MAC-EYE: a Tendon Driven Fully Embedded Robot Eye

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1. Introduction

This work shows the possibility of designing a robot eye with kinematics and actuation similar to those of the human eye. In particular, we tried to exploit the spherical shape of the eye and to study the feasibility of a tendon based actuation mechanism which could implement *Listing's Law*. The robot presented consists of a sphere hold by a low friction support. Four independent tendons, actuated by DC motors, allow the proper rotation of the eye. A suitable placement of the insertion points of the tendons on the eye-ball, as well as their routing to the motors have been investigated. Simulations have shown that the proposed configuration meets the motion requirements specified by *Listing's Law*.

2. Saccadic Movements and Listing's Law

In the following we will focus on saccadic motions, and to *Listing's Law* which specifies the eye's orientation during saccades.

Listing's Law. There exists a specific eye orientation with respect to the head, called *primary position.* During saccades any eye orientation, with respect to the *primary position*, can be described by a rotation axis, $\mathbf{v}$, belonging to a head fixed plane, $\mathcal{L}$. The normal to plane $\mathcal{L}$ is the eye's direction of fixation at the *primary position.*

Fig. 1 shows the geometry of Listing compatible rotations.

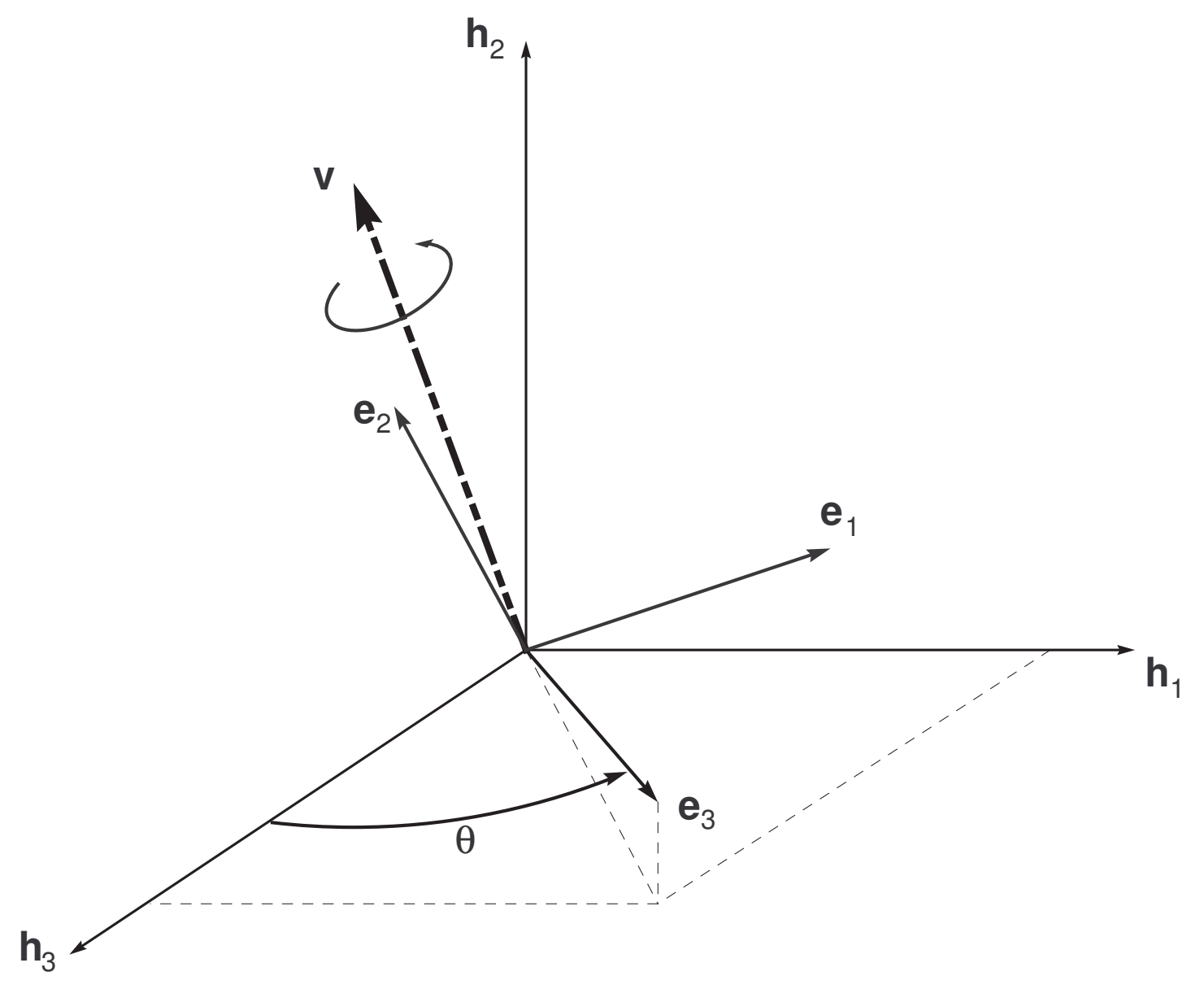


