Concept of an Active Optical Subsystem for Use in an Ophthalmic Implant

Ingo Sieber, Thomas Martin, Georg Bretthauer, Ulrich Gengenbach
Institute for Applied Computer Science
Karlsruhe Institute of Technology
76344 Eggenstein-Leopoldshafen, Germany
e-mail: ingo.sieber@kit.edu

***Abstract*—This paper describes the concept of an active optical subsystem for use in a demonstration model of an ophthalmic implant in the context of human centered systems. The active optical subsystem consists of the three principal components optics, actuator, and amplification linkage. The main focus of the work presented is on the robust concept and mode of operation of the active optical subsystem.**

Keywords-robust design; tolerance analysis; freeform optics; optical modeling and simulation; design optimization; ophthalmic implant

I. Introduction

In ophthalmology, restoration of the accommodation ability of the human eye is still an unsolved problem. The process of accommodation means the adjustment of the refraction power of the human eye with respect to the object distance. The loss of the ability to accommodate is due to an aging process of the human eye leading to a stiffening of the lens. Different approaches for restoration of the accommodation ability are currently under discussion [1]-[4], but none of them solves the problem in its entirety [5].

The concept of the Artificial Accommodation System (AAS) follows a mechatronic approach and will be implantable into the capsular bag of the human eye [6]. The following components represent the functional units of the AAS:

- An active optical subsystem,
- an information acquisition system,
- an information processing system,
- a communication unit,
- housing, and
- an energy supply system.

Figure 1 shows a schematic representation of the AAS [7]. There are depicted the main components and the position of the implanted system within the capsular bag of the human eye. A demonstration model of such an implant solution was designed and realized at a scale of 2:1 [8].

The active optical subsystem is of vital importance to the implant since the optical performance of the AAS depends on its reliable function.

The article is organized as follows: Section 2 presents the active optical subsystem of the AAS with all its components. Section 3 covers the set-up of the demonstration model and shows exemplarily its mode of action. The paper is completed by the conclusions drawn in Section 4.

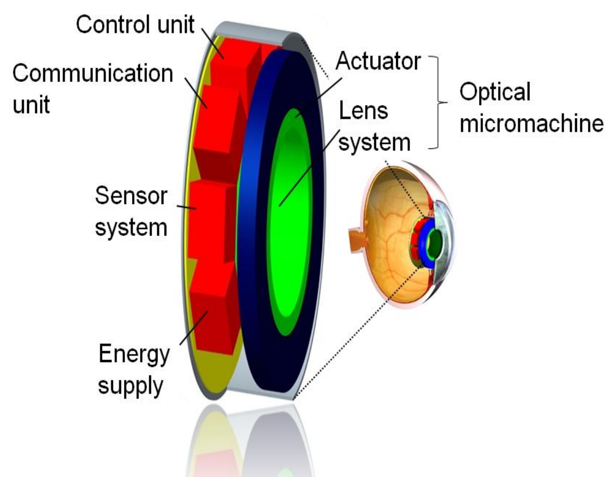

Figure 1. Schematic representation of the AAS and its position within the capsular bag of the human eye [7].

II. The Active Optical Subsystem

The three principal components of the active optical subsystem are presented and discussed in the following subsections.

A. Optics

Figure 2 shows a sketch of the optical components used in the demonstration model of the ophthalmic implant. The ray path is from left to right. The AAS features a modular concept, where the housing as well as optical surfaces integrated in the housing will be used for different optical principles. Originally, the housing was designed for an optical subsystem using an axially moveable lens to adjust refraction power [9]. Hence, the optics integrated in the housing are negative aspheric lenses. The first lens integrated in the housing is for beam expansion, the second lens integrated in the housing has the task to focus the rays on the retina (or camera chip in case of the demonstration model). Both optics are described by aspheric surfaces [7].

Manufacturing of the housing with its integrated optics was realized using a precision glass molding process. The influences of the manufacturing tolerances were analyzed by measuring the molded surfaces and a subsequent integration of the measured data into the optical simulation model [10].

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The task of the varifocal optics inside the housing (between the optics integrated in the housing) is to adjust the refraction power due to the visual requirements. One optical

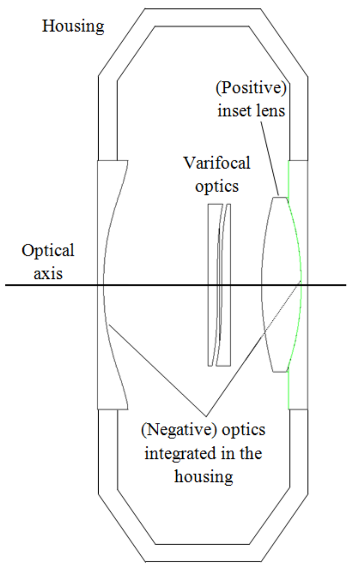

Figure 2. Optics of the demonstration model.

concept, which can be used as varifocal optics is the principle invented by Alvarez and Humphrey in 1970 [11]. According to this principle, the refraction power is varied by a mutual shift of two cubic-type lens parts perpendicular to the optical axis as shown in Figure 3. To combine the above described housing design with this varifocal concept, an aspherical inset lens has to be designed to add a positive refraction power to the negative lens of the rear side (see Figure 2) [7].

