r}; p = \frac{tp}{tp + fp}; r = \frac{tp}{tp + fn} \quad (5.1)$$

Where tp, fp and fn stand for number of true positive, false positive and false negative cases, respectively [40].

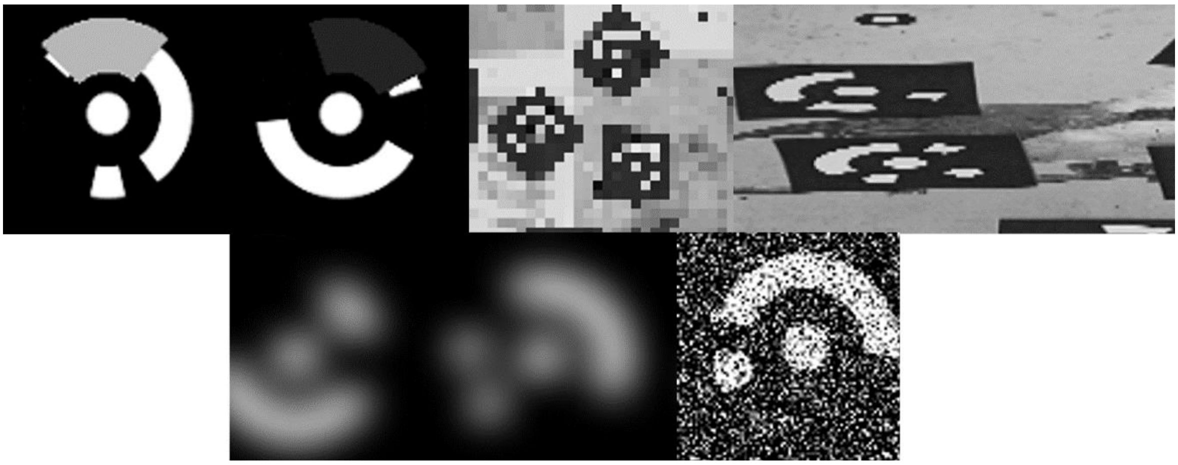

Fig. 5-7 Examples of corrupted targets from the datasets.

6 RESULTS AND DISCUSSION

The section Results and Discussion is arranged according to the workflow of the measurement system methods. This section mainly introduces, summarizes, and links the findings of the attached Papers A, B, C, and D. The content of the papers is as follows:

- Paper A: Enhancing the robustness of the circular coded target system for camera calibration; research on the error correction of the cyclic codes; solution of Objective 1, scientific Question 1, and Hypothesis 1.
- Paper B: Development of the camera calibration method of the forging measurement system cameras; its verification in the industrial environment; solution of Objective 2.
- Paper C: Research on the accurate forging edge detection method; Solution of Objective 3, scientific Question 2, and Hypothesis 2.
- Paper D: Development of the forging measurement system; demonstration of its feasibility in the industrial environment; solution of Objective 4.

Paper A dealt with the robustness of the circular coded target system. A circular coded target system for industrial applications was developed (further called ICCT, industrial circular coded target system). By using the code library generator, a library of 60 fifteen-bit target codes was generated. The minimum distance between the codes in the library was 3. Therefore, the error correction can theoretically withstand up to 1 bit completely changed or 2 bits occluded or damaged. In addition, other methods were proposed to make the system more robust to common image effects. The proposed methods were verified based on a target system benchmark and compared with the circular coded target system proposed in [35] (further SA, state-of-the-art), TRITOP (GOM) target system and ArUco [40] target system.

The experimental verification of the robustness of the target system to code occlusion up to the area equivalent of 2 bit segments was performed. The results showed excellent ICCT performance (recall over 0.9) up to an occluded area of approx. 1.5 bits equivalent, where the probability of recognition rapidly decreased. On the other hand, the precision in the whole interval was exactly 1. The results are in accordance with the assumptions because the target damage behaves likely like occlusion (unknown value); thanks to the similarity condition; the probability of code confusion is low. The advantage of this error correction method was demonstrated against the compared target systems, which ICCT overperformed. The recall of the other compared target systems began to rapidly decrease immediately. The exception was the ArUco target system, which recall decreased approximately linearly. This effect occurred despite the fact that this system used error correction. However, this was apparently the effect of using the same code occlusion path for circular coded and ArUco target systems. Moreover, the occlusion of the target code was studied up to the occlusion area of 7.5 bit segments, to study the precision of the target system. ICCT and the target system presented in [35] showed a similar precision of approx. 0.97, while the TRITOP and ArUco did not show any target confusion at all. Although the values were close, the confusions can be problematic in some applications. However, in case of ICCT, this was compensated by a significantly higher recall compared with the other circular coded target systems. The comparison with ArUco, which achieved absolute precision despite its error correction feature, was again problematic, due to the use of the same patch for both target systems, which used a different design.

