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CONSTRUCTION OF A CILIA-INSPIRED CARRIAGE SYSTEM

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DEDICATION

The authors want to thank and to dedicate this paper to their beloved, and in July 2017 deceased academic supervisor and colleague Mrs. Dipl.-Biol. Danja Voges. R.I.P. We will miss you!

ABSTRACT

Hair-like appendices, so called *cilia*, occur on the surface of cells of *prokaryotes* as well as *eukaryotes*. In coordination with each other, these *eukaryote cilia* perform coordinated movements, which allow them either to locomote themselves or to move objects along their surface. Even multi-directional transport could be observed. For industrial issues, this phenomenon could be used as a paragon to design mechanisms on microscopic and macroscopic level to sort and redistribute sensitive components, which cannot be handled by conventional grippers. This article describes the design process and realization of a macroscopic demonstrator for this principle. It can be shown, that the bio-inspired idea of a mechanical implementation of *cilia*-like object-transportation in air may be successfully embodied on macroscopic scale.

Index Terms – artificial cilia, bio-inspiration, carriage system, macroscopic transport

1. INTRODUCTION

A type of hair-like extensions occurs on the cell membrane of *prokaryotes* as well as *eukaryotes*. For *eukaryote* cells these extensions are called *cilia* (singular *cilium)*. In harmonization with each other, the *cilia* are performing a coordinated movement, which allows the *eukaryotes* to locomote or to transport objects, for example the removal of *mucus* in human lungs. Even a multi-directional transport can be observed [KOECKE et al. 2000].

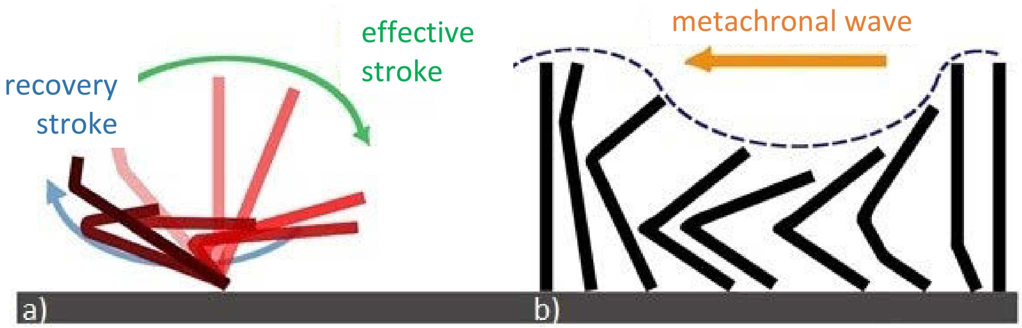

Fig. 1: Schematic illustrations of motion sequences of *cilia* movement following [PALAGI et al. 2013].. a) Effective and recovery stroke of a *cilium,* b) 2D-representation of the metachronal wave originating by the harmonization of adjacent *cilia*

The transport is realized by a metachronal wave which is created along the tip of the *cilia* across the array. The motion sequence of a *cilium* and the metachronal wave originating by the harmonization of adjacent *cilia* is shown schematically in Fig. 1. For industrial issues this could be used on microscopic and macroscopic level to sort and redistribute sensitive components, which can't be handled by conventional grippers.

2. STATE OF THE ART

Several studies try to create and to evaluate the possibility to use the unique way of *cilia* movement, either in liquid or air, to transport objects, to sort them or to mix liquids. Up to date the majority of the research teams replicate the *cilia* movement as close to biology as they can. In the course of this magnetic [SHIELDS et al. 2010; TSUMORI et al. 2015; ZHOU et al. 2015], pneumatic [ROCKENBACH et al. 2015], optical [OOSTEN et al. 2009], mechanical, electrostatic [JIANG et al. 2014; TOONDER & ONCK 2013] or piezoelectric driven [HATSUZAWA et al. 2003; OH et al. 2009] as well as biological [KIM & BREUER 2007] approaches are used to make technical use of the biological paragon *cilia*. Most of the ideas have been realized on a microscopic level, which is highly demanded for the use in microelectromechanical systems (MEMS).
Newest approaches to the topic of *cilia*-inspired material transport present a method for 3D-printing arrays made out of *cilia*-like hair [OU et al. 2016]. Via oscillation of this array they are able to realize for example the transport of an object. Direction of transport is influenced by the design of the hairs themselves.
In general, approaches suitable for the use on a macroscopic level are lacking because of the increasing energy consumption at higher scale rates.