Figure 1: *geometry of Listing compatible rotations.*

From the kinematic point of view, during saccades, at any time t, the rotation of the eye can be conveniently described by a unit quaternion:

$$q = \left(\cos\frac{\theta}{2}, \mathbf{v}\sin\frac{\theta}{2}\right), \qquad (1)$$

where $\mathbf{v} \in \mathcal{L}, |\mathbf{v}| = 1$, and θ is the amount of rotation with respect to the *primary position*. The derivative of (1) is:

$$\dot{q} = \frac{1}{2}\,\tilde{\omega}\;q, \qquad (2)$$

where quaternion $\tilde{\omega} = (0, \omega)$ and ω is the angular velocity of the eye. By expanding (2) we obtain:

$$\dot{q} = \frac{1}{2}\left((\omega\cdot\mathbf{v})\sin\frac{\theta}{2}, \omega\cos\frac{\theta}{2} + (\omega\times\mathbf{v})\sin\frac{\theta}{2}\right). \qquad (3)$$

In order to guarantee the condition $\mathbf{v} \in \mathcal{L}$, we must have $\dot{\mathbf{v}} \in \mathcal{L}$, for any ω, then from (3) the following equality must hold:

$$\mathbf{h_3}\cdot\left[\omega\cos\frac{\theta}{2} + (\omega\times\mathbf{v})\sin\frac{\theta}{2}\right] = 0. \qquad (4)$$

Expression (4) leads to the formula:

$$(\omega\cdot\mathbf{h_3}) = \omega\cdot(\mathbf{h_3}\times\mathbf{v})\tan\frac{\theta}{2}, \qquad (5)$$

stating that the angular velocity of the eye is constrained to a plane $\mathcal{P}_\omega$ passing through $\mathbf{v}$, and whose normal forms an angle of $\frac{\theta}{2}$ with axis $\mathbf{h_3}$, see fig. 2. This property is usually called *half angle rule*.

