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The state-of-the-art in biomimetics

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Abstract. Biomimetics is a research field that is achieving particular prominence through an explosion of new discoveries in biology and engineering. The field concerns novel technologies developed through the transfer of function from biological systems. To analyze the impact of this field within engineering and related sciences, we compiled an extensive database of publications for study with network-based information analysis techniques. Criteria included publications by year and journal or conference, and subject areas judged by popular and co-occurring terms in titles. Our results reveal that this research area has expanded rapidly from less than one hundred papers per year in the 1990s to several thousand papers per year in the first decade of this century. Moreover, this research is having impact across a variety of research themes, spanning robotics, computer science and bioengineering. In consequence, biomimetics is becoming a leading paradigm for the development of new technologies that will potentially lead to significant scientific, societal and economic impact in the near future.

1. Introduction

Biomimetics is the development of novel technologies through the distillation of principles from the study of biological systems. Biomimetic technologies arise from a flow of ideas from the biological sciences into engineering, benefiting from the millions of years of design effort performed by natural selection in living systems (Bar-Cohen, 2006a). This transfer of function from the natural world to artificial devices has driven novel research agenda across many disparate disciplines, from materials science and architecture to computer science and robotics. More recently, advances in robotics have facilitated the development of biomimetic robotics inspired by the different design plans found in the animal kingdom. Such biomimetic artefacts can provide excellent models of their biological counterparts, allowing us to ask and answer questions about the biological system that cannot be addressed through experiment alone. We emphasize that it is the transfer of function from biology to the machine that allows biomimetics to test hypotheses from the biological sciences, otherwise there is a danger of merely blind copying or mimicry of design principles with no further insight into the living system. In this sense of transferring biological function, biomimetic systems can thus provide a test-bed for theoretical ideas in biology and a means for generating biological solutions to challenges in science and technology, and we may consider them an implementation of "living machines".

Over the last decade there has been an explosion of important discoveries within the many research topics comprising biomimetics. The societal and economic impacts expected to emerge from these advances will have future benefits for our health and quality-of-life, due to advances in information and computation technologies, robotics, brain-machine interfacing and nanotechnology applied to life sciences. Given this potential of biomimetics, many international funding initiatives are underway to drive the field forward. However, for the field to fully realize its potential, it is necessary to have information gathering and coordination initiatives that can inform policy makers on appropriate strategic decisions. A recent initiative towards this goal in the European research area is the Convergent Science Network (CSN) of biomimetic and biohybrid systems (http://csnetwork.eu), which facilitates surveying and roadmapping exercises combined with other coordination actions for bringing researchers in the field together. Activities include organizing *Living Machines: The First International Conference on Biomimetic and Biohybrid systems* (Prescott et al, 2012), from which selected papers will be published in *Bioinspiration & Biomimetics*.

This article is a survey of the state-of-the-art of biomimetics based on an information analysis of a comprehensive database of publications on biomimetics in engineering and related sciences. While there are already many excellent reviews of biomimetics (Bar-Cohen, 2006b; Vincent et al, 2006; Barthelat, 2007; Teeri et al, 2007; Pfeifer et al, 2007; Fratzl, 2007; Bhushan, 2009; Bongard, 2009; Helms et al, 2009; Gebeshuber et al, 2009; Johnson et al, 2009; Wilson et al, 2010; Nagel and Stone, 2011; Nosonovsky and Rohatgi, 2012; Rawlings et al, 2012), such accounts usually emphasize

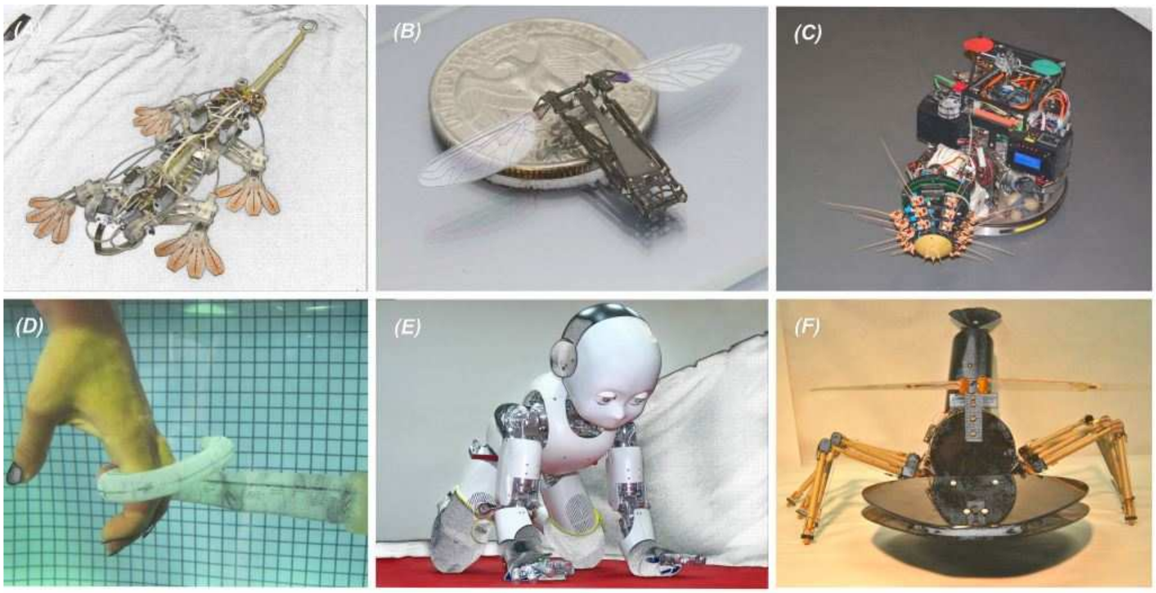

Figure 1. Examples of biomimetic robots.
(A) Stickybot: Gecko-inspired climbing-robot developed at Stanford University (Kim et al, 2008) (photo credit: Mark Cutkosky). (B) Robobee: Insect-like micro-air vehicle from the Harvard Microrobotics Lab (Sreetharan et al, 2012) (photo credit: The Harvard Microrobotics Lab). (C) Shrewbot: rodent-like, whiskered robot developed by Bristol Robotics Laboratory (Prescott et al, 2009; Sullivan et al, 2012) (photo credit: Ben Mitchinson). (D) Robotic octopus tentacle: developed at the University of Pisa, Italy (Mazzolai et al, 2012) (photo credit: Cecilia Laschi). (E) iCub: a child-like humanoid robot developed at the Italian Institute of Technology (Metta et al, 2008), (photo credit: Lorenzo Natale). (F) Robot lobster: developed at North-Eastern University (Ayers et al, 2011) (photo credit: Daniel Blustein).