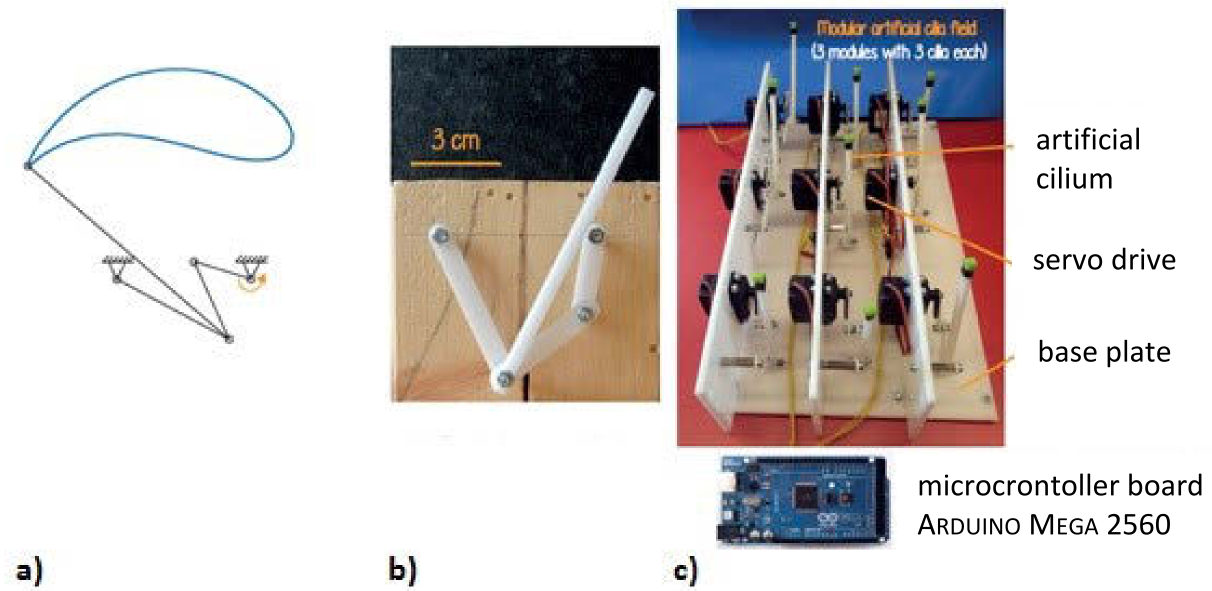

Fig. 2: Project Cilia I [VOGES et al. 2014]
a) Schematic representation of the concept for a *cilia*-inspired transport mechanism,
b) Mechanic solution of a), c) Mechanic solution of a demonstrator where *cilia* movement was imitated with the help of a modular approach with single *cilia*-inspired elements.

The project Cilia I at the Group of Biomechatronics (TU Ilmenau, Germany) tried to show that the biological paragon of *cilia*-inspired movement can also be used on a macroscopic level. They imitated the *cilia* movement using modules of coupling gears as single *cilium*-inspired effector elements (see Fig. 2a) and 2b)) assembled in an array (see Fig. 2c)) [VOGES et al. 2014]. By synchronization of the single modules they were able to create a metachronal wave along the array and to realize a bidirectional transport.

3. MATERIAL AND METHODS

The aim of this work is to create a transport system with functional elements moving like a *cilium* (see chapter 1). The *cilium* can be seen as effector element (or functional element) following the concept of a biomechatronic system [WITTE & SCHILLING 2017]. In preparation of the design process, several control possibilities and *cilia* appearances were evaluated. Individual components were simulated, constructed and produced.

3.1 Initial stages of solution

The project Cilia II explored different concepts to realize the transport function on a macroscopic level. A selection of explored technical principles is shown in figures 3 to 6.

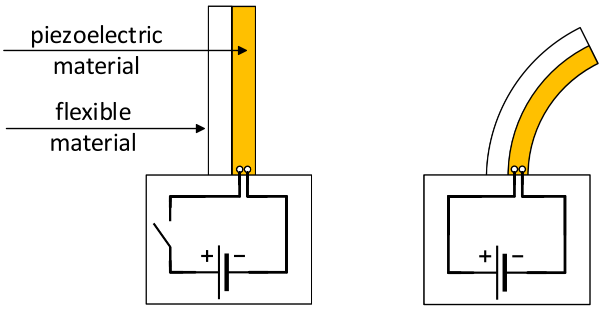

Fig. 3: Electric principle using piezoelectric materials to create the movement of a *cilium*. Current flow (right) leads to deformation of piezoelectric material (yellow) which bends the whole *cilium*. Reversibility of the piezoelectric effect leads to a recovery movement supported by the flexible material when current flow is switched off (left).

