TRIZ-based algorithm for Biomimetic design

Conference at ETRIA, in Lisbon, 2012

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Abstract

The article reveals opportunities and obstacles for cross-domain and cross-cultural knowledge transfer. Both interfaces are clearly present in biomimetics (the engineering branch that borrows ideas from biological field for introducing them into the technology). Biomimetic methodology needs to deal with key differences between domains (biology studies Life, engineering creates machines) and cultures (science describes and models, while engineering prescribes and produces). Due to the complexity of mentioned methodological issues biomimetics still remains case-study-based discipline with no guaranteed success of investments.

Current paper offers the detailed explanation and procedures for biomimetic design. Authors discuss obvious and reveal invisible obstacles for mimicking living systems and the specifics of application of different TRIZ tools in cross-cultural and cross-domain knowledge transfers and present the algorithm for biomimetic engineering based on TRIZ. As a conclusion the list of axioms for biomimetic design is presented and the procedures for biomimetic design based on such axioms are suggested.

1. Introduction

The need of cross-domain and cross-cultural knowledge transfer is clearly present in biomimetics – the engineering branch that takes ideas from biological systems and transfers them into the technological implementation. Engineers and scientists in collaborative biomimetic projects face serious differences between domains' methodologies (science describes and models, while engineering prescribes and produces) and cultures (biology studies living systems, engineering creates machines). Due to the complexity of mentioned methodological issues biomimetics still remains purely empirical discipline with no scientific methodology and therefore using just a "good old" trial-and-error method and inspirations (method of "scientifically accidental hit of a solution"). Earlier we have introduced TRIZ as a missing link in biomimetic's methodology that turns it into theoretically grounded science [2], [7]. The aim of this study is to provide the precise procedures and detailed methodological interface of biomimetics.

We present the algorithm to overcome some serious methodological issues that biomimetics is facing now. In this paper first we will describe the methodological and cultural incompatibilities of Biology and Engineering, then we suggest the resolution of these contradictions by TRIZ and its application on the example of a project, which was done for Philips. The project called "ARTIC" aimed to create microfluidic actuators for moving, pumping and mixing liquids at the micro-litre scale, for which living systems demonstrate a wide range of mechanisms. For example, organisms of all sizes move liquids with cilia and flagella and their derivatives. They are ancient and universal, which proves their reliability.

Microfluidic actuation in engineering is a relatively young technology and has not accumulated large experience and traditions, which generate psychological inertia of experts. Therefore this domain is open 2 for novelty coming from different disciplines, e.g. biology. But the procedures of searching, comparing and selecting an appropriate living prototype, its analysis and exposure of required mechanisms, are still not yet well defined and actually absent in the contemporary engineering. In most cases, direct and verbatim copying is not successful because of the enormous complexity of living systems and the impossibility of making a perfect functional copy. A simplified version of biological prototype may be not efficient at all comparing to the conventional engineering system and thus discredit the very concept itself of taking ideas from living Nature. Moreover, if we create the most perfect copy of some living creature, we must realise that it will inherit not only the advantages of the prototype, but the shortcomings as well (e.g., do we need the toothache, which would accompany a perfect denture?). That means that "interpretation" from biological "language" into a technological one is not trivial, but promising.

2. Hidden obstacles in biomimetic design. Four Axioms of Biomimetics

So, let us start form the list of obstacles that stop biomimetics to become a science with its own theory and methodology.

2.1. The first serious obstacle appears when we need to find the right paragon for an engineering "copy" at the very beginning of the project.

The core of this obstacle is incompatibility of the requirements to the classification systems in biology (which was created for sorting and catalogisation of the enormous biological diversity) and engineering (which is required for searching the desired properties, functions/effects and solutions). Existing lists, catalogues and classifications of biological systems, their functions and effects, are not particularly useful for engineers, because they are made by biologists mostly for the needs of biologists. The main differences of the requirements of biologists and engineers are shown in the table 1.

