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Datum
29.12.2017

Subject: Review of PhD Thesis of Ing. Bronislav Pribyl, C.j.: 255/1493/2017

Dear Prof. Ing. Tomas Hruska,

attached you will find my opinion and review about the submitted Thesis by Ing. Bronislav Prybil towards his PhD degree. I find the thesis timely and up to the state of the art, very well written, and suitable for the desired degree.

Regards

Prof. Dr.-Ing. Reinhard Koch
Director of the Institute of Computer Science
Dean of Technical Faculty

Review of PhD Thesis

Camera Pose Estimation from Lines using Direct Linear Transformation

submitted by Ing. Bronislav Pribyl at Faculty of Information Technology at Brno University of Technology.

Mr. Pribyl has submitted a thesis work of 85 pages in English, structured in 6 chapters and including a list of 74 cited references, plus 2 appendices of 20 pages and a list of 11 authored and co-authored publications. The work is concerned with novel derivations of camera pose estimation based on line features. Lines are important primitives in man-made scenes, however they have not seen a lot of research as opposed to point features, in parts due to the fact that the representation of 3D lines in not as straight forward as its counterpart using points. Mr. Pribyl concentrates on *Linear* algorithms for the estimation of Perspective camera pose from n (3D to 2D) Line correspondences, also termed LPnL. Similar approaches for point correspondences (LPnP) already exist. A straightforward approach from projective geometry is the Direct Linear Transform (DLT) that is capable to linearily estimate pose in projective space, and for intrinsically calibrated cameras also in Euclidean space. Linear estimates are desirable since they do not need starting values and obtain a unique solution. The downside of these approaches are typically estimates with too many degrees of freedom, since the constraints for minimal solutions are typically nonlinear. Hence, enforcement of theses constraints needs to be applied separately, again in a nonlinear manner, like Bundle Adjustment in the case of Camera Pose and 2D-3D feature correspondences.

The research question of this thesis hence it to obtain novel linear algorithms for camera pose from lines features, which are more accurate, robust, and fast than the existing state of the art algorithms, and to handle line features in a consistent way similar to point features.

Content of the thesis

The work is structured in six chapters. Chapter 1 (Introduction, 2 pages) shortly introduces to the problem, motivates the work and states the research question. Chapter 2 (Basic concepts, 11 pages) introduces the notation, the necessary mathematical concepts, and especially parametrization of 3D lines with minimal and linear over-parametrisations, like Plücker coordinates, and projection equations of lines. Chapter 3 (Pose Estimation from Lines, 12 pages) introduces linear (algebraic) and nonlinear (iterative) solvers, and especially the linear subclass of DLT solvers for lines, either by endpoint representation, or by Plücker representation.

Chapter 4 (Pose Estimation from Lines using DLT, 20 pages) is the core of this thesis. If reviews related and state of the art methods, especially in the context of the DLT approach, and introduces a set of algorithms needed for solving the task. Special care is taken to achieve fast, accurate and robust solutions to the pose estimation problem. This includes pre-normalisation for conditioning the equation system, and outlier handling of noisy measurements. Two main results were already published beforehand, (I, 2017) in the CVIU journal, and (II, 2015) in BMVC conference, both being prime venues for his publications. In total three algorithms have been developed for this task: DLT-Lines (adopted from Hartley-Zisserman), DLT-Plücker-

Lines (own II) and DLT-Combined-Lines (own I). The three algorithms differ w.r.t. the line representation: while DLT-Lines treats lines as connection between two 3D-points in scene space, DLT-Plücker-Lines uses Plücker representation, and Combined-Lines tries to combine both. The algorithm (I) is a hybrid between point and line representation and the combination is not straightforward. Especially the “optimal” extraction of pose is not fully clear, since it involves a linear combination of results with an interpolation parameter *k*, that is not fully explained by the theory. A heuristic numeric minimization yields *k=0.7* . However, analysis of all algorithms in Chapter 5 show experimentally the usefulness of this heuristic decision.

Chapter 5 (Experimental Evaluation, 21 pages) analyses in detail all algorithms w.r.t. accuracy, robustness to outliers and noise, and speed. I liked especially the thorough and in-depth analysis and comparison with recent state of the art algorithms. In parallel to this work, a set of related results were published by Xu e.a., TPAMI 2916 [68], and that work clearly competes with the work in this thesis as recent state of the art. However, the analysis shows that the work (I) of Pribyl can clearly compete with those findings. Mostly both algorithms are on par, while for some parts the algorithm (I) even performs better. Summary 5.5 lists the advantages of this approach. Chapter 6 concludes the work with a comparison and states that the research goal has been achieved.

Evaluation of the work

In this section I would like to follow the guidelines by answering the questions from your request form.

As stated above, the presented work and the related publications are timely and up to the state of the art, even advancing it in some parts. An important research question has been answered and a novel algorithm for handling perspective pose from lines has been developed. The work is original and it will bring forward the research area, by designing a combined 3D Point and 3D Line algorithm. So far, points and lines have been treated separately, now a combination of both important spatial features are possible. There still will be further work necessary to analyze how to optimally fuse both entities, rather than the heuristic interpolation with *k=0.7*. However, that would be another, new research question. Pribyl has stated this correctly as future work in his concluding section.
The results have already been published in high-ranking conferences and journals, and the publication list shows that Bronislav Pribyl has published more and related work (11 publications as first or co-author in total). This shows the high research capablility of Mr. Pribyl at large, which I can attest.
The thesis itself is extremely good to read, with clear structure, very clear algorithmic details that will allow reimplementation of the work, and an extremely good experimental validation section. I personally enjoyed reading this thesis.

In my opinion this doctoral thesis fully meets the requirements to obtain the doctoral title PhD and to proceed with the required next steps.

Prof. Dr.-Ing. Reinhard Koch Kiel, December 29, 2017