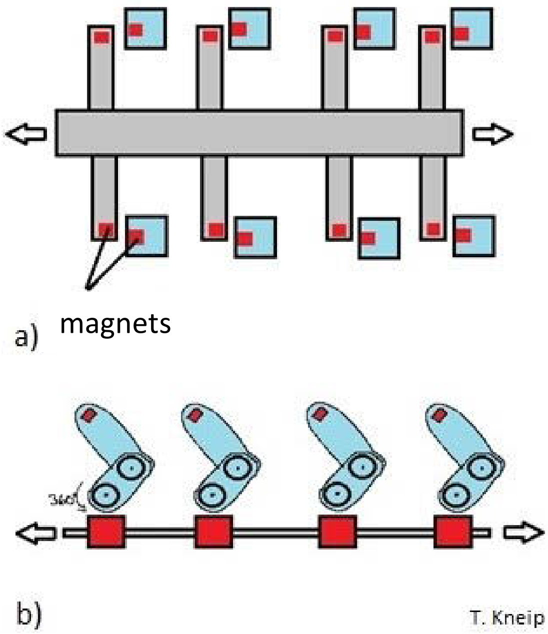

Fig. 4: Mechanic principle with rigid *cilia* (light blue) based on a magnetic approach. Magnetic elements are marked red. (a) top view, b) lateral view).

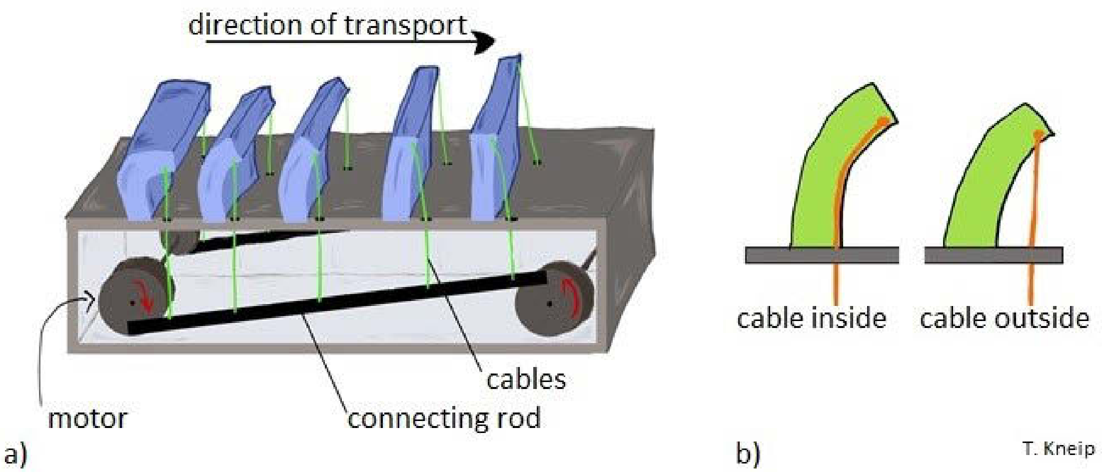

Fig. 5: Mechanic principle with cables and a connecting rod to realize the bending of a single effector element as well as the synchronization between the effector elements. Effector elements are realized as flaps instead of single *cilia*. a) Overview of the demonstrator with five effector elements (blue) connected with cables (green) to the central rod. The rod is driven by a motor leading to a contrariwise movement at the rotational joints at the end of the rod (red). b) Possibilities for leading the cable (orange) inside (left) or outside (right) of the flexible effector element (green).