Table 1. *Incompatible and very often contradictive requirements to the data: why mutual understanding between biologists and engineers is not easy.*

№	Classification for a biologist	Classification for an engineer
1	Descriptive information	Prescriptive information
2	Classification is genetic (taking into account the kinrelations) and therefore objective. This is not always related to a single function or context.	Classification is user-oriented and therefore subjective. It can be adjusted for the convenience of use of a different user.
3	The purpose is purely theoretical, detecting and discovering the most fundamental laws of matter and natural mechanisms that generate the diversity of life.	Highly practical. Quick, easy, precise search/access (based on various parameters and for different contexts) of the most relevant prototype.
4	Classification is based on morphology.	Classification needs to be based on structure, function and context and also should be not only static, but dynamic as well.
5	Attention is focused on the past and present, detailing the palaeontology and phylogenesis of the system.	Attention is focused onto the future (design and implementation of the artificial system), which is where the reward and benefit are.
6	Biological diversity is "good". A biologist searches for and describes new entities to make the list as	Excessive diversity (biological or technological) is "bad". An engineer is overloaded by the biological

	full, as possible and tries to classify the new objects as precisely, as possible. Valuation of the biological entities is absent.	diversity (e.g., 30 thousand species of fishes is not easy to deal with), thus his choice of a prototype is often nearly random, because of lack of objective criteria for selection and valuation. Thus technical valuation for biomimetic classification is essential.

A classification of biological data that satisfies engineers should be open and allow the inclusions of new entities and also allow options that are not present in contemporary organisms. These options are the main resource for biomimetic devices to be developed as they use the advantages of both life and technology. We can consider these obstacles mentioned above as physical contradictions and address them with TRIZ separation principles. The resolutions for these contradictions are the following:

1. Descriptive vs. prescriptive information. Request should be descriptive ("what?"), the answer – prescriptive ("how"). This can be achieved by using existing biological classifications, but not a biological taxonomy.

2. Subjective vs. objective purposes/aims of using the prototypes. Change the scale – spatial, structural or temporal (swap the contexts using 9-Windows Operator). Classification of behaviour (in broad sense) rather than morphology will work for biomimetic engineering.

3. Past vs. future. Retrospective classifications from biology are not so helpful for engineers. Engineering targets the result of the function and sustainable engineering cares about the global consequences of the their activity. Classification should be predictive.

4. Diversity of suggested solutions from biology vs. Ideal Final Result (single solution) for engineering. This contradiction leads us to the very interesting subject: the possibility of making user-centred science (also this has a direct link to the contradiction number 2). Precise problem definition at the initial stage of biomimetic design is the solution for this issue. Function and context should be clearly stated and the problem in the form of conflicting requirements should be formulated. Context definition narrows the choice of biological prototypes. Revealed constraints direct the search towards the suitable biological paragon.

2.2. The second obstacle is complexity of living systems – for example, cells are equally complex as ecosystems. Direct copying of natural prototypes looks as not the easiest and the most efficient biomimetic strategy. Moreover, copying can cause disappointment and even discredit the very idea of biomimetic approach itself because of extreme complexity of living prototypes *[1]*. Literal transferring of the solution from living systems into engineering may later cause unexpected problems: to foresee and prevent the shortcomings of future products we need to know the limits of functional capacities of living systems that are chosen as paragons for engineering design.

2.3. Another reason for disappointment with biomimetics is that very often chosen natural prototype does not match strictly to the mode and conditions of the operation of the targeted device. The search for the most relevant natural prototype requires highly professional biologists of broad profile on board. This is cross-cultural obstacle – engineers and biologists speak different "languages". The most successful projects include an engineer with biological education or biologist with engineering education. We suggest teaching TRIZ to biologists to be able to understand engineer. TRIZ-educated biologist is an ideal partner in biomimetic project.

2.4. After the prototype (-s) is/are found and agreed, the next step is "interpretation" from the biological "language" into engineering procedures and means. This non-trivial process also appears similar to translation from any language. The result often does not look like the prototype, but behaves like it. For example, Russian expression "a white crow" should be translated into English as the idiom "black sheep". Biomimetic design procedure is structured and consists of iterations and loops between stages. This technique is based on TRIZ (Theory of Inventive Problem Solving – Russian acronym ТРИЗ – *Теория Решения*

Изобретательских Задач) with sufficient improvements and adjustments to the biological peculiarities that distinguish the biological systems from the technological ones.

The resolutions of the four main problems of biomimetics described above lead us to the formulation of the following axioms for a biomimetic design:

Axiom of simplification: reduce the functionality of a biological prototype for the engineering design.

Axiom of interpretation: instead of copying interpret the essence of a biological mechanism, structure, function or strategy.

Axiom of ideal result: If you still want to copy, do not copy the means of providing a function, copy the result of the function.

Axiom of contradictions: translation of "What?" (Engineering target/question) into 'How?" (Answers from biology) should be done via aggravated statement of conflicting requirements.

3. Algorithm for biomimetic design

There are at least four different layers of copying natural phenomena: copying objects/structures, process (actions, function and behaviour), the result of the process, the impression of the result of the process. Each of these "layers" has their own peculiarities for knowledge-transfer procedure and requires different TRIZ tools to assist. The main stages of this algorithm are developed in the research project dedicated to artificial cilia design [3]. Each stage consists of precise description of the procedure and suggests TRIZ tools relevant to assist.

So the stages of a biomimetic design are:

Stage 1. Define the main function (-s) of a device, its environment, time, and size scale. Use TRIZ tools for problem definition.

Stage 2. Make a list of parameters that are essential for the performance of the main function: formulate the requirements for a biological prototype. Express the challenge in the form of conflicting requirements. Define the contradictions.

Stage 3. Look for prototypes in biology. "Dissect", analyse and classify them according to the main functional requirements. Reveal the main parameters of function/behaviour and formulate the requirements for engineering implementation. Reveal the contradictions.

Stage 4. Describe the behaviour of the bio-prototype using "9 Window" Operator. Define the required attributes for each element of the system and its environment. Extend the list of the properties by adding the opposites to every parameter.

Stage 5. Arrange the parameters that are relevant to the main function in a table with the parts of our system variables in columns and rows.

Stage 6. Find a combination of the most desirable, possible and affordable parameters for a biomimetic device that does not necessarily exist in living Nature, but can be implemented with the help of engineering. Combine incompatibles by using 40 inventive principles.

Biomimetic approach to engineering does not end with choosing right living prototype. It is only the first step. It opens new engineering opportunities in design as we can see the whole range of possibilities that are not realised yet in living nature. Such non-existing combinations of various parameters give the range of opportunities for engineers to develop a prototype of artificial actuators, where advantages of living and engineering systems are merged together. "Creepy", "Crawly", "Metachron" and "Rotochron" are biomimetic creatures presented in this paper; they employ non-existing combinations of natural principles and mechanisms, which provide the required effect [5].

4. "Creepy", "Crawly", "Metachron" and "Rotochron"

Biomimetic creatures born by the algorithm for biomimetic design Following the algorithm steps let's see how the solution concepts appear. Due to the limits of the length of the paper we will not describe all the stages in full details.

Stage 1. Define the main function (-s) of a device, its environment, time, and size scale. The challenge was to provide movement of viscous liquids at micro-scale level. There was no any humanmade system that can move viscous liquids at the micro scale, so there was no engineering solution to this problem yet. That is why we looked for the solution in biology. But we have the list of available technologies that were used for different purposes, and they may be suitable for research and engineering (microchips, magnetic liquids, thin membranes technology and computer modelling techniques). We needed to answer another question – why we cannot use these technologies straight away? To summarise: the required function is pushing viscous liquid in one (controllable) direction at microscale level.

Stage 2. Make a list of parameters that are essential for the performance of the main function: formulate the requirements for a biological prototype. Express the challenge in the form of conflicting requirements. Define the contradictions.

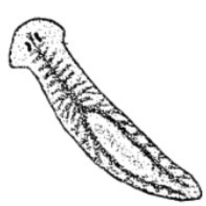
The problem is: pushing liquid in one direction, while recovery stroke the liquid returns to initial position due to its high viscosity and small volume of the micro-chip environment.

Stage 3. Look for prototypes in biology. "Dissect", analyse and classify them according to the main functional requirements. Reveal the main parameters of function/behaviour and formulate the requirements for engineering implementation. Reveal the contradictions.

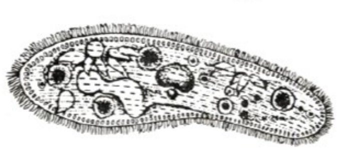
We made the catalogue of all possible ways of moving liquids in living nature [5], [8]. This catalogue contains more than fifty different mechanisms suitable to be a prototype for the engineering device.

And it appeared that actuation with the help of cilia is the most suitable for engineering. Cilia work perfect in all living systems but some of their attributes are not applicable and even harmful for artificial device.

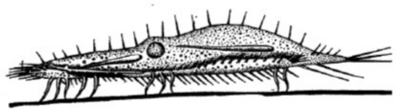
For example, flat worms (e.g., Planaria maculata) live in or near water and are totally covered with cilia. The concerted metachronal (wave-like) movement of the cilia provides smooth locomotion along surfaces. Most ciliated infusorians (e.g., Paramecium caudatum) and flagellated organisms (e.g., Volvox globator) provide locomotion with cilia and/or flagella. The body of the animal does not usually move as well, for instance by wriggling. Infusorians with cirri (e.g., Stylonichia mytilus) are not very common. Cirri are longer and thicker than cilia and are rigid. This shows that small effectors such as cilia can be amalgamated into tiny legs that can walk on a solid surface (Fig1, images are from [10]).



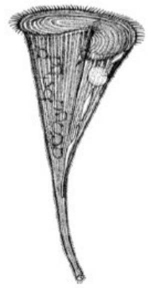
1 Flat worm, *Planaria maculata*



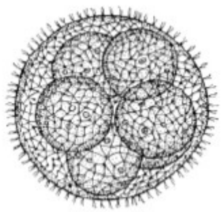
2 Ciliated infusoria *Paramecium caudatum*



3 *Stylonichia mytilus*



4 *Stentor polymorphus*



5 Flagellated organism *Volvox globato*r

Figure 1. *Natural prototypes for a biomimetic artificial cilia actuator.*

Cilia in a macro-organism create a constant flow of liquid with suspended particles. Normally the direction of flow is constant. Membranelli (flat triangular structures formed by the amalgamation of several cilia) create a paddle or a blade, which has a bigger area and thus can be more effective than a single cilium. Cilia and membranelli of sessile aquatic animals (e.g., Stentor globator) operate as manipulators because the organism is anchored to the substrate. The enormous diversity of living creatures that use cilia employs only a surprisingly small number of the available features/parameters. The same parsimony has been found in other biological structures, e.g. the morphology of coiled shells [6], [9]. This type of analysis thus allows us to escape from the biological paradigm with its inherent limitations due to morphology and phylogeny since we are presented with more possibilities than exist in nature.

Table 3. *Natural and artificial cilia: biological facts and engineering artefacts.*

Animate biological cilia	Preferred artificial cilia
Structure: radial symmetry gives 360 degrees operation	Structure: bilateral symmetry of frontal projection and asymmetrical rigidity in side-view projection asymmetry gives 2-D operation.
Functionally: universal	Functionally: specialized
Shape of a cilium is typically round.	Cilium should be flat.
Metachronal reciprocated motion is combined with other types of actuation and/or with hierarchically organised geometrical effects. Reversible switch to any direction	Metachronism is essential for the performing of the main function. Type of actuation: normally all types of rotation. Actuation in a single direction
Active (internally actuated)	Passively driven (externally actuated)
Function of liquid transport is supported on multiple hierarchical levels of the whole complex organism ("a device").	We need to consider what other functions in the supersystem can support the main function of the device. This increases complexity. The device should be simple.

So, ideal artificial cilium should be rigid, possess asymmetrical functionality (i.e., generate pushing force only in the course of the effective stroke and be soft and flexible during the recovery stroke) and the whole cilia “carpet” should work metachronously. The list of the key parameters for the biomimetic product is: motility, controllability from outside (externally driven), asymmetry of action – in other words, rigidity (in effective stroke) and flexibility (in recovery stroke). Flexibility can be achieved by either plasticity or elasticity. Ideally we need to achieve the advantages of natural cilia by the means that currently available in engineering. The main contradiction is: in the effective and the recovery strokes we need contradicting requirements for the cilium:

a) adaptability and versatility;
b) rigidity to have enough strength and force to push the liquid. So, cilia should be rigid and soft.

Stage 4. Describe the behaviour of the prototype system using TRIZ 9 Windows Operator. Define the required attributes for each element of the system and its environment. Extend the list of the properties by adding the opposites to every parameter defined in the stage 3. The compulsory set of parameters should cover all six classes of variables that make any behaviour possible: entity (structured substance) behaves (energy and information) in environment (space and time). The template for the parameter search is given in our Biomimetic manual in the resource section an briefly looks as following:

- Changed/varied properties of cilium provide the asymmetrical movement of the liquid.
- Changed/varied properties of the base provide the asymmetrical movement of the liquid.
- Changed/varied properties of the environment (groups of cilia) provide the asymmetrical movement of the liquid.

– How these properties could be possibly changed is described in the next stage of the algorithm.

Stage 5. Arrange the parameters in a table with the two parts of our system variables in columns and rows to investigate how the desired function could be possibly achieved by different parts of the system components.

Only two elements of the system can provide the movement of liquid on a micro-scale – bristles (cilialike objects) or the base – walls of the micro-pump. We arranged the properties of cilia and base in the form of binary tree of paired opposites (thesis – antithesis structure is typical for classification). To define the “design space” of logical possibilities we presented the combination of properties of cilia and a base in the matrix (table 3).

Table 3. *Logically possible combinations of important parameters of cilia/bristles and base: grey cells – existing engineering products, green cells – living systems, orange cells – biomimetic solutions.*

Cilia / Base			Dynamic				Static			
			Passive		Active		Passive		Active	
			Flexible	Rigid	Flexible	Rigid		Rigid	Flexible	Rigid
Dynamic	Active	Flexible			1. *Planaria* Symmetric cilia and base			6. Creepy Asymmetric cilia, symmetric base		
		Rigid	8. Metachron Asymmetric cilia, fragment-ed base					7 Crawly: Asymmetri c cilia, fragment-ed base		

	Passive	Flexible			2. *Volvox* Symmetric cilia and base	3. *Stylonichia* Symmetrical cilia and base				
	Passive	Rigid			4. Lung cilia Symmetrical cilia and base		9. Shoe brush Symmetric cilia and base.	10. Hair comb Symmetric cilia and base.		
Static	Active	Flexible			5. *Stentor* Symmetric cilia, asymmetric base.					
Static	Active	Rigid								
Static	Passive	Flexible					12. Door mat Symmetric cilia and base			
Static	Passive	Rigid	13 Rotochron Asymmetric cilia, symmetric base.					11. Rasp Asymmetric cilia, symmetrical base.		

1 – Flat worms (e.g., Planaria maculate), (Fig. 1).
2 – Most of ciliated infusorians (e.g., Paramecium caudatum,) and flagellated organisms (e.g., Volvox globator, Fig.1).
3 – Infusorians with cirri (e.g., Stylonichia mytilus, Fig. 1).
4 – Cilia as a part of macro-organism, (e.g., human lung cilia). .
5 – Cilia and membranelli of the sessile aquatic animals (e.g., Stentor coeruleus, Fig.1).
6 – Our invention: artificial device with passive rigid asymmetrical cilia and active flexible elastic actuating basement ("Creepy") (Fig. 4).
7 – Our invention: artificial device with passive rigid asymmetrical cilia and active rigid fragmented actuating basement ("Crawly")(Fig. 5)
8 – Our invention: artificial device with passive morphologically asymmetrical movable cilia with active fragmented actuating basement with slacks providing a metachronal actuation, i.e., travelling wave ("Metachron" Fig. 4).

Artificial entities are represented by macro-scale devices/products:

9 – Shoe brush
10 – Hair comb
11 – Rasp, cross-country skis with elk's skin
12 – Rubber door mat with bristles
13 - Our invention: Rotochton (Fig.6)

It is very interesting to note that living systems and traditional engineering devices are using different combinations of the parameters of the base and the bristles. There are no any existing engineering devices for moving water at the micro-scale based on bristles, so as an example we used the devices built to perform different functions but similar actions – moving/removing objects from one point to another asymmetrically. The first and obvious thought could be that biomimetic device should combine the useful parameters of living prototype and the parameters that are preferable for engineering process. But you can clearly see from the table 3 that biomimetic solutions use neither biological, nor engineering combinations. The actual purpose of the biomimetics is to find the way to achieve the RESULT of the behaviour of living system by non-living engineering means. So, it should not be a surprise that such new engineering means are the subject for invention and patent. What is a surprise is that the mechanism of getting these new engineering means is based on a combination of parameters that are directly opposite to living prototypes and common engineering solutions. Biomimetic "creature" is built consistent with neither living, nor conventional technological principals, because they are constructed on the opposite parameters to what conventional engineering would suggest and what nature presents. So, the next step is to implement such a "neither, nor" recommendation.

Stage 6. Find a combination of the most desirable, possible and affordable parameters for a biomimetic device that does not necessarily exist in nature, but can be implemented with the help of engineering. Combine incompatibles by using 40 inventive principles.

Before coming up with assumption described above (biomimetic device targets conjunction of biology with technology, but technical implementation strategies are neither biological nor conventional technological), we varied the parameters that are important for bristles and for the base to make the device working. As it is very difficult to actuate and control every single individual cilium, we decided to delegate these functions to the basement. As a result we developed a device with externally driven (passive) stiff asymmetrical cilia on an active flexible elastic actuating basement. We called it "Creepy" (Figure 2, a, b). The main body of the device is segmented perpendicularly to its longitudinal axis and the segments are joined by elastic elements. Every segment is provided with rigid needles ("cilia") bent in one direction at an angle of 30 degrees. Being attached at the point A the whole array can be stretched and then returned to its initial position. All segments begin moving synchronously. This reciprocating motion can move objects placed on the surface with the rigid asymmetrical needles due to their polarised direction.

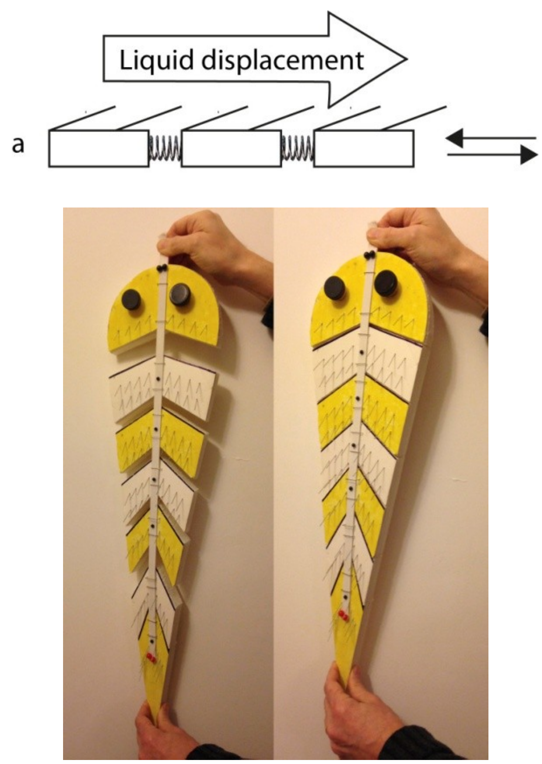


Figure 2: *"Creepy" – a ciliar actuator*

a - Side view shows segments A, B, C, rigid "cilia" and elastic elements connecting segments;
b - Model in stretched and contracted positions – segments are painted in contrasting colours.

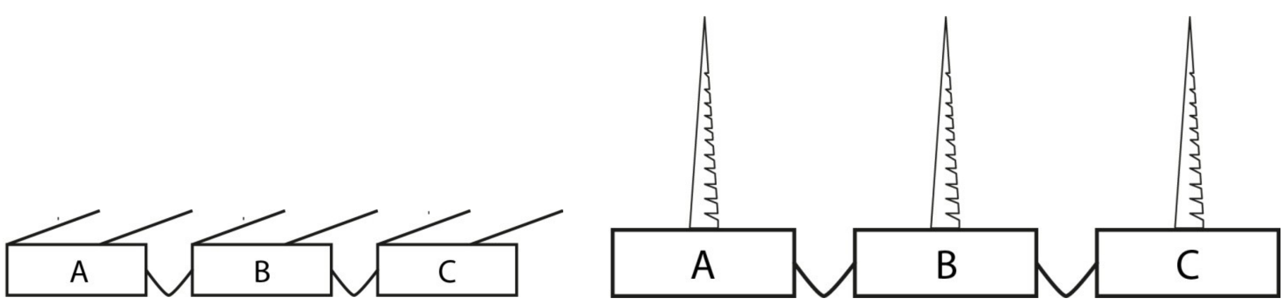
Figure 3: *"Crawly" – a ciliar actuator*

a - Side view;

b - Model showing longitudinal segmentation – the chevrons show the displacement of segmented parts.

By different combination of the parameters we designed another biomimetic device "Crawly" with passive rigid asymmetrical cilia and an active rigid segmented basement that actuates the movement

(Figure 3, a, b). This model is also provided with the needles bent at 30 degrees and the moving parts are joined with elastic elements. For the "Crawly" we segmented the foundation longitudinally. The central part of the device moves to-and-fro relatively lateral parts. All segments begin moving synchronously.

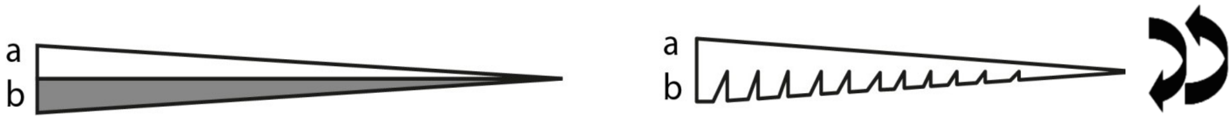


a) Metachronal wave is achieved by the looseness of the joints

b) Microfluidic actuator with morphologically asymmetrical cilia.

Figure 4. *Biomimetic actuator: "Metachron"*

The central moving part is made as a wedge for easier moving. The reciprocating movement transports an item placed on the needled surface functioning like a conveyor belt. As liquid at the micro scale level has high viscosity, it will be moved by the rigid asymmetrical cilia, which cover all the surface of “Crawley”.



a) The difference in stiffness between the two sides (a, b) of a cilium provides asymmetry for effective and recovery strokes.

b) Different behaviour of cilium in effective and recovery stroke due to one-sided segmentation.

Figure 5. *Asymmetric cilium*

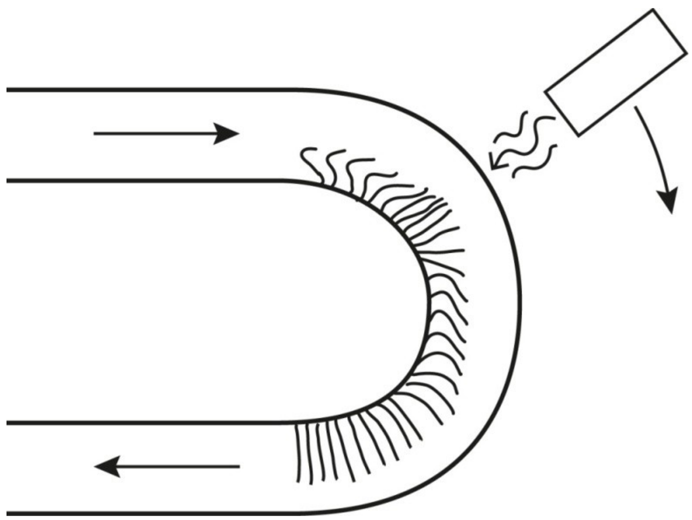


Figure 6. *Rotochron: External orbiting electro-magnetic field driver with narrow beam activating magneto-sensitive cilia*

The next device we have built was one with an active fragmented actuating basement when loose joints provide the metachronal wave. We called this model “Metachron” (Figure 4, a, b). The moving parts of these devices work synchronously, but this array provides a traveling wave. Similar to “Creepy” and “Crawly” it is actuated by reciprocation.

To get maximum effect, beating cilia must act differently in effective and recovery strokes. In effective stroke they must be stiff, but in recovery stroke – relaxed and flexible, just like living cilium.

The main function of a cilium is to create a fluid flow by asymmetrical beating – effective and recovery strokes. In the effective stroke cilium should be rigid, but in the recovery stroke – relaxed and flexible. In the living cilia this is provided by the functional asymmetry of the morphologically symmetrical internal structure, which also works as an actuator itself – an analogue of a linear electric motor, where linear elements are actively sliding or connected to one another at different stages of the motion cycle. An artificial cilium is inevitably simpler, because it is much easier to make it passively driven by external sources of energy – electro-magnetic or electro-static fields or active basement. But biomimetic cilium should still provide asymmetrical effective and recovery strokes. This can be achieved if the two sides of the cilium are of different stiffness or by small cuts perpendicular to the main axis along the cilium (Figure 5). Note that this functional effect is achieved by structural changes and actuation mechanism that is totally different from living prototypes.

Such morphologically asymmetrical cilia can be attached to the basement of “Metachron” (Figure 4 b), which will provide a real metachronal traveling wave of asymmetrically moving cilia – the main requirement of the current project.

We can also investigate the possibility of using static base, which is technologically more feasible. This direction of thinking leads us to development of another biomimetic creature, which got the name “Rotochron”. “Rotochron” provides the traveling wave and asymmetry of cilia operation.

We have achieved this effect by rotating of the external actuator (powerful electromagnet), which is orbiting congruently the semi-circle (bow-shape) channel with cilia (Figure 6). This metachronic wave (like in peristaltic pump) combined with the asymmetric reciprocation of cilia provided the required effect – transportation of the viscous liquid along the channel. The challenge was accomplished by imitating of the natural behaviour of live cilia to obtain the required effect and create a biomimetic microfluidic pump.

CONCLUSIONS

1. The theory of biomimetics that we develop is based on four initial axioms and their practical outcome in the form of algorithm.

2. Each of the six stages of the algorithm requires different TRIZ tool to support the process.

3. “Creepy” and “Crawly” are biomimetic “creatures” that employ the mechanisms, which are not in use in living nature, but which are possible to implement with the means of engineering. Final biomimetic device looks and operates neither like a living prototype nor conventional technological device.

4. In spite of the fact that biological systems operate with or within liquids in different forms and scales, the set of actuators and principles of action are amazingly similar. Cilia, bristles, tentacles, paddles, membranes/fins form poly-systems at any scale. A wave-like movements cause the metachronic undulation, peristalsis and their derivatives. Similar morphological structures (tubes, funnels, branching pipe-works, spirals/helices, suckers, etc.) also can be found in living systems of nearly any size – from micro- to macro. This gives us an idea that the functional properties of all those mechanisms have much in common and can be employed for biomimetic engineering at all ranges of scales.

5. Biomimetic design process does not end up with choosing right living prototype. It opens new engineering opportunities in design as we can see the whole range of possibilities that are not realised yet – both in living nature and technology [5]. Such non-existing combinations of parameters can inspire us to develop devices with the mutually enhancing advantages of natural living and artificial engineering systems.

ACKNOWLEDGEMENTS

The work was carried out and supported by the EU ARTIC project. The authors are grateful to colleagues of the ARTIC consortium for fruitful discussions.

References

[1] Bogatyreva O.A, Bogatyrev N.R. Complexity in living and non-living systems / Proc. Of international TRIZ conference, Philadelphia, USA, 16-18 March 2003, p. 16/1- 16/6.

[2] Bogatyrev N. R. Ecological engineering of survival. – Novosibirsk, Publishing house of SB RAS, 2000, 184pp.

[3] Bogatyrev N.R. The living machine. The Journal of Bionic Engineering, 2004, N2, 2004 p. 79-87.

[4] Bogatyrev N.R., Bogatyreva O.A., 2003, TRIZ and Biology: rules and restrictions. - Proc. Of International TRIZ conference, Philadelphia, USA, 16-18 March 2003, p.p. 19/1 -19/4.

[5] Bogatyrev N.R., 2008, Microfluidic Actuation in Living Organisms: a Biomimetic Catalogue. In "Proceedings of the First European Conference on Microfluidics", Bologna, p.175.

[6] Gueron S., Levit-Gurevich K., Liron N., Blum J.J., 1997, Cilia internal mechanism and metachronal coordination as the result of hydrodynamical coupling. – "Proceedings of the National Acadamy of Sciences USA", vol. 94, pp. 6001-6006.

[7] Vincent J.F.V., Bogatyreva O.A., Bogatyrev N.R., Bowyer A., Pahl A.-K. (2006). Biomimetics – its practice and theory. J. Royal Society Interface, 3: 471-482.

[8] Bogatyrev N.R., Vincent J.F.V. (2008). *Microfluidic actuation in living systems*. ARTIC internal report.

[9] Raup D.M., Michelson A. (1965). *Theoretical morphology of the coiled shell*. Science, 147: 1294- 1295

[10] Dogel V.A. (1975). *Zoology of Invertebrates*. Moscow, Publ. House "Vysshaya Shkola", 560 pp.