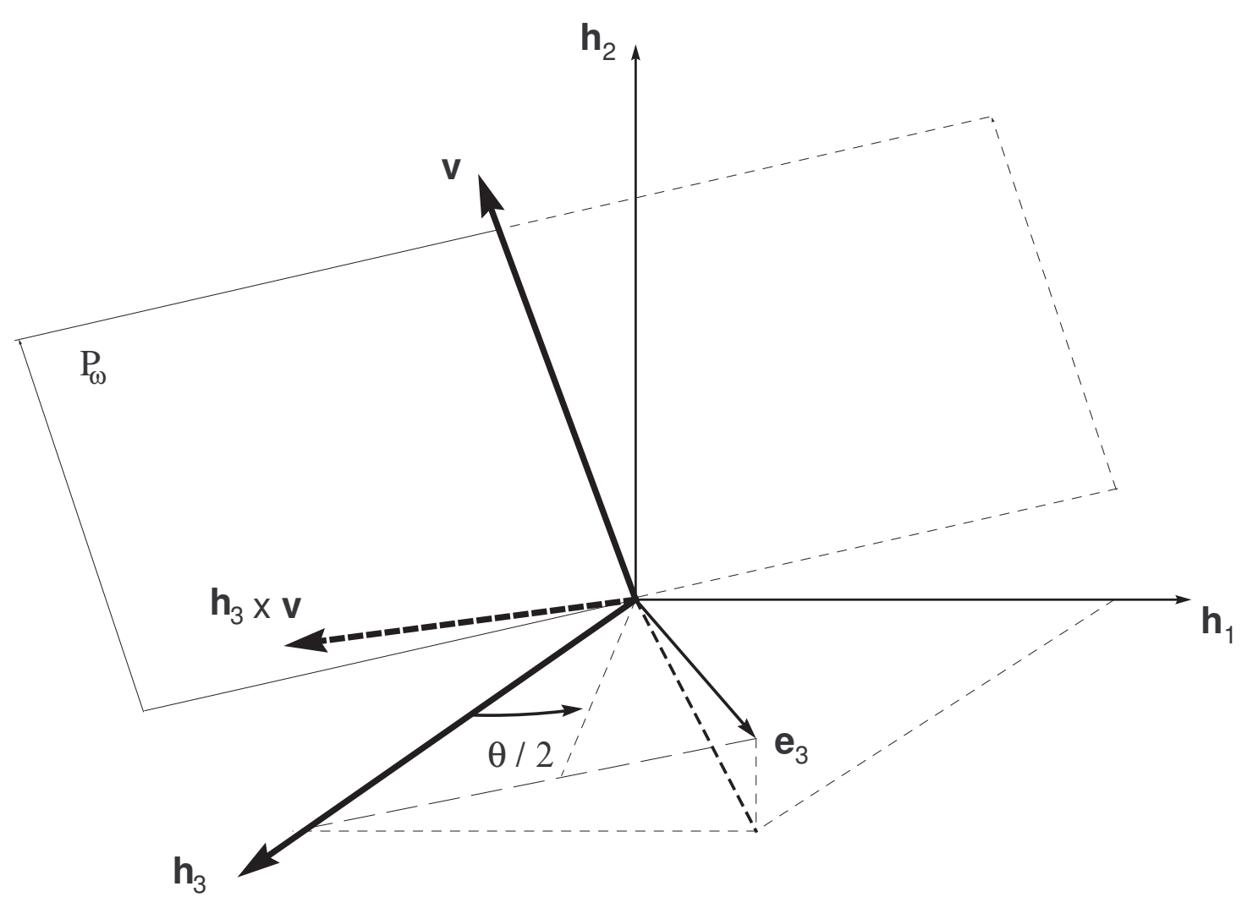
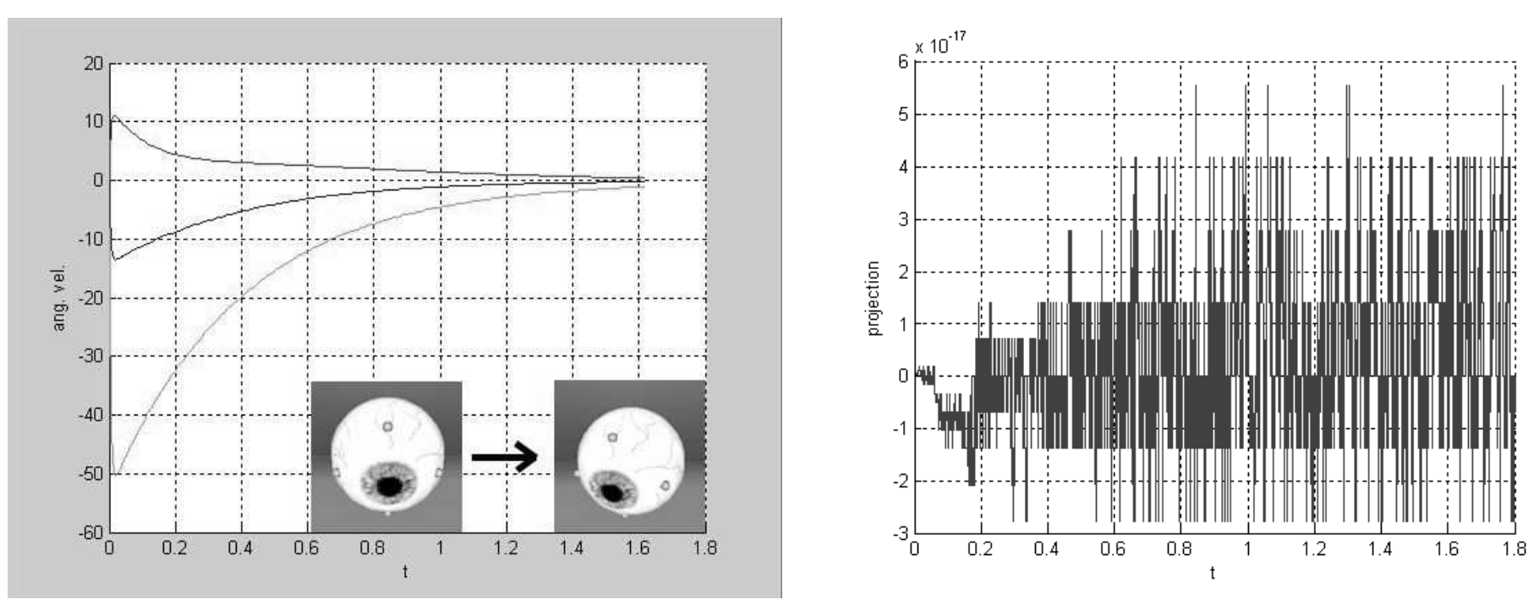


