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Review of the PhD thesis

"Automated Identification of Changes from Cultural Heritage Surfaces"

by Sunita Saha, M.Sc. Eng.

Supervisor: Prof. Robert Sitnik, PhD. Eng.

The scientific problem considered in the thesis

The scientific problem considered in the doctoral thesis of Sunita Saha covers an important and up-to-date research subject: the development of methods to identify, quantify and visualise surface changes of cultural heritage objects over time. Cultural heritage objects, which are often unique in their character and value, undergo continuous deterioration, especially when exposed to harmful environmental or human influence. The negative influence is typically stronger when the objects are made available to the public in either closed or open exhibition spaces. Examples of such objects include cultural heritage artefacts in museums or private collections, sculptures and monuments, historical interiors and buildings, as well as decorative utility items of particular cultural or historical value. Monitoring and analysing the changes accumulating over time on surfaces of cultural heritage objects, on the one hand, can help preserve the objects in a close to original state and, on the other hand, can be an invaluable tool for documenting and performing reconstruction and conservation works as well as assessing the outcome when such works are performed. The change detection mechanism should be automatic or semi-automatic to be useful and efficient. In addition, the changes should be quantified and presented to domain experts in an easy-to-interpret way. These are precisely the goals Sunita Saha set for herself in her thesis.

Automatic change detection on complex surfaces poses important research challenges. The first challenge is proper identification of the type of change on the surface, which may belong to three broad categories: no-change, loss or deposit of the surface material. Given that any part of the surface may change unpredictably, understanding the span and category of change and its quantification becomes difficult. The second challenge follows from the fact that the measurements are taken at two different points in time (typically distant), which results in nearly unavoidable differences in the acquisition process. Such differences would severely affect the outcome if they were not adequately considered in the change detection method.

Addressing the challenges mentioned above requires the development of methods for normalising the measurements of surfaces taken at different points in time and conditions,

elaborating computational methods for detecting, quantifying, and characterising the changes, and developing methods for visualising the results. An integral part of this type of research must be the verification and validation of the proposed approach in both fully controlled simulated conditions as well as on real examples of cultural heritage objects with the participation of domain experts.

In summary, the subject of the doctoral thesis of Sunita Saha constitutes an important and complex scientific problem in the discipline of mechanical engineering.

The solution to the scientific problem proposed in the thesis

In the presented PhD thesis, Sunita Saha has described new segmentation methods to detect, quantify and visualise changes emerging on the analysed surfaces. The original contribution of the thesis consists of two parts.

In the first part, a new approach to change segmentation based on the acquisition and comparison of 3D data is presented. The approach permits quantifying and visualising changes on a surface by comparing 3D measurements performed at two different points in time. Four different methods of calculating distances between measurements have been proposed: Point-to-Point Absolute Distance, Point-to-Point with Direction, Point-to-Point along Normal Vector, and Point-to-Point Projection along Normal Vector. The mathematical description is complemented with high-level algorithms providing insight into possible implementation. Following the description of distance calculation methods, the overall change-based segmentation algorithm is presented. It consists of four phases: calculation of sampling distance, noise analysis, local distance histogram analysis, and segmentation. An important characteristic of the described approach to segmentation is its partial resilience to changes in acquisition parameters, including noise, sampling density, and alignment errors. Dynamic adaptation of thresholds enables domain experts to highlight the critical changes while disregarding the others, contributing to the practical usability of the presented approach.

The second part describes a new method of robust supervised segmentation of RTI data. Two types of coefficients: PTM (Polynomial Texture Maps) and HSH (Hemispherical Harmonics) are considered as a basis for segmentation. The coefficients are normalised to enable the use of data collected with changing RTI acquisition parameters. In a supervised process, with the use of image annotation, an LDA (Linear Discriminant Analysis) discriminant model is built. The model, called trained data, can be later used to analyse newly acquired data. A formal mathematical description is complemented with algorithms demonstrating the possible implementation of the model.

Both proposed methods are adequately compared to previously existing 3D model comparison and image segmentation methods. In addition to the new segmentation methods, Sunita Saha developed and described a user-friendly method of visualisation based on colour maps, which can help users to understand and correctly interpret the outcomes.

