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Review of the Ph.D. thesis of M.Sc. Maciej M. Bartuzel

The reviewed Ph.D. Thesis Titled: "*Optical methods for investigating aspects of the human eye dynamics*" is the result of the research performed under the supervision of Drs Maciej Szkulmowski from Department of Biophotonics and Optical Engineering, Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Torun, Poland, and D. Robert Iskander from Faculty of Fundamental Problems of Technology, Department of Biomedical Engineering, Wroclaw University of Science and Technology, Wrocław, Poland as well as co-supervision of Prof. Norberto López-Gil from Facultad de Óptica y Optometría Universidad de Murcia, Murcia, Spain. The thesis has been arranged into four main paragraphs. The first two are summarizing the biological and engineering background of the proposed work. The next two are describing two significant studies performed by the Ph.D. candidate. Finally, the thesis is summarized by Concluding remarks and further work section. Additionally, the thesis includes lists of symbols, a list of acronyms, and a description of the Scientific activities of the Ph.D. candidate. Research presented here has been performed at two sides and funded by two different funding sources. Work-related to the FreezEye Tracker has been performed at Nicolaus Copernicus University and funded by the project titled „*FreezEYE Tracker - ultrafast system for image stabilization in biomedical imaging*" (POIR.04.04.00-00-2070/16-00) carried out within the TEAM TECH program of the Foundation for Polish Science co-financed by the European Union under the European Regional Development Fund (P.I. Maciej Szkulmowski). The work related to the Defocus vibrations and visual acuity has been performed at Universidad de Murcia and funded by the National Science Centre (Poland) under the PRELUDIUM funding scheme, project no. 2015/17/N/ST7/03814. (P.I. Maciej M. Bartuzel)

Based on the scientific activities list, Ph.D. candidate authored nine peer-reviewed manuscripts, three as a first author. All three first-author manuscripts have been published in the top tear optical journals; one of them has been assigned as editor's pick. He also has one patent application and 27 conference presentations, including eight as the first Author presented at well recognized international meetings.

Two major studies presented in the thesis include the development, testing, and validation of a novel, non-invasive, ultra-fast eye tracking device - called FreezEye Tracker and experiments exploring the effect of defocus vibrations in a defocused optical systems using a custom made adaptive optics setup. The thesis is written very well, and it is a pleasure to read such a comprehensive description of the subjects. The first chapter includes in-depth and very detailed review of the optics of the human eye and its dynamics related to the oculomotor system. It focuses specifically on the eye ocular aberrations as

well as on the oculomotor system, described from the anatomical and physiological perspective outlining the basic types of eye movements and their kinematic characteristics. The second chapter includes comprehensive historical overview of the scanning laser ophthalmoscopy and methods of the eye tracking, with focus on posterior eye trackers. Shack- Hartmann wavefront sensing and the principles of adaptive optics are also described. The third chapter presents a detailed description of components and challenges that were overcome during the development of a FreezEye Tracker device. This includes a description of 1240 fps MEMS-based two-dimensional microscanner with an active aperture of 1 mm. Additionally, two subsystems working simultaneously with the tracker, a wide-field scanning laser ophthalmoscope and fixation path with a modified Badal stage optometer, are also presented. Artificial eye experiments used to estimate the FreezEye Tracker tracking performance are shown together with in vivo experiments with the human subjects proving the FreezEye Tracker feasibility of precise extraction of the eye movements and its kinematic parameters with very high temporal resolution. The fourth chapter describes and demonstrates the effects of defocus vibrations on a visual acuity of non-emmetropic human eye. Additionally, eye performance is simulated using real measured wavefronts allowing calculation of visual Strehl ratios based on optical transfer function. The last chapter briefly summarizes the main results of the thesis and provides an outlook on future work. The Author emphasizes that the FreezEye Tracker shows a high potential to be relevant in future studies of eye movements in the context of neurological diseases, where quantitative biomarkers can be extracted from ocular motion parameters allowing early detection of such a condition. He also points out that with respect to the dynamic optical defocusing, it is not clear whether this image-improving mechanism exists in nature in the real eyes. However, one potential source of dynamic defocus changes could be the crystalline lens wobbling effect caused by fast ocular movements.

The major strength of the thesis are the spectacular experimental results that nicely link the historical review with presented instrumentation and system development. Some of the results represent state-of-the-art accomplishments in the field of tracking eye movements. Additionally, despite the very large area of presented research, the thesis is easy to read thanks to the sufficient level of details provided by the Author, including interactive hyperlinks to the list of symbols and acronyms. Therefore, I have no concerns regarding editing, as well as the merit of the thesis. The presented results are of the highest level, and therefore the Author clearly proved his ability to present research aims as well as main research results. I hope that this work will continue beyond what is presented in this thesis.

Minor Comments:

Page ix, “Nicolaus Copernicus Unversity", University is misspelled.

Page 32. Who is Petval?

Page 32. Zernike polynomial “did not become the ANSI Standard.” The ANSI standard was created of reporting ocular aberration using Zernike polynomials.

Figure 1.3 b) the lens should not be perfect as this is the source of aberrations.

Also, wavefront is defined in one plane, pupil plane of the system.

Eq 1.6 Argument of cos and sin should in in brackets ().

Page 45, better description of the stellar main sequence should be used. The main sequence is a continuous and distinctive band of stars that appears on plots of stellar color versus brightness.

Page 55 last sentence “optical lever method” is used twice.

Page 56. “Pupil tracker” is often used instead of eye tracker.

Page 96. This statement is not always true: “If the wave aberrations of the system are known, then they can be corrected by wavefront shaping”

Page 101. Deformable Mirror (DM) rather than Adaptive mirror (AM) is more common name describing this class of wavefront correcting devices.

Page 101 Sentence: ”these were not real AM systems,” should be “not real AO systems”

Fig 3.8, 3.9, 3.10… 3D Zemax plots are not that useful. Use standard Zemax views. Also “Angular position” is called field.

Page 101: it would be good to cite the frame rate of AO system from 1997 Junzhong Liang, David R. Williams & Donald T. Miller

Fig 3.11 One should use name Pupil Plane and Image / retina plane.

Page 130. Authors claim that 785 nm is visible. It would be useful to define visible spectral range in the introduction.

In Chapters 3-4 it would be good to include the tables with lists of elements of the setups and their specks.

Fig 3.27 I do not see this:” The regions shaded in green indicate blinks.”

In conclusion, I attest that the Ph.D. Thesis of M.Sc. Maciej M. Bartuzel fulfills the requirements for Ph.D. theses according to bill on the academic titles and steps and request that it will be qualified for public defense. Additionally, I request for the distinction of the thesis based on the very high scientific merit and significance of the work presented by the candidate, as well as an excellent form and contents of the thesis “*Optical methods for investigating aspects of the human eye dynamics*”.

Best Regards,

Robert J. Zawadzki