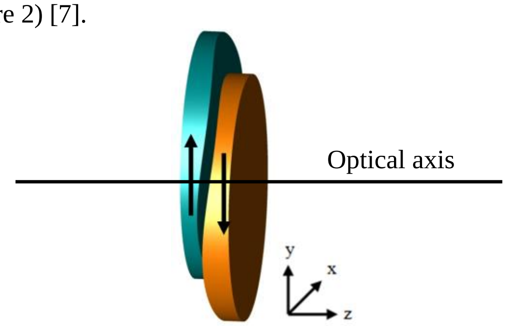

Figure 3. Alvarez-Humphrey optics.

Alvarez-Humphrey optics were studied extensively [12–14] and proposed for different technical [15]–[17] as well as ophthalmic applications [18], [19]. The opposing surfaces are conjugated and of cubic shape. Design parameters of the Alvarez-Humphrey (AH) lenses are the lateral movement v of the lens parts and the "form" parameter A determining the shape of the lens surface. The polynomial description of the surface sag is given by (1):

$$z(x,y) = A((y - v)x^2 + 1/3(y - v)^3). \quad (1)$$

The relation between the lateral movement v and the change of refraction power ΔD is given by (2) [20]:

$$\Delta D \sim A\, v. \quad (2)$$

Adjustment of the refraction power by means of a lateral shift of lens parts is advantageous in all applications where the space available along the optical axis is limited, as is true for the demonstration model at hand. Requirements of the optics and its design are presented in [21]. To compensate for aberration effects as well as for manufacturing tolerances a comprehensive design approach was used [22] resulting in a robust freeform surface of the AH optics, which is represented by a polynomial of seventh order using 35 parameters [7]. Also the robust design of the AH optics results in two different descriptions of the opposing freeform surfaces violating the conjugation of the original AH concept. The AH optics was manufactured by two competing processes: ultraprecision diamond machining and microinjection molding. While diamond machining is suitable only for small series fabrication microinjection molding is a replication process with the potential of mass fabrication [23, 24]. For both processes the effect of manufacturing tolerances on the performance of the optical subsystem was analysed and compared against each other by simulations based on a measurement data enhanced model [25].

B. Actuator

As described above, design parameters of the AH optics are the lateral mutual shift of the lens parts, v, as well as the form parameter A. To preserve a constant ΔD a reduction of v, which is requested to minimize the actuation stroke, leads evidently to a higher value of A (see (2)), which in turn significantly increases aberration effects and hence limits imaging quality. As a trade-off a maximum mutual shift of the lens parts of 180 µm with an actuator rest position at 40 µm displacement allows for a change of 4.6 dpt in optical power and was found to be a reasonable compromise for the demonstration model [26].

The requirements of the actuator with respect to cycle lifetime, power consumption, fail-safe behavior, response time, and space can be found in [26]. As the final actuator for the demonstration model a piezoelectric stack actuator (Noliac A/S, NAC2001-H06, Noliac, Kvistgaard, Denmark) was chosen. This actuator offers a nominal stroke of 4.9 µm of which a maximum of 2.9 µm is used during operation [27].

C. Amplification linkage

To provide a maximum lateral shift of a lens part of 140 µm (resulting in a displacement of the lens part of 180 µm on basis of the actuator rest position of 40 µm) an amplification ratio of around 48 of the maximum actuator stroke of 2.9 µm is required. For reasons of miniaturization and reduction of assembly processes, a monolithic design with flexure hinges was selected. The planarity of the linkage enables a Deep Reactive Ion Etching (DRIE) process for fabrication of the linkage in single-crystal silicon [26]. Figure 4 shows the linkage manufactured by DRIE fulfilling the transmission requirements [26]. The opening in the upper part of the linkage is the host structure for the piezoelectric stack actuator. The lens parts are to be assembled into the round mounts in the middle of the linkage. Minimum structure

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widths of about 24 µm were realized by means of the DRIE-process. The linkage is enclosed by a solid frame serving both as interface to the subsystem mount and as handling frame during system assembly.

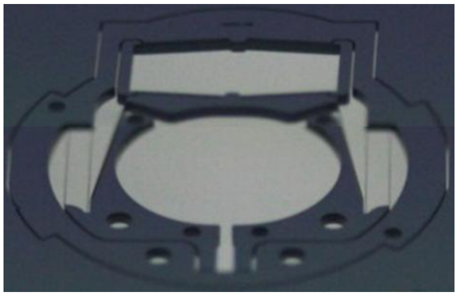

Figure 4. Silicon linkage manufactured by DRIE [7].

