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ATTESTAZIONE

Io sottoscritto Carlo Santulli, professore associato nel settore scientifico disciplinare ING-IND/22 - Scienza e tecnologia dei materiali presso l'Università degli Studi di Camerino attesto che nella pubblicazione scientifica:

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il mio contributo specifico, sia nell'attività di ricerca e didattica pregressa alla pubblicazione che nella produzione della pubblicazione, ha riguardato gli aspetti della Scienza e tecnologia dei materiali come la biomeccanica, i materiali biomimetici, le prestazioni, il progetto dei materiali e le tecnologie di produzione.

mentre il contributo di Carla Langella, sia nell'attività di ricerca e didattica pregressa alla pubblicazione che nella produzione della pubblicazione, ha riguardato gli aspetti del disegno industriale come quelli relativi alla metodologia di progetto di prodotti industriali, alla metodologia di biomimetic e hybrid design, ai caratteri morfologici dei prodotti e alla loro relazione con i bisogni e con i comportamenti d'uso, ai caratteri produttivi e prestazionali.

Camerino 10 gennaio 2020

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Introducing students to bio-inspiration and biomimetic design: a workshop experience

Carlo Santulli · Carla Langella

Abstract In recent years, bio-inspired approach to design has gained considerable interest between designers, engineers and end-users. However, there are difficulties in introducing bio-inspiration concepts in the university curriculum in that they involve multi-disciplinary work, which can only possibly be successfully delivered by a team with integrated competencies. The aim of this work is summarising the results of the first workshop on bio-inspired design carried out at the Hybrid Design Lab of Seconda Università di Napoli, involving Year 2 students of the BSc in Industrial Design. The common theme proposed for their projects was "Bio-inspired design of sport". Ideally, a sport item would need to respond to a number of exigencies, including safety, comfort, zero-energy balance and/or use of renewable energy sources, multi-functionality. The common aim of the projects was investigating in which cases bio-inspiration can assist in the fulfilment of the above exigencies. The students were asked to present examples from nature and, via an abstraction process, to apply them to the design of sport items. Finally, they were required to clarify the nature and the extent of bio-inspiration in their projects. Some of the projects, which were considered more interesting and realisable, are reported and briefly commented, especially on the nature, extent and appropriateness of their bio-inspiration. A test for feedback has been given to the students, whose scope, structure and general outcome is also discussed.

Keywords Biomimetics · Design workshop · Bio-inspired design · Materials selection

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Introduction

The inspiration from a natural system, also referred to as *bio-inspiration*, is now becoming a widespread practice in design: in spite of the limited number of patented products which can be considered fully inspired to nature, the incorporation of biological concepts and functions in design objects is increasingly common (Vincent 2009). Bio-inspiration is not to be intended as a formal imitation of the natural geometry, aimed at mimicking functions and morphologies of natural structures, which has been more precisely termed as *bio-morphism* and has been a paradigm in modernist art (Mann 1990). In contrast, bio-inspiration would rather imply transferring to the culture of design new qualities and strategies inspired to nature, via an abstraction process.

This process requires establishing a correlation by analogy between the design issues to be addressed and the solutions offered by nature. The analogy between the problem to be solved and the natural solution may be conceived at different levels, as suggested by Langella (2007). These are described in Table 1, giving also some references, when the inspiration from nature may appear less straightforward.

In other words, hybrid design is inspired by the integrated processes on which the existence of biological systems and the equilibrium of their ecosystems is based. This does not mean, as pointed out by Ball (2001), having a too optimistic, or Panglossian, vision of nature, but rather translating the "code" offered by biology, and applying it to the culture of design. This would offer new strategies, qualities, expression and production tools capable of outlining evolutionary scenarios compatible with the exigencies of sustainability, flexibility and multidimensionality.

As suggested by Kuhn (1996), a paradigm in a project defines *what is to be observed*, *the kind of questions to be asked in relation to this subject*, *how the above questions need to be structured, and what is the interpretation to be given to the results obtained*. Translated in terms of hybrid design, this implies that the designer, as inspired by nature, states which are the *issues* to be resolved, which are the *obstacles* in addressing them, then defines a *concept*, and evaluates if this is *realisable*.

Table 1 Forms of bio-inspiration and related examples

Level of analogy	Meaning of the analogy	Typical biological contexts
Architectural	Mimicking the organisation of structures built by living creatures e.g., in buildings or in systems (Nakrani and Tovey 2007)	Termites nests, beehives
Morpho-structural	Mimicking biological microstructures to obtain specific properties	Cells, bones, shells
Biochemical	Observation of biochemical mechanisms (e.g., photosynthesis, bioluminescence)	Plants, fireflies, some fishes
Functional	Understanding and repeating the logic of *specific features* aimed at some function	Super-hydrophobic surfaces (e.g., shark skin, lotus) (Nosonovsky and Bhushan 2009)
Behavioural	Transfer of some behavioural modes e.g., protection, reaction to environment	Exoskeletons, armour-like skins
Organisational	Transfer of organisation strategies e.g., redundancy, self-adaptation, autonomy, self-organisation	Sensory and neural systems

Renovation of university curriculum and bio-inspiration

Using bio-inspiration for the development of new products and devices requires the students to acquire new educational tools, in principle based upon the appropriate selection of design and manufacturing technologies, but not limited to these. In addition, a renovated and more multidisciplinary curriculum would also be needed, including a wider knowledge of materials science, chemistry and biology (Vincent 2009). However, the most significant part of this renovation is likely to be centred on an increased interaction between the disciplines. This would enable the student not only to elicit some information from the relevant branch of science, but especially communicating with experts using appropriate technical definitions, so to apply the above knowledge to the specific design issue.

The importance of a more focused university curriculum to provide the students with the capability of using innovative design tools, such as inspiration from nature, has been recently recognised: this has been proposed mainly on the mechanical engineering curriculum, although the interest may be more general, leading to a systematic transfer of concepts from biology to engineering by trying to use in this field the contradiction matrix based on TRIZ (Bruck et al. 2007). TRIZ relies on the study of the patterns of problems and solutions: in this sense, it may assist designers in conceptualising i.e., bringing to the surface and expressing in measurable variables, all the consequences of a given design problem. An important assumption in TRIZ is that design problems are supposed to be generated by the presence of contradictions i.e., positive and negative effects, both embedded in the same principle or in the same structure. For example, adopting a high power engine in a car would lead to accelerate it, but also charge it with more weight, then, as a consequence, decelerating it. The contradiction matrix is aimed at clarifying which of the 40 principles, on which TRIZ is based, have been used most frequently to solve a problem involving a particular contradiction (Wen et al. 2008). For example, if in design the need arises of improving the weight of a moving object without reducing the intensity of force available, a solution may be increasing the frequency of the force applied. This approach may be perceived as quite simplistic when dealing with nature. As a matter of fact, to use bio-inspiration, the first step is understanding why a given solution has been adopted during natural evolution to solve some problem: only after this, the variables which are improved or reduced may be possibly defined.

In the specific case of mechanical engineering design, an approach in three phases towards teaching bio-inspired design has been proposed. This includes a database development and outsourcing, based on logical and functional characteristics, not dissimilarly from TRIZ, referred to as *functional description template*, a concurrent fabrication and assembly technique, and finally an innovative curriculum for bio-inspired product realization (Low et al. 2001). The position of curriculum innovation as the final stage of this process is quite debatable nevertheless. The principal reason for this is that the knowledge of some biological principles e.g., the hierarchical organisation of natural structures from the cell upwards and a few examples of evolutionary processes, would be needed to be able to make a fuller and sounder use of the database.

One of the main perspectives about the use of materials in bio-inspired design is trying to encompass the full picture of materials selection. This would involve physical (e.g., mechanical, thermal, electrical) properties or otherwise measurable parameters (e.g., cost, or environmental impact at end-of-life through LCA), as well as expressive and sensorial characteristics, such as e.g., texture. This implies that education about the use of materials in design is not based on rote learning basic “rules for use”, but rather on a “form follows function” philosophy, which can be referred to as a Bauhaus approach (Holm 2006). Two difficulties arise in this respect: the first is that expression through materials does involve intangible experiences as well, which are related to the use of materials, but do not involve comparing, let alone measuring variables or even different degrees of satisfaction (Rognoli and Levi 2004). The second issue, which is more specific of bio-inspired design, is that a clear understanding of the function (or functions) which the natural structure is designed to perform is required: in other words, the designer (or another professional teaming with him/her) would need acquiring and appropriately using multidisciplinary knowledge.

Biological qualities become, therefore, the new references for a culture of design oriented to sustainable development and at the same time innovative in terms of materials and technologies (Vincent et al. 2006). Biomimetics, defined as "the abstraction of good design from nature", would enter into design in one of the forms reported in Table 1 as suggested by Vincent and Mann (2002). This multi-disciplinary process requires a tailored methodology in order to try to integrate in design suggestions coming from the different disciplines involved. The present work is precisely aimed at reporting and commenting on one of the first attempts to introduce bio-inspired design in an Italian university curriculum.

Methodological approach

The approach followed in this work is founded on the consideration that design in nature is not focused to keep variables (be them physical or expressive) in a definite range of values. In other words, the lowest degree of refinement for measurements involves the selection between a "good" and a "bad" case for the specific design problem, therefore between two opposite characteristics or sensations. In nature, this is overcome through materials hierarchization: building the structure by self-assembly of a large number of hierarchy levels starting from dimensions of a few nanometres (and below) means that the macroscopic properties of the material cannot always be defined and measured microscopically. For example, in the case of geckoes' adhesive foot, the opposite concepts of "smooth" and "rough" cannot simply be separated, since these do not exist at the nanometric level. The spatulae terminations of the gecko foot are designed as "fitted for use", offering an induced dipole attraction suited to allow reversible adhesion to the surface (Rizzo 2006).

Also, the consideration of expressive variables e.g., linked to comfort or to ergonomy, is difficult to be integrated in a typical Ashby-diagrams based approach (Ashby 2005). Ashby diagrams are aimed at selecting materials according to the desired macroscopic properties (mechanical, thermal, electrical, etc.) and on the relative cost of the suitable candidate materials, proposing then hybrid materials if no materials offer an adapted range of values of that variable. This is also useful in industrial design: however, it needs to inserted in a more global vision. This means reflecting on the issue to be solved and possibly modifying the design by a trial-and-error iterative process, including also expressive variables, which means modifying, sometimes quite profoundly, the characteristics of the desired design object.

A methodology for design has therefore been proposed for research activities carried out in the Hybrid Design Lab. This includes a number of steps, namely:

1. Analysis of the design domain and setting the boundaries for the unresolved exigencies;
2. Individuation of design issues;
3. Analysis of present solutions available for the issue, analysing technological and design artefacts and their limits;

4. Individuation of the solutions to similar problems observable in nature, through the elaboration of a list of possible analogies and of biological systems capable of inspiring principles and strategies useful for an innovative project;
5. Concept definition, using an integrated process between traditional design tools and bio-inspiration;
6. Translation of references in design solutions (conceptual, material, structural or formal); taking into account opportunities offered by technology and materials science;
7. Elaboration of the final design solution and verification of feasibility;
8. Prototyping, engineering and patenting.

In this way, the three phases of production, service and reintegration in natural cycles become design references to propose manufacturing processes, products and strategies for resource-saving, which are both innovative and environmentally sustainable.

Workshop structure

Year 2 undergrad students, which take part in the workshop, have been received basic training in Year 1 on design and materials, focusing on materials physics and basic chemistry. During the course of Matter design (Design della materia) in the First Term of Year 2 they have been introduced to biomimetics and to some of the most successful and suggestive cases of bio-inspired design (such as Velcro, structural adhesives from geckos, development of biological sensors inspired to insects, and auto-cleaning surfaces inspired to lotus leaves) during the course. During the introduction to the workshop, they were asked to reflect to some of the possible approaches to hybrid design, which are summarised in Fig. 1.

Subsequently, some of the characteristics of hybrid design, as they are presented in biomimetics literature e.g., in Barthelat (2007 and Bonser and Vincent (2007), were described. In particular, a number of possibilities of interpreting evolutionary design have been offered to the students. The discussion concerned how evolutionary design resulted in survival of species which were able to defend themselves, possibly regenerate their

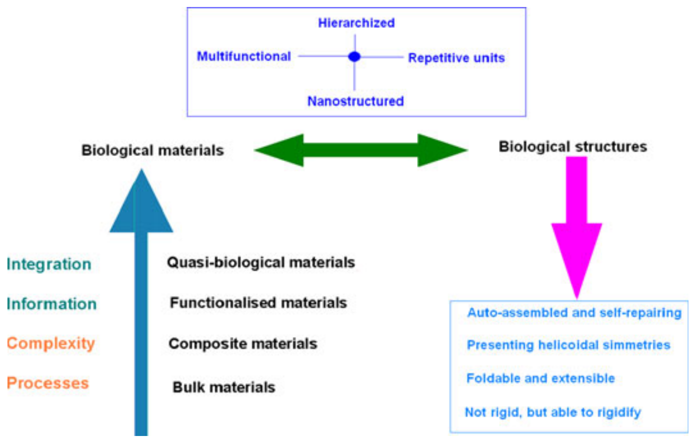


Fig. 1 Materials and structures “tree” for hybrid design [modified from (Langella 2003)]

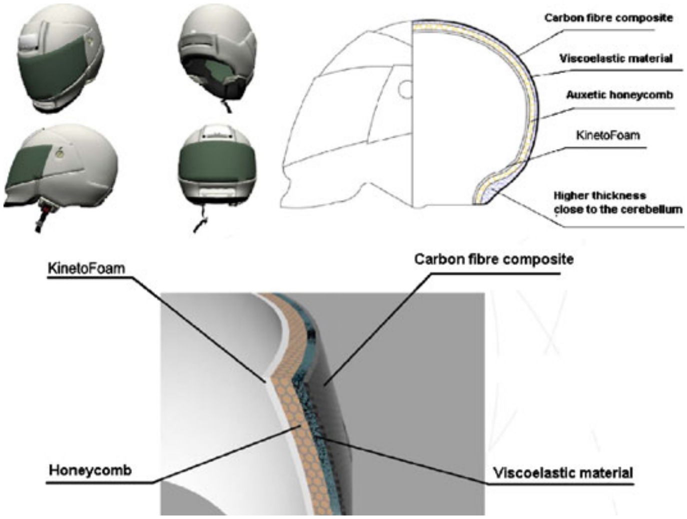


Fig. 2 Item for sport protection

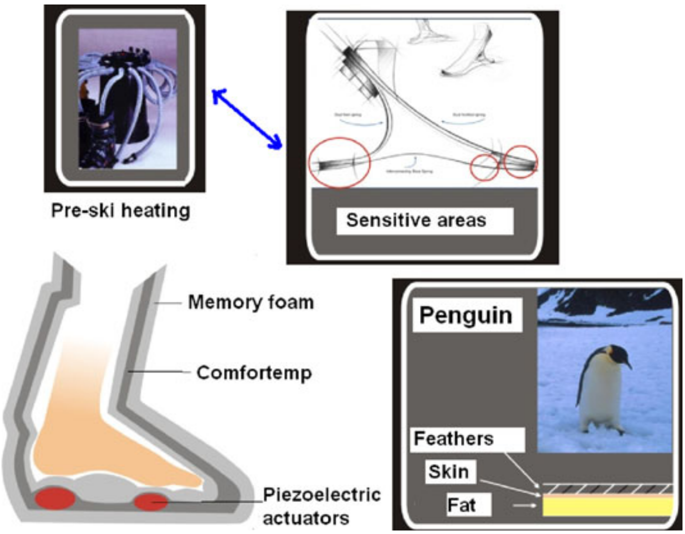


Fig. 3 Penguin feather inspired ski boots

abilities and respond to the environment. These qualities were developed e.g., in terms of sensing capacities, use of repetitive structures for self healing and reversibility of actions for fast escape (Karana et al. 2004). In practice, successful nature design adapts its structure to the function, uses multi-functionality, is not "obsessed" by rigidity, and compensates for the presence of defects (or even uses defects to modify the design according to varying mechanical loads, as in plant fibres; Jeronimidis 2004).

After this phase, the specific application object of the workshop was introduced. In particular, the students were asked to reflect on their (or their friends') sport experience, to find

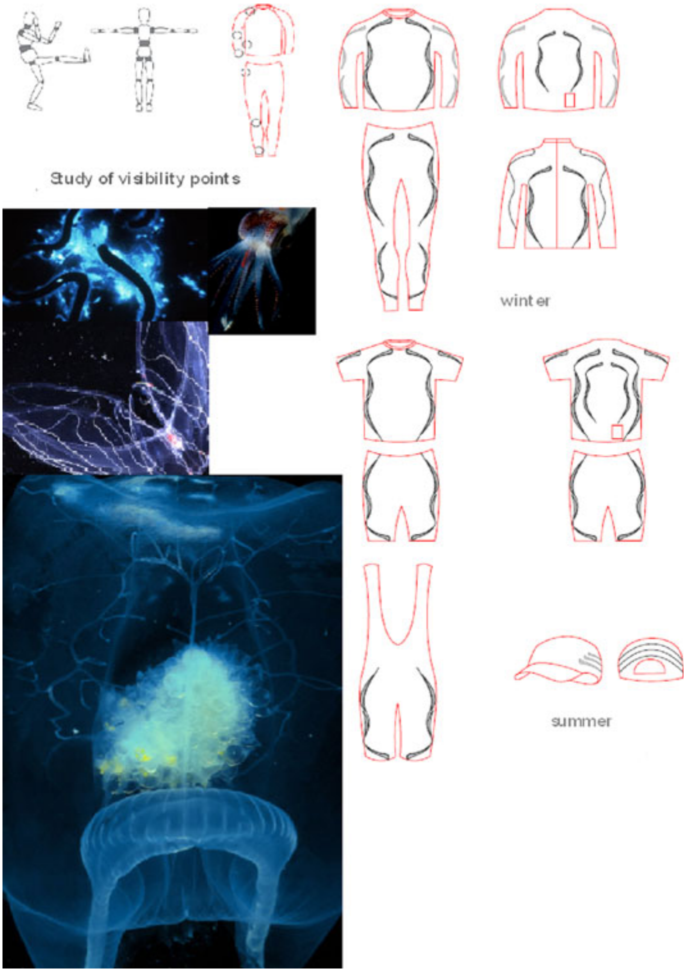


Fig. 4 Items for nightsport

out if they are aware of any unresolved issue. Once they have clarified what the issue is about and what is likely to cause it, they are asked to look if nature may have a solution for it.

The method suggested to realise these projects comprised the definition of a number of aspects:

- The *unresolved needs* that the project would aim to address and the solutions available so far;
- *Similar problems* observable in nature, through the elaboration of a list of possible analogies and biological systems, able to inspire principles or strategies useful for an innovative project;
- The *concept*, through a process of integration between the traditional design tools and the inspiration to the biological references.

Learning objectives that were envisaged for the workshop, in particular as regards bio-inspiration, were the following:

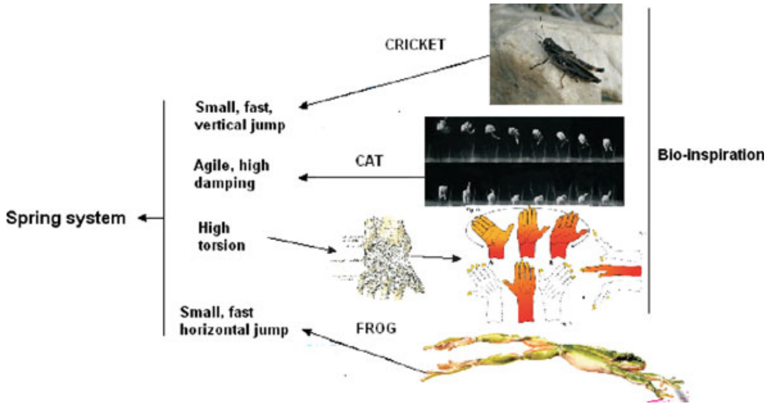


Fig. 5 Study of jumping for handball shoes

- Acquire an awareness of the needs arising in sport activities and define the specific physical (e.g., force, energy intensity of light), physiological (e.g., colour matching, visibility, sense of comfort) and technical (e.g., number of working cycles) variables that need to be measured and tailored to the requirements
- Investigate in what sense nature may have been more effective in resolving similar problems: in particular, try developing a suitable analogy between the problem in nature and the design issue, getting acquainted about the "biological rationale" of the solution adopted in nature, as from the relevant literature
- Consider the possible alternative design options, in terms of geometries, mass distribution and materials selection, which could be appropriate, and try to select one of them with full awareness of the trade-offs

As it is exposed in Fig. 1, the fact that biological structures are built by a number of hierarchical levels, starting from the single cell, allow them preferring helicoidal symmetries, disposing the cells at an angle with respect to the lower ones, as described in Fratzl and Weinkamer (2007). This principle enables on-going correction of defects during self-assembly and ensures that rigidity is only given to the structure when needed, reducing in general energy consumption by a system of reversible folding and extending, well diffused e.g., in flowers and leaves (Patil and Vaijapurkar 2007), but also in proteins (Roder et al. 2006).

The above biological possibilities would need to be transposed into project solutions, as for concept, materials, structure or shape, taking into account the opportunities offered by materials science and technology. The students were left the choice to concentrate on a single final product, or investigate a wider area of concern in sport. In either case, comments on feasibility were required, in the view of possible prototyping or patenting of the design product (or range of products). A biomimetics database, available in the Dept., was provided for initial investigation, but students were asked to carry on critically their research on all the possible information sources.

General outcome of the students' investigation

This offered indications on the students' perception of the main unresolved problems in nature, namely. Of course, it was obvious the local emphasis on some problems, since most of the students live in a heavily urbanised area, such as the outskirts of Naples. This needs not to be necessarily perceived as a limitation, because design can be viewed as a local process which becomes global after production.

The majority of projects were found to concentrate on one of the three aspects:

- Safety (especially road safety e.g., at night)
- Performance (esp. efficient and safe jumping and anti-slip)
- Comfort (adaptability to body structure, user exigencies and sport environment)

The following step was to look at nature for possible examples of bio-inspiration. A large number of examples from the students were taken out of a simple mental association (e.g., jumping with frog or grasshopper, or light with firefly), in which not necessarily a sound rationale is established for bio-inspiration, based on the function that these skills fulfil in the biological organism. In other cases, formal imitation of the structure was prevalent, such as for example in animals with armoured skin for impact protection, rather irrespective of whether the prevalent impact events from which the design aims protect are of similar nature to those the animal undergoes. It is also noteworthy that bio-inspiration from plants was quite limited (apart from considerations on leaves' folding): most projects concentrated on animals.

Discussion on the proposed projects

Some of the projects, which were considered more interesting and realisable, are reported and briefly commented upon, especially on the nature and extent of their bio-inspiration in Table 2.

Some considerations may be traced on bio-inspiration as it appears from the projects: one observation is that a sounder analysis on the design domain, including a thorough study of the available solution for the issue, did not always allow identifying a single possible source for bio-inspiration. Rather, as for example in the case of the project involving a study of jumping and hopping for handball shoes, inspiration from multiple biological features was attempted: this may result in an increased complexity, but also suggests to the students suitable ways for clarifying the concept.

On the other side, as in the remora-inspired project and in the camouflage project, the main interest, to avoid complications from knowledge of relevant biology, may be shifted to a formal imitation (patterns, texture) rather than an inspiration from the functions the nature performs.

In general, from an engineering and sustainability point of view, one of the most crucial points was that the large majority of students used in their projects shape memory polymers and alloys, innovative LEDs, auxetic honeycombs, piezoelectric, etc. In a sense, bio-inspiration was in some cases perceived as a way to bypass with some added design value the usual constraint on costs and weight. This is something we aim to correct in future workshops. It is worthy to note, however, that most materials used were provided with specifications by manufacturers: these were also discussed, at least qualitatively.

Another issue was that most projects led to quite complex multi-material structures, where the problem of junction was only conceptually resolved. Only in a few cases (e.g., the canvas/rucksack project) there was considerable reasoning to apply a multifunctional single material, a route which considerably simplified design.

Table 2 Summary of most interesting students projects

Project	Inspiration	Characteristic features	Comments on bio-inspiration
Items for sport protection	Armadillos	Inspiration from armadillo skin should provide helmets with more resistance to impacts with limited (if any) increase in weight (Fig. 2).	The complexity of nine-banded armadillos (*Dasypus novemcinctus*) skin at the level of surface patterning was not really exploited in design. That said, there are a number of other more appropriate references (e.g., turtles), which present a simpler structure, fully aimed at protection.
Ski boots	Penguin feathers	Sensitive areas are protected through a variable thickness multi-material (foam and smart non-woven mat) integrated with piezoelectric for thermo-regulation (Fig. 3)	The principle of variable thickness and variable surface exposition of penguin feathers has been correctly applied. Integration between materials and structural complexity represented an additional burden, not completely solved.
Canvas/rucksack	Beech and hornbeam leaves	A rucksack, based on folding structures, able to store for later use electrical energy during movement and standing, and integrating a "cocoon" tent for one person	Here, inspiration was limited to folding process: to improve the practical result, it was suggested to move from typical rucksack and tent tissue (e.g., polyester canvas) to more natural materials, to see whether it would be easy to retain multi-functionality or not.
Items for night-sport	Fireflies	Study of minimum number and location of points that need visibility at night in different seasonal situations. Extensive use of LEDs (Fig. 4)	More attention was dedicated to the number of illumination points than to the amount of light needed for each of them (which would possibly require studying bioluminescent organisms other than fireflies).
Antiperspirant clothes	Praying mantis and gaboon viper	Camouflage of the areas wetted by perspiration (mainly for fashion appearance of sport shirts)	Camouflage is a very complex area, which students mostly under-evaluated: a study of the most suitable colours and patterns should have been carried out, including possibly "tailored" colour matching (as reported in (Norman et al. 2001))
Handball shoes	Crickets, cats, frogs	High-jumping and safe landing, as required in the sport practice: jumping and hopping in animals has been thoroughly analysed (Fig. 5)	Trying to model the jumping was not easy, involving biomechanics concepts, which were beyond the students' knowledge. Thus, the comparison between species was mostly qualitative and did not include a "scaling effect" calculation to be applied to human jumping in the specific sport case.

