DEVELOPMENT OF A MULTI-CAMERA CORNEAL TOPOGRAPHER
Using an Embedded Computing Approach

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Abstract: A multi-camera corneal topographer is presented in the paper. Using this topographer, the corneal surface under examination is reconstructed from corneal images taken synchronously by a number of calibrated cameras. The surface reconstruction is achieved by the joint solution of several partial differential equations (PDE's), one PDE for each camera. These PDE's describe the phenomenon of light-reflection for different overlapping regions of the corneal surface. Both algorithmic and implementation issues are covered in the paper.

1 INTRODUCTION

Due to the high refractive power of the human cornea, the knowledge of its detailed topography is of great diagnostic importance. Examination devices, such as keratometers, corneal topographers, and examination methods used in ophthalmology for exploring and measuring these topographies have a relatively long history (Jongsma et al., 1999). Nowadays, the corneal topographers are used in a wide range of ophthalmic examinations. They are used in the diagnostics of corneal diseases, in contact lens selection and fitting, in planning sight-correcting refractive surgical operations, and in their post-operative check-ups just to mention a few (Corbett et al., 1999). Also, dynamic properties – e.g., the average build-up time – of the pre-corneal tear-film can be examined and measured using fast-operation corneal topographers (Németh et al., 2002).

The majority of the measurement methods applied in the presently used corneal topographers rely on the specularity of the pre-corneal tear film that is coating the otherwise non-specular corneal surface. In these topographers, some bright measurement pattern of known and well-defined geometry, e.g., a concentric system of bright and dark rings (Placido rings), is generated and displayed in front of the eye. The reflection of this pattern on the pre-corneal tear film is photographed by one or – in recent topographer arrangements – several cameras. The distorted virtual image, or images taken by the camera are then analysed, and the corneal surface is mathematically reconstructed. Based on this reconstruction, maps showing the topography of corneal surface and its local optical properties (e.g., refractive power map) are computed and displayed.

In case of healthy and regular corneal surfaces, the presently available corneal topographers generally produce good quality corneal snapshots, and based on these, precise and reliable optical power maps are generated.

However, even for healthy and regular surfaces,

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a small impurity, or a tiny discontinuity in the precorneal tear film can produce a significant and extensive measurement error, if too simplistic measurement patterns, e.g., a Placido ring-system, is used by the topographer device.

1.1 Reconstruction of Specular Surfaces

The mathematical reconstruction of specular surfaces has been an active area of research. Savarese and his co-authors, for example, concentrated on the local reconstruction of specular surfaces. For a given pair of object-point and image point, there are – in general – infinite number of specular surface-patches the could cause a light-ray emitted from the object-point to reach the image-point. In order to find out which of these patches is the real one, it is necessary to gain further information. This information could concern the global shape of the specular surface (e.g, planar, spherical, or a general second-order surface). Sufficient conditions for the uniqueness of the local reconstructions are provided in (Savarese et al., 2004).

Others – such as (Bonfort and Sturm, 2003), (Fleming et al., 2004), (Kickingereder and Donner, 2004) – published methods for global reconstruction of specular surfaces. Each of these methods relies on the smoothness of the surface to be reconstructed and uses several views – i.e., several cameras – to make the unique reconstruction possible.

The unit normal vector of a given specular surface-patch is the same no matter which camera of a multi-camera arrangement looks at it. Although, a normal vector itself cannot be seen, it can be calculated from the reflection of a light-ray at the given surface-patch. For an unknown smooth, convex specular surface – viewed by several cameras – those points are located on, or near to the surface for which the corresponding unit normal vectors – calculated from two or more views – are approximately the same. This observation is the basis of the voxel-carving method suggested by (Bonfort and Sturm, 2003). This method can be used only for those surface-patches that reflect the measurement pattern into more than one camera.

A mathematically more elegant approach was proposed by (Kickingereder and Donner, 2004) for global specular surface recognition. In their approach, the description of light-reflection by a smooth specular surface takes the form of a total differential equation. The partial differential equation-based method proposed in Sect. 2 is to some extent similar to their approach.