Figure 2: *half angle rule geometry.*

3. Robot Eye Model

The robot eye-ball has been modelled as an homogeneous sphere with 3 rotational DOFs, and actuated by the action of 4 extra-ocular muscles (EOMs). The EOMs have been modelled as thin wires of fixed length connected on one side to the eye-ball and to springs at the second end. Starting from the insertion points on the eye-ball, EOMs are routed to fixed *point-wise* pulleys placed on the rear of the eye-ball. The EOMs follow the shortest path from their insertion points to the corresponding pulleys.

Simulations have shown that symmetric configuration of the insertion points and of the pulleys with respect to the center of the eye-ball ensures Listing compatible rotations for any pattern of forces applied by the EOMs, fig. 3.



(a) (b)

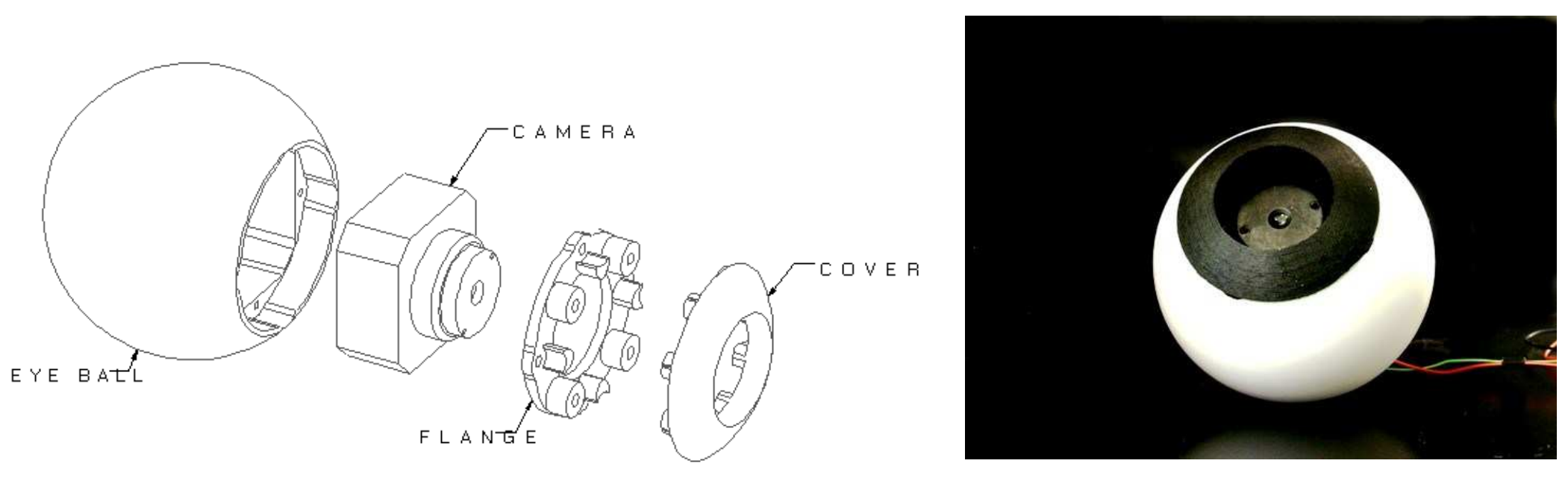
Figure 3: *(a) components of angular velocity; (b) component of the rotation vector orthogonal to Listing's Plane during a generic saccade from a secondary to a tertiary position.*

4. MAC-EYE Design and Implementation

The robot eye consists of various modules shortly described in the following.

4.1 The Eye-Ball

The eye ball is a $38.1mm$ diameter precision PTFE sphere CNC machined to host a CMOS camera, and to route the power supply and video signal cables to the external electronics, fig. 4.