Fig. 3 shows an electric principle with *cilia* made of a combination of flexible material (for example silicon) and a piezoelectric material. For this principle the reverse piezoelectric effect was used, where the result of an applied electrical field is the generation of a mechanical strain. The piezoelectric effect is a reversible process, so that the material bends back to its initial position when the electrical field is switched off.
Fig. 4 shows a mechanic principle schematically, which is based on a magnetic approach. The separate *cilia* made of rigid materials are moved by magnetic field modifications via implemented joints.
Fig. 5 shows another approach based on a mechanic principle using compliant materials. Every effector element is realized as a flap instead of a single hair-like element or *cilia*. Each effector element is connected to a cable. The cable can be led outside or inside of the element (see Fig. 5 b)). Motion or bending of an effector element is realized by pulling at the cable. All cables are connected to a rod, to realize a metachronal wave (see Fig. 5a)).

3.2 Macroscopic demonstrator

The principle implemented into the demonstrator is a modification of the mechanic principle with cables and connecting rod shown in fig. 5 and described in chapter 3.1. It is shown schematically in fig. 7. Bowden cables are used to realize the bending of every single effector element. Synchronization between the effector elements is realized using a gear drive and a single drive (not shown in fig. 7).

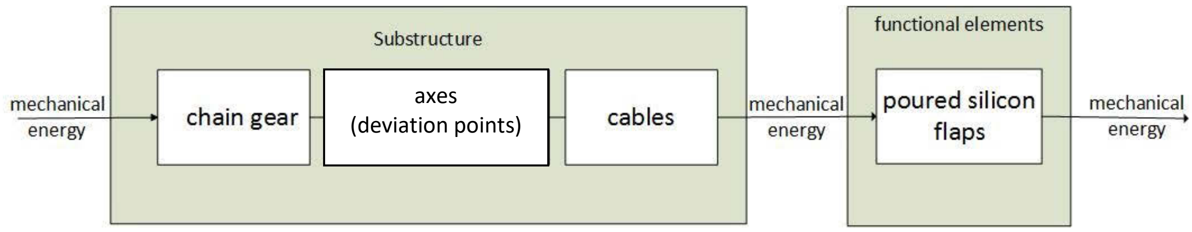

Fig. 6: Block diagram of the drivetrain to move an object over the flaps.

Further research and work in the study presented focused on the effector or functional elements and not on the substructure (cp. fig. 6). For a first demonstrator, the rotation of the axes of the chain gear is induced by a hand driven chain gear in the substructure of the setup. This allows the coordinated movement of the flaps and to transport an object with the size of a playing card in one direction.

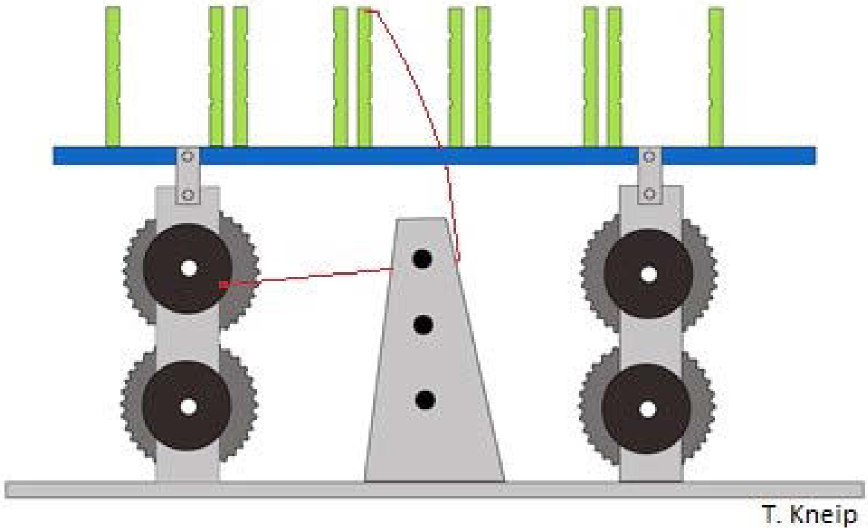

Fig. 7: Mechanic principle of a *cilia*-inspired demonstrator for macroscopic transport. The flexible effector elements (green) are bended using cables (red) and a gear drive.

3.3 Effector elements

Additional to the different control units (see chapter 3.1), the advantages and disadvantages of an array build out of multiple *cilia* and an array build out of flaps were discussed (see fig. 8 and tab. 1) during the design process of the demonstrator. Flaps are achieved by combining several *cilia* to one single unit.

