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Robust intraocular acquisition of the accommodation demand using eyeball movements

Liane Rheinschmitt, Fabian Ritter, Jörg A. Nagel, Ulrich Gengenbach, Helmut Guth and Georg Bretthauer
Karlsruhe Institute of Technology (KIT)
Institute for Applied Computer Science
Karlsruhe, Germany
Email: liane.rheinschmitt@kit.edu

***Abstract*—The Artificial Accommodation System is a mechatronic lens implant that will restore the ability of the human eye to accommodate. Therefore, the accommodation demand has to be acquired. One possibility is to measure the vergence angle of the eyeballs in reference to an external field. Using the earth magnetic field as reference the proof of this measuring principle was possible. Still there are drawbacks like high responsivity to interferences and limitations of the measuring range. The new approach is to use the gravity field as reference and thus reduce the responsivity to interferences. The measuring range can be expanded by combining both sensing principles.**

I. Introduction

The Artificial Accommodation System is an intraocular lens implant that will restore the ability of the human eye to accommodate to different focal lengths [1], [2]. It is a fully integrated autonomous mechatronic micro system that will be implanted into the lens capsular bag using standard implantation techniques known from cataract surgery. Therefore all components of the subsystems have to fit into the limited volume inside the capsular bag. One subsystem is the active optical element that consists of a lens system and an actuator to vary the refractive power of this lens system e.g. using the displacement of one of the lens components [2]. The diameter of the optical area is 5 mm. The electronic components are placed in the ring-shaped volume around the optical element. A sensor system will acquire the accommodative demand. Furthermore, a control unit, a power supply system and a system for the communication between the implants of both eyes are integrated. In Fig. 1 a schematic model of the Artificial Accommodation Systems and its internal components is shown.

The energy will be supplied using inductive coupling [3] and will be stored in a battery so that autonomous operation is possible for at least 24 hours. The dynamics of the system are derived from the time used by the natural lens to accommodate: 700 ms [4]. Resulting from these implant requirements, the requirements for the sensor system are to be

- small-sized
- energy-efficient
- dynamic.

The sensor system can only use information available from within the capsular bag to acquire the accommodation demand. One approach is to use the movement of the eyeballs [5].

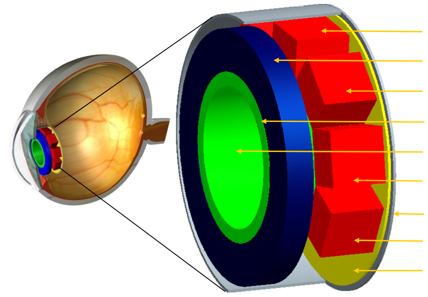


Fig. 1. Schematic model of the position of the Artificial Accommodation and its internal components within the capsular bag of the human eye.

II. Measurement of the vergence angle

The aligning movement of the eyeballs in order to fixate a target is called vergence movement [6]. It is realized using the eye muscles to rotate the eye balls about the rotation axis r (Fig. 2). The knowledge of the vergence angle between the fixation lines of the eyes and the distance between the two eyes allow for the calculation of the distance between target and eyes using trigonometry. To obtain the vergence angle, the orientation of each eye can be measured using an external reference field. The amplitudes of the field measured at the axes x and y are analyzed and therewith the angle of the sensor within the external reference field α can be determined for each eye L (left) and R (right). After communication of the measurement results between the implants, the vergence angle β and thus the distance to the target and the accommodation demand is obtained. Using a three axis sensor, the tilt caused by misplacement of the sensor due to the implantation or the assembly process can be compensated.

The required accuracy for the measurement of the vergence angle is derived from the wish to measure the accommodation demand with minimum required accuracy of ± 0.25 dpt [5]. The minimum accuracy of the vergence angle is therefore $\pm 0.77°$.

