INSTITUTE OF **MACHINE**
AND **INDUSTRIAL DESIGN**

FME

Faculty of Mechanical Engineering
Brno University of Technology

## Review of Doctoral Thesis

| **1. PhD candidate** |
|---|
| Ing. Jakub Hurník / Jakub.Hurnik@vut.cz |
| **2. Name of PhD programme** |
| Design and Process Engineering (Mechanical Engineering Design) |
| **3. Title of PhD thesis** |
| Measurement of Shape and Dimensions of Forgings |

| **4. Principal supervisor** |
|---|
| doc. Ing. Daniel Koutný, Ph.D. / Daniel.Koutny@vut.cz |
| **5. Co-supervisor** |
| Ing. Aneta Zatočilová, Ph.D. / zatocilova.a@fme.vutbr.cz |

| **6. Reviewer** |
|---|
| Dr Samanta Piano/ Samanta.Piano@nottingham.ac.uk |
| University of Nottingham |

| **7. Overview of the scope of PhD thesis**[1] |
|---|
| **Good** |
| **In this dissertation, the main aim of the PhD research study is clearly stated, providing a clear understanding of the overall objective that the research is designed to achieve.**<br>**In addition to outlining the main aim, the dissertation presents and discusses the limitations of existing optical methods. This helps to provide context for the research and demonstrates the need for the new research study, highlighting the importance of the research question and the potential impact of the research outcomes.**<br>Moreover, the dissertation includes specific, measurable, and achievable objectives that are directly aligned with the research questions and the main aim of the study. The methods used in the study are well-presented and are appropriate for the proposed research, ensuring that the research design is sound and capable of producing reliable and valid results. The results obtained are also adequately presented, with a clear description of how they are related to the research questions and the objectives of the study. Furthermore, the dissertation effectively discusses how the proposed methods improve upon existing ones, highlighting the significance of the findings and the potential impact on the field. |

[1] Overview of the scope of PhD thesis is a short description of objectives of PhD thesis's research and summary of main findings and scientific achievements.

**8. Significance of the topic and clarity of problem statement**

**Good**

The aim of this project is to investigate and recommend appropriate measurement systems for assessing the shape and dimensions of forgings. Accurate measurements of forgings are crucial for several reasons, including quality control, ensuring compliance with required specifications and standards, and avoiding the need for additional processing or rejection. Precise measurements also help guarantee that forgings fit and function correctly, which is particularly important in complex mechanical systems. In industries such as aerospace and automotive, where safety is of utmost importance, accurate measurements are vital to meet the necessary safety standards and avoid any risk of failure. Finally, measurements can also aid in identifying areas where excess material is used, resulting in cost savings through material reduction. Therefore, the measurement of the shape and dimensions of forgings is essential for ensuring quality, fit and function, safety, and cost control, among other benefits. While some of these reasons have been highlighted, a more comprehensive explanation would be advantageous.

**9. Knowledge of existing literature**

**Good**

The literature review provides a comprehensive overview of existing research in the field of forging measurements systems, covering a range of approaches for measuring and analysing the forging process. The dissertation presents the literature review in a well-organized and effective manner, categorizing the different measurement systems into two broad categories of passive and active methods. For each category, the dissertation provides examples of different methods, along with their applications and limitations.The candidate demonstrates an ability to provide a thorough and well-organized literature review, which establishes a strong foundation for the research that follows. The literature review helps the reader to understand the context and significance of the research question, as well as sets the stage for the development of novel measurement techniques or the improvement of existing ones.

**10. Choice of methods and technical soundness**

**Good**

In the dissertation, a clear justification of the method used is not sufficiently given. However, the measurement system workflow is well described, and the main steps are presented in a clear and logical manner. This helps the reader to understand the technical details of the method and how it was applied in the research study.One strength of the dissertation is that it details methods to benchmark and compare the proposed methods with established techniques. This demonstrates an awareness of the importance of validation and provides a framework for evaluating the performance of the proposed methods.Overall, the methods used in the dissertation are technically valid and suitable for the proposed research. While a clearer justification of the method used would have further strengthened the study, the detailed description of the measurement system workflow and the methods for benchmarking and comparison provide confidence in the reliability of the results.