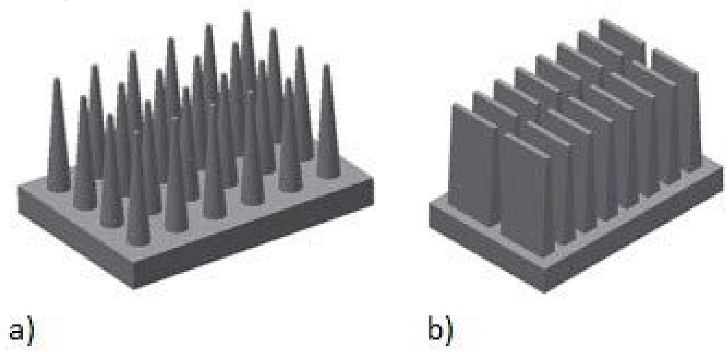

Fig. 8: Different forms and arrangements of effector elements for realizing a *cilia*-inspired carriage system. a) array built out of single *cilia,* b) array built out of flaps.

Tab. 1: Advantages (+) and disadvantages (-) of an array formed with single *cilia* in comparison to an array formed with flaps. (++/-- has a higher weighting)

array of cilia	array of flaps
+ close to nature	- high degree of abstraction
+ mobile in all directions	- can only move in two directions
-- high quantities	++ small quantities
-- small bearing surface	++ large bearing surface

The result of this discussion shows that an array built out of flaps is the better solution, if bidirectional transport and a higher level of abstraction are acceptable. Flaps allow using a lower quantity of effector elements while at the same time increasing the bearing surface compared to a construction of an array with *cilia* as effectors. A larger bearing surface leads presumably to a more stable transport of an object.

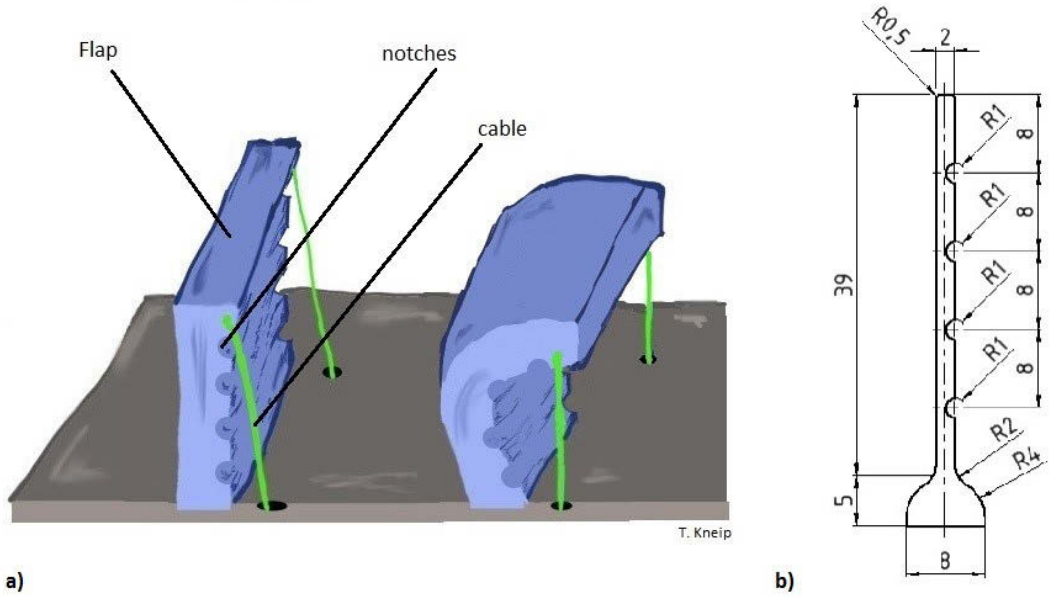

Fig. 9: Effector elements for a *cilia*-inspired transport mechanism.
a) Schematic drawing of the bending of *cilia*-inspired flaps as effector elements (position of start and end),
b) Technical drawing of a *cilium* designed with *AUTODESK INVENTOR® PROFESSIONAL 2015*

The flaps (see fig. 9) were designed in *AUTODESK INVENTOR® PROFESSIONAL 2015* and analyzed by means of finite element method (FEM) with *ANSYS®* (Version R17.0 Academic).

Different possibilities of *cilia* appearances were analyzed and fabricated. Goal criteria were:

- small necessary force to pull the flap down and
- maximum bending of the effector element at constant force.

