Doctoral thesis (hereinafter referred to as "thesis"), title of the thesis:

Theoretical and Experimental Determination of the Amount of Information in Human Ocular Biometric Characteristics

Name of the doctoral student (hereinafter referred to as "student"), name and surname:

Ing. Lukáš Semerád

Name and institution of the reviewer (full name of the reviewer, full name and country of the institution):

Torfi Thorhallsson

Háskólinn í Reykjavík (Reykjavik University), Iceland

Please state your opinion on the following aspects of (I) the student's thesis and (II) the student's overall achievements, and (III) state your conclusion (a minimum of approx. 300 characters foreach item below is recommended):

I. Thesis

Appropriateness and relevance

Is the area addressed by the thesis appropriate to the particular scientific discipline of the thesis and does the thesis address relevant problems within the chosen area?

The retina as a biometric identifier is of particular interest as the sole visible part of the central nervous system with a rich and individual structure. The fact that the retina is not exposed, makes it hard to tamper with, but at the same time proves a challenge for the acquisition of retinal images. These technical challenges are the subject of extensive research by the student's research group and the specific problem of characterizing unique biometric features is a relevant one within this area.

A summary of the contributions of the thesis

From your point of view, please summarize what the goal of the thesis is, what the main contributions of the thesis are, and whether the thesis has achieved the chosen goal.

Please indicate also specific contributions of the student.

The goal of the thesis is to investigate the possibilities of using the vascular structure of the human retina as a basis for biometric identification. In particular, the thesis proposes using the location of vessel bifurcations and crossings in a normalized retinal coordinate system as a biometric identifier.

An algorithm for the automatic extraction of vascular features in retinal fundus images is developed and tested on a set of about 900 real images from varied sources giving a true positive rate of 70.7% when compared to manually extracted features. In comparison, the consistency of manual extraction was between 86.5 and 93.5%. A simple recognition scheme based on nearest neighbour search is also presented.

The set of extracted feature locations is then used to estimate the spatial distribution of features in the images, the inherent resolution of retinal images for the task of separating vascular features, and

the median number of features per image. From this information, the entropy of the proposed biometric identifier is computed as 340 bits, which is well over the number of bits required to uniquely encode every human being.

To compensate for the low availability of real images, a synthetic retinal image generator is proposed that grows the vascular network using Bezier curves, drawing on published observations on bifurcations in the human retina. The spatial distribution of biometric features in a set of generated images is shown to share characteristic traits with the distribution of features in real images.

In addition, the thesis provides an overview of the effects of the most common pathologies (diabetes and age-related macular degeneration) on the structure and visibility of the vascular system in retinal fundus images. A set of methods is presented that automatically detects the presence of pathologies. Further, a set of synthetic pathological retinas is generated using a generative adversarial network model trained on 1200 real pathological images.

The goal can be considered met.

The thesis states that the work has been done by the student with (1) contributions on image generation from master's theses supervised by the student, and (2) contributions from BSc theses on the detection of pathologies. The nature and extent of these contributions could be specified more clearly.

Novelty and significance:

Please assess the level of novelty of the results and their significance for the given scientific area, for its further development, and if applicable for possible applications in practice.

The proposed set of retinal features have the potential to be used as a powerful biometric identifier. The biometric entropy presented here provides a theoretical upper bound on the uniqueness of the identifier. The automatic detection and recognition methods can play a role, but first the effects of varying imaging conditions and pathologies on the identifier need to be quantified.

Where the thesis falls short is in the presentation and comparison to the state-of-the-art. While the methods used by the student are duly cited, there is no in-depth overview of existing biometric identifiers computed from retinal images or similar methods from related fields. No attempts are made to compare the results of detection, recognition, or image generation presented in the theses to the prior art.

To evaluate the novelty of the results it would be proper to include more on the state-of-the-art. As an example, a new survey on synthetic biometrics [1] cites five papers specifically describing the generation of retinal fundus images as well as a number of papers on vascular image generation using a variety of methods. The work presented in this thesis may pre-date some of these publications, but they should nevertheless be considered for review.

Evaluation of the formal aspects of the thesis:

Please evaluate formal qualities of thesis and its language level.

