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REVIEW

Biomimetics and the case of the remarkable ragworms

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Abstract Biomimetics is a rapidly growing field both as an academic and as an applied discipline. This paper gives a short introduction to the current status of the discipline before it describes three approaches to biomimetics: the mechanism-driven, which is based on the study of a specific mechanism; the focused organism-driven, which is based on the study of one function in a model organism; and the integrative organism-driven approach, where multiple functions of a model organism provide inspiration. The first two are established approaches and include many modern studies and the famous biomimetic discoveries of Velcro and the Lotus-Effect, whereas the last approach is not yet well recognized. The advantages of the integrative organism-driven approach are discussed using the ragworms as a case study. A morphological and locomotory study of these marine polychaetes reveals their biomimetic potential, which includes using their ability to move in slippery substrates as inspiration for novel endoscopes, using their compound setae as models for passive friction structures and using their three gaits, slow crawling, fast crawling, and swimming as well as their rapid burrowing technique to provide inspiration for the design of displacement pumps and multifunctional robots.

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Introduction

The field of biomimetics (or bionics) is growing rapidly both as an academic discipline, as is evident from the number of new dedicated journals and the almost exponential growth in research papers (Fig. 1), and as way of providing innovative technology as can be seen in the growth of biomimetic-related patents (Bonser 2006). However, the field is still lacking an analytical framework, although recent studies have started to rectify this by developing a standardized method to transfer ideas from nature to technology (Vincent et al. 2005, 2006; Vincent and Mann 2002). In this paper, I attempt to add to the framework by discerning between three different approaches to biomimetics: mechanisms-driven biomimetics, which is based on the study of a specific mechanism; focused organism-driven biomimetics, which is based on a model organism from which one function is sought to be imitated; and integrative organism-driven biomimetics, where multiple functions of the model organism provide inspiration. The first two approaches are relatively well known and commonly applied, but in this paper I discuss the potential of the third approach by using the ragworms as an example. However, I first give a brief overview of the field of biomimetics. This is not meant as an exhaustive review of the field as this has already been dealt with adequately in recent papers (see Bar-Cohen 2006; Vincent 2006; Vincent et al. 2006; Vincent 2005a).

Since the earliest days of toolmaking, man has tried to imitate nature. In prehistoric times this included wearing fur

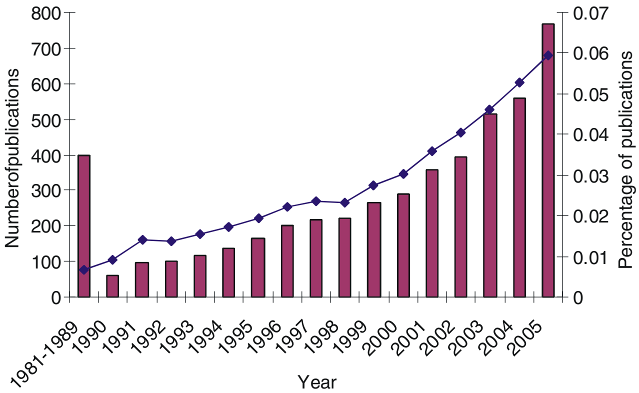

Fig. 1 Publications containing words with the root biomimetic in the title, abstract, or keywords. The data is obtained from searching the ISI Web of Science database (SCI-EXPANDED, The Thompson Corporation, 2006) using the term biomimetic (*asterisk*) in the topic field. The *bars* show the number of publications found in the database for each year and the *line* represents the percentage of publications out of the total number of publications in the database for each year

to keep warm and the development of bone and stone tools to emulate the teeth and claws of animals (Vincent 2005b). However, the ingenuity of man was not limited to blindly copying nature and soon human technology started to diverge from it. The most conspicuous example of this is, of course, the invention of the wheel. However, contrary to popular belief, a few animals actually use wheel-like locomotion in the form of rolling. The most common form is to roll down a slope to escape from predators. This can be seen in the desert spider *Carparachne aureoflava*, which positions its legs around its body to make it round and thus roll down sand dunes to escape predatory wasps, (Henschel 1990) and in the salamander *Hydromantes platycephalus*, which curls up into a ball and rolls down the volcanic slopes, on which it lives, when disturbed (Garcia-Paris and Deban 1995). Another example comes from the plant world. The Russian thistle (*Solsala tragus*) or tumbleweed is an annual flowering plant inhabiting dry environments. It starts out as a normal bush but as it matures it grows more spherical and when it dies it breaks free of its root. The bush can then spread its seed over a large area thanks to wind-powered rolling (Carnes et al. 2003). Active rolling in nature is rare, but the stomatopod *Nannosquilla decemspinosa* uses backward summersaults, where they roll as a true wheel for 40% of the time, to return to the water if they are cast ashore on sandy beaches (Full et al. 1993). However, despite the above-mentioned examples, except for the bacterial flagellar motor, no true axles and wheels are found in nature. Nature has, however, continued to inspire either by supplying concepts or in some cases even providing a full design. A case of the latter is the early unsuccessful attempts at building flying machines. In as early as 1488 Leonardo da Vinci designed a flying machine based on bats and 400 years later Otto Lilienthal built gliders based on an avian design. Although the first successful aeroplane, built by the Wright brothers in 1903, involved a radical new design, it was based on the pioneering work done by Lilienthal. Furthermore, it is likely, as Vogel (1992) points out, that humans would never have had the determination and conviction of eventual success, had insects, bats, and birds not been around to show that flying is possible.