**11. Quality, originality and significance of the results**

**Good**

The results of the research have been summarised and connected to the current state of knowledge in the field. This indicates that the researcher has taken care to contextualise their findings and ensure they are relevant to current understanding. However, while the methods and results have been discussed and justified, the research could benefit from a more comprehensive analysis of uncertainty. This would involve a deeper exploration of the limitations and potential sources of error of the proposed measuring instrument and process, which could help to confirm the reliability of the outcomes. Additionally, the research could have been more critical in its discussion of the results. In particular, the candidate should consider potential alternative explanations for their findings and assess the strengths and weaknesses of their approach more thoroughly.

**12. Quality of attached papers**

**Very good**

The papers presented in this dissertation demonstrate the high quality of the research carried out by the candidate. The papers are published in international journals with good impact factors or presented at conferences, indicating that they have been well received by the scientific community and are contributing to the advancement of knowledge in the field. This is a significant achievement and reflects the candidate's ability to conduct research at a high level of competence. These papers clearly showcase the results of the candidate's research and the contributions they have made to the field. The fact that they have been published in international journals indicates that they have undergone a rigorous peer review process and have been recognized as good-quality research. Overall, the papers presented in the dissertation represent a significant accomplishment for the candidate and provide evidence of their ability to conduct good-quality research in the field.

**13. Overall assessment, strengths and weaknesses (based upon the above evaluation categories 8–12)**

**Good**

Overall, the dissertation appears to be well presented and the research questions and aims are well aligned with the needs of the industry 4.0. The methods employed by the candidate seem appropriate and the outcomes of the research appear to be valuable contributions to the research field. However, the investigation of uncertainty methods to assess the quality of measurements could have been highlighted more in the work. This is an important aspect of research in any scientific field, including in the context of industry 4.0. The uncertainty in measurements can have a significant impact on decision making and quality control processes, and it is important to understand and quantify this uncertainty in order to make informed decisions.In addition, it would have been beneficial to compare the proposed methods to established standards that can provide a basis for evaluating the quality of the measurements and the overall reliability of the research findings.In summary, while the dissertation appears to be a valuable contribution to the research field, there is always room for improvement and further investigation. Evaluating uncertainty methods and comparing them to appropriate standards could have provided additional insight and strengthened the overall findings of the research.

| 14. Questions and comments |
|---|
| Some potential questions that could be asked during the viva:<br>1.In the introduction *contact measurement techniques* are mentioned, but they are not included in the state of the art, can the candidate briefly explain these techniques?<br>2. What is the need to investigate/proposed new optical techniques?<br>3. The literature review summarises various optical techniques. Could the candidate provide a justification for the choice of method used in this work?<br>4. The hardware used consists of 2-3 cameras. How can the candidate ensure that these cameras are sufficient to cover the required measuring volume? Additionally, can the images captured by this system accurately measure the manufactured part?<br>5. Can the candidate explain how the VDI/VDE standard have been applied to the presented experiment?<br>6. Can you give a comprehensive explanation of precision and accuracy and how you have evaluated these in your work?<br>7. How the *confusion of code* is been defined and assessed? Can the candidate give a briefly explanation?<br>8. In Paper B it is mentioned that the camera external parameters need to compensate for the small movements of the camera, can the candidate expand this concept?<br>9. Can the candidate explain how the presented work will impact the state of the art?<br>10. What is the potential future work that could result from this research? |

| 15. Conclusion |
|---|
| PhD thesis is an independent scientific work that presents a novel solution to a significant problem in the research area and demonstrates the candidate's ability to conduct independent research. |
| **YES** |

| 16. Date and signature | |
|---|---|
| **28/02/2023** | |

Please note

A. *Evaluate categories 7 to 13 using the following scale: unacceptable, acceptable, satisfactory, good, very good, excellent. The qualification of 'excellent' should only be given for a PhD Thesis in the top 3% of the research in your field of expertise.*
B. *E-mail the completed form to:* Klara.Javorcekova@vut.cz

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## Review of Doctoral Thesis