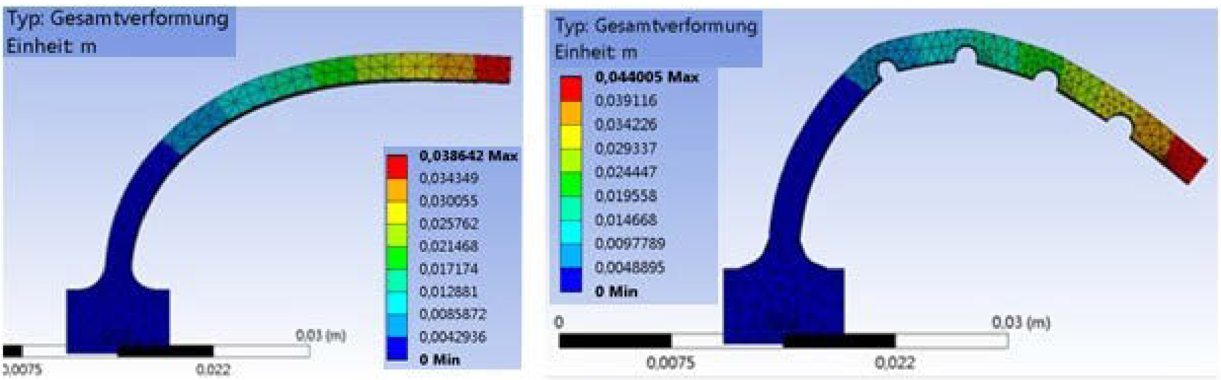

Fig. 10: Finite element analyses of the bending behavior of a flap as effector element.
left - flap without notches, right - flap with notches to define and optimize the bending degree.

FE-analyses (see fig. 10) showed that a flap with a thickness of 2 mm might be a good compromise to realize a good and stable transport. That's because these parameters ensure that the flap is thick enough, so that it will not bend immediately when it is touched by an object. But it is also not too thick, so that the force for bending down the flap is very low. Furthermore, notches give a possibility to optimize the bending degree of the flaps while using a constant force to bend the flap (see fig. 9 b)).

The effector elements were produced using two different fabrication methods. One type of effector elements was poured from silicon with a shore hardness of A 43 using a negative form which was modeled in *AUTOCAD®* and printed out of polylactides (PLA) with a fused deposition modeling 3D-printer (*ULTIMAKER 2, Ultimaker B. V.*). The other type of effector elements was printed out of flexible thermoplastic directly using another fused deposition modeling 3D-printer (*MAKERBOT® REPLICATOR™ 2X*). The effector elements were tested concerning their bending and duration characteristics by means of an endurance test and a load test with different weights (10 g to 100 g).

For endurance test, the experimental setup shown in fig. 11 was used. The flaps were fixed and bended for 3.300 times with 16 bends/minute. The angle was set to a maximum of 90 degrees. Both types of flaps (3D-printed and the poured ones) showed no signs of wear after the test. Because of lower force requirements to bend the flap and a better performance regarding the recovery movement poured effector elements were used for further tests.

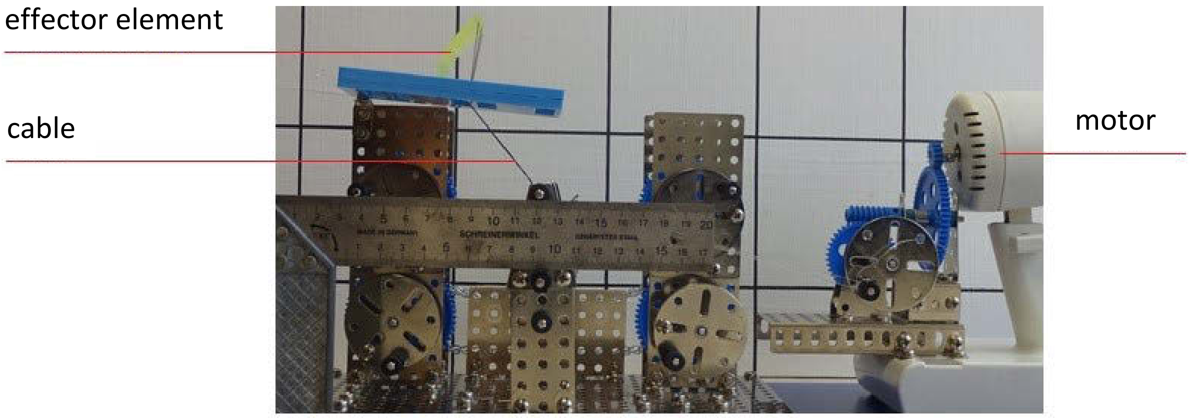

Fig. 11*:* Experimental setup for the endurance test of a single effector element.