An important part of the thesis is the analysis of the application of the presented approaches to real cases of cultural heritage objects. In the case of the change segmentation method based on analysis of 3D data, five real cases were analysed (lion sculpture, school globe, ceramic tile, stone slabs, and museum wall). In the case of the segmentation method based on RTI analysis, four cases were considered (iron object with filiform corrosion, artificially aged iron coupons, Roman coin and Swiss coin, and metal box). It is worth noting that the

objects well represent real cases occurring in cultural heritage conservation practice. On a positive note, worth mentioning is the consideration of not only the cases in which the proposed methods perform well but also those that show their limitations. This permits understanding the strengths and weaknesses of the proposed methods as well as the limitations of their applicability.

Concluding this part of the review, Sunita Saha solved the scientific problem posed in the thesis, developing methods for change segmentation based on analysis of 3D scanned geometry and RTI appearance attributes.

The originality of the proposed solution to the scientific problem

The solution proposed by Sunita Saha to the problem of automated identification of changes on the surfaces of cultural heritage objects is highly original. The proposed methods are compared and contrasted in the thesis with the existing solutions. The originality and high quality of the scientific results are confirmed by Author's scientific publications in high-impact journals. In particular, the segmentation method based on geometry comparison presented in Chapter 3 has been described in the paper "*Segmentation of Change in Surface Geometry Analysis for Cultural Heritage Applications*", published in the Sensors journal (21(14):4899, 2021). In turn, the method of segmentation based on RTI appearance comparison presented in Chapter 4 has been presented in the article "*Supervised segmentation of RTI appearance attributes for change detection on cultural heritage surfaces*", published in the Heritage Science journal (10(1):1–15, 2022).

Analysis of the literature and state of the art in the field

The doctoral thesis of Sunita Saha demonstrates the Author's deep theoretical knowledge and familiarity with the latest scientific research results in the domains of change assessment of cultural heritage surfaces as well as 2D and 3D imaging and segmentation methods.

Chapter 2 of the thesis provides a comprehensive review of the literature and state of the art in imaging and image segmentation, including supervised and unsupervised techniques, feature extraction techniques, and segmentation using a stack of images. Further, principles of geometry-based and appearance-based change assessment methods are presented in detail. In the literature analysis, more than 90 positions are cited, a large part of which are topical publications in prestigious scientific journals and proceedings of scientific conferences.

Concluding the overview of state of the art, Sunita Saha identifies three essential gaps in the current scientific literature concerning the assessment and categorisation of geometrical surface changes based on their locality, the use of RTI modelling techniques for appearance extraction over time, and making the change detection insensitive to the acquisition devices and the quality of the measurement data. These three elements are the main focus of the research subsequently presented in the thesis.

Author's ability to independently conduct scientific research

The segmentation methods proposed by Sunita Saha in the thesis have been published as articles in highly-cited scientific journals: Sensors (IF 3.847/2021, MEiN 100 pts.) and Heritage Science (IF 2.843/2021, MEiN 140 pts.). In both articles, Sunita Saha is the first

author, which indicates her important role in achieving the scientific results described in the articles and the thesis.

Sunita Saha is also a co-author of two more articles submitted to highly-ranged scientific journals, which describe results presented in the thesis, two book chapters, and seven papers published in conference proceedings.

Editorial and linguistic quality

The thesis is written in English, and the writing style is generally good and easy to follow. Spelling mistakes and punctuation errors are rare. A slight shortcoming is the lack of consistency in using certain key terms, such as "change-based segmentation" vs "changed-based segmentation" and "train data" vs "training data".

The overall structure of the thesis is excellent, with a clear distinction between the non-original and original parts. Each original chapter is divided into methodology, implementation, results and discussion, followed by a summary, which greatly facilitates understanding. The conclusions and final remarks chapter provides a concise summary of the thesis's contributions and directions for future works.