The response of ICCT on the image scale and observation angle showed that the proposed target system was capable of identifying targets with a center diameter as low as 3 px and observation angles as low as 7°. The results were comparable to those of the ArUco system in both cases. From the other circular coded target systems examined, TRITOP achieved better results and managed to recognize comparable small targets, but its observation angle limit was 27°. The proposed excellent target performance was achieved thanks to target segmentation based on Canny edge operator with upscale, to provide more smooth results, and robust sorting method based on ellipse fitting. Regarding image blur, the best results were achieved by TRITOP. ICCT and SA are both based on a Canny edge detector, which performs poorly under a high level of blur. A heavy drop in target recall was recorded around $\sigma = 4$. The worst result in this data set was achieved by ArUco (a heavy drop around $\sigma = 2.5$). On the other hand, TRITOP target system proved to be sensitive to image noise. ICCT and SA were less sensitive and ArUco achieved the best results. However, this problem was caused by the segmentation method, based on the Canny edge operator. By increasing σ input of the Canny operator, the target segmentation became significantly more robust, overperforming ArUco target system.

Overall, the proposed target system was evaluated as effective, overperforming the compared target systems in occlusion up to area of 2 bits, offering great performance both on scale and observation angle datasets (comparable to ArUco and overall overperforming both SA and TRITOP) and offering great robustness to both image blur and noise (overperforming AruCo and performing comparably with SA; TRITOP system proved great results on Blur dataset, however, performed poorly under image noise). The proposed ICCT target system was also verified by application in the heavy industry environment to calibrate cameras of a forging measurement system. Future studies could include improving the target library generator, by implementing an optimization method to find an optimum set of calibration target codes (similarly to [41]), and further minor improvements in the recognition algorithm.

In **Paper B**, the calibration method for the cameras of the forging measurement system was proposed. This method was based on space resection and used a circular coded target system, presented in Paper A. The method worked in two steps, allowing the on-line camera exterior parameters calibration to compensate for small camera movements. The calibration accuracy was verified under both laboratory (meas. volume approx. $1.5 \times 1.5 \times 0.5$ m) and industrial conditions (meas. volume approx. $6 \times 6 \times 1.5$ m). In both cases, the reprojection error was below 0.1 px, which was close to the value observed in [8]. The assumed error of camera calibration on silhouettes reconstruction in laboratory and industrial environment was 0.03 and 0.24 mm, respectively. This result was evaluated as satisfactory. The effect of hot atmosphere and air lens surrounding the forging was also examined. Based on the results, the reprojection error increased up to 2.5 × both in the laboratory and industrial environment. The increase in the reprojection error was approximately in agreement with the results presented in [17] (in both cases in thousandths of percent, although different air lens shapes were present). Therefore, this effect was considered as clarified and was not further studied. An alternative way of camera calibration was proposed – the cameras could be calibrated shortly before the forging is placed in the scene, to prevent the influence of air lens and heat haze. Future studies could focus on the implementation of the camera calibration method based on epipolar geometry.

The focus of **Paper C** was the development of an edge detection method for the measurement of forgings, based on their silhouettes. The main idea was to use the subpixel edge detection method and subsequent filtering based on complementary information about the edge quality measures from the image. To verify the effectiveness of the proposed methods, the developed method was compared with the method presented in [1], which used edge detection with pixel precision and uniform weight filtering. The experiment was carried out in both the laboratory and the industrial environment (two-camera system).