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| **6. Reviewer** |
|---|
| doc. dr. Drago Bračun/ Drago.Bracun@fs.uni-lj.si |
| University of Ljubljana |

| **7. Overview of the scope of PhD thesis**[1] |
|---|
| **Very good** |
| Precise open die forging is very important to achieve the correct shape of forgings and thus reduce the amount of post-processing, reduce scrap and increase the quality of the product. This dissertation focuses on the development of a silhouette-based measurement system for dimensional control of large glowing forgings. Laser-based measurement systems typically lead the way in this type of measurement due to their accuracy and insensitivity to environmental effects. However, their disadvantage lies in the safety aspects and high price. The ideal solution for dimensional control would be to measure only with cameras that are spatially distributed throughout the forge and capture images of the forgings from a safe distance. The development of such a system, sufficiently accurate and insensitive to disturbances from the environment, is a great challenge that has not yet been properly solved. The main objective of this work is to investigate the characteristics and limitations of the silhouette-based measurement method. In this regard, the work has several sub-objectives with the main goal of reliable camera calibration, accurate edge detection and measurement to validation in an industrial environment. The work includes a literature review, a summary of the missing knowledge, the objectives of the work, scientific questions and hypotheses, explanation of materials and methods, and results and discussion. In addition, there are four scientific papers in which the candidate explains the main achievements, from the improvement of the robustness of the circular coded target system for camera calibration, the system calibration performed in parallel with each measurement, |

[1] Overview of the scope of PhD thesis is a short description of objectives of PhD thesis's research and summary of main findings and scientific achievements.

improving immunity to interferences from the forge workshop, to the validation of the system in an industrial environment.

**8. Significance of the topic and clarity of problem statement**

**Very good**

The measurement of large forgings is of great importance to forging industry, as the shape and dimensional inaccuracies of heavy forgings must be constantly monitored to prevent deviations and to correct them when necessary. This includes measuring the length, diameter, and especially the straightness of the axis. The problem is clearly defined. In short, to investigate the characteristics and limitations of the measurement approach based on object silhouettes in the industrial environment when measuring heavy forgings. In this respect, the work has four objectives. First, to investigate the application of an error correction method for circularly encoded targets used in camera calibration for industrial environments. The goal is to achieve reliable camera calibration. Second, to develop an online camera calibration method based on resection of space to prevent dimensional instability. Third, to research an accurate edge detection method for measuring forging silhouettes, and fourth, to develop a forging silhouette measurement system and test its precision in an industrial environment. In addition, there are two scientific questions (1) How to implement error correction method in cyclic codes decoding of circular coded targets used for camera calibration? and (2) How to suppress corrupted edges during silhouette measurement? For each of these questions, the hypothesis and reasons are stated. I evaluate that the problem statement is clearly stated.

**9. Knowledge of existing literature**

**Very good**

The thesis includes a literature review with 63 references from different fields, from the review of measurement methods for measuring glowing forgings to the different algorithms used in the process. I evaluate that the literature review is sufficient and adequate.

**10. Choice of methods and technical soundness**

**Very good**

The thesis focuses on the goal of improving silhouette-based measurement method through research, development, and systematic evaluation. The study systematically evaluates existing active and passive optical measuring methods and proposes the original solutions from the system conceptual design, image processing to system calibration and validation using experimental data collected in laboratory and industrial environments, with particular attention to the effects of the industrial environment. I would rate the technical soundness as high since the work uses appropriate methods, techniques, tools and addresses potential sources of bias and error.

**11. Quality, originality and significance of the results**

**Very good**

An important component of the silhouette-based measurement method is the multi camera calibration and its verification in an industrial environment. To measure the dimensions of forgings, the distance of the cameras to the forging and their mutual position must be determined. Unlike the laboratory environment, the industrial environment is unstable because of subsequent changes due to vibration of heavy equipment, high temperatures, and dust, and the calibration is not stable over time. The originality of the presented method lies in the calibration, which is performed in parallel with each measurement. For this purpose,

coded patterns are used, which are placed near the forging so that they are visible in all images taken from different angles. For this method to work, the exact distances between the coded patterns must be known in advance, and most importantly, the coded patterns must be made of such materials and placed in such a way that they survive near the forging, where there is strong thermal radiation, a lot of dust, and the possibility of mechanical damage, which is disadvantage of the proposed method. For this purpose, the research paid special attention to improving the robustness of the circular coded target system for camera calibration. In addition, for accurate measurements, the original image processing was developed to detect the edges of the forgings in the images. The research also confirms the influence of an irregular forging cross-section on the determination of the diameter and improvements when using multiple cameras from different angles. In summary, significant original results have been obtained with great potential for application in the industrial environment.