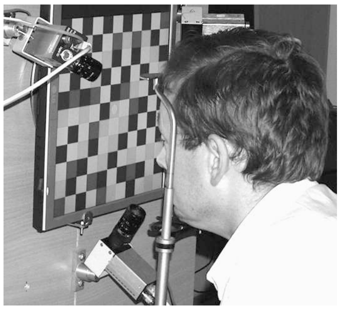

Figure 1: Taking corneal reflection images with the proposed multi-camera corneal topographer arrangement. A special colour-coded measurement pattern is used.

2 THE PROPOSED TOPOGRAPHER ARRANGEMENT AND RECONSTRUCTION METHOD

2.1 The Multi-camera Topographer Arrangement

The proposed corneal topographer arrangement consists of an embedded computer for handling user interactions and multiple camera inputs, generating various measurement patterns and computation; a TFT display that is used for displaying the measurement-pattern; and up to four colour cameras – mounted rigidly on the display – aimed at the patient's eye. A 3-camera arrangement is shown in Fig. 1.

It has been pointed out in the Introduction that a measurement pattern that is more complex and more informative than the frequently used Placido ring-system is required for robust corneal measurements, and particularly for the proper identification of corresponding object and image locations. To this end, the use of various colour-coded measurement patterns were suggested by (Griffin et al., 1992) and (Sicam et al., 2007).

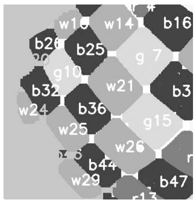

Figure 2: A part of the reflected colour-coded measurement pattern after colour segmentation and labeling.

In Fig. 1, a novel colour-coded measurement pattern – displayed in front of the patient's eye – is shown. It uses four colours, namely, red, green, blue, and yellow, and ensures the unique identification of a 3-by-3 field-neighbourhood, even if it is rotated and its squares are distorted. In Fig. 2, a part of such a reflected image is shown after colour segmentation, morphological filtering and connected component labelling.

The measurement pattern itself was generated by a backtracking algorithm. Presently, this colour-coded measurement pattern is used in conjunction with a simple black-and-white one that is shown in Fig. 3.

Each of the white circular spots of the latter is placed in the centre of a red, green, blue, or yellow square. The black and white measurement pattern is used for determining the image grid-points with a sub-pixel accuracy, while the colour-coded one is used to ensure robust point-to-point correspondence.

2.2 The Mathematical Reconstruction of the Corneal Surface

Mathematically, the tear-film coated corneal surface is modelled with a smooth, convex surface F. This surface is described and sought in preferably chosen spatial polar-coordinate systems. Each of these polar-coordinate systems corresponds to one of the cameras of the topographer arrangement.

In Fig. 4, one of the mentioned polar coordinate systems is shown. Its origin B is placed in the camera's optical centre and its axis is the optical axis BB' of the camera.

The surface F – that is the corneal surface – is described in the following form:

$$F(x_1,x_2) = S(x_1,x_2)\hat{x} \qquad (\hat{x} = (x_1,x_2,1)^T)$$

Here, $S(x)$ $(x = (x_1,x_2))$ is the distance – measured from B – of the intersection point P defined by the light ray starting from B in direction $\hat{x} = P_xB$ on one hand, and the specular surface F on the other.

The propagation of light from the points of the measurement pattern to the distorted image, i.e., P_yPP_x, is described in the mentioned polar coordinate system. By doing so, a mapping is identified between the points P_y of the measurement pattern and

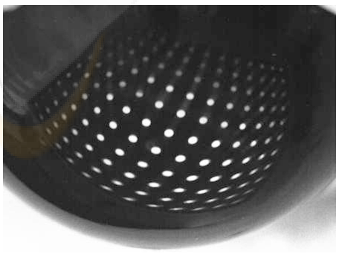

Figure 3: A simple measurement pattern being reflected by an artificial cornea.

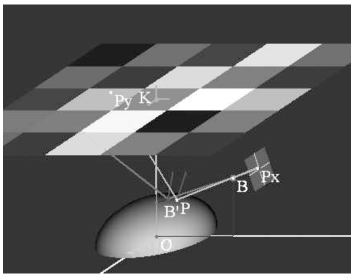

Figure 4: The spatial polar-coordinate system fixed to one of the cameras of the arrangement.

the points P_x of the camera-image. It follows from the conditions prescribed for the mathematical surface – that models the specular corneal surface – that this mapping is one-to-one.