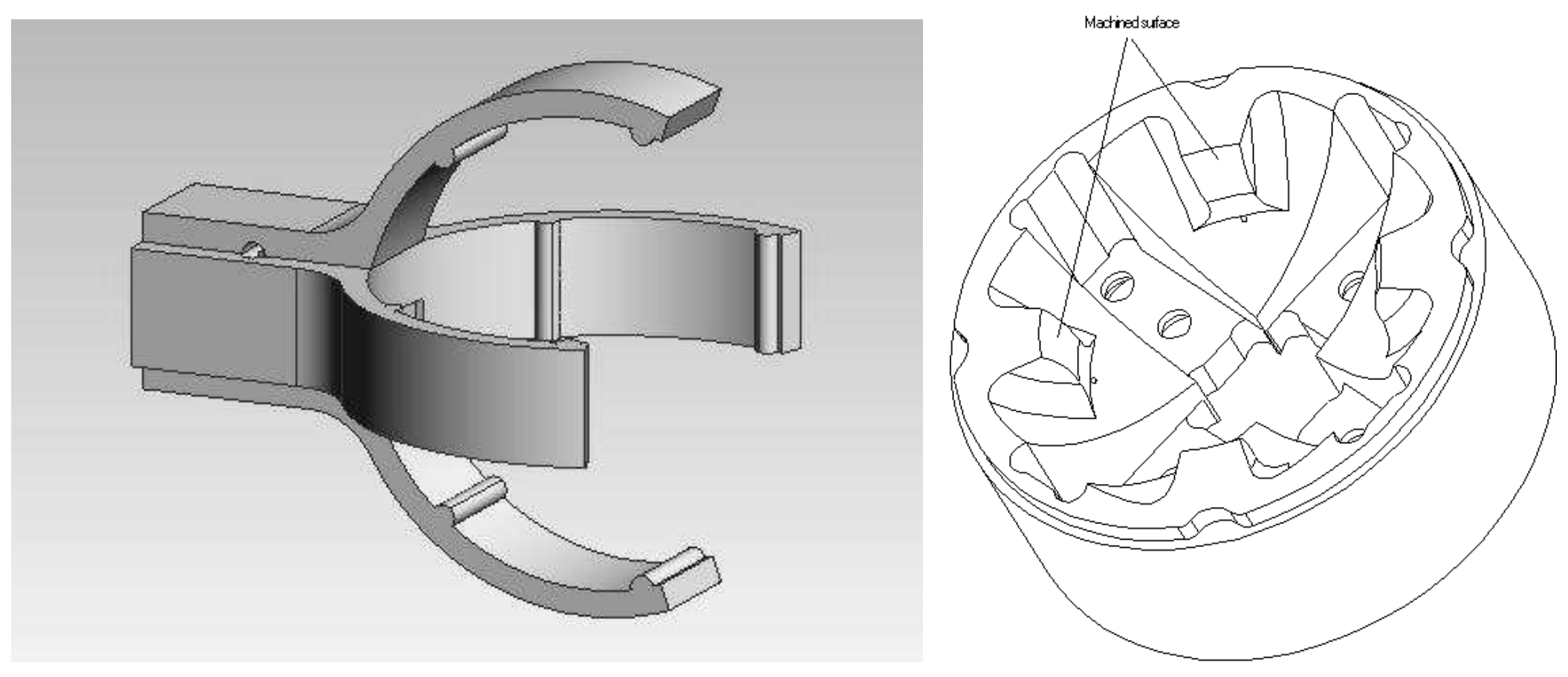


(a) (b)

Figure 4: *(a) exploded view of the eye-ball; (b) assembled eye-ball.*

4.2 The Eye-Ball Support

The eye ball is supported by a PTFE part shown in fig. 5.a, hold by a supporting flange, 5.b.



(a) (b)

Figure 5: *(a) CAD model of the eye-ball support; (b) detail of the flange supporting the eye-ball.*

The role of the flange is also that of ensuring the appropriate routing of the EOMs from their insertion points on the eye-ball to the actuation motors.

