URN (Paper): urn:nbn:de:gbv:ilm1-2014iwk-180:7

58th ILMENAU SCIENTIFIC COLLOQUIUM
Technische Universität Ilmenau, 08 – 12 September 2014
URN: urn:nbn:de:gbv:ilm1-2014iwk:3

The Cilia Field as a Paragon for Technical Macro Transport

Voges, D.; Fremerey, M.; Hörnschemeyer, D.; Krekeler, M.;
Schomburg, K.; Schilling, C. & Witte, H.

Group of Biomechatronics, Department of Mechanical Engineering, Technische Universität Ilmenau, Germany

ABSTRACT

As a part of a student design project of the biomedical engineering studies the movement of cilia (small, flexible hair like rods), and their possible function as an alternative to the transport belt (conveyor) was considered in more detail. As a result, a macro model of a single cilium was designed and a modular cilia field containing 3 x 3 = 9 of those technical cilia manufactured. A proof of transport function could be established.

Index Terms – artificial cilia · transport · bioinspiration · biomimetics · mechanics of propulsion · modular cilia field

1. BIOLOGICAL INSPIRATION

Cilia (Latin for eyelash, singular *cilium*) can be found in the animal kingdom within single cells, in protozoa as well as in organ systems like the respiratory tract. Cilia on the surface of a protozoa assist in the locomotion (= motile cilia), whereas cilia on the cell surface of a fixed cell serve in the transportation of biological fluids (e.g. *mucus*) (= non-motile or primary cilia) [2].

Ciliary movement is a complex three-dimensional motion sequence. Two phases in the motion sequence can be distinguished: the effective and the recovery phase (stroke) (see Fig. 1). A defined trajectory exists in ciliary movement regardless of its stroke frequency and the associated angular velocity at the cilium tip during the effective stroke. During the effective stroke, the medium that is to be transported is moved in the direction of the stroke due to the force produced by the cilia. The turning point for the transition from the effective stroke to the recovery stroke and vice versa is similar even at higher stroke frequencies. Thus, a conclusion can be made that the inner structures and/or the inner phase mechanism determine the turning point. There is evidence that the structures responsible for the execution of the strokes and the generation of the movement are contained mainly in the cilia and not on the cell surface [1, 3].

Within a cilia field, wave motions are generated in two coordinate directions. In one direction, all of the neighbouring cilia have a synchronized stroke motion, and in the other direction, perpendicular to the other, metachronous waves (like movements of a grain field in the wind) are formed. The metachronous waves are due to the fact that cilia move with a certain phase shift to one another.

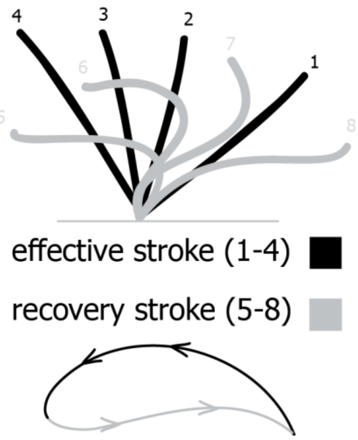

Fig. 1: The beating of the cilliary motion occurs in two phases (top, based on Pearson Education, 2006)
The 2D trajectory of the non-reciprocal ciliary motion (bottom)

