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RESEARCH IN BIO-INSPIRED DESIGN - WHAT IS ITS CURRENT FOCUS?

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Abstract: Bio-inspired design is an increasingly popular creativity and innovation method. Using bio-inspired design, designers tap nature with its almost unlimited pool of inspirations for technical solutions. A challenge of bio-inspired design is finding promising biological systems and identifying analogies which can be transferred to solve a technical problem. For these challenges, the profound understanding of the biological system is necessary. This can require further research. To understand the current focus of bio-inspired design research, we analyse journal publications from 2015/16 and 2006. The analysis provides an overview of the biological systems and organization levels currently in focus. Moreover, we regard the technical products resulting from the bio-inspired designs. The results show designers which biological systems and organization levels have been researched for bio-inspired design so that knowledge on them can directly be used for further technical developments. The blank spots of research are identified which can provide unexplored biological inspirations.

Keywords: *biomimicry, biomimetics, design-by-analogy*

1. Introduction

Bio-inspired design - taking nature as inspiration for the development of technical products is an increasingly used innovation approach (Lepora et al. 2012). But bio-inspired design does not mean copying a detail or function of an organism. The designer has to understand the biological system and learn from biology's methods and principles before transferring an analogy from nature (Nachtigall, 2002, p.3). The pool of biological systems is vast and largely unexplored for bio-inspired design. Therefore, research plays an important role for bio-inspired design and bio-inspired products are often the result of bi-disciplinary research. As such, accounts of research and development of bio-inspired products are regularly published on conferences or in journals (Lepora et al., 2012). To understand which part of the vast pool of possible biological systems have already been explored for bio-inspired design, these publications can provide useful information. Therefore, in this work which is based on Domke (2016), we analyse publications on bio-inspired design from two journals. Our aim is to understand which biological systems have been explored in detail for bio-inspired design and which types of technical products have been developed. Moreover, we regard the focus of research ten years ago and compare it to today's focus to understand if there is an emerging trend of research.

2. Background

Although bio-inspired design is often regarded as a new approach, regarding the historical development of bio-inspired design shows that human inventions have been inspired and influenced by nature since the Stone Age. If we report about the history of bio-inspired design, we can begin with Leonardo da Vinci (1452-1519). As a historical pioneer, the Italian inventor presented a model of a flying machine based on the flight of birds. Leonardo da Vinci tried to understand the flight of birds and to transfer their principles to an aircraft made of willow-weaved ropes and linen-lined flaps for humans (Nachtigall, 2002, p. 39f). In 1576, the Englishman Matthew Baker (1530- 1613) began to design a novel vessel on the order of John Hawkins. The aim was a type of galleon, which should be characterized by low water resistance, high speed and good maneuverability. Fast swimming fish like the codfish or mackerel served as a biological inspiration for the underwater hull (Nachtigall et al., 2013, p.4). The first German patent in bio-inspired design was registered by Raoul Heinrich France (1874- 1943) for a "new shaker" development. The aim of his invention was to develop a shaker which spreads its content uniformly in all directions. He used the poppy head as a biological system for this bio-inspired design (Nachtigall et al., 2013, p.18). In 1948, the famous Velcro® closure was invented inspired by burs. Burs grow, for example, on thistles (Carduus spec.), horse thistles (Cirsium spec.) as well as on agrimonies (Agrimonia eupatoria). After a forest walk, the Swiss Georges de Mestral (1907- 1990), examined the burs that stuck in his dog's fur and was inspired to design the Velcro® closure (Nachtigall et al., 2013, p.46). Other designers did not regard specific biological systems, but general natural strategies: For example, Rechenberg (1994) regarded evolution and its four parameters mutation, recombination, isolation and selection. He analysed the evolutionary strategy of articulated plates under different environmental conditions. His research shows that the evolutionary strategy optimization actually leads to the expected theoretically foreseeable optimum (Rechenberg, 1994).

Reviewing the history of bio-inspired design reveals that a multitude of biological systems have served as inspiration and that different technical systems have been developed. At a first glance, there seem to be no tendencies regarding the type of biological systems used as inspiration or the type of technical systems that were developed. In this work, we therefore analyse the focus and trends of bio-inspired design today to detect the well explored areas and the blank spots of bio-inspired design research.

3. Research approach

To examine the focus of bio-inspired design research, we analysed publications in two journals. This section describes the research approach, i.e. the research questions (3.1), the selection of journals (3.2) and the analysis approach (3.3)

3.1. Research questions

Nature offers an enormous pool of inspirations for the development of technical products. Research in bio-inspired design is conducted increasingly and the amount of scientific publications is growing (Lepora et al. 2012). Bio-inspired design is defined as the application of knowledge about biological systems in research and development for solving technical problems and developing technical inventions and innovations (VDI 6220, 2012). In this work, we therefore only analyse publications that describe concrete technical inventions. We do not consider publications on biological research or on the improvement of previously developed bio-inspired products. To put a figure on the portion of bio-inspired transfer in publications, we pose the first question:

1. How many publications describe a concrete bio-inspired design?

We classify biological systems according to biological systematics (kingdoms, classes, families, and species). The initial point of this work was the question of diversity of biological systems already considered as well as technical solutions based on them. Therefore, we pose the following questions:

2a. Which animals and plants are in focus in bio-inspired design research?

2b. Which are the trends regarding kingdoms or classes considering the last decade?