A general constraint using an external reference field for the acquisition of the vergence angle is that at certain

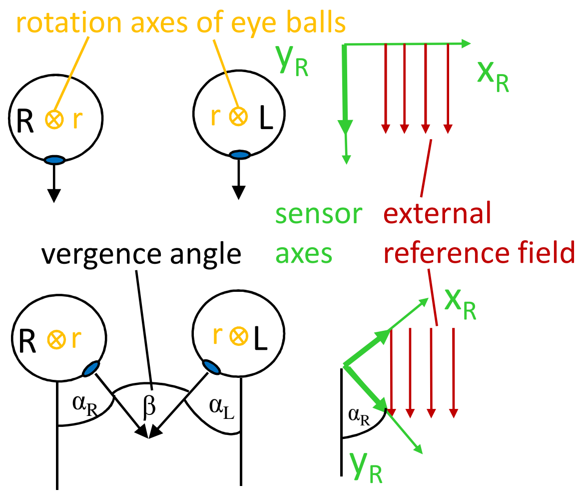


Fig. 2. Determination of the vergence angle of the eyeballs using a two-axis sensor that detects the orientation within an external reference field.

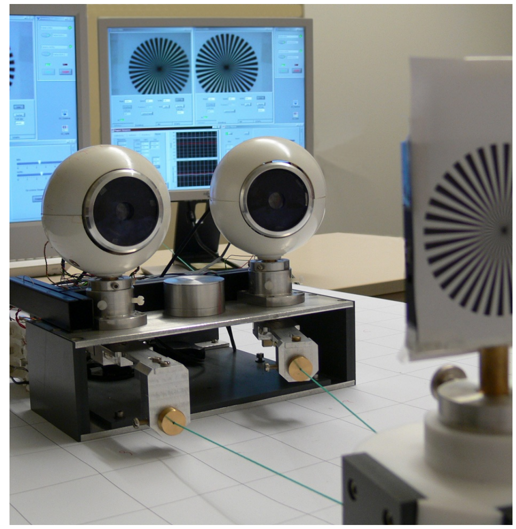


Fig. 4. Demonstrator of the Artificial Accommodation System in scale 5:1 proving the working principle of the acquisition of the accommodation demand using compass sensors.

angles of vision, determined by the tilt of the head or of the eyeballs, the orientation of the sensors can not be obtained. At the most favourite position the rotation axis of the vergence movement is perpendicular to the field lines. Thus the maximum measurement values of the external field can be obtained (Fig. 3 top). At the worst angle of vision the rotation axis of the vergence movement is parallel to the field lines. The change of the vergence angle is not detectable (Fig. 3 bottom).

Tilting the head from the best angle of vision towards the worst, the detectable amplitudes decrease. At which angle of vision the vergence angle can still be obtained depends on the sensor resolution.

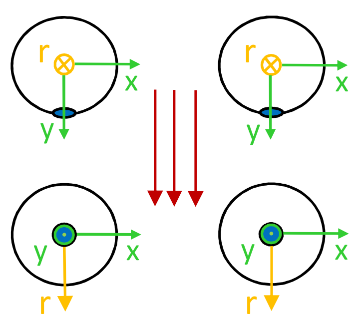


Fig. 3. Dependence of the measured external field on the angle of vision around the x-axis.

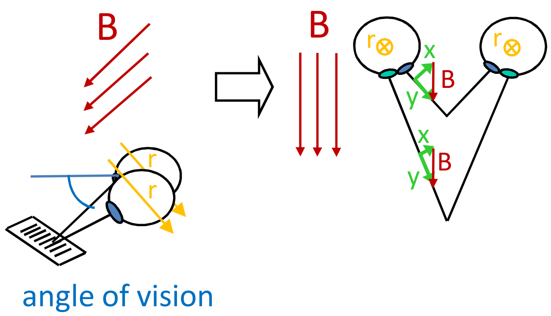
The measurement of the vergence angle can be simulated extracorporally by rotating artificial eyeballs. It was implemented into a 5:1 demonstrator shown in Fig. 4. The external field used as reference is the earth magnetic field. Therefore, compass sensors where placed into each eyeball. With this setup, the proof of principle was possible [7].

But measuring the earth magnetic field does have several drawbacks. The most severe is its high responsivity to interferences. These interferences can result from static magnetic fields as produced by loudspeakers in mobile phones or earphones. Another cause are deflections of the earth magnetic field within a building or near metal parts. The energy consumption is relatively high since the measurement principles for the detection of magnetic fields are usually magnetoresistive and therefore require a current flow.