The first finding was the confirmation of the advantage of subpixel edge detection in both the laboratory and industrial environment. The median error decreased in both cases by approx. 50% and 30% in the case of axis straightness measurement and object diameter measurement, respectively, compared to edge detection with pixel precision. A higher improvement could be expected (the accuracy of the subpixel edge detection method utilized is up to 1/100 px). However, this subpixel accuracy can be achieved in an ideal image. The lower increasement of accuracy can be explained as the effect of non-ideal edge contrast and object circularity in the laboratory environment, edge disturbances and heat haze in the industrial environment, and camera calibration error or minor simplification in the case of 3D geometry reconstruction method in both cases.

Regarding the filtering method, it was found that edge and axis filtering in the laboratory environment does not offer any improvements due to uniform edge contrast and no significant local edge disturbances. However, in an industrial environment, where strong local edge disturbances appeared, filtering helped reduce the axis measurement sigma error by 53% and the maximum error by 77%. The improvement was significantly lower for the diameter measurement (sigma by 7% and maximum error by 15%), due to the rapidly changing diameter along the forging axis. The advantage of the weighted filtering, based on the complementary information of the image, was then studied. It was found that in case of axis straightness, both edge gradient direction and magnitude can be used as weights, significantly overperforming the filtering with uniform weight. The best results were achieved by using edge weights based on the direction of the edge gradient. Compared to uniform weight filtering, the sigma error decreased by 34% and the maximum error by 64%. On the other hand, for the object diameter filtering, the weight based on edge gradient magnitude turned out to be the most advantageous, overperforming the uniform weight filter by 11% in the case of both axis straightness and maximum error. The lower improvement was also explained as an effect of the rapidly changing diameter along the forging axis.

Overall, the proposed methods achieved by a 50% lower sigma and by a 63% lower maximum error compared to the state-of-the-art method [1], in the case of axis measurement in industrial environment. However, the methods performed comparably in the case of forging dimeter measurement. This was explained again as the effect of rapidly changing forging diameter along its axis and the effect of a stronger diameter filter used in the case of the state-of-the-art method (moving average against weighted parabola fitting, although with windows of the same size). Finally, the precision achieved by the proposed methods in the industrial environment was ± 0.5 and ±1 mm for the measurement of the forging axis and diameter, respectively. Based on the pixel equivalent of these values, comparable values as in case of forging measurement in laboratory were achieved thanks to the proposed methods, suppressing the interfering effects of the industrial environment (despite the higher error of forging diameter measurement).

The above-mentioned results do not include the effect of potential poor forging circularity. By studying the repeatability of the measurement with rotation around the forging axis, an approx. three-times greater measurement error was recorded. In the case of forging axis measurement, the same trend of measurement error was recorded across the compared methods. Weighted filtering with weights based on edge gradient orientation performed the best, helping to suppress less representative edge segments. In the case of the measurement of the diameter of the forging, all compared methods performed similarly, showing that the advantages of more accurate methods are dominated by the effect of circularity of the forging. Therefore, future studies included the method of assembling more observations, from different viewpoints, in one measurement, achieving a better determination of the forging cross section.

The **Paper D** dealt with the further development and feasibility demonstration of the system for forging measurement. From the method point of view, the main novelty was the introduction of three-camera and multi-view observation measurement in this application, in order to solve the above-mentioned problem of a poorly determined forging cross section. In addition, the ability of the system to measure the circularity, based on forging silhouettes, was studied. Moreover, the obtained results of the proposed measurement method were verified by comparison with those of the independent measurement system (based on laser scanning). Such experiments have not yet been carried out and demonstrate the feasibility of the proposed measurement system.

The study of repeated measurements showed a high level of outliers in the case of forging diameter and circularity measurement. These outliers are the result of a rapidly changing forging diameter along its axis and an inaccurately defined forging origin. Therefore, 10% of the outliers were removed in the case of measuring the diameter and circularity of the forging in the further analyzes. The third (added) camera decreased the measurement error by 13 – 15%. Moreover, by using the multi-view method, a decrease of the measurement error with square root of the observation number was recorded, which is in correspondence with the global assumption. However, the best results were achieved when the observations were evenly distributed around the forging axis. For the rotation of the forging around its axis by 30° between observations, six observations were the most effective in determining the forging geometry. This was assumed based on significant drop in the measured repeatability error. This means that forging cross section deviations were not strictly random in dependence to their polar coordinates. The cross section rather showed limited complexity, and neighboring observations can therefore show systematic similarities. However, six observation measurement offered 64 – 71% lower measurement error compared to a single observation. Overall, the precision of a six-observation measurement was ±0.5 mm for the both forging axis straightness and diameter measurements (95% confidence interval). A different situation was recorded in the case of circularity measurement, where the result is calculated based on extremal values. Therefore, in case of low number of observations, a systematic error was observed. The systematic error was significant for up to 10 observations. However, in the case of 11 observations, the recorded error was ±0.6 mm (95% confidence interval including systematic error).