Bio-inspired design grows to become a research field that creates many successful bio-inspired technical systems (VDI 6220, 2012). However, it has not been researched which fields of industry already use bio-inspired design approaches. Therefore, we pose the following questions:
3a. Which technical systems are the result of bio-inspired design research?
3b. Which are the trends regarding bio-inspired technical systems regarding the last decade?
Often, a designer searches for a partial solution for a single function of a complex technical system. Accordingly, research for bio-inspired design has to focus on a part of a biological system, such as a biological process, the material, the structure, an organ or a specific function. To identify the focus with regards to biological levels of organization we pose the following questions:
4a. Which levels of organization are in focus in bio-inspired design research?
4b. Which are the trends of organization levels used for bio-inspired design regarding the last decade?

3.2. Selection of publications

Considering 18.000 publications on the topic of bio-inspired design covering the years 1995– 2011, 57 percent were published in journals and 43 percent on conferences. For this paper, we decided to analyse publications of the two journals "Bioinspiration and Biomimetics" and "Journal of Bionic Engineering". These two journals belong to the 12 journals with the highest numbers of publications per year and deal with a wide diversity of technical bio-inspired design in contrast to other journals such as biomaterials (Lepora et al., 2012). For this investigation, publications from the latest editions of the journals in 2015 and 2016 ("Journal of Bionic Engineering": Vol. 12, Issue No. 3 and 4, Vol. 13 Issue No. 1; "Bioinspiration and Biomimetics": Vol. 10 Issue No. 4-6, Vol. 11 Issue No. 1 and 2) were considered. They represent recent bio-inspired transfer in research and industry. To compare the recent tendencies of bio-inspired design with those in the past, publications of the year 2006 were analysed ("Journal of Bionic Engineering": Vol. 3 Issue No. 1-4; "Bioinspiration and Biomimetics": Vol. 1 Issue No. 1-4)

3.3. Analysis approach

For research question 1, we asserted whether a publication describes a bio-inspired transfer that results in a technical invention. All other papers were not considered for the further analysis (research questions 2 to 4). As to research question 2, the biological systems described in the remaining publications were categorized according to biological systematics. These include "kingdom", "phylum", "class", "order", "family", "genus" and "species". In this work, we focused on the categories "kingdom", "class", "family". The level of species was not analysed because many publications do not name the species explicitly. Regarding research question 3, a possibility to classify the bio-inspired technical system was necessary. BIOKON, an international network of experts, universities and other people involved in bio-inspired design, defined the technical areas: "light construction & materials", "surfaces", "fluid dynamics, swim & fly", "biomechatronic & robotics", "communication & sensors", "optimization" and "architecture & design" (BIOKON 2016). In this work, the classification areas "optimization" and "architecture & design" were waived, as they can be integrated into the other technical areas.
For research question 4, bio-inspired design was classified according to different levels of organization. Levels of organization characterize life from microscopic scale, such as molecule and cell, up to the global scale of the whole planet. Every natural phenomenon contains all biological levels of organization (Campbell, 2008). The 10 levels used here are: "molecule", "organelle", "cell", "tissue", "organ/ organ system", "organism", "population", "biocoenosis", "ecosystem" and "biosphere". From molecule started, the focus regarding the organism and his environment gets wider from level to level and the complexity increases (Campbell, 2008 and Hacco, 2002).
For research questions 2, 3 and 4, we differ between "very frequent application", "frequent application" and "infrequent application". "Very frequent applications" describes all levels or systems with a percentage share of more than 20 percent of all publications on bio-inspired design. "Frequent application" describes all levels or systems with a percentage share of 10 to 20 percent and "infrequent application" describes all levels or systems under 10 percent.

4. Results

To answer the first research question, we analysed all 151 publications of the latest editions of the journals in 2015 and 2016 (until June 2016) from the journals "Bioinspiration and Biomimetics" and "Journal of Bionic Engineering". As to research question 1, the analysis showed that only 74 publications describe a bio-inspired transfer resulting in a technical invention. On the other hand, about half of the publications are related to bio-inspired design only in broader sense without describing a concrete bio-inspired transfer. Those publications describe basic research, support of biological research or the optimization of previously developed bio-inspired inventions. The 74 publications treating bio-inspired design were used for the further analysis.

4.1. Biological systems

To answer research question 2, we classified the biological systems described in the publications in the biological systematics of Ernst Mayr. We focused on the categories "kingdom", "classes" or "families". As we analysed the biological kingdom, we found a difference between the focus on the two kingdoms "plants" and "animals": In 92 percent of all 74 publications, the described biological systems are animals, only 5 percent described plants. Three percent described "others" which includes for example raw materials of the earth. In the next step, we evaluated the share of the biological classes and families. The analysis for the kingdom of plants is negligible as only four different plant species are described in the analysed research publications. In the following diagram, Figure 1 on the left side, we show the percentage distribution of the different classes. Insects and mammals come off with the highest portions of 30 and 25 percent. When considering these two classes separately, it is possible to identify tendencies of biological families used for bio-inspired design. In the class of mammals, we identified four different families. One specific biological family is often in focus for bio-inspired research: the family of humans. The family of humans and the family of dolphins can be arranged in the cluster of "very frequent application". The other two mammal families "dog" and "mole" were investigated only for special problems and we classified these families in the cluster of "infrequent application". In the world of insects, it is not possible to find such clear trends: Although the insects are the most frequent biological system, no accumulation of a special family used for bio-inspired design can be identified. However, we identified the families of grasshoppers, butterflies, ants and cockroaches as families with "frequent application". The class of fishes is used in 12 percent of 74 publications - it is the third-strongest class. In contrast to these three classes, birds as well as reptiles amount to only 9 percent of the publications and fall in category "infrequent application". Regarding these classes in detail, one family of reptiles stands out. In the research area of adhesion, the focus is on the family of geckos. Therefore, this family can be considered as "very frequent application".

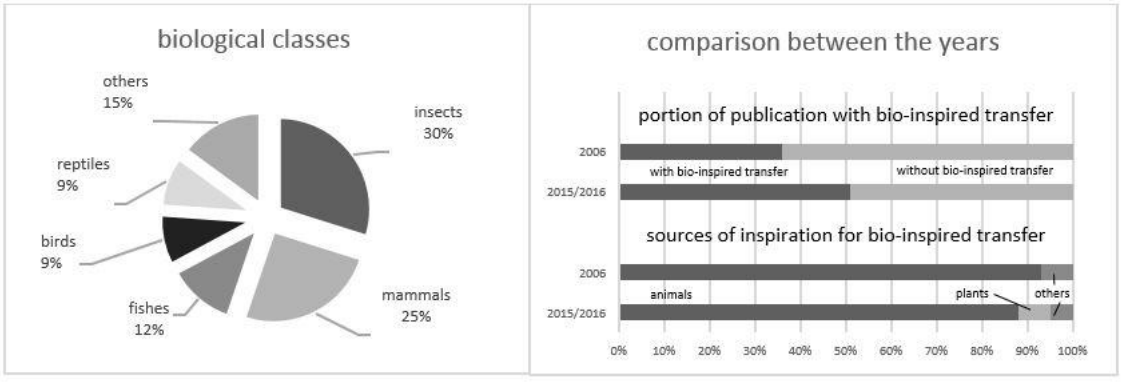

Figure 1. Portion and comparison of biological systems

To sum up, the families of humans, dolphins and geckos were clustered as "very frequent application" for bio-inspired design. Grasshoppers, butterflies, ants and cockroaches constitute a cluster of "frequent application" and all other animal families could be placed in a third cluster "infrequent

application". To answer the research question 2b the right diagram of Figure 1 shows a comparison between the years 2006 and 2015/16. The top bar of the three years indicates the percentage of publications with bio-inspired transfer: Comparing 2006 to 2015/16, the portion of publications describing a bio-inspired transfer increased. The other two bars show the share of the two kingdoms per year: In the year 2006 the share of plants for bio-inspired design was zero percent and of animals 93 percent. In the years 2015/ 2016 the percentage of plants was 7 percent and of animals it was 90 percent.

4.2. Bio-inspired technical systems

The bio-inspired technical systems were classified according to the five technical classification areas "lightweight and materials", "surfaces and interfaces", "fluid dynamics, swim and fly", "biomechatronic and robotics" and "communication and sensor", as described in section 3.3. On the left diagram of 2, all the five technical areas are shown with their share of bio-inspired design. "Biomechatronic & robotics" make up the biggest portion with 59%. All inventions of robots, vehicles, medical technology and other machines count to this area. The bio-inspired technical systems of the fields of "lightweight and materials" and "fluid dynamics, swim and fly" form the cluster "frequent application" for bio-inspired design. We identified a share of 15 percent for each area. The two areas “communication & sensor” and “surface/ interface” together represent only 11 percent.

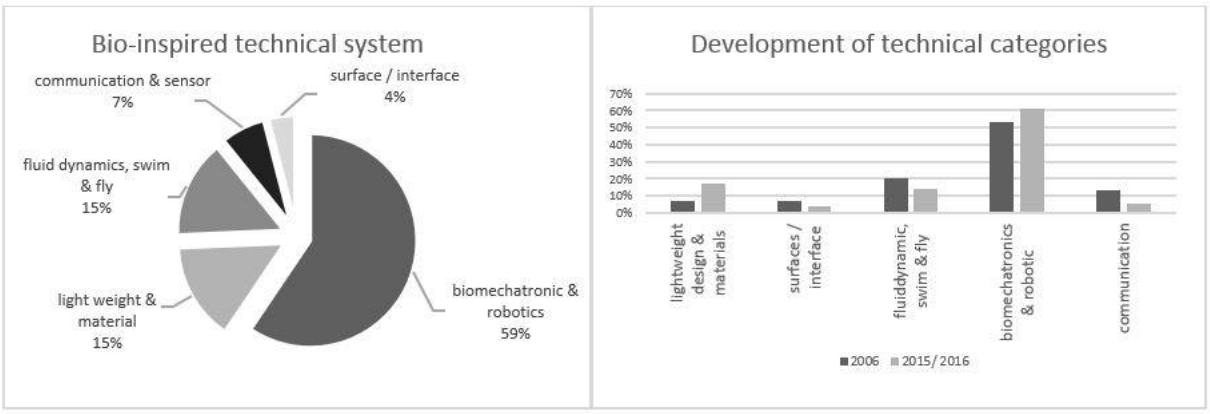

Figure 2. Portion and development of technical systems

As the comparative analysis for the biological systems over the years, we analysed the trends regarding bio-inspired technical systems to answer research question 3b. Presented in Figure 2 on the right diagram, we used a comparative analysis for all technical areas described in the publications between the year 2006, shown by the first pillar, and the years 2015/ 2016, shown by the second pillar. For the technical areas “biomechatronic and robotics” as well as “lightweight design & materials”, a rise of bio-inspired design is visible. This shows that not only the development of these technical areas becomes more popular and more important but also the transfer of analogies from biological systems as a development approach. In contrast to this, we identified a decrease of bio-inspired development regarding the technical areas “surfaces/ interface”, “fluid dynamics, swim & fly” and “communications”.

4.3. Levels of organization

For research question 4, we analysed the levels of organization of the biological systems described in the publications. Six out of 11 levels of organization were used in 74 publications with bio-inspired design. According to the three criteria, the levels of organ systems, organs and tissue make up the cluster of "very frequent application". A possible explanation for this is that these levels of organization allow designers an investigation of the aspect of the biological system to be transmitted

with bare eye. The biological levels of organization "population", "cell" and "molecule" form a cluster of infrequent application. To answer the research question 4b, we conducted a comparative analysis regarding the levels of organization 2006 and 2015/16. Looking at the right diagram in Figure 3, a minimal increase of the lower levels of organization like “molecule”, “cell”, "tissue" and “organ” can be identified.

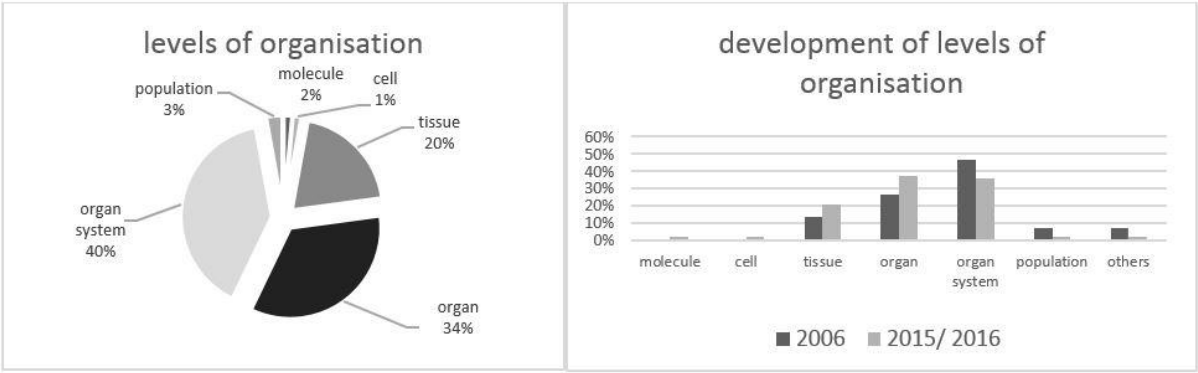

Figure 3. Portion and development of levels of organization

5. Discussion

The analysis described in this work shows a number of results: As both journals, according to their description, report about bio-inspired design, a large portion of bio-inspired designs was expected. The result of the analysis yielded a share of only 49 percent of bio-inspired transfer in all 151 publications. Frequently, articles on topics such as the support of biology through technical aids, or the optimization of an already existing bio-inspired product are published. The question arises to what extent it is useful to link so many different research areas to bio-inspired design. The analysis shows that although there is a diversity of biological systems, the publications describe especially biological inspirations from the animal kingdom. The classes of mammals and insects are notably frequently used. This raises the question why the focus is placed on animals and especially these animal classes. One possible explication is the currently strongly growing development in the areas of robotics and industry 4.0. The development of a robot is often connected to the consideration of nature. The degree of familiarity of the living being and the at least superficial similarity between living beings and robots influence the designer's choice. Moreover, another behavior can explain the frequent use of the same animal classes: even though only the partial solution for a sub-function or property of the robot is needed, in a number of cases several characteristics of the selected biological system are transferred. For example, engineers find a solution for a movement problem in geckos and copies the shape of the legs, the feet as well as the function of adhere at vertical walls without considering if there is a more suitable shape for each function (M. Carlo, 2006, Journal of Bionic Engineering, see Appendix). Thus, a copy of a biological system is created without questioning individual analogies.

6. Conclusion and outlook

The aim of this work was to analyse the focus of bio-inspired design research: which biological systems have been explored in detail for bio-inspired design and which types of technical systems have been developed? An analysis of the status of bio-inspired research and development was carried out based on the presented basics of bio-inspired design. We considered publications from two bio-inspired design journals of the years 2006, 2015 and 2016 for this analysis. Only 49 percent of the analysed publications describe bio-inspired transfer (research question 1). The analysis described in this work allows to identify specific areas that are mainly used for bio-inspired design. The biological systems were investigated down to the classification levels of the biological family. Particularly noteworthy is the animal kingdom with the classes of mammals and insects as very frequently used biological systems. In addition to the classification levels, we categorized the biological systems

described in the publications with regards to biological organization levels. A trend towards the levels tissue, organ and organ system can be identified. Furthermore, as to the bio-inspired technical systems, in the area of biomechatronic and robotics bio-inspired design was very frequently applied compared to other areas. Table 1 summarizes the results:

Table 1. Summary of results

		Very frequent applications	Frequent applications	Infrequent applications
Biological system (research question 2a)	**Biological kingdom**	animals		plants
	Biological class	insects, mammals	fishes	birds, reptiles
	Biological family	humans, dolphins, geckos	locusts, butterflies, ants, cockroaches	bees, mosquitos, stag beetles, and others
Technical system (research question 3a)	**Technical classification**	biomechatronic & robotics	light weight, fluid dynamics, swim & fly	communication & sensor, surface & interface
Levels of organisation (research question 4a)	**Levels**	tissue, organ, organ system		cell, population, molecule

The comparison between the year 2006 and years 2015/16 shows a growth in use of bio-inspired design. Over the years, the consideration of the plant kingdom started from zero in 2006, but grew slightly (research question 2b). In the technical categories (research question 3b) only the "lightweight design & materials" and "biomechatronic & robotics" were more in focus in the years 2015/16 than before. What do those results mean for the future of bio-inspired research and development? For the research of bio-inspired design applications, this work can serve as a foundation. It offers the possibility of a further more detailed analysis for the identification of clusters as well as the comparison of different years. Future research into the "white spots" of bio-inspired design could explore the plant kingdom or other animals which have not yet been explored for bio-inspired design. Mostly designers focus on already known animals such as humans, dolphins or geckos but there are other animals that can provide solutions. In this work, we have identified a preference of the animal kingdom but we are sure that the nature offers some solutions for technical problems in the plant kingdom, too. Designers should widen their search for biological inspirations, if possible in collaboration with by biologists.

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All publications of "Bioinspiration and Biomimetics" with bio-inspired design

Author	Y	Vol	Issue	Titel	Biological classification of transmitted organism: Kingdom	Class	Family	Levels	Product classification	Technical solution
Utku Çulha et al.	2016	Vol. 11	No.2	Enhancement of finger motion range with compliant anthropomorphic joint design	animal kingdom (animalia)	mammal (mamalia)	humane (hominidae)	organ	biomechatronics & robotic	robotic hands
A Diamond et al.	2016	Vol. 11	No.2	Classifying continuous, real-time e-nose sensor data using a bio-inspired spiking network modelled on the insect olfactory system	animal kingdom (animalia)	insect (insectum)	n.a.	organ system	communication & sensors	classifying real-time, continuous datasets
Dongri Kim et al.	2016	Vol. 11	No.2	A bio-inspired device for drag reduction on a three-dimensional model vehicle	animal kingdom (animalia)	bird (aves)	n.a.	organ	fluiddynamic, swim&fly	drag reduction for vehicle
M Taghavi et al.	2016	Vol. 11	No.1	Self sufficient wireless transmitter powered by foot-pumped urine operating wearable MFC	animal kingdom (animalia)	fish (pisces)	n.a.	organ system	biomechatronics & robotic	wearable energy generator based on MFC (foot-pump)
Eoin Parle et al.	2016	Vol. 11	No.1	Buckling failures in insect exoskeletons	animal kingdom (animalia)	insect (insectum)	n.a.	tissue	lightweight design & material	failure by buckling of thin walled tubes
Guido C H E de Croon	2016	Vol. 11	No.1	Monocular distance estimation with optical flow maneuvers and efference copies: a stability-based strategy	animal kingdom (animalia)	insect (insectum)	n.a.	organ system	biomechatronics & robotic	flying robots
Raphael Furrémont et	2016	Vol. 11	No.1	Bi-directional series-parallel elastic actuator and overlap of the actuation layers	animal kingdom (animalia)	mammal (mamalia)	humane (hominidae)	tissue	biomechatronics & robotic	robotics applications - SPEA
Sigrid Zobl et al.	2016	Vol. 11	No.1	Morpho peleides butterfly wing imprints as structural colour stamp	animal kingdom (animalia)	insect (insectum)	nymphalidae	organ	surfaces & intersurfaces	color-producing nanostamp
Ziyu Ren et al.	2016	Vol. 11	No.1	Hydrodynamics of a robotic fish tail: effects of the caudal peduncle, fin ray motions and the flow speed	animal kingdom (animalia)	fish (pisces)	bluegill sunfish	organ	biomechatronics & robotic	biomimetic flapping based and fin undulatory locomotion (...)
Christina T Bauer et a	2015	Vol. 10	No. 6	Hierarchical macroscopic fibrillar adhesives: in situ study of buckling and adhesion mechanisms on wavy substrates	n.a.	n.a.	n.a.	n.a.	lightweight design & material	hierarchically structured adhesives
D T Polet et al.	2015	Vol. 10	No. 6	Rapid area change in pitch-up manoeuvres of small perching birds	animal kingdom (animalia)	bird (aves)	chickadees (paridae)	organ system	fluiddynamic, swim&fly	manoeuvrable air vehicles
Payam Zahadat et al.	2015	Vol. 10	No. 6	From honeybees to robots and back: division of labour based on partitioning social inhibition	animal kingdom (animalia)	insect (insectum)	bees (apidae)	population	biomechatronics & robotic	underwater robots
Jiegang Peng	2015	Vol. 10	No. 6	A study of amplitude information-frequency characteristics for underwater active electrolocation system	animal kingdom (animalia)	fish (pisces)	n.a.	organ system	communication & sensors	AIFC phenomena for active electrolocation sensor
Neil Lazo et al.	2015	Vol. 10	No. 6	Optimized bio-inspired stiffening design for an engine nacelle	vegetable kingdom (plantae)	n.a.	n.a.	tissue	lightweight design & material	structure with optimized performance at minimized weight (...)
Shuhei Ikemoto et al.	2015	Vol. 10	No. 6	Shoulder complex linkage mechanism for humanlike musculoskeletal robot arms	animal kingdom (animalia)	mammal (mamalia)	humane (hominidae)	organ	biomechatronics & robotic	robotic arms
Matthew R Webster et	2015	Vol. 10	No. 6	Structure of tracheae and the functional implications for collapse in the American cockroach	animal kingdom (animalia)	insect (insectum)	blattidae	tissue	fluiddynamic, swim&fly	new microfluidic systems
Valentin Zaitsev et al.	2015	Vol. 10	No. 6	A locust-inspired miniature jumping robot	animal kingdom (animalia)	insect (insectum)	acrididae	organ system	biomechatronics & robotic	unmanned ground vehicles
L Vannozzi et al.	2015	Vol. 10	No. 5	Self-assembly of polydimethylsiloxane structures from 2D to 3D for bio-hybrid actuation	animal kingdom (animalia)	n.a.	n.a.	molecular	biomechatronics & robotic	3D rolled PDMS structures ofr bio-hybrid actuation
Erik D Engeberg et al.	2015	Vol. 10	No. 5	Anthropomorphic finger antagonistically actuated by SMA plates	animal kingdom (animalia)	mammal (mamalia)	humane (hominidae)	organ	biomechatronics & robotic	robotic finger
Gerrit Staufenberg et	2015	Vol. 10	No. 5	Impact and hardness optimisation of composite materials inspired by the babassu nut (Orbignya speciosa)	vegetable kingdom (plantae)	arecales	palm tree (arecaceae)	tissue	lightweight design & material	biomimetic fibre composite with good combination of (...)
A Winzen et al.	2015	Vol. 10	No. 5	Particle-image velocimetry investigation of the fluid-structure interaction mechanisms of a natural owl wing	animal kingdom (animalia)	bird (aves)	barn-owl (tytonidae)	organ	fluiddynamic, swim&fly	small flying air vehicles
Zhijing Wu et al.	2015	Vol. 10	No. 5	Vibration isolation by exploring bio-inspired structural nonlinearity	animal kingdom (animalia)	insect (insectum)	n.a.	organ	biomechatronics & robotic	passive vibration control
Kin Chung Denny Fu	2015	Vol. 10	No. 5	Extracting motor synergies from random movements for low-dimensional task-space control of musculoskeletal robots	animal kingdom (animalia)	mammal (mamalia)	humane (hominidae)	organ	biomechatronics & robotic	musculoskeletal robots - human-like robotic arm
Daniel-Ioan Curiac et	2015	Vol. 10	No. 5	Imparting protean behavior to mobile robots accomplishing patrolling tasks in the presence of adversaries	animal kingdom (animalia)	n.a.	n.a.	organ system	biomechatronics & robotic	mobile robots - patrol robots
Nathan Phillips et al.	2015	Vol. 10	No. 5	The effect of aspect ratio on the leading-edge vortex over an insect-like flapping wing	animal kingdom (animalia)	insect (insectum)	n.a.	organ	biomechatronics & robotic	autonomous flapping vehicles
Bruce D Miller et al.	2015	Vol. 10	No. 4	Towards highly-tuned mobility in multiple domains with a dynamical legged platform	animal kingdom (animalia)	n.a.	n.a.	organ system	biomechatronics & robotic	mobile robots in challenging and changing terrains
R S Russo et al.	2015	Vol. 10	No. 4	Biomechanical model of batoid (skates and rays) pectoral fins predicts the influence of skeletal structure on fin kinematics: implications for bio-inspired design	animal kingdom (animalia)	fish (pisces)	n.a.	organ	biomechatronics & robotic	autonomous underwater vehicles
Chen Li et al.	2015	Vol. 10	No. 4	Terradynamically streamlined shapes in animals and robots enhance traversability through densely cluttered terrain	animal kingdom (animalia)	insect (insectum)	blattidae	organ system	biomechatronics & robotic	robotic, aircraft, vehicles
Hiroto Tanaka et al.	2015	Vol. 10	No. 4	Flexible flapping wings with self-organized microwrinkles	animal kingdom (animalia)	bird (aves), insect	n.a.	organ	biomechatronics & robotic	flapping wings, future flapping-wing aerial robots
Jana Goyens et al.	2015	Vol. 10	No. 4	Built to fight: variable loading conditions and stress distribution in stag beetle jaws	animal kingdom (animalia)	insect (insectum)	lucanidae	tissue	lightweight design & material	designing very robust structures in an efficient way
Bingbing An et al.	2015	Vol. 10	No. 4	Bioinspired toughening mechanism: lesson from dentin	animal kingdom (animalia)	n.a.	n.a.	tissue	lightweight design & material	development of novel man-made engineering materials
A P Maertens et al.	2015	Vol. 10	No. 4	Efficiency of fish propulsion	animal kingdom (animalia)	fish (pisces)	n.a.	organ system	fluiddynamic, swim&fly	quasi-propulsive efficiency
Jihoon Kim et al.	2015	Vol. 10	No. 4	Experimental and numerical study of a dual configuration for a flapping tidal current generator	animal kingdom (animalia)	mammal (mamalia)	dolphin	organ	fluiddynamic, swim&fly	flapping tidal current generator
J H Yan et al.	2015	Vol. 10	No. 4	A miniature surface tension-driven robot using spatially elliptical moving legs to mimic a water strider's locomotion	animal kingdom (animalia)	insect (insectum)	water strider (gerridae	organ	biomechatronics & robotic	surface tension–driven robot
Yasuhiro Fukuoka et a	2015	Vol. 10	No. 4	Energy evaluation of a bio-inspired gait modulation method for quadrupedal locomotion	animal kingdom (animalia)	n.a.	n.a.	organ system	fluiddynamic, swim&fly	bio-inspired gait modulation method
Cagdas Tuna et al.	2015	Vol. 10	No. 4	Tactile soft-sparse mean fluid-flow imaging with a robotic whisker array	animal kingdom (animalia)	mammal (mamalia)	n.a.	organ system	communication & sensors	alternative environmental sensing technology (in dark or ...)
Cheng Shao et al.	2006	Vol. 1	No. 1	Cooperative optimal control: broadening the reach of bio-inspiration	animal kingdom (animalia)	insect (insectum)	formicidae	population	communication & sensors	iterative, pursuit-based algorithm
Robert L Karlinsey et	2006	Vol. 1	No. 1	Nucleation and growth of apatite by a self-assembled polycrystalline bioceramic	earth	n.a.	n.a.	tissue	lightweight design & material	new mode for the bioinspiration of hydroxyapatite and other(...)
V V Pavlov	2006	Vol. 1	No. 2	Dolphin skin as a natural anisotropic compliant wall	animal kingdom (animalia)	mammal (mamalia)	oceanic dolphins	organ	fluiddynamic, swim&fly	design of multipanel anisotropic compliant walls
David A Helweg et al.	2006	Vol. 1	No. 2	Using a binaural biomimetic array to identify bottom objects ensonified by echolocating dolphins	animal kingdom (animalia)	mammal (mamalia)	oceanic dolphins	organ system	communication & sensors	dolphin biomimetic sonar
C Menon et al.	2006	Vol. 1	No. 2	Active articulation for future space applications inspired by the hydraulic system of spiders	animal kingdom (animalia)	joint-legged invertebr	n.a.	organ system	biomechatronics & robotic	active articulation for future space applications
Jan Wessnitzer et al.	2006	Vol. 1	No. 3	Multimodal sensory integration in insects—towards insect brain control architectures	animal kingdom (animalia)	insect (insectum)	n.a.	organ system	biomechatronics & robotic	adaptive behaviour in robots
Renaud Barate et al.	2006	Vol. 1	No. 3	Design of a bio-inspired controller for dynamic soaring in a simulated unmanned aerial vehicle	animal kingdom (animalia)	bird (aves)	diomedeidae	organ system	fluiddynamic, swim&fly	controller for dynamic soaring(simulated glider
Wang Zhang et al.	2006	Vol. 1	No. 3	Biomimetic zinc oxide replica with structural color using butterfly (Ideopsis similis) wings as templates	animal kingdom (animalia)	insect (insectum)	nymphalidae	organ	surfaces & intersurfaces	Nano-structured colorful zinc oxide replicas
R J Bomphrey	2006	Vol. 1	No. 4	Insects in flight: direct visualization and flow measurements	animal kingdom (animalia)	insect (insectum)	n.a.	organ	fluiddynamic, swim&fly	micro-air vehicles
Kamran Mohseni	2006	Vol. 1	No. 4	A formulation for calculating the translational velocity of a vortex ring or pair	animal kingdom (animalia)	head-feet (Cephalop	n.a.	organ system	biomechatronics & robotic	helmholtz vortex ring generator

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Author	Y	Vol	Issue	Titel	Biological classification of transmitted organism: Kingdom	Class	Family	Levels	Product classification	Technical solution
Jizhuang Fan, Yu Zhu	2016	Vol.13	No. 1	Chaotic CPG Based Locomotion Control for Modular Self-reconfigurable Robot	animal kingdom (animalia)	n.a.	n.a.	organ system	biomechatronics & robotic	self-reconfigurable Robot
HyunGyu Kim, Dong[	2016	Vol.13	No. 1	Hexapedal Robotic Platform for Amphibious Locomotion on Ground and Water Surface	animal kingdom (animalia)	reptile	corytophanidae	organ system	biomechatronics & robotic	hexapedal Robotic Platform
Saber Mahboubi Hey	2016	Vol.13	No. 1	Two Bioinspired Mobile Manipulators with Rolling Locomotion	animal kingdom (animalia)	reptile, insect	n.a.	organ system	biomechatronics & robotic	mobile manipulators(robots
Wenru Chen, Caihua	2016	Vol.13	No. 1	On Adaptive Grasp with Underactuated Anthropomorphic Hands	animal kingdom (animalia)	mammal (mamalia)	humane (hominidae)	organ	biomechatronics & robotic	underactuated anthropomorphic robotic hands
Zuqiang Yang, Zhou	2016	Vol.13	No. 1	Bio-inspired Collision-free 4D Trajectory Generation for UAVs Using Tau Strategy	animal kingdom (animalia)	n.a.	n.a.	organ system	biomechatronics & robotic	collision-free 4D trajectory generation, multiple unmanned(...)
Yiwei Zhao, Jianing W	2016	Vol.13	No. 1	The Morphology and Reciprocation Movement of Honeybee's Hairy Tongue for Nectar Uptake	animal kingdom (animalia)	insect (insectum)	bees (apidae)	organ	biomechatronics & robotic	microfluidic pump
Yongchao Zhang, Shi	2016	Vol.13	No. 1	Fabrication and Characterization of Gecko-inspired Dry Adhesion, Superhydrophobicity and Wet Self-Cleaning	animal kingdom (animalia)	reptile	gecko	tissue	surfaces & intersurfaces	polydimethylsiloxane microfiber surfaces
J.S. Binoj, R. Edwin R	2016	Vol.13	No. 1	Morphological, Physical, Mechanical, Chemical and Thermal Characterization of Sustainable Indian Areca Fruit Husk Fibers (Areca Catechu L.) as Potential Alternate for Hazardous Synthetic Fibers	vegetable kingdom (plantae)	arecales	palm tree (arecaceae)	tissue	lightweight design & material	alternate for hazardous synthetic fibers
Satoyuki Kawano, Sak	2016	Vol.13	No. 1	Systematical Experiment for Optimal Design of Vibrating Flow Pump with Jelly-fish Valve	animal kingdom (animalia)	n.a.	n.a.	organ system	biomechatronics & robotic	vibrating flow pump with jelly-fish valve - a novel artificial(...)
Jun He, Feng Gao	2015	Vol.13	No. 4	Type Synthesis for Bionic Quadruped Walking Robots	animal kingdom (animalia)	mammal (mamalia)	n.a.	organ system	biomechatronics & robotic	quadruped walking robots - responding to nuclear accidents
Lei Cai, Zhendong Da	2015	Vol.12	No. 4	Modulating Motor Behaviors by Electrical Stimulation of Specific Nuclei in Pigeons	animal kingdom (animalia)	bird (aves)	pigeons (columbidae)	organ system	biomechatronics & robotic	flying robots
Dan Zhou, Yan Gao, h	2015	Vol.12	No. 4	Fabrication of NiTi Shape Memory Alloys with Graded Porosity to Imitate Human Long-bone Structure	animal kingdom (animalia)	mammal (mamalia)	humane (hominidae)	tissue	lightweight design & material	NiTi shape memory alloy
Nenad Ignjatovic, Zor	2015	Vol.12	No. 4	Enhanced Osteogenesis of Nanosized Cobalt-substituted Hydroxyapatite	earth	n.a.	n.a.	tissue	biomechatronics & robotic	bone tissue reconstruction
Christin Hundertmark	2015	Vol.12	No. 4	Diatom-inspired Plastic Deformation Elements for Energy Absorption in Automobiles	vegetable kingdom (plantae)	diatomophyceae	n.a.	cell	lightweight design & material	energy absorption in automobiles in the case of lateral(...)
James Andrew Smith	2015	Vol.12	No. 3	Effect of Hind Leg Morphology on Performance of a Canine-inspired Quadrupedal Robot	animal kingdom (animalia)	mammal (mamalia)	canidae	organ	biomechatronics & robotic	quadrupedal robot
Meiling Wang, Minzh	2015	Vol.12	No. 3	A Unified Dynamic Control Method for a Redundant Dual Arm Robot	animal kingdom (animalia)	mammal (mamalia)	humane (hominidae)	organ	biomechatronics & robotic	dual arm robot
Qinyuan Ren, Jianxin	2015	Vol.12	No. 3	A Data-driven Motion Control Approach for a Robotic Fish	animal kingdom (animalia)	fish (pisces)	n.a.	organ system	biomechatronics & robotic	robotic fish
Han Zhou, Tianjiang H	2015	Vol.12	No. 3	Bio-inspired Flow Sensing and Prediction for Fish-like Undulating Locomotion: A CFD-aided Approach	animal kingdom (animalia)	fish (pisces)	n.a.	organ system	fluiddynamic, swim&fly	underwater locomotion controllers
Diansheng Chen, Key	2015	Vol.12	No. 3	Mechanism of Locust Air Posture Adjustment	animal kingdom (animalia)	insect (insectum)	acrididae	organ	biomechatronics & robotic	jumping robots
Sanket Jaiswal, Sreek	2015	Vol.12	No. 3	Instability Analysis of Mosquito Fascicle under Compressive Load with Vibrations and Microneedle	animal kingdom (animalia)	insect (insectum)	culicidae	organ	biomechatronics & robotic	dynamically stable vibration-assisted microneedle
Qin Lian, Cheng Chei	2015	Vol.12	No. 3	Biphasic Mechanical Properties of in vivo Repaired Cartilage	animal kingdom (animalia)	mammal (mamalia)	n.a.	tissue	lightweight design & material	3D printed scaffolds
Jin Tong, Wenfeng Ji	2015	Vol.12	No. 3	Design and Tests of Bionimetic Blades for Soil-rototilling and Stubble-breaking	animal kingdom (animalia)	mammal (mamalia)	moles (talpidae)	organ	biomechatronics & robotic	blades for soil-rotoilling and stubble-breaking
Yuanning Liu, Fei He	2015	Vol.12	No. 3	The Improved Characteristics of Bionic Gabor Representations by Combining with SIFT Key-points for	animal kingdom (animalia)	mammal (mamalia)	humane (hominidae)	organ	biomechatronics & robotic	gabor filters
Hai-bin Duan, Dao-bo	2006	Vol.3	No. 2	Novel Approach to Nonlinear PID Parameter Optimization Using Ant Colony Optimization Algorithm	animal kingdom (animalia)	insect (insectum)	formicidae	n.a.	biomechatronics & robotic	nonlinear PID controller
Min Yu, Ai-hong Ji, Zl	2006	Vol.3	No. 2	Effect of Microscale Contact State of Polyurethane Surface on Adhesion and Friction	animal kingdom (animalia)	reptile	gecko	organ	biomechatronics & robotic	biomimetic gecko foot
Menon Carlo, Sitti Met	2006	Vol.3	No. 3	A Biomimetic Climbing Robot Based on the Gecko	animal kingdom (animalia)	reptile	gecko	organ system	biomechatronics & robotic	climbing robots
Dai-bing Zhang, De-w	2006	Vol.3	No. 4	A Bionic Neural Network for Fish-Robot Locomotion	animal kingdom (animalia)	fish (pisces)	n.a.	organ system	biomechatronics & robotic	fish-robot
Young-Sam Cho, Hou	2006	Vol.3	No. 4	Numerical Analysis of the Adhesive Forces in Nano-Scale Structure	animal kingdom (animalia)	reptile	gecko	tissue	biomechatronics & robotic	attachable nano-scale structures