The discourse is for the most part clear and the use of references, figures, and tabular data is as to be expected. The description of algorithms is done in words and could be helped by adding pseudo-code where appropriate and by providing a link to source code.

The discourse of the thesis could be improved by clearly stating the purpose and approach of the work to be presented at the start of each section and chapter. The discourse would also be helped by adding conclusions at the end of each chapter.

This thesis is written in English. The use of vocabulary is for the most part accurate, and there are no spelling mistakes. However, the sentence structure and grammar often differ from standard usage in the English language, making the line of thought unnecessarily imprecise or difficult to follow. While this may be inevitable to some degree for any non-native writer, it is crucial to proofread and improve the most critical sections of the thesis. This encompasses, as a minimum, the abstract as well as the introduction and conclusion chapters.

Quality of publications

Has the core of the thesis been published at an appropriate level? Please judge the quantity and quality of the publications. When judging the quality, please take into account internationally recognized standards (WoS/Scopus quartiles, CORE ranks, specific knowledge of flagship publication channels of a given community, etc.) in a way appropriate for the given area of the thesis.

In the CV submitted, the student lists two internationally published book chapters and three conference papers that cover the core topics presented in the thesis.

- SEMERÁD Lukáš (80 %) a DRAHANSKÝ Martin. Retinal Vascular Characteristics. Handbook of Vascular Biometrics. Advances in Computer Vision and Pattern Recognition. London: Springer International Publishing, 2019, s. 309-354. ISBN 978-3-030-27730-7 - kapitola v knize.

- SEMERÁD Lukáš (90 %) a DRAHANSKÝ Martin. Retina Recognition Using Crossings and Bifurcations. Applications of Pattern Recognition. London: InTech - Open Access Publisher, 2021, s. 77-94. ISBN 978-1-78985-332-2 – kapitola v knize.

- SEMERÁD Lukáš. Processing and generation of retinal images for medical purposes. Berlín, 2019 – přednáška - vyžádaný příspěvek na mezinárodní konferenci, 41th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), 2019.

- KOLÁŘ Radim, SEMERÁD Lukáš (20 %), DRAHANSKÝ Martin, ODSTRČILÍK Jan, HÁJEK Josef a BOROVSKÝ Ján. Bimodal Eye Imaging System for Biometric and Medical Applications. In: Security and Protection of Information 2015. Brno: Univerzita Obrany, 2015, s. 83-95. ISBN 978-80-7231-997-8.

- SEMERÁD Lukáš (50 %) a DRAHANSKÝ Martin. Biometric entropy of retina. In: Proceedings of Information and Digital Technologies 2015. Žilina: Žilinská univerzita v Žiline, 2015, s. 291-293. ISBN 978-1-4673-7185-8.

Copies of two further publications or manuscripts were submitted, but the state of publication is not clear.

Based on the above, the core of the thesis appears to have been published at an appropriate level, although I cannot comment on the ranking of the publication outlets relative to other outlets in this area.

II. Student's overall achievements

Overall R&D activities evaluation:

Does the student's thesis, the results included into it, and possible other scientific achievements listed in the list of scientific activities indicate that he/she is a person with scientific erudition and creative abilities?

Yes.

Assessment of other characteristics (optional):

More characteristics of the student may be added here (e.g., awards, grant participation, international collaboration, etc.).

The student visited Reykjavík University, Iceland in August 2022 and gave two talks on biometrics and the biometrics of the retina showing command of the subject.

III. Conclusion

The conclusion should contain an explicit statement saying whether, in your opinion, the thesis and the student´s achievements until now meet the generally accepted requirements for the award of an academic degree (in accordance with Section 47 of Act No. 111/1998 Coll., on higher education institution).*

Yes it does, but the specific suggestions made above should be taken into account when preparing the final version of the thesis.

* Short overview of both the Act and corresponding internal BUT regulations is enclosed.

[1] A. Makrushin, A. Uhl, and J. Dittmann, "A Survey On Synthetic Biometrics," IEEE Access, pp. 1–1, 2023. Conference Name: IEEE Access.

Reykjavík, 13.03.2023

Signature of the reviewer: