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Methodical approach to implement biomimetic paradigms in the design of novel engineering and space systems

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ABSTRACT

The success of biological organisms in solving problems encountered in their environments is attributed to the process of natural selection, the rigors of this process ensuring the efficacy of the results. Biological systems represent the fruits of optimisation through trial-and-error that has been in progress over billions of years, and the 1.7 million species that have been catalogued so far can be seen as a vast resource for the inspiration of scientists and engineers. Biomimetics tries to extract concepts from biological systems that will allow the design of better, novel solutions, not merely imitating organisms' characteristics but distilling aspects that can be applied effectively from complex integrated systems. Problems that biological systems face are often similar to those faced by engineers. Given the effectiveness with which some of these have been overcome, biologically inspired concepts should be considered seriously when designing new solutions. Although humans have been being inspired by nature for a long time, this process has been on an ad hoc basis. With the continuing emergence of biomimetics as a distinct scientific discipline, the systematic search for biomimetic solutions to particular problems is an increasingly important focus. Adaptability, autonomy, miniaturisation, holistic design, reliability, robustness, self-repair, self-replication are the main traits that can be found in many biological organisms that are of particular interest in space systems design, with its particular requirements and constraints. This paper proposes the basis for a biomimetic design process that is generally applicable, comprehensive and systematic in the search for solutions. Potential routes for the development of this methodology are discussed, and the need for such work is reviewed and motivated with examples from previous and ongoing work.

1 Introduction

Biomimetics is a maturing engineering discipline concerned with extracting ideas from biology for the design of new, engineered systems. The objective of this process is not merely to copy a biological system, but to select and interpret principles used by the system and apply them in ways and combinations suitable for achieving the objectives of the engineering system, which may be very different from those of the original organism.

Objectives of organisms relate to survival, with the process of natural selection driving organisms to evolve to be able to thrive in their environment. It may be considered, therefore, that biological systems in general are satisfying solutions, optimised to be good enough to allow the genetic reproduction of the organism. We define a satisfying biomimetically engineered solution to be one for which quantitative analysis shows that it is both feasible and potentially a useful alternative to competing solutions.

While this overriding objective differs from those required of engineered products, biological systems often excel in areas where engineered systems have shortcomings. For instance, many biological systems, in comparison to engineered analogues, can be seen to have advantages in characteristics such as lightness, robustness, low volume, energy efficiency, autonomy and flexibility. Examples are given in this paper of developing research into designs based on biological systems, where some of these advantages are apparent.

In a review of biomimetics with relevance to space performed in collaboration between ESA's Advanced Concepts Team and a consortium led by the University of Essex, technology areas relating to ESA's technology tree [2] where biomimetics might have relevance were identified in the definition of an ESA biomimetic technology tree [1]. Particular technology domains where biomimetics might be applied were power, control, automation, telepresence and robotics, life and physical sciences instrumentation, mechanisms and tribology, structures and pyrotechnics, ECLS and ISRU, and materials and processes [1].

At this relatively early stage in the establishment of biomimetics as a distinct engineering field, no general methodology for its practice has yet been defined. Such a definition would benefit the field in several practical areas, as well as contributing to the maturing of this growing field. We present a basis for systematic biomimetics in this paper, having reviewed the subject, and possible future work in this area is discussed. For the purposes of this work, relevant terminology is described, to define a biomimetic methodology built by beginning with fundamental concepts in the design of a generalised and systematic approach.

2 Terminology

For the purposes of this attempt at defining a biomimetic method, we present several definitions.

Function - a task achieved by a system or subsystem

Characteristic – a distinctive quality of a system, such as lightness, robustness, autonomy, and efficiency.

Principle – the means by which a system is able to perform a function with a certain characteristic or characteristics

Level of abstraction - Qualitatively, the level of abstraction of a biomimetically engineered system is a measure of how similar it is to its biological analogue. A method of measurement of level of abstraction may be to compare the principles employed in each system, the manner in which these principles are applied, and the resultant characteristics of the system. We define that a high correlation from this comparison indicates a low level of abstraction and vice versa.

System Abstraction - we define this as the level of abstraction at system level. That is, as a whole, how does the engineered system compare with the biological system in terms of its characteristics, principles and methods?

Principle and Characteristic Abstraction – We define this as the level of abstraction of individual Principles and Characteristics. Are the same methods used in the implementation of the principle? Are the same principles used in the achievement of a characteristic?

3 Examples of Biomimetics for Space

To illustrate the potential of biomimetic designs in space engineering, brief introductions are given below to a selection of previous research carried out in collaboration between ESA's ACT and various industrial and academic partners. Further discussions on the relevance of biomimetics to space science may be found in literature [1,12,15,16].

Biological joints display attractive properties with regard to strength-to-weight and strength-to-encumbrance ratios, selective and controllable compliance, dynamic capabilities, inherent multifunctionality (providing capability in both constraint and sensing), and in inherent compliance that allows homeostasis under disturbance. In collaboration between the University of Bologna and the ACT, a novel joint was designed with these properties [17].

While it was found that joint models based on the human knee exist, design at a higher level of abstraction allowed the design of a novel joint. The principal functional parts of the knee that were considered were ligaments and sphere to sphere pairs, that in particular geometry give the knee its specific articulation properties, as well as some of the other benefits listed above.

By modeling this system as two bodies connected by stiff rods incorporating combinations of spherical and universal joints, subsequent mathematical analysis and optimisation produced a new joint mechanism, offering two degree of freedom movement in a limited range, with a number of potential advantages for various applications.

Mobility is an attractive area of biomimetic research in relation to the design of space systems, potentially exploiting new approaches to extraterrestrial exploration through inspiration by the many locomotion systems used in nature. One example of research in this area is the design of a passive locomotion system based on the mobility concept used by the Russian thistle [14].

In collaboration with the Helsinki University of Technology, this natural system that employs passive locomotion for seed dispersal over a wide area, through coupling of its structural design with ambient wind, was taken as a basis for the design of a Martian rover. Feasibility of systems based on both completely passive locomotion and hybrid systems that also include a ballast drive system, for overcoming obstacles, steering and active control, were considered.

Digging capabilities are also often required in surface probes. With mass and volume a driving factor in any space system, miniaturised systems would clearly be an advantage in some cases. Ready designed, miniaturised digging systems may be found in many insects, two of which were studied in detail in collaboration with D'Appolonia, the University of Bath, the University of Surrey and EADS Astrium in two separate studies [1,12,11].

Snodgrass presented his studies of the morphology of ovipositor valves of the female locust in 1935, in which a cyclical opening and closing of the valves enables digging. The geometry of this system means that this motion causes one valve to excavate soil, while the other pulls the system down the hole such that reaction force is not required from the rest of the animal. Conventional rotating drills require force to be applied from outside the drill bit. Preliminary analysis has shown that a miniaturised digging system based on this system may be suitable for use in space for digging or sampling in certain soil conditions.

Sirex Noctilio, a kind of woodwasp, was the second biological system studied. Its ovipositor employs a reciprocating longitudinal motion of two valves to cut through wood. In this case backwards-pointing teeth on the valves provide reaction force for digging. A conceptual design has been constructed to explore the feasibility of application of these principles in an extraterrestrial digging device, and potential applications have been identified. Assessment of relevant micro-manufacturing techniques has assessed current capabilities for producing microstructured components analogous to the biological valves, with similar dimensions.

Both of these systems have the potential to offer advantages over current solutions. However, much further work is required in assessment of their feasibility and potential capabilities.

Mitigation of the effects of long transfers on future long duration manned space flight, in terms of impact on both the life support system and the psychological well being of the crew. If humans could hibernate during such missions, as several mammalian orders do, requirements of the LSS might be reduced and the unconscious crew would not have to endure the psychological rigours of a long flight. In collaboration with the University of Helsinki, the technical feasibility of inducing such a hypometabolic state in humans was studied [10].

Torpor in animals can be seasonal or non-seasonal, and is generally characterised by a significant drop in body temperature to near ambient conditions, decrease in heart and respiratory rates, and a decrease in oxygen consumption. While the mechanisms to induce these changes are not well understood, such that human hibernation is still a long way off, available knowledge was used to explore ways in which these principles might be implemented in humans. Various chemicals were identified that may induce hibernation-like symptoms in the human body, and gene regulation was suggested as a possible option to enabling human hibernation in the future.

While the requirements on some elements of LSS could be relaxed with human hibernation, extra equipment would be required for support and monitoring hibernating astronauts. With this preliminary study in place, progress in this area may be monitored, in case this becomes a viable option in the future.

4 Towards a General Methodology

4.1 Defining the Problem

Many novel ideas for engineered systems may be extracted from nature, but up to now such extraction has been on an ad hoc basis, relying on expert knowledge from disparate fields. No general methodology has been defined that would define a systematic process, covering all areas of biomimetics from the beginning to the end of a design. As a maturing engineering discipline, biomimetics should benefit from such a definition. In the following sections, we take a bottom-up approach to the design of such a methodology, specifying what is desired, identifying the challenges inherent in such an undertaking, and reviewing the state of previous work in this area.

Ideas for biomimetic designs may come from biology, where study of organisms that display interesting properties may lead to some development in engineering. Expert knowledge provided from biological study is critical at this stage, in identifying the particular means by which organisms perform their functions.

On the other hand, some perceived deficiency or need in a man-made system might prompt an engineer to look to nature for inspiration. Many engineering fields have been identified that may benefit from biomimetic designs. For space systems in particular, previous work has identified several branches of ESA's technology tree [2] where biomimetics might be applied to provide useful alternatives to current solutions [1]. That the biomimetic process can start with input from such a wide range of fields is a first hurdle in the definition of a general process.

Translation of designs from a biological to an engineering context is perhaps the most critical, and most difficult part of the biomimetic process. As stated before, biomimetics does not seek to merely copy biological systems, but to apply aspects of their design to achieve functions in an engineered system with different objectives and constraints. Referring again to the various space technology areas that biomimetics may be applied to, the difficulty in generalising a design process may be understood, as even for non-biomimetic design processes design methods vary between disciplines. In addition, the principles and methods employed in various biological systems and subsystems are highly variable. Furthermore, it can be seen from examples in the previous section that new technologies are offering an increasing number of previously unavailable options in engineered analogues of biological systems. Clearly, when deciding how best to apply biological paradigms into an engineered design, numerous options are available.

An additional barrier to consensus throughout the biomimetic community is that not only are many different disciplines covered, but also most engineers practicing biomimetics are specialised in one area. Indeed, participants in biomimetic research are often not specialists in biomimetics specifically, but utilise aspects of biomimetics as a tool for their actual areas of concern.

4.2 Background of Systematic Biomimetics

A desire for a systematic biomimetic is felt for a number of reasons. As mentioned before, the transfer of ideas from biology to engineering has been on an ad hoc basis. Generally, this means that the opportunity for a biomimetic design only arises when the function, principles and characteristics of a particular biological system are discovered, only then can they be applied in a novel engineered system [3]. Furthermore, in translating a biological design to an engineering design, many solutions are possible, incorporating different combinations of the principles and characteristics of the original system, as well as different combinations of all the technologies and methods available to the engineer. Reduction of the element of chance in these design processes, while supporting the experience of experts should be a primary goal of such an undertaking.

Various efforts have been made towards systematic biomimetics. Most so far have been focused on the systematic transfer of ideas. For instance, databases have been developed for the matching of biological systems to potential engineering applications [4,5,6]. In bionics2space.org [5] and the University of Bath's biological effects database [6], through careful categorisation of the functions of biological systems, biological systems with attractive characteristics can be classified by function to allow a systematic search for potential solutions. While the utility of such strategies is highly dependent on the appropriate functional classification of systems, these represent a first step towards automated tools for biomimetics, in initial problem/solution matching, and a framework for closer collaboration between biologists and engineers.

Originating from Russia, and therefore not widely known in the west, the TRIZ methodology has been proposed as a framework for systematic biomimetics, where careful functional classification is a primary feature. In application to the generation of novel solutions from patents, it has been shown to provide not only reliable descriptions of problems, but can also be used to provide strong indications towards potential solutions. However, when implemented with high functionality, this particular option for biomimetic design requires expert interaction to find solutions, and is therefore observed to be unsuitable for automation [7].

That the focus of progress towards systematic biomimetics has thus far mainly concerned matching suitable solutions to particular applications is unsurprising when considering the wide ranges over which biomimetics may be practiced, as discussed in the previous section. Discussion of systematic engineering in general can be found in Pahl and Beitz [8]. The focus of our discussion will be on how such methodology relates to the peculiarities of biomimetics. Work concerning such systematic engineering methodology in conjunction with the TRIZ system in particular can be found in [9]. The additional complications particular to biomimetic engineering, in the interaction of various disciplines in biology and engineering, the extraction of relevant ideas from a biological design, and the translation of these ideas into workable solutions, the definition of a detailed general strategy is a challenging goal.

Further to the discussion above we define the following requirements for a potential biomimetic methodology

- generally applicable across all technical disciplines utilised in biomimetics
- generally applicable across all relevant biological disciplines
- does not, through its application, exclude any possible satisfying solutions
- describes the biomimetic process, from beginning to end
- is a useful tool for the biomimetic engineer

Beginning with only the most fundamental of biomimetic concepts, we wish to build a structure fulfilling these criteria from which the broadest possible range of further options for development may be derived. For example, it is hoped that by building from fundamental parts methodology may be kept general where appropriate to allow automation of parts of the process. For this reason, the definitions made in the terminology section are broad. With such a structure, and subsequent elaborations, the following benefits might potentially be provided: -

- a guide to Biomimetic engineering for those new to the field
- opportunity to perform a systematic search for biomimetic solutions, accounting for many possible matches, and levels of system abstraction
- a tool for the biomimetic engineer, facilitating the tasks required in the design process
- allow the biomimetic design process to be analysed and improved
- allow the definition of further tools, potentially for both the improvement and automation of parts of this process

Challenges in such a definition, summarised from above, include

- the range of engineering disciplines over which Biomimetics can be applied
- the range of levels of abstraction possible in translation of the design, where many options are often not obvious
- the ad hoc nature of much of the biomimetic design performed so far

4.3 Process Flow: Baseline Definition

With the previous discussion in mind, we attempt to construct a basic process flow as a basis for further development, which can be seen in Figure 1.

Contained in this process flow is the beginnings of the guide to biomimetic engineering that is desired. In addition, the progression of the main tasks may also enable a basis for defining the stage of development of a particular biomimetic design. The main stages of the design process have been split into parts that appear to be able to be sensibly decoupled, allowing decision functions to be implemented to define a basic systematic search structure.

The constituent parts of this basic flow are described below. A simple hypothetical example is presented to illustrate its implementation.

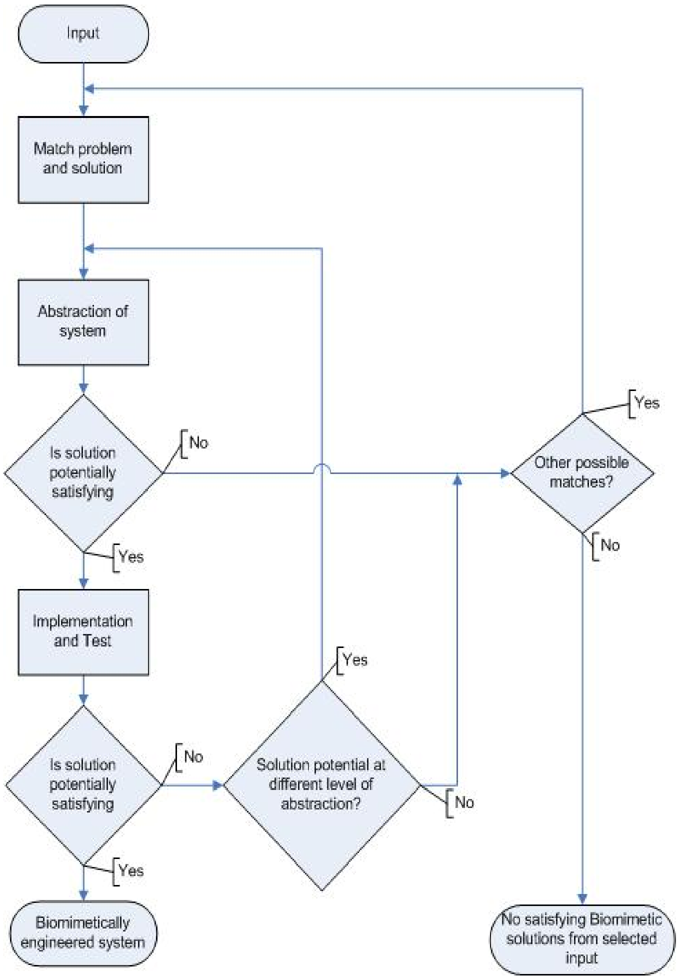

Figure 1: Basic generic flow for a general, systematic process for biomimetics

Input and Output

We define that the input to this structure to be an identified engineering problem for which a solution is sought, or an attractive biological system or subsystem, which uses principles that may be thought to be applicable in engineering systems. The final product should be a satisfying engineered solution, taking inspiration from some subset of the principles of a biological analogue.

We will take the example of the design of a flying device as our illustrative example. At this stage, it might be considered that the input would be the problem of taking inspiration from nature to design a flying device.

Matching Problem and Solution

In the case of a biological input, this process describes the search and identification of an engineering problem that may benefit from principles used in the biological system and vice versa. Numerous possible matches may be found from either input.

Referring to our example problem, the flight of many animals could be considered, such as any number of birds or insects, or perhaps the limited gliding capabilities of a mammal such as a flying squirrel. From these options, many different methodologies and capabilities for flight might be considered, such as gliding, hovering, flight at the small scales of insects etc.

We will consider a generic match of a bird that exhibits both flapping and gliding motion. The particular system dealing with flight is the wings in this case, which perform several distinguishable functions in providing propulsion, aerodynamic lift, and steering.

System Abstraction

This process describes the process of translating the biological design into engineering terms. The output of this individual box being a concept design, taking inspiration from a subset of the principles used in the biological system and accounting for engineering methods, enabling technologies and techniques that will allow the implementation of the concept. As discussed before, many different options are possible as output from this stage.

At a qualitative level, many different factors may be considered in the design of a system analogous to our generic bird, for which we will give a small selection of examples.

Having identified the functions related to flight in wing systems in the previous stage, the principles that enable these functions must be analysed. Broadly speaking, flapping motion provides propulsion, aerodynamic lift is enabled by the shape of the wings, and steering through both manipulation of the orientation of the wings as a whole and manipulation of the shapes of parts of the wings.

Characteristics of the flight systems of birds may now be considered, in relation to the principles identified. Among the advantages of these systems are that the functions identified are provided at relatively low weight, while keeping the structures involved strong enough to perform their function in a robust manner. These characteristics are provided using the principle of the use of structures and materials with high strength to weight ratio. Some additional identifiable principles are the use of flexible and self-healing structures that add to the characteristic of robustness.

In considering the options for implementation for these principles in a concept design, one might consider each individually, while bearing in mind the synergies between them, for instance considering the use of deformations of the wing for both flapping and steering. Through systematic variation, possible options may be generated, changing both the choice of principles to be implemented and the method of their implementation.

Examples of biomimetics applied in different disciplines where designs may be considered at various levels of abstraction include the following selected examples.

During study of the hibernation applied to humans as described in section 3, different approaches taken by animals to hibernation were reviewed. The known principles of each mechanism were studied in turn, and methods to simulate these biological processes in humans were suggested [10]. While mechanisms for hibernation are not well known, potential implementations at relatively high level of abstraction might be considered if, for example, a principle of hibernation such as resetting the body's temperature set point is induced through the introduction of drugs rather than the various natural mechanisms employed by animals.

Study of biomimetic drills involved the design of macro scale prototypes, in addition to concept design and simulation of micro scale analogues. Clearly, a higher level of abstraction is exhibited in the design of macro scale devices in this case, whereas micro scale versions may use more of the principles inherent to the original insect systems, such as the use of micro structured functional features and the digging principles relevant at smaller scales [1,11,12].

In the design of embedded strain sensors inspired the campaniform sensilla of insects, designs may be considered using strain measurements around small holes that locally amplify deformations in conventional materials. Implementation in fibre composites might allow for designs more similar to those exhibited in the insect, where structural fibres stretch around small holes, reducing the impact on structural strength [13].

Implementation and Test

Ending the previous process with the production of a concept design means that the peculiarities of biomimetics need not be considered during this stage. However, one should bear in mind that while implementation from a concept design might be a common process, biomimetics seeks to find novel solutions. Many emerging technologies are allowing previously unavailable options in mimicking biological systems, such that care should be taken to take developing technologies and techniques into account.

Decisions

Decision boxes have been implemented in this structure to indicate the criteria involved in a generic systematic method. The questions posed relate to three distinct issues – the range of problem/solution matches available to a given input, the range of options available when considering the level of abstraction of the biomimetic system, and whether or not a biomimetic solution is possible from a given input. Since numerous possible solutions are available from the outputs of the matching and system abstraction processes, the decision loops implemented indicate a general methodology for the systematic repetition of these stages where required, to explore as many options as necessary or desired.

At both points where decisions must be taken as to whether to proceed to the next design step, the questions relate to the perceived potential of the chosen design in leading to a satisfying final solution. The difference between the two lies in the degree to which quantitative criteria may be used in the assessment, with more quantitative work able to be taken into account as the design process progresses.

Returning to our simple example, and further specifying that we wish to design a mechanism to enable flight of a passenger aircraft, an illustrative example of the process flow might proceed as follows.

With the problem of designing a flying device one might try an initial biological analogue of a fly. As the principles underlying its motion are investigated and a concept design constructed, it may be qualitatively decided that the mechanics of insect flight are unfeasible at the scale of a passenger aircraft. The matching process has shown that there are other biological analogues and so the designer returns to try another.

Alternatively, some concept design may be thought to be attractive based on fly motion, such that the design is implement ed. Quantitative analysis may then show that this is still an unsuitable option. The designer must then decide whether this problem is due to the level of abstraction chosen, so that a different implementation of the principles of fly motion might lead to a viable design. If this is not the case and there are still other biological analogues to be tried the designer should again return to start the process with another match.

Let us now say that the generic bird is chosen as an analogue, and abstraction of the design leads to a flapping system to provide propulsion and initial lift, along with a wing shape that provides aerodynamic lift.

Suitable analysis will be required for assessment of potential concepts. In this case, consideration of the system level implications of the design will be important, as well as more specific analysis such as study of the relevant aerodynamic regimes involved.

During implementation, it is found that this system is not feasible. The designer may feel that while this implementation is not suitable, principles used by the bird may be successful in a different design,

Returning to find a different level of abstraction, flapping propulsion is dropped in favour of a gas turbine, while the principle of a structure that provides aerodynamic lift is retained. Subsequent implementation is successful and the biomimetic design process concludes with a satisfying solution.

4.4 Discussion and Elaboration

Following the structure from the previous section, assuming one random choice from the possible range of options as the output of the matching and system abstraction processes it can be seen that this will lead to a search that will consider only so many options as is necessary to produce a satisfying solution, unless no satisfying solution is available.

It is straightforward to imagine different scenarios for a systematic search. For instance, assuming comprehensive methods of problem/solution matching and generating different options for abstraction of the concept design, systematic variation may be employed to explore all possible options. For example, the matching and system abstraction processes might be considered to be iterative loops, performing systematic search for the most qualitatively promising solutions for output.

Of course this is a simplified view, since the principles of systems can rarely be completely decoupled so that they may be considered independently of each other. Careful consideration of the interdependencies of system principles, characteristics and their methods of implementation are critical when considering system principles and combining them into feasible designs.

With regard to the input and matching stages, the major issue is how to address the systematic transfer of ideas from biology to engineering. Broadly speaking, four main options may be identified, essentially with variable interaction with biologists:

1) fostering interaction between biologists and engineers;
2) engineers directing the work of biologists towards areas of interest;
3) biologists directing the work of engineers towards possible systems that might provide attractive solutions;
4) simply the search of biological literature by engineers.

Options 1 and 3 are related to the biomimetic databases discussed previously. While advantages are available in utilising the expertise of biologists, reliance on this expertise may constrain the growth of biomimetic research. Indeed, iterative research by biologists and engineers is advantageous, in that if detail is missing in a system of interest to engineers, this may prompt further research into the relevant biological system. Going further, one might consider that some means for biomimetic engineers to direct biological research to points of interest might be an efficient manner in which to perform biomimetic research. Alternatively, some biomimetic engineers take the approach of simply searching biological literature for relevant information when considering a particular problem. While obviously inefficient in some ways, biomimetic design has been successfully carried out in this manner, with a limited reliance on active participation of biologists.

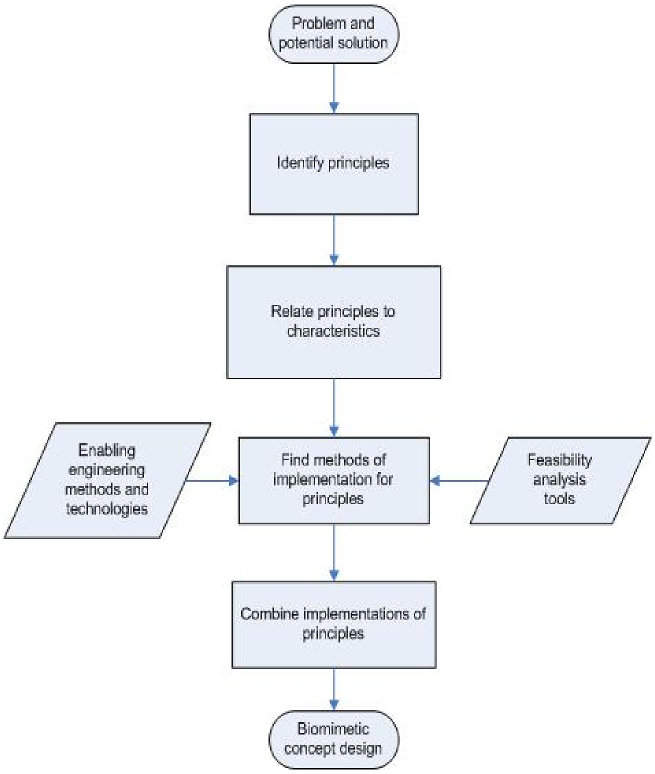

Figure 2: Basis generic flow for system abstraction process of biomimetics

In the case of system abstraction, Figure 2 shows a simple linear flow depicting a possible modularisation of required tasks in the production of the abstracted concept design. As mentioned before, a systematic search might be defined, further to this generic flow, with the principles required for each characteristic of a system considered in turn and employing systematic variation to consider and assess each possible combination.

Consideration of possible methods for implementation is critical in the generation of these possibilities. These may include enabling technologies, design methods and techniques, or software capabilities. This is a principal area in which biomimetics lacks an accepted methodology.

To give an example of possible progress in this area, one may consider again strategies devised for biomimetic matching databases, where through appropriate functional classification, an effective automated tool may be devised to give indications of possible solutions. An analogous need may be found in the process of abstracting the biological system where relevant enabling technologies and analytical engineering methods must be found and combined. Through appropriate classification of engineering methods, perhaps a tool might be designed to give initial indications as to the range of possibilities available in the abstraction of biological systems to engineering analogues. This approach may be particularly relevant in the case of biomimetics, since as has been shown in several examples given in this paper, emerging technologies are increasingly providing previously unachievable options in the mimicry of biological systems, for instance in being able to produce artificial muscles or micro-structured components.

5 Conclusions

Through a selection of research examples, the relevance of biomimetics to space engineering has been illustrated. Numerous other examples of biomimetic research are available in literature, in areas relating directly to space or those that may nonetheless find applications in future missions.

With respect to continuing process of establishing biomimetics as a distinct engineering discipline, the need for accepted biomimetic methodology has been discussed, and progress towards these goals has been reviewed. A basic, generalised, systematic approach has been presented, and possible elaborations have been suggested. Though this process has emphasised a methodical, comprehensive approach, further work must also consider the comparative efficiency of options for progress in this area. For example, while all feasible combinations for the translation of a system should be considered, robust methods to assess feasibility and efficiently discard unattractive options should be discussed.

Biomimetic research is likely to remain an expert driven pursuit for the near future, considering in particular the difficulties in implementing general guidelines across a community that not only covers many different disciplines, but where much work is concerned with only a small area of field. However, with the increasing use of systematic design practices and development and improvement of biomimetic design tools, biomimetics should continue in becoming recognised as a distinct engineering discipline.

While concepts that may have been biologically inspired, such as Velcro, have been found to be useful in the design of space systems, concrete examples of the deliberate practice of biomimetics leading to real systems are yet to develop. The authors are confident that such systems will emerge from the growing body of worldwide research in biomimetics, cementing the role of biomimetics as a tool for space systems design.

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