**12. Quality of attached papers**

**Excellent**

The candidate has published research in three peer-reviewed journals with scientific citation factor:
(1) Circular coded target system for industrial applications, Machine Vision and Applications (IF 2.983, 2021); (2) Enhancing the accuracy of forging measurement using silhouettes in images, Measurement (IF 5.131, 2021); (3) Multi-view camera system for measurement of heavy forgings, The International Journal of Advanced Manufacturing Technology (IF 3.563, 2021);
He also presented his work at scientific conference: Camera calibration method of optical system for large field measurement of hot forgings in heavy industry, Proc. SPIE 11056, Optical Measurement Systems for Industrial Inspection XI, (2019).
I consider the publications and journals mentioned to be of high quality.

**13. Overall assessment, strengths and weaknesses (based upon the above evaluation categories 8–12)**

**Very good**

The dissertation deals with the improvement of the silhouette-based measurement method for dimensional control of large glowing forgings, which is of great importance to the forging industry because the shape and dimensional inaccuracies of large forgings need to be constantly monitored to avoid deviations and expensive low quality. The study systematically evaluates existing active and passive optical measurement methods and proposes original solutions, paying particular attention to the disturbances of the industrial environment. The method, as conceived, is very practical for use in the workshop. Install spatially distributed cameras in the forge, take pictures of the forgings from a safe distance and calculate something from the images. However, the problem lies in the vibration of the heavy equipment, high temperatures and dust, and consequently the calibration is not stable over time. The originality of the presented research lies in the calibration, which is performed in parallel with each measurement. For this purpose, coded patterns are used, which are placed near the forging so that they are visible in all images taken from different viewpoints. For this method to work, the exact distances between the coded patterns must be known in advance, and most importantly, the coded patterns should be able to withstand strong thermal radiation, a lot of dust, and also mechanical damage, which is a drawback of the method. The candidate is aware of this problem and pays special attention to improving the robustness of the circular coded target system for camera calibration and proves that his method can achieve acceptable accuracy. To this end, several other details are also improved, such as the original image processing to detect the edges of the forgings in the images, or the influence of an irregular forging cross-section on the determination of the diameter. The candidate has published three research papers in peer-reviewed journals with scientific citation factor and at a SPIE conference, which is also an indicator of the high quality of the research work that brings the method of passive forging measurement closer to implementation in the industrial environment.

| 14. Questions and comments |
|---|
| Forging begins at temperatures above 1200°C, when the forge is bright yellow, and continues until it cools to about 800°C, when it becomes dark red. So the forging changes brightness and colour. How does this affect the measurement uncertainty of your system? Please explain how the variation in brightness affects the perception of the edges of the forging and to what extent this affects the measurement of the diameter?<br><br>Is it possible to measure during forging when the workpiece is in motion?<br><br>The axis of the forging may not coincide with the axis of rotation of the manipulator's gripper. Does this have any effect on the accuracy of the measurements and the determination of the axis?<br><br>Suppose that the forging is not perfectly round, but has an elliptical shape, for example. How does this affect the determination of the diameter by your method? Can you describe the ellipticity of the cross section or are you limited to a regular circle? What about a rectangular cross section?<br><br>The environment in the forge is very demanding. During forging there are vibrations and temperature radiation. Scale falls off the forged pieces, which causes a lot of dust. How do vibrations affect the positional stability of calibration targets? How do dust-related visual obstructions affect calibration stability? How is the effect of thermal radiation on the lifetime of targets assessed?<br><br>Do the targets interfere with the process of handling forgings on the workshop? |

| 15. Conclusion |
|---|
| PhD thesis is an independent scientific work that presents a novel solution to a significant problem in the research area and demonstrates the candidate's ability to conduct independent research. |
| YES |

| 16. Date and signature |
|---|
| **20/02/2023** |

Please note

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B. *E-mail the completed form to:* Klara.Javorcekova@vut.cz