Table 2 continued

Project	Inspiration	Characteristic features	Comments on bio-inspiration
Swimming/surf sock	Remora fishes	Patterning of the socks, aimed at providing a variable adhesion force, as the remora cartilage ventouse (Fig. 6)	Here, the bio-inspiration was quite formal: it was not completely clear to the students how really a variable adhesion force could be reached just by applying pressure. In principle, it was also suggested that reversibility of the adhesion process was not a problem, although this has to be verified for a realistic number of operation (stick-unstick) cycles.

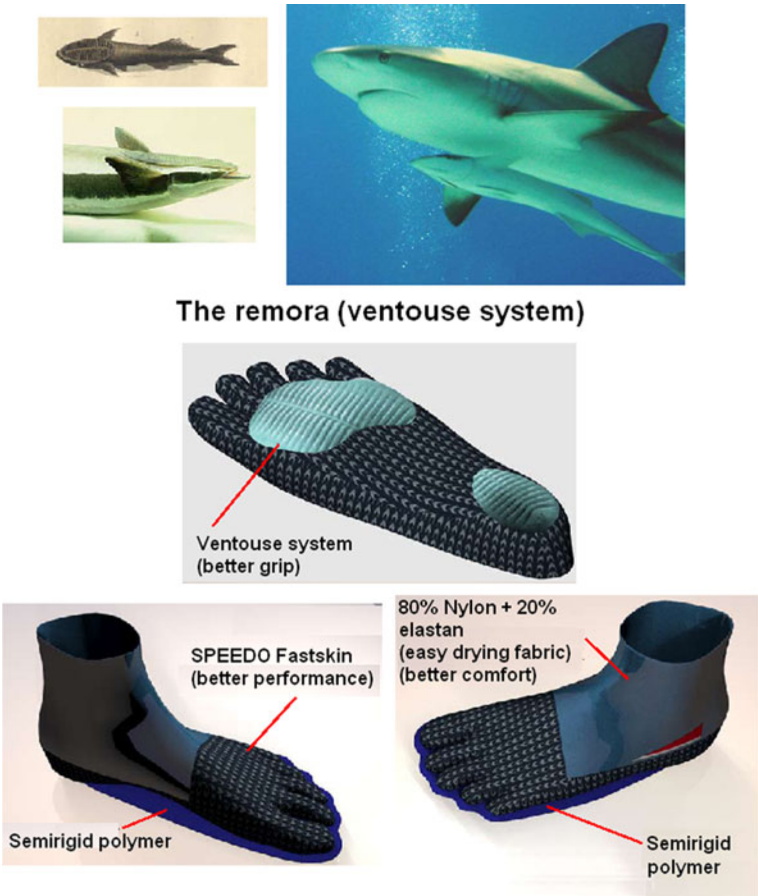


Fig. 6 Surf boots inspired to the remora ventouse system

Verification of results from the workshop

In addition to the above mentioned critical discussion on projects, a test was also disposed for measuring the feedback from students, especially as regards materials use and selection in bio-inspired design. This test was structured in three parts, as reported in Fig. 7a. In particular, the three parts in which it is divided would be aimed to solve a number of difficulties which have been observed in applying bio-inspiration to the development of the concept.

More specifically, the three parts concentrate on different themes, the first one being centred on a "rational" selection of materials, aimed particularly at understanding the engineering and structural features present in the design, the second one focuses on costs and feasibility, both at the local/global level, whilst the third one aims at asking for a believable end-of-life scenario, which would be ideally "embedded" in design already.

In practice, the test assignment included three open questions (a test sample, translated in English, is presented in Fig. 7b). Initial results, acquired during evaluation, suggest that the principal difficulties were in clarifying the main points of interest of the design concept, which would allow it being developed. More specifically, a realistic idea of the costs involved has almost always been reached. Also, a thorough attention has been given by most students to the disassembly procedure: however, sometimes an over-simplification of the related issues has been encountered. The number of parts forming the single design item and their relative geometry has in most cases been clearly defined. However, the complexity of fabrication technology has in some cases been underestimated (this has been typically true, when dealing with layered structures, such as the one considered in Fig. 2). A number of projects gave preference to the application of "bio-inspired" materials in the design concept, such as Velcro and lotus effect-based films. However, these have not always been integrated in a suitable way in the design item, possibly underestimating the difficulties in using them on surfaces with geometries different from the fully planar one.