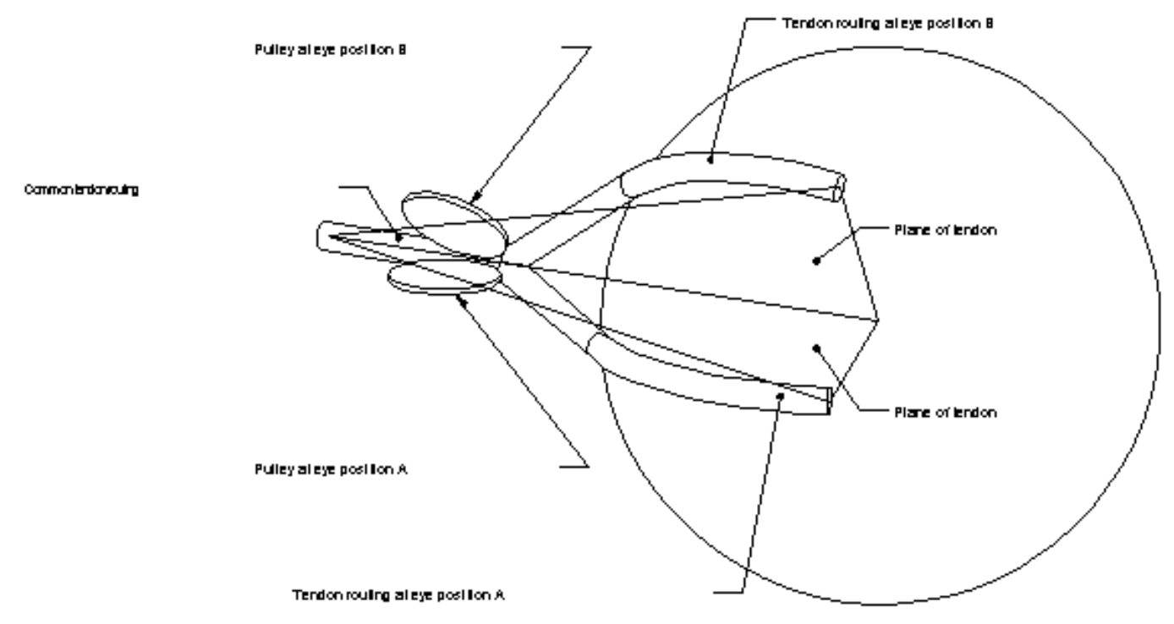


Figure 6: *sketch of the tendon's paths.*

Each EOM is assumed to be routed through a pulley which can tilt about an axis $\mathbf{c}$ passing through the eye center, fig. 6. The resulting EOM's path is then planar for each eye orientation. In order to implement this model, the surface obtained by the envelope of the *tilting* pulleys, for any possible Listing compatible eye orientation, has been machined, as shown in fig. 5.b.