subjects that are part of the authors' expertise and research priorities. Instead, our aim is to provide a complementary survey to these existing reviews from the viewpoint of a more objective statistical survey across the field of biomimetics in engineering and related sciences. In particular we focus on four main questions: Where is biomimetic research published? How rapidly is the subject of biomimetics expanding? What subjects does biomimetics encompass? And are there research communities within biomimetics? By focussing on these questions, our intention is that the answers will clarify the current state of the fields comprising biomimetic research, how these fields evolved to their present state, and where they appear to be heading in the future.

2. Background to biomimetics

Biomimetics can, in principle, extend to all fields of biological research from, physiology and molecular biology to ecology, and from zoology to botany. Promising research areas include system design and structure, self-organization and co-operativity, new biologically active materials, self-assembly and self-repair, learning, memory, control architectures and self-regulation, movement and locomotion, sensory systems, perception, and communication. Biomimetic research, particularly at the nano-scale, should also lead to important advances in component miniaturisation, self-configuration, and energy-efficiency. Another key focus is on complete behaving systems in the form of biomimetic robots that can operate on different substrates on sea, on land, or in the air. A further central theme is the physiological basis for intelligent behaviour as explored through neuromimetics – the modelling of neural systems. Exciting emerging topics within this field include the embodiment of neuromimetic controllers in hardware, termed neuromorphics, and within the control architectures of robots, sometimes termed neurorobotics.

Historically, the term 'biomimetics' was first used by Otto Schmitt during the 1950s, when he made a distinction between an engineering/physics approach to the biological sciences, which was termed 'biophysics', and a biological approach to engineering, which he termed biomimetics. Schmitt is also credited with establishing the field of biomedical engineering, which now encompasses the important discipline of biomaterials that retains its strong connections to biomimetics. A related term used in engineering is 'bionics', which was introduced by Jack Steel of the US Air force to mean copying and taking ideas from nature (popularized in Daniel Halacy's book *Bionics: the Science of Living Machines* (Halacy, 1965)). Another term that is now commonly used is bio-inspired or biologically-inspired, such as in the modern discipline of biologically-inspired computing. Bio-inspired computing tends to focus on bottom-up, decentralized approaches to computation such as genetic algorithms, in contrast with the more traditional top-down approach of artificial intelligence. Terms such as neuro-based and brain-based are also now beginning to be used, where the emphasis is more specifically based on the central nervous system of animals.

3. An information analysis methodology

To strive to be as objective as possible with this report, we adopted a methodology in which the state-of-the-art was surveyed using techniques from information analysis. An important aspect of this type of analysis of large data sets is how the results are visualized. Friedman (2008) stated that the 'main goal of data visualization is to communicate information clearly and effectively through graphical means... To convey ideas effectively, both aesthetic form and functionality need to go hand in hand...' Accordingly, we used a variety of traditional and modern visualization techniques, including pie charts, word clouds and connected graphs, to give a range of perspectives on the implications of the analysis.

Our general strategy was to construct a comprehensive database of publications on biomimetic research in engineering and related sciences, using general web-based resources for journals and conferences, such as IEEE Xplore, Elsevier's Scopus and the Thomson Reuters Web of Knowledge. A range of synonyms for biomimetics were used as search terms, comprising: biomimetics, biomimetic, bionics, bionic, biomimicry, bioinspired and bioinspiration. The focus of the present study was specifically on

Abbreviation	Journal	Publisher	Impact (2011)	Papers (2011)
BIOMATERIALS	Biomaterials	Elsevier	7.4	55/1007
BIOINSPIR BIOMIM	Bioinspiration & Biomimetics	IOP	2.0	89/89
J BIOMED MATER RES A	Journal of Biomedical Materials Research A	Wiley	2.6	18/270
LANGMUIR	Langmuir	ACS	4.1	48/1936
ACTA BIOMATER	Acta Biomaterialia	Elsevier	4.9	27/454
J MATER SCI	Journal of Materials Science: Materials in Medicine	Elsevier	2.3	18/285
J BIONIC ENG	Journal of Bionic Engineering	Elsevier	1.0	25/52
ADVANCED MATERIALS	Advanced Materials	Wiley	13.9	27/789
NATURE	Nature	NPG	36.0	20/841
BIOPHYS J	Biophysical Journal	Cell	3.7	6/696
BIOMED MATER	Biomedical Materials	IOP	2.1	27/170
IEEE T SYST MAN CY	IEEE Transactions on Systems, Man & Cybernetics	IEEE	2.1	7/109

Table 1. Leading journals publishing research on biomimetics.
Journals are taken from the left-hand chart in Figure 2, and represent the leading journals ranked by total number of research papers on biomimetics. The journals listed in this table were selected by having greater than 100 publications in biomimetics. The abbreviations used in the key in Figure 2 are given along with the full journal name. The publisher, 2011 impact factor, number of papers in biomimetics in 2011 and total number for 2011 are also given.

biomimetics in engineering and related disciplines, and hence we narrowed the search to include only papers in engineering, physics, mathematics, robotics, computer science, and related disciplines. The resulting database was then analyzed to infer the general breakdown of the field, for example by year, journal or conference, and subject area judged by common words in the title.

The implementational details of this methodology are given in two appendices, on database construction (Appendix A) and database analysis (Appendix B). In particular, we describe how the information was extracted from the online databases in a form that could then be analyzed from a standard desktop personal computer. In total, we extracted approximately 18000 publications on biomimetic research covering the years 1995 to 2011. Our analyses consisted of a series of tests, including: analysis of year and journal or conference in which they were published; a survey of biomimetic publications by topic based on the most frequent terms in the titles of papers; and then an analysis of community structure within the connected network of papers linked by pairs of words in the titles that co-occur together.

We emphasize from the outset that there are two main limitations of this information analysis approach. First, papers not clearly labeled as biomimetic research, by their title or otherwise, were not included in our database, even though their content might be considered as clearly biomimetic. Second, papers may be incorrectly labeled as being biomimetic even though their subject matter is not. These are unavoidable limitations of the information analysis tools and database information that are presently available. As such, the approach adopted here identifies those papers that have been labeled as biomimetic by their authors, and we assume that the results obtained on this dataset are representative of biomimetics as a research field.

Abbreviation	Conference	Abstracts & papers (2011)
ROBIO	Robotics & Biomimetics	536/536
SPIE	International Society for Photonics and Optics	62/2800
ICAL	International Conference on Automation & Logistics	42/107
EMBC	Engineering in Medicine & Biology Conference	23/2100
ICRA	International Conference on Robotics & Automation	19/1032
IROS	Intelligent Robots & Systems	8/719

Table 2. Leading conferences publishing research on biomimetics.
Conferences are taken from the right-hand chart in Figure 2, and are ranked according to the total number of publications on biomimetics. The conferences listed in this table were selected by having greater than 100 publications in biomimetics. The abbreviations used in the key in Figure 2 are given along with the full conference name. The number of papers or abstracts in biomimetics published in 2011 are also given along with the total for the conference.

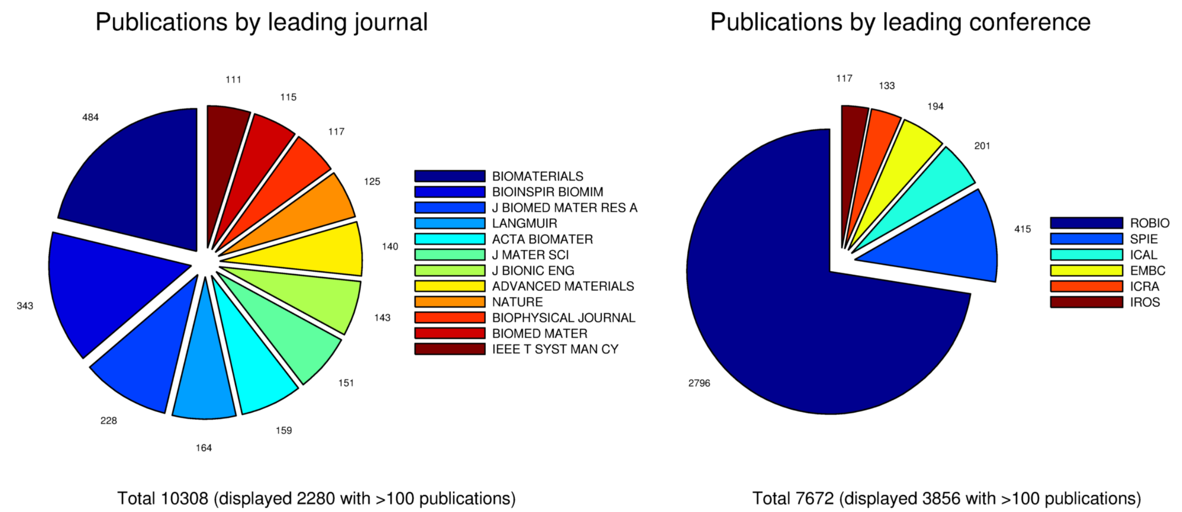

Figure 2. Journals and conferences publishing research on biomimetics.
The pie charts represent the proportion of papers on biomimetics published in the leading journals and conferences ranked by total number of publications. A total of nearly about 10300 biomimetic publications in journals and 7700 in conferences were considered. The legend gives abbreviations for these journals and conferences, with a key for the complete names given in Tables 1 and 2.

4. Where is biomimetic research published?

The first question was in which journals and conferences is biomimetic research published? We then considered secondary queries, such as the impact of the journals and the proportion that biomimetics comprises of the total published content.

From a total of about 18000 biomimetic publications in the database, close to 10300 (57%) were published in journals and 7700 (43%) in conference proceedings. Altogether, 1925 distinct journals and 1543 distinct conferences had at least one publication on biomimetics. The 57% to 43% overall split for journals to conferences compares with an approximate split of 11% to 89% for papers from just the IEEE Xplore database, 63% to 38% for papers from Scopus and 89% to 11% for papers from the Web of Knowledge. Based on these statistics, biomimetics overall has a higher proportion of research published in journals than conferences. However, there are considerable differences between databases due to differences in coverage. In particular, the IEEE database favors engineering and robotics and thus contains more biomimetics papers from conferences, consistent with a culture of dissemination through conferences publications in those subjects.

The twelve leading journals in biomimetics ordered by total number of publications are visually displayed with a Pie Chart (Figure 2A), with only journals having greater than one hundred publications in biomimetics shown in the figure. Further details of the leading journals are given in Table 1, including the journal abbreviation (to interpret the labeling in Figure 2), publisher, 2011 impact factor and biomimetic publication in 2011 compared to the total journal output. The top five journals in order of publication number are: Biomaterials (Elsevier) with a total of 484 papers, followed by Bioinspiration and Biomimetics (IOP) with 343 papers, the Journal of Biomedical Materials Research A (Wiley) with 228 papers, Langmuir (ACS) with 164 papers and Acta Biomateriala (Elsevier) with 159 papers. The content of these journals are split over general biomimetics and materials science in medicine. At present Bioinspiration and Biomimetics is publishing the most papers on biomimetics per year, followed by Biomaterials and then Langmuir.

The six leading conferences that cover biomimetics are displayed in a Pie Chart (Figure 2B), which were selected according to those with greater than one hundred publications in biomimetics. Further details given in Table 2, including the journal abbreviation and the number of biomimetic publications in 2011 compared with the total number of publications that year. The top three conferences in biomimetics are: Robotics and Biomimetics (ROBIO) with a total of 2796 papers, the International Society for Photonics and Optics (SPIE) with 415 papers and the International Conference on Automation and Logistics (ICAL) with 201 papers. Clearly, ROBIO dominates the research output on biomimetics published in conferences, giving around a third of all conference papers on the robotic aspects of biomimetics. In addition, ICRA and IROS also focus on robotics, particularly automation and intelligent systems, and are regarded as leading conferences on robotics with highly competitive publication requirements. Five of the six leading conference are sponsored by IEEE, which indicates the emphasis of these applications of biomimetics in relation to engineering and technology.

5. How rapidly is the subject of biomimetics expanding?

Our next question concerns how rapidly biomimetics is expanding as a subject area. From counting the number of publications each year in our database, we see that in the first decade of this century there has been an explosive growth in biomimetic research, with the number of published papers each annum doubling every two to three years (Figure 3). From a relatively small field in the mid-1990s of less than one hundred

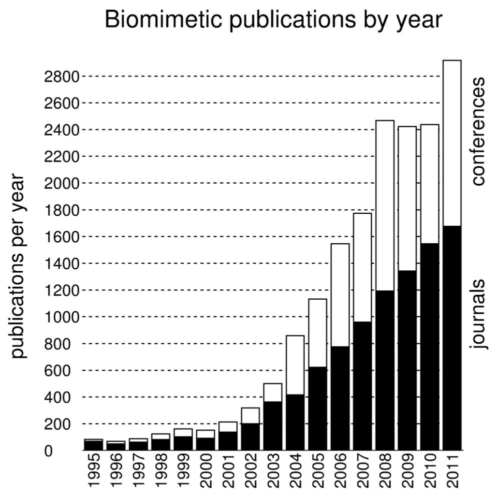

Figure 3. Growth of biomimetic research.
The bar chart plots the number of papers published each year in biomimetics starting from 1995. The blue bars indicate the proportion of journal papers and the red bars the proportion in books and conference.

papers per year, biomimetics has expanded exponentially thereafter to reach critical mass of several hundred papers per year by 2002, a mature field with greater than 1000 publications per year by 2005, and currently has close to 3000 publication per year. Over the last 15 years, this growth has far outpaced that across science in general, which averages close to 6% per year (doubling every 13 years) (Larsen and von Ins, 2010). Furthermore, the rapid growth in biomimetics has not yet saturated, so this expansion compared to science as a whole is expected to continue for the near future.

Based on this analysis, there is at a boom in bio-inspired research. Leading discoveries in biomimetics have laid the foundations for large areas of present and future research. This changing research landscape should lead to changes in the composition of academic departments. We expect that a greater number of researchers, research groups and departments in leading universities will be explicitly focussed around biomimetic research. This is consistent with the range of biomimetic research groups belonged to by the subscribers to the Convergent Science Network of biomimetics and biohybrid systems (http://csnetwork.eu/members_list).

This expansion in biomimetic research and technological development is also reflected in the increased numbers of publications within individual journals and conferences (Figure 4). In some cases, this has been from the creation of new journals and conferences in biomimetics that have since flourished, in particular the journal Biomimetics and Bioinspiration (2006-) and the conference proceedings for ROBIO (2004-). In other cases, this expansion has related to a change of focus of journals and conferences that have been established for many years, such as the journals Biomaterials (1980-), and the conferences ICRA (1984-) and IROS (1988-). The rapid expansion of ROBIO as a conference is clearly evident in Figure 4, compared with a more modest but still appreciable expansion of the other conferences.

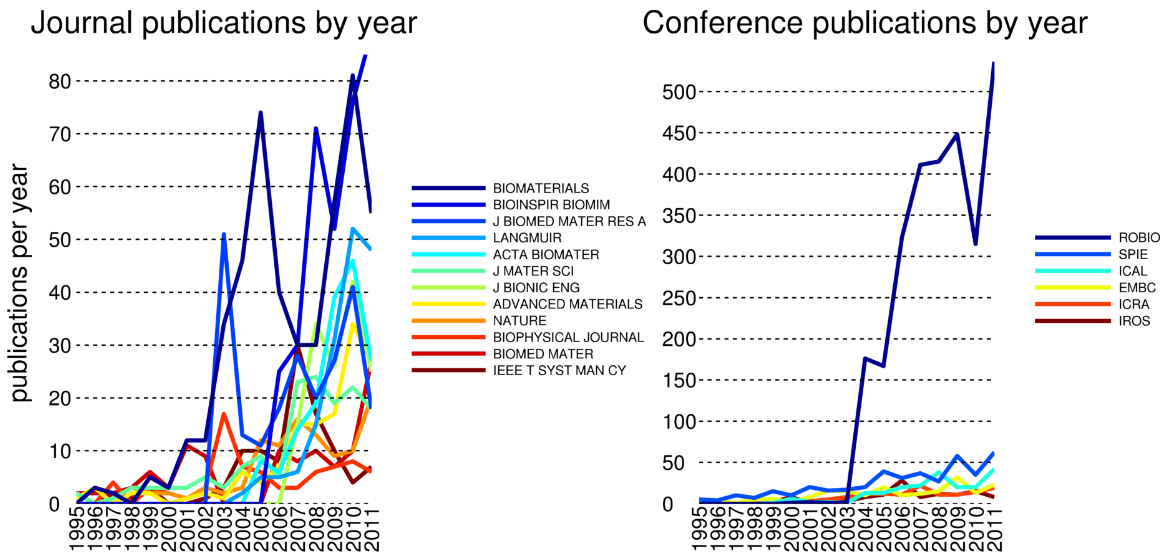

Figure 4. Growth of biomimetic journals and conferences.
The plots shows the number of papers published each year in biomimetics for the leading journals (left panel) and conferences (right panel) starting from 1995. The legend gives abbreviations for these journals and conferences, with a key for the complete names given in Tables 1 and 2.

As these developments in robotics and engineering are translated into technology, they have the potential for significant societal and economic impacts. The growth of technological transfer is seen from a corresponding rise in patents granted in biomimetics (Bonser, 2006; Bonser and Vincent, 2007). By a similar procedure to the present analysis of academic publications, Bonser searched the United States Patent and Trademark Office (USPTO) from 1985 to 2005 for the keywords 'biomimetic', 'bionic', or 'biologically inspired'. He then found that the cumulative number of patents approximated the leading half of a sigmoid distribution (Bonser, 2006, Fig. 1). That being said, we would comment that even though his data clearly shows a remarkable growth in patents on biomimetics (of about 100 per year in 2005) there does look to be little evidence for the claimed saturation from the presented data. Since patents secure the legal right to exploit an invention but are expensive to prepare, the very act of patenting an invention indicates that the inventor has some confidence that a product has fair chance to be brought to market. Hence, Bonser's patent study indicates that rapid development of new technologies derived from biological models is taking place.

6. What subjects does biomimetics encompass?

The next question for analysis is what are individual topics that make up biomimetic research, and how do they vary in popularity? To answer this questions, we gave a simple pictorial representation of these subject areas in a word cloud (Figure 5), accompanied by the statistics for the one hundred most common topics (summarized in Table 3).

Word clouds, and data clouds more generally, are a visual depiction of the frequency

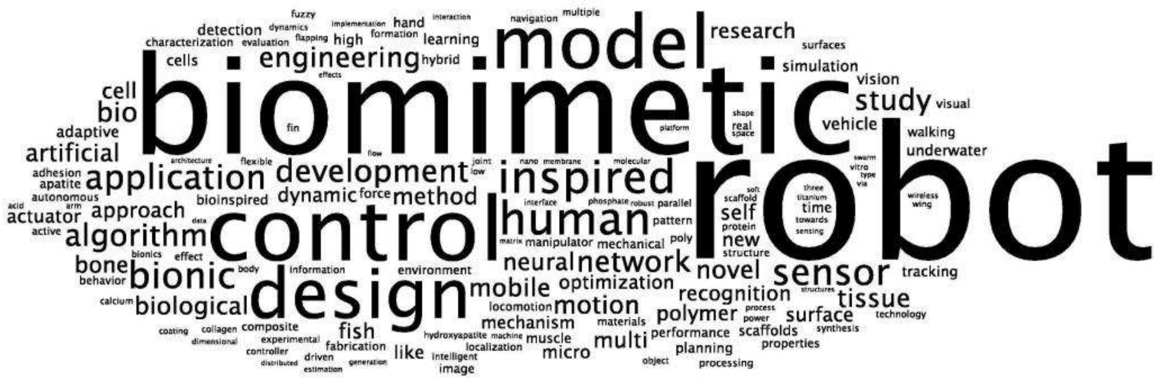

Figure 5. Popular topics in biomimetics.
The word cloud shows the popularity of terms occurring in the titles of papers on biomimetic research. Word size is proportional to the frequency of word occurrence.

Word	Frequency (%)	Word	Frequency (%)	Word	Frequency (%)	Word	Frequency (%)
biomimetic	17.5	composite	2.7	fish	1.7	active	1.2
robot	13.0	development	2.7	mobile	1.6	collagen	1.2
based	11.6	bone	2.6	optimization	1.6	assembly	1.2
model	7.5	novel	2.6	effect	1.6	vision	1.2
design	6.8	materials	2.4	simulation	1.6	underwater	1.2
control	6.7	new	2.3	learning	1.5	membranes	1.1
bionic	5.7	synthesis	2.2	high	1.5	acid	1.1
inspired	4.1	method	2.2	mechanical	1.5	behavior	1.1
application	3.9	approach	2.2	characterization	1.5	peptide	1.1
human	3.8	bioinspired	2.1	formation	1.5	nano	1.1
analysis	3.5	research	2.1	detection	1.5	vitro	1.1
study	3.4	properties	2.0	fabrication	1.4	force	1.1
engineering	3.3	neural	2.0	hydroxyapatite	1.4	scaffold	1.1
sensor	3.2	like	1.9	vehicle	1.4	technology	1.1
tissue	3.2	protein	1.9	calcium	1.4	planning	1.0
structure	3.1	motion	1.9	adhesion	1.3	experimental	1.0
polymer	3.0	recognition	1.9	hybrid	1.3	environment	1.0
artificial	3.0	actuator	1.8	molecular	1.3	pattern	1.0
surface	2.9	cells	1.8	performance	1.3	effects	1.0
self	2.8	mechanism	1.8	poly	1.3	phosphate	1.0
network	2.7	surfaces	1.8	muscle	1.3	processing	1.0
algorithm	2.7	multi	1.8	apatite	1.3	visual	1.0
bio	2.7	micro	1.7	membrane	1.2	3d	1.0
cell	2.7	dynamic	1.7	time	1.2	structural	1.0
biological	2.7	scaffolds	1.7	adaptive	1.2	information	1.0

Table 3. Top one hundred most common topics in biomimetics. Topics are taken from the titles in a database of around 18000 publications on biomimetics.

of words within a larger set obtained by scaling the font size of each word within the cloud by its frequency of occurrence. The clouds used in this report place the words randomly, with the overall layout determined mainly by aesthetics and readability. Technical details of how the word clouds were constructed are described Appendix B on database analysis, although we note here that common but uninformative terms such as parts of speech were excluded from this analysis. Note that since the area of word scales with the square of its font size, word clouds tend to emphasize the most common words while filtering out those words that are less frequent.

Given that the database was constructed from papers concerned with biomimetics, it is expected that many of the leading concepts in the word cloud (Figure 5) relate directly to the overall subject area of biomimetics and its synonyms such as bionic and bio-inspired. Furthermore, words indicating the biomimetic research process are also popular, such as ‘based’, ‘model’ and ‘design’. Overall, the second most popular concept for this database is ‘robot’. This indicates that much of contemporary biomimetic research published in the Engineering journals is focussed on applications in robotics, as reinforced by ‘control’ being another popular term. Our interpretation of this Robot-Control pairing of concepts is that the control of robots is as important a problem as designing and building the hardware itself. Indeed, in many ways there have been huge advances in building robots due to progress in microcomputer-based technology. However, the utilization of these sophisticated devices lags behind the effortlessly smooth control displayed by apparently primitive insects or infant animals. The fact that control is a key concept in biomimetics indicates that a main research topic is to take inspiration from how animals control their bodies and sensory systems.

Other, less common, topics from the word cloud indicate a wide variety of research taking place in biomimetics. A broad variety of research topics are directly inspired by nature, including polymers, composites, fish, muscle, collagen and vision. Some terms are taken directly from biomedical research, such as bone, tissue and cell, reflecting the large impact of biomimetics upon this research area. This emphasis on biomedical research is consistent with the journals Biomaterials and Biomedical Materials Research being leading publications for biomimetic research. In addition, concepts from control engineering and artificial intelligence are also represented, including model, network, algorithm, simulation, learning, adaptive and optimization. These subject areas are consistent with biomimetics being published in robotics and engineering journals and conferences, such as the IEEE journal Transactions on Systems, Man and Cybernetics and the conferences ROBIO, IROS and ICRA.

7. Are there research communities within biomimetics?

Our final questions are concerned with the topography and inter-connectedness of biomimetics as a research field. A specific point of interest is whether the field of biomimetics functions as a coherent whole or fractures into distinct fields with little connection between disparate areas. We comment that there have been several academic networks concerned with biomimetics, many of which have had a specific interest area. However, it is not clear that these endeavors have caused biomimetics to fracture into separate disciplines, in that they the individuals title their work based on a biomimetic sub-discipline to which they belong. To determine if there are sub-disciplines of biomimetics and what these are, we instead consider a network analysis of common nomenclature in the titles of papers.

To address these questions, we use techniques from network theory to analyze the connectedness of biomimetic research. We begin with the most frequent topics in biomimetics that were discussed in the previous section and displayed in Figure 5. We

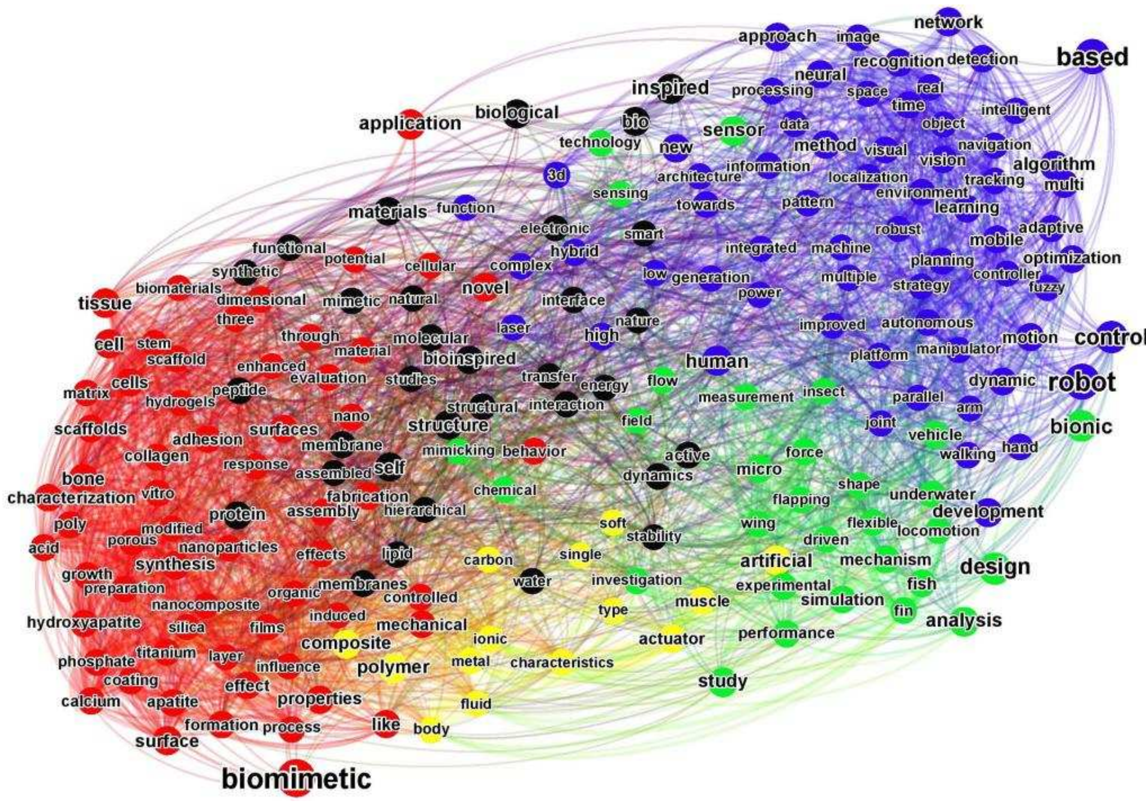

Figure 6. Connectedness of popular terms in biomimetics.
Two words in the word cloud Figure 5 are considered connected if they co-occur within the same titles, with the co-occurrence frequency giving the connection strength. A Force Atlas algorithm was applied to these node words and connections strengths, which pulls together connected terms. The graph is colored according to a modularity analysis, which finds communities within the connected network, where a community is defined to be a group of nodes that have denser intra-connections but sparser connections with other communities.

then quantify the connectedness between pairs of topics by their co-occurrence within publication titles, defined from a statistical measure of their tendency to pair together relative to their chance level of random co-occurrence (Appendix B). Interpreting the frequent biomimetic terms as nodes on a graph, this co-occurrence measure defines the strength of the connections between these nodes. The results of such an analysis are displayed in Figure 6, with the thickness of the connections proportional to the co-occurrence measure between topic pairs and the size of the topic words proportional to their frequency (as in Figure 5). The positioning and color of the connections and nodes relate to further analysis that we describe below.

For ease of interpretation, the top fifty word pairs are also shown in Table 4. Some of these word pairs are from phrases such as 'three dimensional', which are not informative about how research areas are related but do serve to bind such terms together for interconnection with other terms. Other word pairs are more informative about how areas of research are related. For example, 'flapping' with 'wing' indicates

Word A	Word B	Co-occurrence measure	Word A	Word B	Co-occurrence measure
three	dimensional	72	fin	fish	17
real	time	68	investigation	experimental	16
flapping	wing	64	insect	wing	16
phosphate	calcium	55	autonomous	underwater	16
fluid	body	36	assembly	self	16
stem	cells	33	muscle	artificial	16
assembled	self	32	mechanical	properties	16
underwater	vehicle	29	preparation	characterization	15
lipid	membranes	29	image	processing	15
acid	poly	29	bio	inspired	15
pattern	recognition	29	robust	controller	15
power	low	29	engineered	tissue	15
transfer	energy	26	between	interaction	15
insect	flapping	25	titanium	phosphate	15
coating	titanium	25	metal	polymer	15
controller	fuzzy	24	wing	vehicle	15
parallel	manipulator	23	machine	interface	15
neural	network	20	fin	underwater	14
flapping	vehicle	20	mimetic	bio	14
coatings	phosphate	19	navigation	mobile	14
flexible	fin	19	localization	mobile	14
tissue	engineering	19	porous	scaffolds	13
autonomous	vehicle	18	stem	cell	13
metal	composite	18	flapping	micro	13
information	processing	17	mimetic	peptide	13

Table 4. Top fifty most common word pairs in biomimetics. Words are taken from the titles in a database of around 18000 publications on biomimetics, and the pairings measured by the frequency of co-occurrence relative to chance.

that inspiration from biology is key theme for flying robots, while 'underwater' with 'vehicle' indicates an application of biomimetic robotics.

Related terms can then be positioned together by use of network analysis, for which we used the Gephi visualization software and toolkit (Bastian et al, 2009). First, we applied a Force Atlas algorithm, which pulls together strongly connected nodes while repelling all other nodes (further details in Appendix B). In consequence, terms that tend to occur together are positioned closely on the graph while words that infrequently co-occur are positioned further apart. This positioning is shown on Figure 6. The next stage of the investigation used a modularity analysis to looks for communities that tend to group together within the network. This modularity analysis results in a modularity score of 0.4, which is greater than the threshold of 0.3 usually taken to indicate community structure. This result implies that there are distinct communities, or groups of terms that are more densely connected together within their community than to the other communities.

Five communities are evident from the modularity analysis, which are denoted with the distinct colors in Figure 6. Our interpretation of these communities are that they relate to: (1) Robotics (blue) – covering traditional robotics with an emphasis on having control and intelligent, autonomous operation that is based on biology; applications include computer vision, walking robots and manipulators; methods include pattern recognition, neural networks, and other areas of machine learning. (2) Ethology-based robotics (green) – with the emphasis on constructing robot hardware based on animals; examples include flying robots based on insects and birds, and underwater robots based on fish. (3) Biomimetic actuators (yellow)– in particular, artificial muscle and its underlying technologies in material science. (4) Biomaterials science (red) – with an emphasis on biological materials such as bone, tissue and collagen, and their assembly and fabrication. (5) Structural bioengineering (black) – with the emphasis more concerned with the micro-structure of the biological materials.

Therefore, overall biomimetics as a subject areas is fairly well inter-connected, indicating that it may be considered a single discipline. Within this connectivity, the field does form distinct communities, as was confirmed by observing that each community has a recognizable theme.

8. Summary of main results

By applying an information analysis to a comprehensive database of publications on biomimetics over the last fifteen years, we could answer a set of strategic questions about the past, present and future of the research field.

First, where is biomimetic research is published? From a total of nearly 18000 biomimetic publications, about 57% were published in journals and 43% in conference proceedings (Figure 2). Across the databases there was a large variation in these proportions, with the IEEE database finding a much greater proportion of conference papers than the other databases, presumably related to different publishing strategies in engineering and computer science compared with other disciplines. Overall, the top five journals were (Table 1): Biomaterials (Elsevier), Bioinspiration and Biomimetics (IOP), Journal of Biomedical Materials Research A (Wiley), Langmuir (ACS), and Acta Biomateriala (Elsevier). The top six conferences were (Table 2): ROBIO, SPIE, ICAL, EMBC, ICRA and IROS. Of these, ROBIO (Robotics and Biomimetics) dominated the publication numbers, comprising more than a third of the conference output.

Second, how rapidly is the subject of biomimetics expanding? From a relatively small field of tens of papers in the mid-1990s, biomimetics has expanded exponentially thereafter to now reach nearly 3000 papers per year (Figure 3). The subject area has doubled in size every two to three years, far outstripping the modest expansion of about 6% per year for science in general (Larsen and von Ins, 2010). Based on this finding, there is a boom in bio-inspired research, with leading discoveries in biomimetics laying the foundations for large areas of present and future research. As these developments in robotics and engineering are translated into technology, they have the potential for significant societal and economic impacts. This growth of technological transfer is also seen in the rapid rise of patents granted in biomimetics (Bonser, 2006; Bonser and Vincent, 2007), indicating that a rapid development of new technologies derived from biological models is taking place

Third, what subjects does biomimetics encompass? The results of this analysis are displayed in a word cloud of frequent terms in biomimetic research (Figure 5). As expected, the word biomimetic is the most popular word. Then, perhaps more revealingly, other leading terms are 'robot' and 'control', which suggests that a main thrust of biomimetic research is to take inspiration from how animals control their bodies and sensory systems for application to robotics. Other concepts from the word cloud indicate a wide variety of research in biomimetics, including the taxonomy and abilities of biological organisms, terms from biomedical research and bioengineering, and concepts from computer science and artificial intelligence.

Finally, are there distinct research communities within biomimetics? This question was addressed with techniques from network theory applied to a graph of frequent biomimetic topics linked given by common pairings within the titles of papers. Terms that are strongly connected can then be pulled together on the graph while disparate topics are pushed apart (Figure 6). Applying a modularity analysis to this network showed that the field of biomimetics was well-connected and may thus be considered a single discipline. Underlying this inter-connectivity was a community structure into five identifiable research themes: robotics and control; ethology-based robotics; biomimetic actuators; biomaterials science and structural bioengineering.

9. Conclusions

Biomimetics is a research field that is achieving particular prominence through a wide variety of new discoveries in biology and engineering. By applying an information analysis to a comprehensive database of publications on biomimetics over the last fifteen years, we answered a set of strategic questions about the past, present and future of the research field. The most notable result was that there has been a rapid expansion of publications on biomimetics from the mid-1990s to present day, doubling every two to three years to now reach a mature field of nearly 3000 papers per year. Furthermore, the field is still expanding, and so more growth can be expected. The second main result was that there are a number of distinct themes that biomimetics can be partitioned into, which we identified as robotics and control; ethology-based robotics; biomimetic actuators; biomaterials science and structural bioengineering. Taken together, these findings indicate that biomimetics is becoming a dominant paradigm for robotics, materials science and other technological disciplines, with the potential for significant scientific, societal and economic impact over this decade and into the future.

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Appendix A. Database construction

The IEEE Xplore database (http://ieeexplore.ieee.org) was used as a source of papers on biomimetics published in IEEE journals and conferences. The Thomson Reuters Web of Knowledge database (http://apps.webofknowledge.com) and Elsevier's Scopus (http://scopus.com) were used for other journals and conferences. The search within the Web of knowledge was restricted to engineering, physics, biophysics, robotics, computer science, mathematics and mathematical computational biology, while the search within Scopus was restricted to engineering, physics, computer science, mathematics, neurosciences and the decision sciences. These terms restricted the type of biomimetics that we consider to that published in engineering and related sciences. We did consider use available searches within areas of biology, but our experience was that this resulted in many papers on just pure biology without any clear relation to engineering or technology. A range of synonyms for biomimetics were used as search terms, comprising: biomimetics, biomimetic, bionics, bionic, biomimicry, bioinspired and bioinspiration. The search engines in the two databases matched the terms with stored metadata for each document, including the title, publication title, abstract and author-defined keywords for each published paper.

Since the information analysis was carried out in MATLAB (Mathworks, MA), it was necessary to first convert the results of the search to a readable document in a non-propriety format. This was achieved in two steps. First, the search results were exported to Endnote referencing software (Thomson Reuters, NY). By default Endnote stores a bibliographic database in a propriety format. However, it does give an option to save this database in XML (Extensible Markup Language), a human readable text-based format that is closely related to HTML (Hypertext Markup Language) used for web-pages.

A separate XML database was saved for each of the biomimetic search terms given above. These were then accessible from MATLAB by loading the text file into a single alphanumeric string. Within XML, the content of the metadata pertaining to each publication is enclosed within standardized tabs. Hence, we could use standard text matching commands within MATLAB to extract the metadata of relevance to the information analysis. Finally, before applying the information analysis, this database of metadata was pre-processed to eliminate repeated entries from overlapping search terms

Appendix B. Database analysis

The metadata from the database of research articles in biomimetics (Appendix A) were then analyzed using a variety of methods.

An initial analysis considered the biomimetic publications by year and journal or conference in which they were published. The results were plotted in figures 2 to 4 and displayed in Tables 1,2, as described in the main text of this article.

The next analysis was to survey biomimetic publications by topic, which was estimated from counting the most frequent terms occurring in titles of papers. One complicating factor is that the most common terms are just words that occur generally in titles, such as parts of speech including 'of', 'for' and 'a'. After experimenting with various methods, we found the most reliable way to remove these was to construct a list of these non-informative terms, and then remove them from the database entries to leave concepts that are informative about the field of biomimetics. These were presented in a word cloud by exporting the list of words and their frequencies to an appropriate web-based tool (wordel; http://wordel.com), which was then manipulated into an appropriate graphical format.

Our final analysis was to break down these topics into overall themes, judged from research terms that occur commonly together. A suitable co-occurrence measure for a pair of words is the frequency that the words occur together in the title population (number of co-occurrences per number of titles) normalized by the product of the frequencies of the individual words in the pair,

$$c(\mathrm{word}_A, \mathrm{word}_B) = \frac{f(\mathrm{word}_A, \mathrm{word}_B)}{f(\mathrm{word}_A)\, f(\mathrm{word}_B)}. \tag{B.1}$$

If the words were independent and randomly distributed, then the co-occurrence measure should equal one; meanwhile, values of c less than or greater than one indicate words occurring together less than or greater than chance, respectively. This co-occurrence measure can then be used to find overall research themes by application of modularity analysis to determine community structure. Co-occurrences between pairs of words defines links between nodes (the words) on an undirected graph, with link strength given by the co-occurrence measure. The network-analysis software Gephi (http://gephi.org) was then used to display the links graphically with related words 'pulled' together by the Force Atlas algorithm (Figure 6). We used standard Modularity and Force Atlas tools within the Gephi software, which are described more fully in the software's documentation (Bastian et al, 2009).

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