To demonstrate the feasibility of the proposed measurement system, it was compared with the laser scanning measuring technique. The results of axis measurement showed great agreement (95% confidence intervals overlap in 98.47% cases, with a mean difference of 0.04 mm). Approx. 50% of overlap was recorded in the case of the forging diameter and circularity measurement. The mean differences were 0.5 and 0.9 mm, respectively. However, this was explained partially as the effect of the outliers and partially as the possible influence of the air lens, which affects the camera system (operating around 680 nm wavelength) more than laser scanning device (operating at 905 nm). However, these numbers were within the point cloud registration error (the mean differences were on the same order). Moreover, the proposed and comparative laser scanning systems were compared from a measurement error point of view. The proposed system surpassed the laser scanning technique in four, six, and eleven observations in the case of forging axis, diameter, and circularity measurement, respectively. From the measurement time point of view, every observation lasted around 10 s. On the other hand, the laser scan was captured in five minutes; therefore, even in case of full 12 observations, the proposed camera system achieved shorter measurement time. However, both measurement techniques could be optimized to achieve significantly lower measurement times, negligible compared to the time of forging operation.

The overall influence of the interference effects was examined. Because previous experiments did not show significant systematic errors, the effect was studied by comparing the repeatability of the measurement under industrial and laboratory conditions (considered as ideal conditions). Comparing the recorded pixel equivalent of repeatability error, the overall influence of interfering effects present in the industrial environment has a significant, but not critical, effect on the random measurement error. The error increased approx. 5–6 ×, 3 × and 3 × in the case of the measurement of axis, diameter, and circularity, respectively (considering the case without outliers of 10%). Despite the increase, the single-observation error pixel equivalent remained under 1 px in the case of axis and diameter measurement. The circularity measurement error was higher; however, it was shown that more observations were needed to measure it accurately. It is also obvious that there are fewer outliers in the results obtained under laboratory conditions. This is supported by the finding that by removing the 10% outliers, the diameter and circularity measurement error did not decrease significantly in the case of laboratory measurements (0.042 vs. 0.033 mm in the case of sigma diameter error), compared to the industrial measurements (2.070 vs. 0.833 mm in the case of the same error).

The significant relative influence was recorded as a result of the high subpixel sensitivity of the measurement system. The possible cause, instead of the influence of interference effects, was a more complex geometry of the forging surface, which contains many plastic forging press marks on its surface and also the shape of the forging itself. In addition, the circularity of the samples was not proportional.

Further studies in this case include the implementation of an accurate subpixel method of forging origin determination, which could eliminate the outliers in the case of forging diameter and circularity measurement. Another challenge is the measurement of different forging cross sections, e.g., square or rectangle, which are defined by more parameters. Another possibility is the combination of the proposed principle with different measurement principles for the determination of forging circularity, for example, laser scanning, similarly as in [45].

7 CONCLUSIONS

The thesis deals with the problem of in-process open-die forged rod measurement. This is a challenge due to the more interfering effects present in the industrial environment. Therefore, common available measurement systems cannot be used without major limitations. Research in this area aims to find a solution. Although the 3D passive measurement method based on forging silhouettes in images potentially offers many advantages in this application, only a little attention was paid to this approach. It is not clear how to implement this method, how to deal with the interfering effects present in the environment, and how it performs. Therefore, in this work, original methods on how to make such a system accurate and reliable under industrial conditions are proposed and examined. This knowledge could be used during the development of a professional optical measurement system for this application in the future.