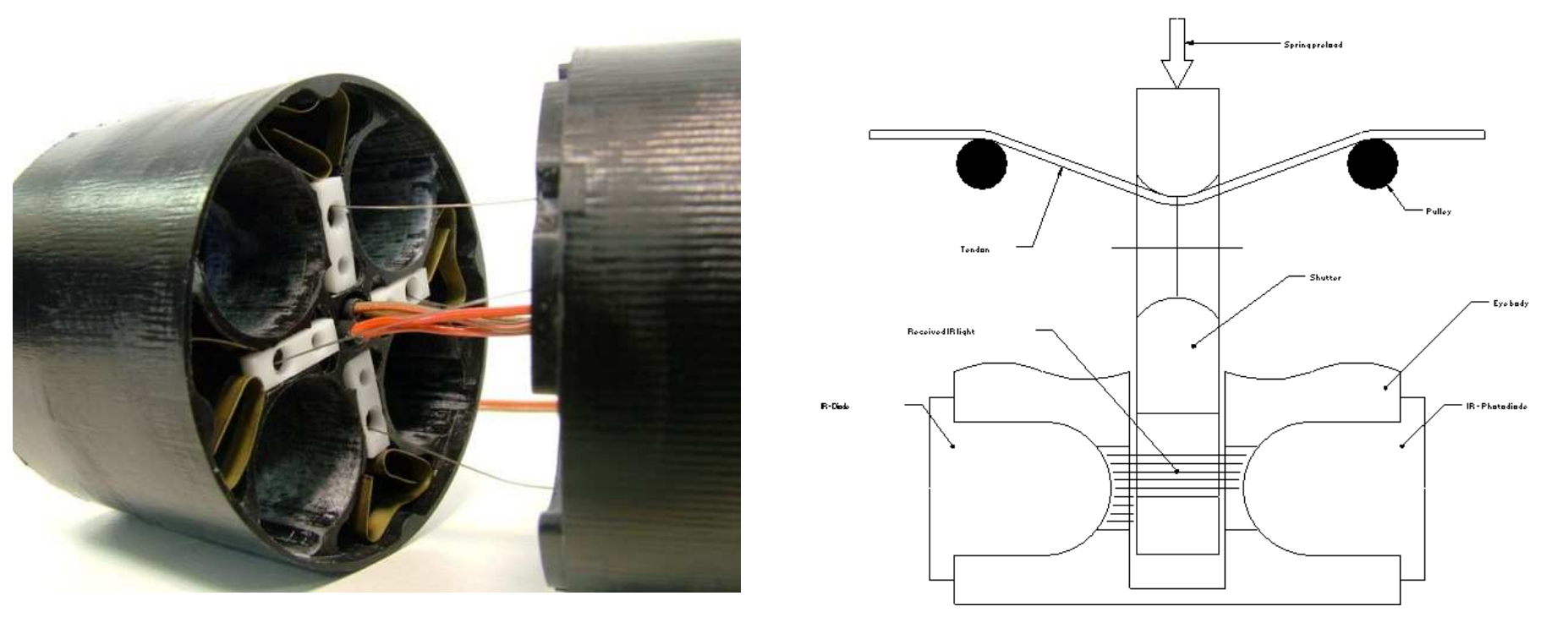
4.3 The Eye Body

The body of the MAC-EYE robot, made of *acetal homopolymer resin*, embeds the four DC motors required to actuate the eye, and the sensors required to control the tension of the tendons. The whole structure weighs about $350g$, has an external diameter of $50mm$ and is $100mm$ long (including eye-ball and rear motor pulleys).

4.4 Tension Sensors

The only sensors used to control the movements of the eye are the encoders of the DC motors and the sensors required to control the tendons' tensions. The use of visual feedback by means of the on board CMOS camera is not part of the present discussion.

The eye is actuated by four tendons made of low friction nylon cables (diameter $0.25mm$). In order to avoid the slackness of the tendons optical tension sensors have been designed to implement a tension closed-loop control, fig. 7.



(a) (b)

Figure 7: *(a) implementation of the embedded tendons' tension sensors; (b) sketch of the tension sensor.*

4.5 Control Architecture

The control architecture is implemented as a two level hierarchical system. A PC based high level digital control module implements a PI-type regulation of the path lengths of the tendons.

A low level controller, fig. 8, implements a PI-type motor velocity control loop in parallel with a P-type tension control loop, both running at $1.25KHz$.

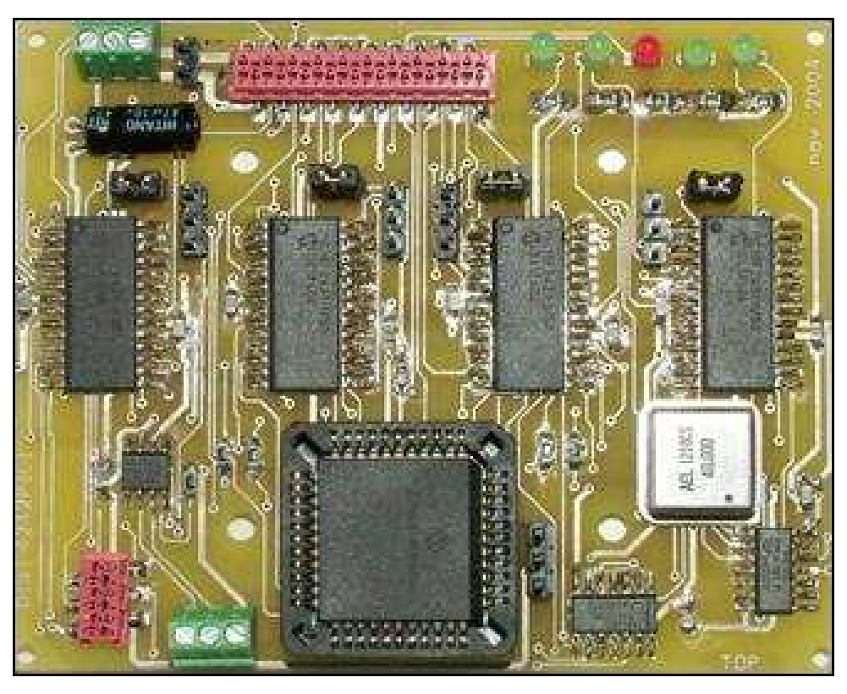


Figure 8: *The embedded real-time controller consists of 4 slave micro-controllers coordinated by a master one.*

The PC based controller and the embedded one communicate through CAN bus (at $125Hz$ rate).