3.4 Phases of movement

An important point to realize the demonstrator described in chapter 3.2 was to split the original *cilia* movement, consisting of one smooth motion with an effective and a recovery part (see chapter 1) into different phases, to provide a transport movement with this type of effector elements. This was done by using different axes with different orientations of the effector elements. Tests have shown that at least four phases are necessary to guarantee continuous propulsion (see fig. 12).

Fig. 3 shows the sequence of the transport. During one cycle, each of these four flaps was bended and returned to its starting position passively.
The phase diagram (see fig. 13 (bottom)) shows the phase shift that is necessary to realize the transport. Periods of contact between the flap and the transport object are marked black.

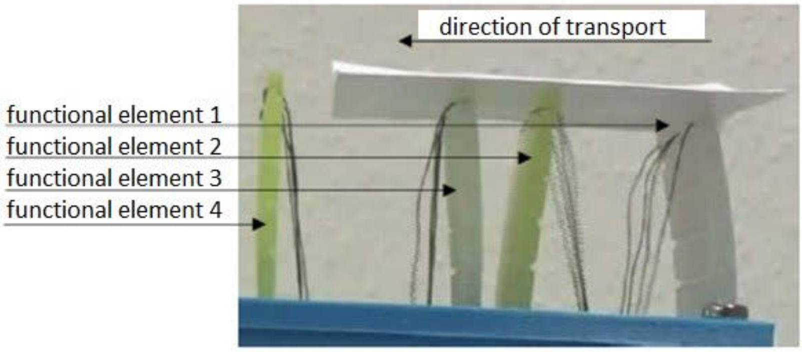

Fig. 6: Experimental structure with four flaps as functional elements at starting position.

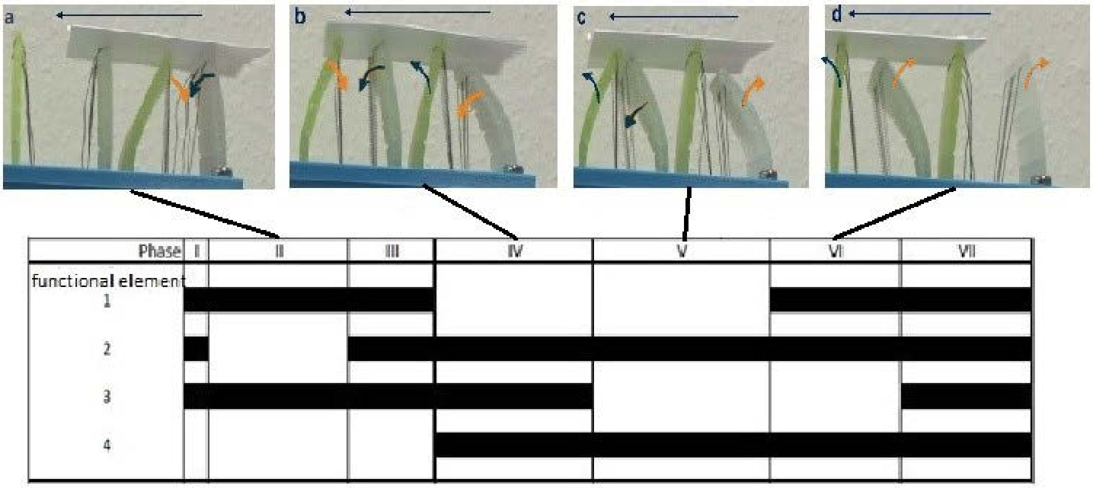

Fig. 13: Phases of movement to transport an object (here: playing card) from right to left. Functional elements are numbered 1 to 4 from right to left. Top - Different phases of movement with effective stroke/flaps in contact with the object (dark blue arrows) and recovery stroke/flaps not in contact with the object (orange arrows). Bottom - Phase diagram of the sequences to realize the transport of an object. During the black marked periods the functional element (flap) is touching the transport object.

3.5 Demonstrator

To evaluate the capability of *cilia*-inspired macroscopic transport-system in air, a mechanical based demonstrator was build (see fig. 14). The clamping devices were 3D-printed using PLA with an *ULTIMAKER 2 (Ultimaker B. V.)*. The remaining parts of the substructure were taken from a metal construction set from the *Eichsfelder Technik EITECH GmbH*.