2. BIOMIMETIC TRANSFER

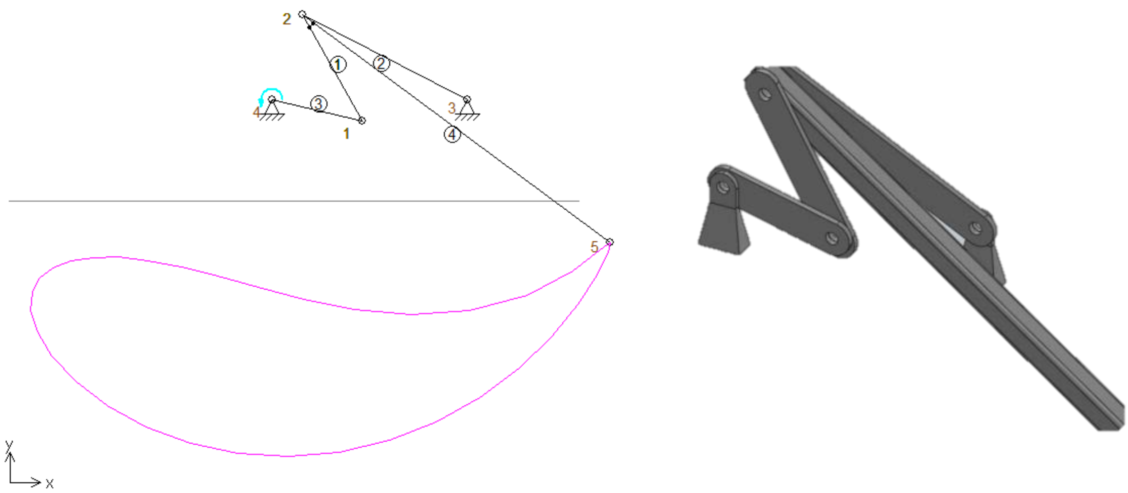

Fig. 2: Design of a 4-bar linkage mechanism in SAM® (Simulation and Analysis of Mechanisms, simulation screen shot) (left)
3D representation of a "cilium" structure in starting position (module in Solidworks®) (right)

The design project focused on the concept of a 2D (planar) movement of the cilia. Using the software SAM® (Simulation and Analysis of Mechanisms), gear mechanisms to mirror the kinematics of the natural cilia's tip (cp. Fig. 1) were derived (Fig. 2, left). In Solidworks®, a corresponding design model was developed (Fig. 2, right). In kinematic simulations, the similiarity of biological and technical motion could be shown (Fig. 3).

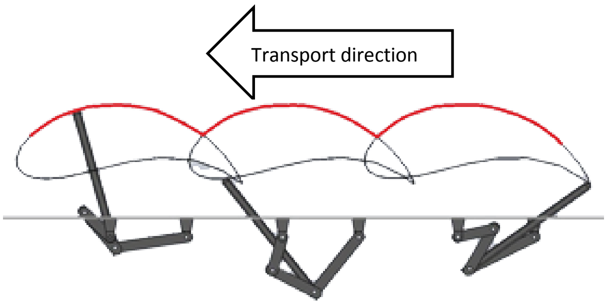

Fig. 3: Side view of a cilium model with the cilium structures in a row.
The trajectories of the cilium tip are shown. The transport direction of the object is displayed in red.
In this model, the object has contact with each cilium tip respectively.

The manufactured functional model consists of nine cilia modules arranged in three parallel rows (Fig. 4). Each cilium is driven by a single servo motor. All drives are controlled by one ARDUINO® UNO processing unit.

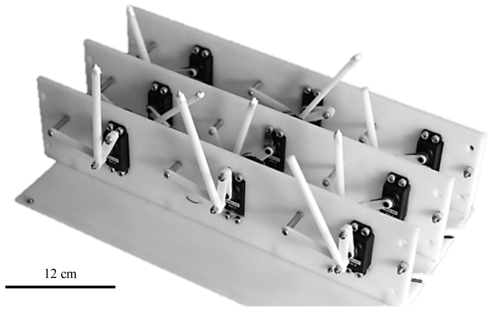

Fig. 4: Technical model of a cilia field.

The cilium tip is covered with silicone, so thread slippage of the transport object is warranted. One cardboard (50 mm x 1010 mm) can already be moved with only one cilium, also a change in direction is possible.

REFERENCES

[1] HILL, D.B.; SWAMINATHAN, V.; ESTES, A.; CRIBB, J.; O'BRIEN, E.T.; DAVIS, C.W.; Superfine, R.: Force Generation and Dynamics of Individual Cilia under External Loading. Biophysical Journal **98**(1), 57 - 66 (2010)

[2] SLEIGH, M.A.; BLAKE, J.R.; LIRON, N.: The Propulsion of Mucus by Cilia. The American Review of Respiratory Disease, **137**(3): 726 - 741 (1988)

[3] TEFF, Z.; PRIEL, Z.; GHEBER, L.A.: The Forces Applied by Cilia Depend Linearly on Their Frequency Due to Constant Geometry of the Effective Stroke. Biophysical Journal **94**(1), 298 - 305 (2008)

CONTACTS

Dipl.-Biol. D. Voges Danja.Voges@tu-ilmenau.de
Dipl.-Ing. M. Fremerey Maximilian-Otto.Fremerey@tu-ilmenau.de
Dr. rer. nat. C. Schilling Cornelius.Schilling@tu-ilmenau.de
Univ.-Prof. Dipl.-Ing. Dr. med. (habil.) H. Witte Hartmut.Witte@tu-ilmenau.de