5. Conclusions

The MAC-EYE robot prototype has kinematics and actuation structure emulating the characteristics of a human eye. In particular, the study has focused on a design which meets the motion constraints imposed by *Listing's Law*.

The MAC-EYE robot has been used to develop the stereoscopic system shown in fig. 9.

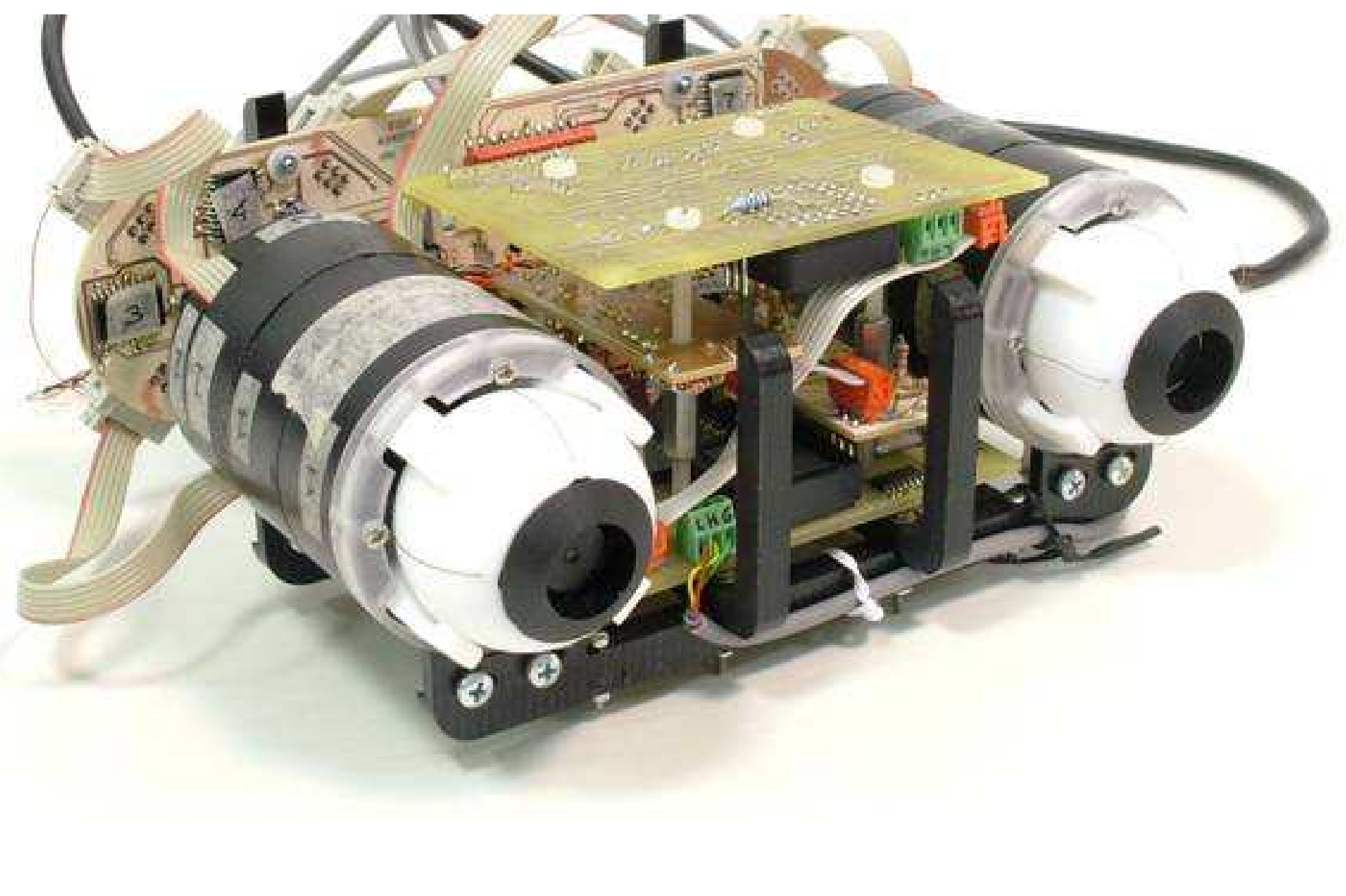


Figure 9: *complete stereoscopic robot system*

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