Reading and analysis of the thesis are facilitated by numerous well-prepared lists and indices (figures, tables, abbreviations, symbols). Moreover, a clear indication in the thesis of such elements as acknowledgements, statements of originality, collaboration, and authorship, as well as information about permissions for copyrighted materials, indicate the Author's high level of professionalism and culture of work.

Critical comments and discussion

The presented thesis is convincingly written, indicating Sunita Saha's deep and up-to-date knowledge in the field, original and valuable scientific contribution, and results of high practical value. However, the thesis also has some flaws and weaknesses.

1. The thesis presents two complementary approaches to the surface segmentation problem. One is based on the analysis of 3D scans, while the other is based on the analysis of surface reflectance. These approaches are discussed and evaluated separately. A question arises as to whether these approaches could be effectively combined, increasing the applicability of the solution and possibly the precision of results. It would be good if such a discussion were included in the thesis.
2. The segmentation method described in Chapter 3 uses sections of the surface described as "known unchanged surface" with an associated "unchanged threshold" to perform cross-alignment between 3D geometries of surfaces captured at different points in time. This approach is good in the case of limited and localised surface changes (e.g., resulting from a physical impact) but may not be suitable for assessing changes that affect the surface in a more uniform way (e.g., as a result of environmental influence), which is visible in Case Study 4. The method of determining the segments of "known unchanged surface" is not precisely described in the thesis. In particular, is there a limit on the number, relative location or size of such surface segments?
3. Four different distance calculation methods based on point-to-point mapping have been proposed and described in the thesis (Section 3.1). These methods are also included in Fig. 3.1, explaining the change-based segmentation pipeline, and presented in detail in Section 3.2 in the form of algorithms. The different distance calculation methods are then

selectively used in particular case studies (Section 3.3.) with different results. Although one can appreciate the wide scope of the presented analysis, a clear indication of which method should be used in which cases is missing. The overall goal of the work is to provide an automatic and easy-to-use change assessment method. Such a method should not include elements subjectively chosen by a domain expert based on a specific case and his/her experience. For example, the proof of concept section concludes that *"To summarize, the P2P_ProjectionAlongNV method allows for the visualization of changes most in line with art conservators' expectations and is recommended for assessing changes on the surface of cultural heritage objects."* However, in Case Study 1, the Author states that *"In this case, the locations of the damages and restoration process (only the addition of material) were well known so to accurately document the work the P2P segmentation method was applied."*

4. The segmentation method based on surface appearance analysis (Chapter 4) employs RTI imaging with monochrome image acquisition. Although monochrome RTI systems may provide better quality and resolution in some cases, the lack of colour reflectance acquisition most likely negatively affects the method's ability to segment typical changes on surfaces of cultural heritage objects. In the thesis, this is demonstrated and discussed in Case Study 9 (which, in fact, does not really focus on the analysis of surface changes but a single state of a coloured object). One can assume that colour reflectance analysis would significantly improve the results of segmentation, not only in this case study but also in other cases discussed in the thesis. Even if an RGB camera could not have been used during the experiments, lighting with different wavelengths (e.g., with RGB LEDs) could be considered or discussed in the thesis.
5. Section 1.3 of the thesis describes the objectives of the work together with a precise goal on the target accuracy δ of the segmentation method, defined as a percentage of automatically segmented pixels/points in relation to the number of pixels/points determined by the conservators. The accuracy levels are set for 98% on simulated data and 90% in detecting changes on actual cultural heritage object surfaces. Although, in some cases, this goal is met (e.g. dominoes segmented with RTI using HSH coefficients as compared to automatically segmented ground truth), there is a lack of reference to these target accuracy in other cases.

The comments presented above should be considered as an element of discussion and do not diminish my generally high assessment of the scientific results achieved by Sunita Saha.

Conclusion

Taking into account the relevance and topicality of the subject matter presented in the thesis, the high quality of achieved scientific results, as well as their proven practical usability, I conclude that the doctoral thesis of Sunita Saha meets the requirements of the Polish Law on Higher Education and Science, and I recommend that it is admitted to public defence.

Moreover, based on the thesis itself and the Author's significant publications in prestigious journals, I suggest granting Sunita Saha a distinction for this work.

Kwiat.