4. CONCLUSION AND PROSPECTS

During this study a demonstrator was realized to show that *cilia*-inspired transport of objects is possible on a macroscopic level in air. As abstraction to the biological paragon flexible flaps were used as effector elements instead of single hair-like *cilia*. This was done to achieve a higher contact area between effector element and object. Furthermore, the flaps have four notches to define, where and with which angle bending should happen (see Fig.). Finally, 24 flaps have been attached to a macroscopic demonstrator. The system has a mechanical drive with a construction using different gears and Bowden cables to pull the flaps down (see fig. 7). As shown in fig. 13 a playing card could be transported unidirectional with this demonstrator.

During implementation of the construction different problems occurred. One main difficulty was the synchronization of the different functional units (see chapter 3.4).
Due to instability of the substructure, the transportation ability is only unidirectional and movements of the compartments lose their coordination after some cycles and have to be adjusted again.

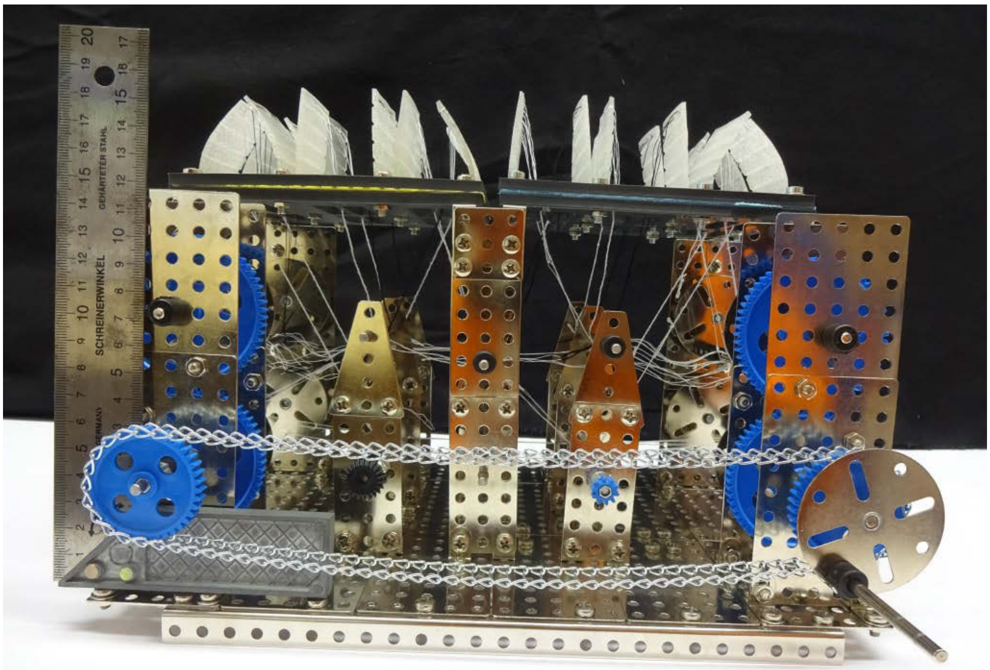

Fig. 74: Final setup of the prototype for a *cilia*-inspired carriage system on macroscopic level. Flaps with notches poured out of silicone were used as effector elements. Bending and synchronization of the effector elements were realized via Bowden cables. The substructure consisting of drive and different gear drives was realized with parts from a construction set from *Eichsfelder Technik* EITECH *GmbH*.

The distances between and sizes of the effector elements can be optimized for different kinds of objects based on their sizes. With the optimization of the size of the components, a sorting mechanism is imaginable as an application of this principle, by letting smaller objects fall through the *cilia*-like flaps and transport bigger objects on top of them.

Tab. *2* shows the main differences between project Cilia I and Cilia II done at the Group of Biomechatronics and described in this article.

Tab. 2: Main differences between the two projects realized at the Group of Biomechatronics at the TU Ilmenau

	Project Cilia I	**Project Cilia II**
Direction of transport	bidirectional	unidirectional
Control unit	mechanical principle	mechanical principle
Line of movement	2D	2D
Functional/Effector Element	Coupling gears as *cilium*	flexible flaps
Material of the effector element)	polyethylenmethacrylat (PET)	silicon (shore hardness A 43)
Size of the object transportable	objects with different sizes	object with the size of a playing card

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