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学　位　論　文　名	Image-based Eye Pose and Reflection Analysis for Advanced Interaction Techniques and Scene Understanding （眼球の幾何・光学解析によるインタラクション技術およびシーン認識に関する研究）
論　文　審　査　委　員	（主査） 教　授　竹村　治雄 （副査） 教　授　八木　康史　　准教授　三浦　克介　　講　師　中澤　篤志

論　文　内　容　の　要　旨

This work proposes a theory of the light transport at the corneal surface of the human eye including multiple eye poses. The theory is subsequently applied to solve two practical problems in scene reconstruction and interaction techniques. Related with these are the solutions to two general problems in scene reconstruction from multiple eye images.

As the eyes are the interface between a human body and the visual information of the physical world, their movements also convey rich details for interpreting a person's affective state, behavior and relation with the environment. Despite having numerous applications in a variety of fields, current approaches to extract information from eyes are lacking, being intrusive, restricted to laboratory conditions and not providing sophisticated ways to integrate the eye with its environment. Recently, the geometric relation between eye and camera, that can be obtained from a face image, has been formalized to analyze light reflections in the cornea of a single eye or in a pair of eyes to recover simple scene structure. Nevertheless, there exist no solutions for relating reflections among multiple eyes, probably imaged by different cameras, with the structure of the surrounding environment. This, however, is crucial to develop sophisticated strategies for geometric eye analysis in arbitrary environments. This study aims to provide a solution.

The first practical problem lies in calibration to obtain display pose in display-camera setups. Understanding the combination of display and camera as a controlled system enables a range of interesting vision applications in non-professional environments, including object/face reconstruction and human-computer interaction, but attempting to do this in average homes has been difficult as current approaches require special hardware and tedious user interaction. This work proposes a novel calibration approach that simplifies this by building on the observation that a user is commonly located in front of the setup and that screen reflections in the cornea of the eye can be extracted from face images. Despite the difficult constraints, results obtained are feasible and should be sufficient for many applications involving non-intrusive calibration-free dynamic setups.

The main question then becomes what accuracy can be expected for scene reconstruction from multiple eye images. For this discussion, significant factors that affect accuracy are identified among individual eye geometry, camera parameters and geometric relation in the setup. Comprehensive experimental evaluation shows that, due to common errors in eye image processing and an unknown shape for the individual eye, scene reconstruction results in a large error and can not be applied directly. To compensate for this, an optimization strategy is developed that exploits geometric constraints within the system to jointly improve eye poses and scene structure. Results show that the method performs accurately and stably with respect to varying subjects, scene alignments, eye positions and gaze directions.

The second practical problem relates to non-intrusive eye gaze tracking in arbitrary environments. Flexible techniques for tracking a person's point of regard enable human-computer interaction and diagnostic studies with a range of applications in different fields. While eye gaze tracking has been an active area of research for over half a century, state-of-the-art approaches share major limitations restricting applications to controlled laboratory conditions with experienced personnel and a high degree of intrusiveness. This work proposes a novel system architecture that overcomes this by building on the observation that projected invisible structured light assigns environment locations with information that can be uniquely identified from corneal reflections. The approach is the first to support arbitrary surfaces and not require geometric calibration. Combined with unobtrusiveness and robustness to practical conditions, it enables a wide range of applications for novel user groups and situations.

Applying invisible structured light projection to corneal reflection analysis provides a solution to the general problem of accurate and robust feature matching among multiple eye images. The existing approach based on the epipolar geometry between a pair of eyes suffers from several shortcomings related to dependency on pose, shape and reflection properties of the eye. Beside eliminating these, the proposed strategy provides a dense matching, is purely image-based and thus, naturally enables feature matching between eye and conventional images. This is crucial for combining eye-specific information such as point of regard, peripheral vision and visual field with high quality image data or scene geometry.

The results of this work have implications on several fields. The findings provide general insight on the application of eye reflections for geometric reconstruction and are an important contribution. Linking eye and environment information can lead to novel insights and understanding.

論文審査の結果の要旨

Christian Nitschke君の論文は、眼球の幾何モデルおよび眼球の表面反射に対するライト・トランス

ポートに関する理論、およびその理論を用いて、眼球の表面反射を用いたディスプレイ・カメラキャリブレーション法、および非接触・非装着型の視線検出手法を導出したものであり、詳細な理論の導出および丁寧な実験を通してその有効性を示したものであり、新規性、有用性ともに高く評価できるものである。

まず、眼球の幾何モデルに関する研究は、様々な関連研究を検討した上で２つの球体を組み合わせたモデルを提案した。これは、眼球本体と角膜を含む球体を組み合わせたものである。これを用いて、様々な状況で画像のみから眼球の姿勢復元が可能であることを示した。

次に、眼球の表面反射に対するライト・トランスポートに関する研究では、外界の光線が眼球表面で反射する、あるいは通過するという状況を想定し、どのような外光がどのように反射するかを理論的に解析し示したものである。これにより、世界座標系中での点から発せされた光が、眼球表面での反射後どのようにカメラにとらえられるかを解いた。

次に、上記の眼球の幾何モデルおよびライト・トランスポートに関するモデルを用いて、設定された未知のディスプレイ・カメラ設置環境において、眼球の表面反射のみを用いてその間の幾何関係を求める（キャリブレーション）方法を示した。この手法は、ディスプレイ表面上に描かれたパターンの眼球表面上での反射像をカメラで観察するのみで、それらの位置関係を求めることを可能にしたものである。

次に、同様の理論を用いて、非接触・非装着型の視線検出手法を開発し、実験を通してその有効性を確認した。この手法は、カメラから得られた眼球の画像から眼球の幾何モデルを用いて目の方向を推定し、同時に、ライト・トランスポートのモデルを用いて環境の光の位置を推定することで、視線検出を実現するものである。

このように当該論文は、眼球の表面反射解析において新規かつ有用な手法を提案しており、視線検出手法の高精度化など様々の応用が可能であり、本研究分野の発展に大きく寄与するものである。よって、博士（工学）の学位論文として価値のあるものと認める。