The thesis begins with a review of the state-of-the-art in this area. The first part of this section is an overview of studies focused on the interfering effects expected in the industrial environment. The second part includes studies on various measurement approaches applied in this area. Based on the review, the interfering effects and ways to deal with them were summarized and evaluated. The measurement approaches are critically compared. Passive 3D optical measurement, based on object silhouettes in images, is evaluated as the best approach for further research, due to its numerous advantages over other approaches and its low level of development in this application. Moreover, such a system has not been examined in the industrial environment. Therefore, the main goal is to examine the properties and limits of this measurement approach in the industrial environment, during the measurement of heavy forgings. The problem is then divided into four main domains: research on calibration targets robustness enhancement, camera calibration method development, research on subpixel edge detection, and feasibility verification of the proposed measurement system. The thesis consists of three journal articles. Moreover, a conference paper was added that covers one of the important topics and connects the publications. Each publication deals primarily with one of the mentioned domains.

The sections Materials and Methods and Results and Discussion are the primary focus of the attached publications. Therefore, both sections are presented briefly. The Materials and Methods section introduces the methods used to achieve high accuracy of the measurement as well as the measurement system robustness to the interfering effects. The original methods providing the robustness of the measurement system and their verification are the focus of this work. These include the robust calibration target recognition method to recognized targets under occlusion, camera calibration method allowing online camera calibration to deal with the dimensionally unstable environment, and robust forging edge detection with subpixel accuracy. Moreover, the hardware setup and verification methods of the experimental system are provided. The Results and Discussion section then summarizes and connects the findings of the studies. The work is a combination of experimental development and applied research. The research topics are presented using the two scientific questions and hypotheses. The main findings of the thesis are as follows:

- The error correction method for circular coded targets can be based on rotation-invariant distance, target code generator, and similarity condition. The assumption was that the 15-bit target library of 60 targets can achieve error correction of up to 1 bit changed or 2 bits occluded. The results confirm this assumption. Moreover, the results prove that the number of false positives or the number of target confusions is comparable to the target recognition method without the error correction. The target system achieves stable results under different negative image effects, such as noise or blur. Therefore, the proposed methods are evaluated as effective. **Therefore, Hypothesis 1 is not falsified in this thesis.**
- Space resection allows accurate camera calibration in industrial environment, including on-line exterior camera parameters. The influence of air lens surrounding the forging on reprojection error is significant, however, the cameras can be calibrated shortly before the hot forging appears on the scene.
- Subpixel edge detection proves the advantage over edge detection method with pixel precision, however, local edge disturbances appear during the measurement in industrial environment. To take advantage of the higher accuracy, edge filtering is needed. The assumption that correctly identified edges have high gradient magnitude and their direction is perpendicular to forging axis, while corrupted edges have lower gradient magnitude and random direction, is confirmed. Weighted edge filtering proves to be a significant improvement over uniform weight filtering in case of axis straightness measurement. **Therefore, Hypothesis 2 is not falsified in this thesis.** The weight based on the edge direction proved to be the most efficient in the case of axis filtering. On the other hand, the weight based on gradient magnitude proved to be more efficient in the case of forging diameter filtering.
- The major error of the forging geometry can appear when there is insufficient forging circularity. To solve this problem, a multi-view measurement method is proposed, achieving accuracy in ±0.5 mm for both forging axis straightness and diameter measurements (95% confidence interval, however, in case of diameter measurement, 10% of outliers were removed). This is achieved in a measurement volume of approx. 6 × 6 × 2 m. Therefore, the feasibility of the forging measurement principle, based on its silhouettes in images, is confirmed.

Although current measurement methods are limited to cylindrical forgings, they can be generalized to other common forging shapes, including rods with square or rectangular cross sections. The system could be used to provide feedback about the dimensional accuracy, for its in-process correction (e.g., axis straightness). This will help to achieve better dimensional accuracy of the forgings and prevent problems during machining due to run-out. In addition, the machining allowances could be minimized, to save material and energy. In the future, this measurement system could become a part of the fully automated manufacturing line, in accordance with industry 4.0 trends.

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AUTHOR’S PUBLICATIONS

Publications related to the topic of this thesis

J. HURNÍK, A. ZATOČILOVÁ and D. PALOUŠEK. Camera calibration method of optical system for large field measurement of hot forgings in heavy industry. In: *Opt. Meas. Syst. Ind. Inspect. XI, Proc. SPIE*. 2019, p. 11056. Available at: doi:10.1117/12.2527693
Indexed in WoS

HURNÍK J., A. ZATOČILOVÁ and D. PALOUŠEK. Circular coded target system for industrial applications. *Machine Vision and Applications*. 2021, **32**(1), 1–14. ISSN 14321769. Available at: doi:10.1007/s00138-020-01159-1
IF 2.983; Q2 (by JIF; Engineering, electrical & electronic)
AIS 0.475, Q3 (by AIS; Computer science, artificial intelligence); WoS, 2021.

HURNÍK J., A. ZATOČILOVÁ, D. KOUTNÝ and D. PALOUŠEK. Enhancing the accuracy of forging measurement using silhouettes in images. *Measurement*. 2022, **194**, 111059. ISSN 02632241. Available at: doi:10.1016/j.measurement.2022.111059
IF 5.131; Q1 (by JIF; Engineering, multidisciplinary)
AIS 0.643; Q2 (by AIS; Engineering, multidisciplinary); WoS, 2021.

J. HURNÍK, A. ZATOČILOVÁ, T. KONEČNÁ and P. ŠTARHA. Multi-view camera system for measurement of heavy forgings. *The International Journal of Advanced Manufacturing Technology*. 2022, ISSN 02683768. Available at: doi: 10.1007/s00170-022-09809-6
IF 3.563; Q2 (by JIF; Automation & control systems)
AIS 0.450; Q3 (by AIS; Automation & control systems); WoS, 2021.

Other publications

VRÁNA, R., VAVERKA, O., ČERVINEK, O., PANTĚLEJEV, L., HURNÍK, J., KOUTNÝ, D., PALOUŠEK, D. Heat treatment of the SLM processed lattice structure made of AlSi10Mg and its effect on the impact energy absorption. In: *Euro PM2019 Proceedings*. 2019.
Indexed in Scopus

MICHALEC, M., V. POLNICKÝ, J. FOLTÝN, P. SVOBODA, P. ŠPERKA and J. HURNÍK. The prediction of large-scale hydrostatic bearing pad misalignment error and its compensation using compliant support. *Precision Engineering*. 2022, **75**, 67–79. ISSN 01416359. Available at: doi:10.1016/j.precisioneng.2022.01.011
IF 3.315; Q2 (by JIF; Engineering, multidisciplinary)
AIS 0.624; Q2 (by AIS; Engineering, multidisciplinary); WoS, 2021.

MICHALEC, M., J. HURNÍK, J. FOLTÝN and P. SVOBODA. Contactless measurement of hydrostatic bearing lubricating film using optical point tracking method. *Proceedings of the Institution of Mechanical Engineers Part J-Journal of Engineering Tribology*. 2022, ISSN 13506501. Available at: doi: 10.1177/13506501221108138
IF 1.818; Q3 (by JIF; Engineering, mechanical)
AIS 0.279; Q3 (by AIS; Engineering, mechanical); WoS, 2021.

CURRICULUM VITAE

Ing. Jakub Hurník
Date and place of birth: 10/12/1991, Brno

Education

- **2017 – 2022** Doctoral study at Institute of Machine and Industrial Design, Faculty of Mechanical Engineering, Brno University of Technology. Topic of the dissertation thesis: *Measurement of shape and dimensions of forgings*.
- **2015 – 2017** Master study at Institute of Machine and Industrial Design, Faculty of Mechanical Engineering, Brno University of Technology. Topic of the diploma thesis: *Optimizing the calibration of the cameras of photogrammetric system designed for the measurement of rotationally symmetric forgings*.
- **2012 – 2015** Bachelor study at Faculty of Mechanical Engineering, Brno University of Technology. Topic of the bachelor thesis: *Hydrogen as an alternative fuel for internal combustion engines*.
- **2008 – 2012** High school – Gymnázium Brno, Vídeňská, 47 - study focused on natural sciences

Awards, achievements

- 2012 – best possible score in the state school-leaving exam of mathematics – 99.8% percentile
- 2017 – PhD talent finalist
- 2020 – Iron A’ design award - Big Trimmer Precious Trimming Machine (mechanical designer)

Teaching activities – seminars:

- 1K – Engineering Drawing Fundamentals
- 2K – Engineering Drawing
- 3CD – CAD
- 4KC – Design and CAD
- RS1 – 3D Digital Technology and CAD
- ZD5 – Master Thesis Project – Results and Discussion
- ZKP – Team Project
- ZRI-A – 3D Optical Digitization and Inspection of Machine Parts

Participations in scientific projects

- 2022: Development of additive and small-production technologies for manufacturing of transport vehicles models (CZ.01.1.02/0.0/0.0 /21_374/0026427)
- 2021 – 2022: Enhancing the bending and tensile strength of composite profiles using 3D guiding and shaping tools (CZ.01.1.02/0.0/0.0/21_374/0026857)
- 2020 – 2022: Research on the mechanical and physical properties of structured material manufactured using additive technologies (FSI-S-20-6296)
- 2020: Research and development of advanced technology of measuring the shape and dimensions of forgings as part of the automated forging process (FW01010098)
- 2018 – 2019: Development of an optical system for the measurement of rotationally symmetric forgings (TJ01000268)
- 2018 – 2019: Development of transtibial prosthesis manufactured via 3D printing (CZ.01.1.02/0.0/0.0/16_084/0010268)
- 2017 – 2020: Development of processing parameters for manufacturing of unique metal parts using selective laser melting (FSI-S-17-4144)

Language skills

Czech, English

Scientific activities

- Advances in computer vision
- New applications of optical measurement
- Multidisciplinary engineering

ABSTRACT

In the process of open-die forging, inaccuracies can appear. These inaccuracies must be measured and corrected. Passive heavy forging measurement, based on their silhouettes in images, potentially offers many advantages in this application. However, regarding forging measurement, this method showed limited accuracy in the literature and was never verified under industrial conditions. Therefore, the aim of this thesis is to examine the feasibility of this method in the industrial environment, by using advanced methods of optical measurement. Interfering effects are discussed, and original methods, working as countermeasures, are proposed. Methods are verified in both the laboratory and the industrial environment. The results suggest the effectiveness of the proposed methods; the accuracy achieved in the laboratory and industrial environment is of the same order. The error is approximately around 1 mm in a measurement volume of 6 × 6 × 2 m for the geometry of the axis and the measurement of the diameter. This result satisfies the demands of an industrial environment. However, the measurement still contains outliers, which are discussed. The knowledge obtained can be used during the development of a professional measurement system for this application. Secondly, the knowledge can be generalized to the measurement of hot objects, or objects in a complex environment, based on their silhouettes. A system for the measurement of forgings could increase the effectiveness of manufacturing and could become a part of automated forging production line in the future.

ABSTRAKT

V procesu výroby těžkých výkovků volným kováním vznikají nepřesnosti, které je třeba měřit a korigovat. Metoda pasivního měření výkovků, na základě jejich siluet v obraze, zde potenciálně nabízí mnoho výhod. V případě měření výkovků ale v literatuře vykazuje relativně nízkou přesnost a nebyla ověřena v průmyslových podmínkách. Cílem práce je proto prozkoumat možnosti využití této metody v reálných podmínkách, které umožní pokročilé metody optického měření. Jsou diskutovány rušivé vlivy prostředí a navrhovány originální metody, jak ovlivnění zmírnit nebo mu předejít. Ty jsou ověřovány v laboratorním i v průmyslovém prostředí. Výsledky potvrzují efektivitu navržených metod; dosahovaná přesnost je porovnatelná s tou dosaženou v laboratorním prostředí. Bylo dosaženo chyby okolo 1 mm v měřicím objemu 6 × 6 × 2 m v případě měření přímosti osy a průměru výkovku. Tento výsledek postačuje požadavkům průmyslového prostředí. Nicméně, měření stále obsahuje odlehlé hodnoty, jejichž výskyt je diskutován. Poznatky obsažené v této práci je možné využít při vývoji profesionálního měřicího systému pro tuto aplikaci. Sekundárně jsou pak zobecnitelné a využitelné při měření horkých objektů nebo obecně objektů v komplexním prostředí na základě jejich siluet. Systém pro měření výkovků by v budoucnu mohl přinést vyšší efektivitu výroby volně kovaných polotovarů a mohl by se stát součástí automatizované kovací linky.