It follows from the physical law of light-reflection, the two-variable function $S(x)$ describing surface F satisfies the following first-order partial differential equation (PDE):

$$\frac{1}{S(x)}\frac{\partial S(x)}{\partial x_j} = \frac{v_j(x) - x_j}{\langle \hat{x}, \hat{x} - v(x)\rangle} \qquad (j = 1,2),$$

where

$$v(x) = |\hat{x}|\frac{k + f(x) - S(x)\hat{x}}{|k + f(x) - S(x)\hat{x}|} \quad ,$$

and function $f(x)$ can be expressed with the inverse of the mentioned $P_y \to P_x$ mapping, that is, with mapping $P_x \to P_y$.

Referring to Fig. 4, $f(x) = KP_y$, where K is the origin of the coordinate system chosen in the plane of the measurement pattern, while $k = OK$ denotes a vector pointing to point K.

In the above PDE $\langle .,. \rangle$ denotes the scalar product of the 3D space.

It follows from the mathematical model described above that surface F can be determined uniquely under the starting condition of $S(0,0) = s_0$, if the $P_y \to P_x$ mapping is known.

A numerical procedure taking discrete values of the mapping $f(x)$ as input has been devised, firstly, to calculate the $P_x \to P_y$ mapping, and secondly, to solve the mentioned partial differential equation for a given

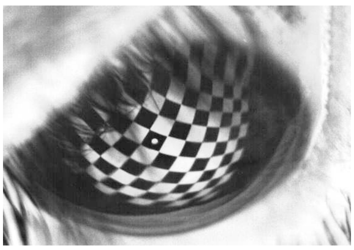

Figure 5: The virtual image of a simple chess board pattern as reflected by a living cornea.

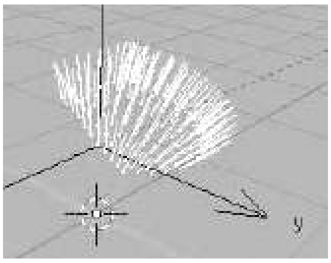

Figure 6: Normals of a surface region reconstructed from one camera view.

camera. In Fig. 6, the reconstructed surface and its normals are shown from a single camera-view.

In simulations carried out for known surfaces, good approximations of the original surfaces and their various curvatures were produced via the mentioned numerical surface reconstruction procedure. From these simulations it has turned out that the surface reconstruction procedure is clearly sensitive to the starting condition s_0, while it is much less sensitive to errors present in the $P_y \rightarrow P_x$ mapping.

In case of a multi-camera arrangement, the solution of the aforementioned PDE must start from a surface-point reflecting the measurement pattern, or more precisely, certain parts of it, to two, or more cameras. Let C_i denote the image of the reflected measurement pattern taken by i-th camera, and F_i the part of the corneal surface actually reflecting the measurement pattern into the i-th camera. The F_i and F_j surface-regions corresponding to the i-th and the j-th cameras of the proposed arrangement usually have overlapping regions. Nevertheless, in few cases, the patient's eye-lids and eye-lashes cover normally overlapping areas that would be important for the accurate surface reconstruction. It can be seen from Fig. 5 that eye-lashes might cause problems as early as the image segmentation stage of the measurement.

An algorithm has been devised that determines the distances of an arbitrarily chosen point of the overlapping surface-region from the i-th and the j-th cameras based on C_i and C_j images. This point and these distances will serve as the starting condition for the i-th and the j-th PDE (corresponding to the i-th and j-th cameras, respectively). After appropriate fitting, the union of the surface-regions will provide the reconstructed surface. Unit normal vectors, and the various curvatures used by the ophthalmologists can be calculated for any surface points.

3 CONCLUSIONS

The majority of the topographers in use, rely on one view only, which is theoretically insufficient for the unique reconstruction of the corneal surface. To overcome this essential measurement deficiency, a multi-camera arrangement is proposed. Several algorithmic and technical means were used to improve detection and surface reconstruction precision. Presently, test measurements are being carried out on artificial and living corneas.

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