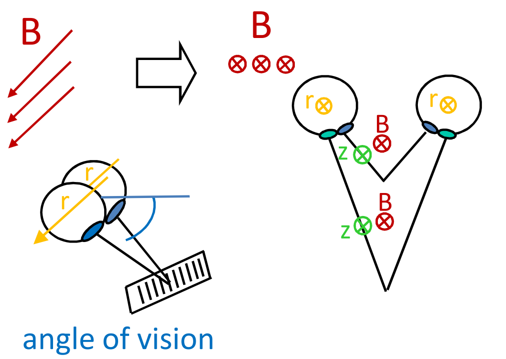
Additionally, the inclination angle of the earth magnetic field differs depending on the position on the globe. Therefore, using the earth magnetic field as external reference, the best and the worst angle of vision depend on the patient's position on the globe. Near the equator the inclination angle of the earth magnetic field is Zero. Thus the highest amplitudes can be measured at a horizontal direction of view, no amplitude can be measured when the angle of vision is 90°, meaning the person looks to the floor or to the ceiling. In Germany, the inclination is about 60°. Fig. 5(a) shows the best angle of vision there to measure the accommodation demand, fig. 5(b) the worst angle of vision, where no change of the vergence angle can be detected. To avoid the worst angle of vision where a detection of the accommodation demand and thus the accommodation of the system is not possible, the patient would always have to know the cardinal points and the inclination angle of the earth magnetic filed at his present location.

III. New reference field

In order to use the sensor principle of measuring the vergence angle of the eyeballs without the drawbacks described above, a new reference source is chosen: the gravity field [8]. Acceleration sensors are used, whose measurement principle is the capacitive acquisition of the deflection of a seismic mass. Most acceleration sensors have a lower power consumption than magnetic field sensors. Interferences are the stabilizing and the micro movements of the eye [6] and head or body movements. Fixation eye movements like



(a) Best angle of vision



(b) Worst angle of vision

Fig. 5. Best angle of vision (a) and worst angle of vision (b) for the acquisition of the vergence angle of the eyeballs using the earth magnetic field in Germany as reference.

saccades have no direct effect, since there is no focusing in this time period.

The angle of vision where no detection of the external field is possible is 0° and thus the horizontal direction of view. This angle does not depend on the patient's position on the globe. Since the preferred angle of vision of a sitting person that needs to accommodate in order to read or work is between 25° and 30° [9], people seldom accommodate at an angle of vision of 0°. It is therefore possible to set the implant's refractive power for the angles of vision around 0° to "desaccommodated" or "far focus" and to measure the vergence angle using the gravity field for all other angles of vision.

In order to test the applicability of acceleration sensors a setup was built using the small 3x3x0.9 mm^3 KXSC7 acceleration sensor. Due to the sensor resolution the measurement of the vergence angle was possible for angles of vision of ±15° and more (Table I). Using sensors with higher sensitivity, e.g. KXTF9 also sized 3x3x0.9 mm^3, the non-detectable angles of vision can theoretically be reduced to ±5° (Table I).

IV. Combination of Independent External Fields

Some situations make an accommodation in direct horizontal view necessary, for example reading a bus timetable. In order to cover all angles of vision the

TABLE I
INACCURACY OF THE MEASURED VERGENCE ANGLE DUE TO SENSOR RESOLUTION FOR TWO DIFFERENT ACCELERATION SENSORS

Angle of vision	Vergence angle inaccuracy KXSC7	KXTF9
1°	*7.13°*	*2.80°*
2°	*4.09°*	*1.60°*
3°	*2.86°*	*1.12°*
4°	*2.20°*	*0.86°*
5°	*1.91°*	**0.75°**
6°	*1.43°*	**0.56°**
7°	*1.25°*	**0.49°**
8°	*1.10°*	**0.43°**
9°	*0.95°*	**0.37°**
10°	*0.82°*	**0.32°**
15°	**0.55°**	**0.22°**
20°	**0.42°**	**0.16°**
45°	**0.20°**	**0.08°**

combination of the independent reference sources earth magnetic field and gravity field is possible. The orientation of these fields does only coincide at the magnetic poles of the earth. The smallest angle between the fields in inhabited regions is 12° in Fairbanks, Alaska. So combining both sources every angle of vision can be covered within every inhabited area. The interferences, static magnetic fields and eye movements, are also independent. One sensor can compensate for the other interfered sensor signal.