III. SET-UP OF THE ACTIVE OPTICAL SUBSYSTEM

Assembly of the AH optics, the actuator, and the silicon linkage yields the varifocal optics. Figure 5 depicts two photographs of the varifocal optics in two different actuation states. On the left hand side, the piezo stack actuator is expanded. The expansion leads to a mutual outward shift of both lens parts and therefore to a relative decrease in refraction power of the optics. On the right of Figure 5 the contraction of the actuator is shown leading to an inward movement of the lens parts and an increase of the optics' refraction power. This effect is visible comparing the grid size in the image: while reducing the refraction power the grid size of the image scales down (Figure 5, left) compared to an increase of refraction power as shown in Figure 5 on the right hand side.

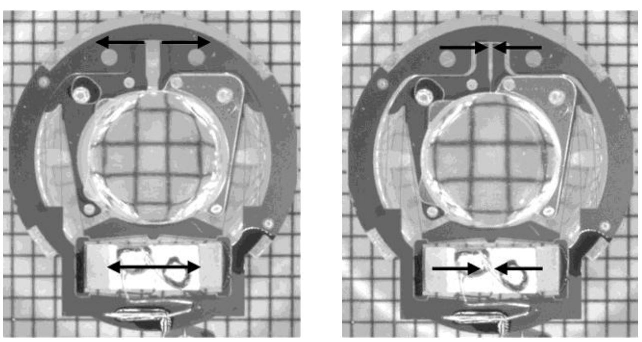

Figure 5. Varifocal optics. **Left**: expanded actuator and decreased refraction power, **right**: contracted actuator and incresed refraction power.

As described in Section 2, the optical subsystem consists of the varifocal optics assembled in a housing where both the entrance and exit windows provide optical power by means of curved optical surfaces integrated in the housing. Since the AAS features a modular concept where varifocal optics of different kind can be exchanged the optics integrated in the housing have to be adapted to the optics used. Combining the negative rear-side optics with an AH optics, an aspherical inset lens has to be designed to add a positive refraction power to the negative lens of the rear side. The exact description of the optics integrated in the housing and the aspheric inset lens can be found in [7]. Figure 6 shows the varifocal optics assembled on its mount in the rear half shell of the glass housing.

Figure 6. Varifocal optics assembled to the rear half shell of the glass housing.

The active optical subsystem combined with a sensor cross and electronics for control, information acquisition & processing, and communication is depicted in Figure 7. The sensor cross of the demonstration model consists of photodiodes and is segmented:

- The central segment is for measurement of the environmental luminance.
- Two outer segments are for measurement of the pupil diameter.

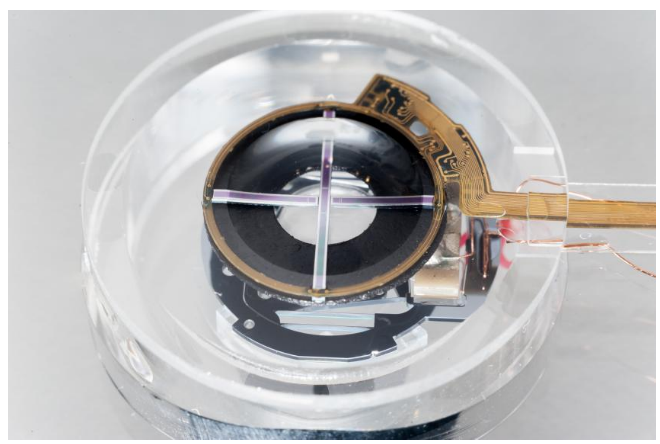

Figure 7. Active optical subsystem consiting of the varifocal optics assembled to the housing.

On the basis of these two measurands the accommodation demand and hence the adjustment of the refraction power can be derived [5].

Mode of action of the active optical subsystem is shown in Figure 8 for two different adjustments of the system's refraction power. On top of Figure 8 a concentric pattern at a distance of approximately 3 m is imaged sharply on a camera chip while the pen in the foreground is out of focus and is imaged only blurred. Readjusting the varifocal optics for the near sight images the pen at a distance of approximately 0.3 m sharply while the image of the concentric pattern appears blurred.

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Figure 8. Active optical subsystem in operation. Top: adjustment mode for imaging of far distant objects. Bottom: adjustment mode for imaging of close objects.

IV. CONCLUSIONS

Restoration of the accommodation ability of the human eye is still an unsolved problem. One possible approach is to replace the presbyopic human crystalline lens by a mechatronic implant. One key component of such a mechatronic implant would be the active optical subsystem consisting of varifocal optics and a tailored actuation principle. As varifocal optics an Alvarez-Humphrey optics is presented, which is able to adjust the refraction power by a mutual shift of two freeform lens components perpendicular to the optical axis. For designing freeform optics, the robust design approach is essential [28] consisting of monolithic integration principles to minimize assembly efforts as well as an optimization of the functional components with respect to robustness against remaining assembly and manufacturing tolerances.

Actuation is conducted by a piezoelectric stack actuator while a silicon linkage provides the necessary displacement amplification. The result leads to a robust design of the active optical subsystem, which is integrated in a demonstration model at a scale of 2:1. A first impression of the mode of action of the demonstration model is shown for imaging objects in two different distances.

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