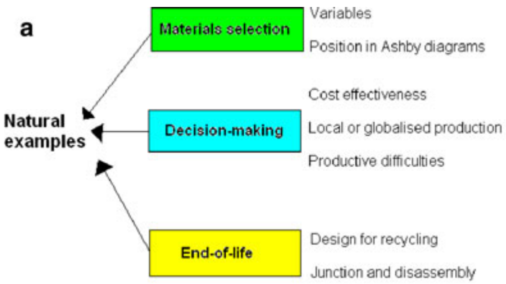
This indicates that the link between bio-inspiration and translation into the project requires some improvement still. This was also indicated in the "Discussion" section, dealing with complexity in materials selection.

The "designed" end-of-life and disassembly and the evaluation of possible life duration for the objects have been found to be difficult points to manage from the students. It is suggested that future workshops will be more focused on these aspects.

Conclusions

This exercise was useful to introduce design students to the significance and possibilities of bio-inspiration: in principle, it was not aimed at producing totally original and patentable products, but rather at supplying the students (Year 2 undergrads) with useful tools for clarifying the conceptual process leading to bio-inspired design. Some different approaches to an effective use of bio-inspiration e.g., materials selection, as from Ashby diagrams, contradiction theory, as from TRIZ, and "form follows function" philosophy can all be integrated in a successful bio-inspired design. However, this requires multidisciplinary (especially biological) knowledge: that should be provided by the University curriculum, which is not the case so far in Italy. The students encountered some difficulties in treating the relevant biological knowledge, especially tending either to not fully appropriate analogies or sometimes "forcing" the bio-inspiration from nature into quite complex (e.g., involving multi-layered materials and difficult junctions) design structures.

a



b

Referring to the design issue which your group project aims solving, discuss:

1. Which variables (mechanical, thermal, etc.) needs to be analysed to perform an accurate materials selection in the project? Sort out at least three variables, suggesting an Ashby diagram that could be particularly useful, even if is not included among those which were supplied and explained during the lectures. Clarify in which position in the diagram would the ideal material to be used in the project be.

2. Knowing which design object (or class of design objects) will be produced to address the selected issue:

   a. Suggest which will be the price range for the object, with 50% approximation (e.g., 200-300 euros, 500-1000 euros, etc.). In the case that the hypothetical price would appear exaggerated for the category or the type of product, clarify which are the concept characteristics that could offer a justified "added value"
   b. Taking into account the considerations in 2a., develop some reasoning on the material to be used and the manufacturing process to be used for production. Reflect, building upon personal knowledge on materials and processes, on the possible difficulties encountered in manufacture.
   c. With reference to your knowledge of local production system of the Campania region, discuss on the possible selection, in terms both of materials and processes, which can facilitate passing to engineering the developed concept. Clarify which production sector you will refer to to start a possible production. Also, state which are the innovative aspects or the special interest of your product, particularly as regards materials use, which you would present to the perspective producer to demonstrate the possible success of your concept, once engineered. In the case local production is deemed not practicable, explain which are the advantages and the drawbacks of a globalised production.

3. The design object can be produced in an only piece, by using an only material, or else in different pieces, which need to form a mechanical continuum through junctions.

   a. Discuss which is the option which has most possibilities to be adopted during operational design, giving sound reasons for that. In particular, in the case junctions are needed, clarify also where they will be placed, quickly drawing them, and which method will be used for them (adhesive bonding, welding, etc.)
   b. Present an end-of-life scenario, giving a reasonable life duration for the design product, suggesting whether there will be non-biodegradable parts and which will be the possible disposal options (e.g., recycling, combustion, landfilling, etc.) and clarifying how the disassembly process could be eased.
   c. Show possible points of structural weakness for the product, in which failure or malfunctions are more likely to occur, and clarify the measures to be taken to reduce the number of failures, or ease the substitution of parts during service.

Fig. 7 **a** Test structure, **b** final assessment sample

In this frame, it can be considered successful, although it needs to be pointed out that the link and integration between the biological and conventional design approach has not always been completely developed, due also to time constraints. Future workshops would also need to reflect on the aspect of materials to be used to mimic the biological ones, and on the requirement of design simplification to facilitate end-of-life scenarios for the design objects.

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