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## Principal supervisor's final report on the PhD study

| **1. PhD candidate** |
|---|
| Jakub Hurník / **jakub.hurnik@vut.cz** |
| **2. Name of PhD programme** |
| Machines and Equipment |
| **3. Title of PhD thesis** |
| Measurement of Shape and Dimensions of Forgings |

| **4. Principal supervisor** |
|---|
| doc. Ing. Daniel Koutný, Ph.D. / **daniel.koutny@vut.cz** |
| **5. Co-supervisor** |
| Ing. Aneta Zatočilová, Ph.D. / **zatocilova.a@fme.vutbr.cz** |

| **6. Stays at other institutions (min. 7 days)** |
|---|
| - |

| **7. Teaching activities** |
|---|
| Course name / Total number of hours<br><br>Engineering Drawing Fundamentals (1K) / 130<br>Engineering Drawing (2K) / 130<br>CAD (3CD) / 182<br>Design and CAD (4KC) / 130<br>Team Project (ZKP) / 13<br>Master Thesis Project – Results and Discussion (ZD5) / 26<br>3D Digital Technology and CAD (RS1) / 18<br>3D Optical Digitization and Inspection of Machine Parts (ZRI-A) / 78 |

| **8. List of main publications** |
|---|
| HURNÍK, J., 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<br>*Journal impact factor = 3.563; Quartile Q2 according to 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
*Journal impact factor = 5.131, Quartile Q1 according to 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
*Journal impact factor = 1.818; Quartile Q3 according to WoS, 2021.*

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
*Journal impact factor = 3.315; Quartile Q2 according to WoS, 2021.*

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
*Journal impact factor = 2.983; Quartile Q2 according to WoS, 2021.*

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*

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*

**9. Assessment of the supervision process**

**Very good**

Justification for evaluation: The main communication with the doctoral student regarding the topic of his thesis was carried out in the form of regular meetings on a monthly basis. The student led his research activities mainly independently. With respect to his field of expertise, he was often coming up with his own innovative solutions and original ideas. The student managed to do the work only with minor methodological advice. Overall, the supervision of the student was without problems, as he was well organized, punctual, and fulfilled his tasks reliably. The tasks he received were done on time and in a good quality. He managed to finish his thesis and the above-mentioned publications despite personal changes in his supervision.

**10. Assessment of the candidate's ability to work independently**

**Very good**

Justification for evaluation: The student proved his ability to work independently. The candidate demonstrated the ability to plan his research, to do the conceptualization, formulate hypotheses, and test them with experiments he designed. On the basis of the experiments, he formulated conclusions with suggestions of possible explanations. Student participated in several research projects and contracts with industrial partners, from the beginning of his studies, he also performed his teaching activities properly,

showing positive feedback from teaching coordinators and students. He proved to be capable to guide student projects, bachelor and diploma theses. In addition, student managed to enlarge the scope of his activities over the thesis topic and utilized his experience in different fields, including the 3D printing of metals or the research and development of hydrostatic bearings.

**11. Assessment of the contribution that the research makes to knowledge in the field**

**Very good**

Justification for evaluation: The doctoral student focused the research on the measurement of heavy forging in a hot state during the forging process. This is a challenging area where common measurement systems cannot be used because of many interfering effects. Student developed circular coding system for reference markers suitable for industry environment. Student also used specialized image processing methods, to achieve high robustness of optical measurement systems under demanding conditions. This knowledge can be used and further developed in other areas of machine vision and optical measurement, where high robustness of measurement is essential. Finally, the concept of an original measurement system for hot forgings was experimentally verified directly in the industrial environment, which brought such a system near a commercial application.

**12. Other comments**

I would also like to mention student's participation on following national grant projects:

- CZ.01.1.02/0.0/0.0/16_084/0010268, Development of transtibial prosthesis manufactured via 3D printing
- TJ01000268, Development of an optical system for the measurement of rotationally symmetric forgings
- FW01010098, Research and development of advanced technology of measuring the shape and dimensions of forgings as part of the automated forging process
- CZ.01.1.02/0.0/0.0/21_374/0026857, Enhancing the bending and tensile strength of composite profiles using 3D guiding and shaping tools
- CZ.01.1.02/0.0/0.0 /21_374/0026427, Development of additive and small-production technologies for manufacturing of transport vehicles models

and also his participation in 7 projects of contractual research with various industrial partners.

**13. Conclusion**

PhD thesis is an independent scientific work that presents a novel solution to a significant problem in the research area and demonstrates the candidate's ability to conduct independent research.

YES

**14. Date and signature**

**27/02/2023**

Please note

A. *Evaluate categories 9 to 11 using the following scale: unacceptable, acceptable, satisfactory, good, very good, excellent.*
B. *In each category 9 to 11 explain reasons for evaluation using between 100–200 words.*
C. *E-mail the completed form to: Klara.Javorcekova@vut.cz*