One possibility to filter and combine the signals of both sensors is using a linear time-discrete one-dimensional Kalman-filter [10]. A Kalman-Filter is a collection of equations allowing the recursive estimation of a system status from values that imply a measurement error. The recursive function can be implemented such that only the results of the last sub-step, here the last measurement of the vergence angle, are necessary.

Fig. 6 shows the prediction-correction-structure of the Kalman-filter. First the future status is estimated using the preceding status of the system. Then these estimations are corrected using measurement data.

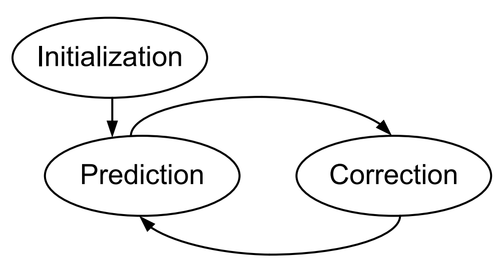


Fig. 6. Structure of a Kalman-filter consisting of prediction and correction.

The Kalman matrix $K[k]$ is calculated using the uncertainty of the prediction $P[k-1]$ and the error of the measurement $R[k]$.

$$K[k] = \frac{P[k-1]}{P[k-1] + R[k]} \quad (1)$$

Therewith the estimation of the system status $\hat{x}[k]$ at the discrete instant of time k is corrected using the measurement data $z[k]$ and the preceding prediction $\hat{x}[k-1]$.

$$\hat{x}[k] = \hat{x}[k-1] + K[k] \cdot (z[k] - \hat{x}[k-1]) \quad (2)$$

Fig. 7 shows the measurement data of the vergence and the Kalman-filtered signal. The advantage of the Kalman-filter e.g. in comparison with an arithmetic filter is the very fast reaction due to the prediction of the dynamics of the system. At constant velocity of the change of the vergence angle there is no time lag at all. Since only the last status of the system is used, the memory requirements for the implementation of the Kalman-filter are very low.

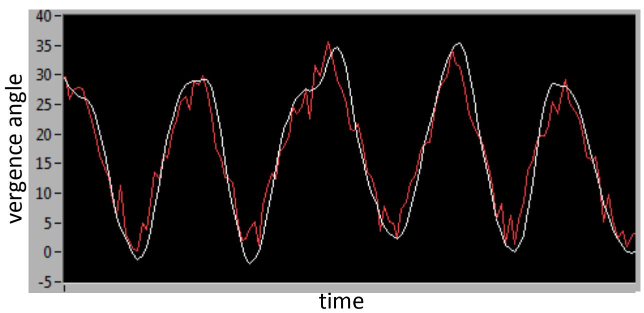


Fig. 7. Measurement data of the vergence angle (red) and Kalman-filtered data (white).

The knowledge of the inaccuracy of the measured vergence angle using the earth magnetic field or the gravity field as reference can be used for weighting the measurement results. Therefore, the angle of vision can be obtained using the acceleration sensor and a test of plausibility can be made for each sensor's result. This information can also be used to implement an energy management. Knowing the angle of vision allows it to use the power consuming compass sensor only when needed. Thus the additional volume consumed by two sensors is compensated by saving battery space.

Another option is to design one sensor only for the measurement of its best angles of vision and the other one for the remaining angles. Thereby, the necessary resolution for each sensor and its size can be reduced.

V. Conclusion

In order to obtain the accommodation demand from inside a human lens implant the measurement of the vergence angle can be used. It was proven that the earth magnetic field and the gravity field suit as external references to obtain the vergence angle. For each external field there are angles of vision where the accommodation demand can not be detected. Using the gravity field these angles can be reduced to $\pm 5°$. Another option is to combine the named independent sources to cover every angle of vision. Therefore, the Kalman filter was introduced as a suitable tool.

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