In the first half of the 20th century the idea that biological studies could provide inspiration for developing new technology was slowly spreading in the scientific community. In the late 1950s the word bionics was used for technological designs and ideas learned from nature; but this word is now more associated with the replacement of body parts with artificial electronic devices, although it retains its original meaning in German-speaking countries (Nachtigall 2001). The word “biomimetic” made its first appearance in the title of a paper by Otto Schmitt in 1969 (Vincent et al. 2006) and was included in Webster’s dictionary in 1974. Biomimetics (or biomimicry as it is also sometimes called) can be used in many contexts that involve the transfer of skills or information from biology to applied science. A more strict definition of the biomimetic approach is given by Franz and Mallot (2000). Their definition of the biomimetic approach is “...if the authors try to implement a mechanism described in the biological literature, and explicitly refer to the biological inspiration of their approach.” Although their paper deals with biomimetics in robot navigation, it is applicable also in a broader context. Since the early 1990s biomimetics has turned into a discipline of its own, with numerous groups and centers spread around the world dedicated to look at natural processes for invention and innovation in a wide range of applied fields. The multidisciplinary aspect of biomimetics is very strong, with many active groups including computer scientists, physicists, chemists, and philosophers working alongside biologists and engineers.

The most famous example of the biomimetic approach is the invention of Velcro. In the late 1940s, a Swiss engineer, George de Mestral, was taking his dog for a walk, when he noticed cockleburs sticking to both his clothes and the dog’s fur. Upon returning home he examined the burs under a microscope and discovered that the surface of the burs consists of hundreds of small hooks. These hooks allow the cockleburs to attach to the tangle of hairs in animal fur and thus they facilitate the spreading of the seeds. By trial and error experiments George de Mestral could, in 1955, patent Velcro, based on the cockleburs. Velcro is a unique two-side fastener; one side with stiff hooks like the burs and the other side with soft loops like the fabric of clothes or animal furs.

A recent and promising example showing the potential of the biomimetic approach is the Lotus-Effect. This effect was discovered by the botanist Wilhelm Barthlott during a systematic scanning electron microscopy study of the leaf surface of some 10,000 plant species (Barthlott and Neinhuis 1997). Barthlott and one of his students observed that species with smooth leaf surfaces always had to be cleaned before examination, while those with a rougher and more irregular surface were almost completely free of contamination. From further studies and experiments they discovered that epicuticular wax crystals cover the surface of rough leaves. Water droplets balance on the top of these crystals maintaining only limited surface contact to the leaf and can therefore roll off easily. The adhesion between dirt particles and crystals is similarly minimized, so the particle is attracted to the larger surface of the passing water droplet and with that removed from the leaf surface. They called this the Lotus-Effect, after the leaves of the sacred lotus or sacred water lily (*Nelumbo nucifera*), which give a particular impressive demonstration of this effect. The Lotus-Effect has significant potential for commercialization and currently a house paint is distributed under the name Lotusan. Further potentially lucrative applications include self-cleaning paint for cars, facades, and roofs (Barthlott and Neinhuis 1997).

Mechanism and organism-driven biomimetics

Biomimetics is a recent addition to the branches of science and, furthermore, being in its nature very orientated toward application, no unified analytical framework, which can connect the diverse biomimetic projects, has yet been identified (but see Vincent et al. 2006). However, two main approached to biomimetics can be recognized currently with a third showing potential (Fig. 2).

Mechanism-driven biomimetics starts with an engineering problem, where the biomimetic approach could be useful. The researchers then look to biology to identify potential solutions found in nature and finally use the best identified biological solution as inspiration to develop an engineering solution. This is the favored method of practicing biomimeticists and it is used widely in multidisciplinary research projects such as BIOmimetic structures for LOComotion in the Human body (BIOLOCH), where researchers turn to biology for inspiration to develop a self-moving endoscope (see "The case of the ragworm"). It is also common practice in biorobotics, where solutions to problems such as robot locomotion, orientation, and control are sought in biology (Delcomyn 2004; Yu et al. 2004; Safak and Adams 2002; Trullier et al. 1997). One disadvantage of the mechanism-driven approach is that in many cases it requires in depth knowledge of both general and specific biology as well as skills in many areas of engineering. A large multidisciplinary research group is therefore often necessary to get useful results. This may, however, change as attempts are made to create biological databases, where engineers facing problems can discover how nature has solved similar problems. One such database is based on including "biological patents" into the TRIZ (the Russian Theory of Inventive Problem Solving) framework (Vincent et al. 2005; Vincent and Mann 2002). If successful, this database should make it considerably easier for engineers to access biological solutions and, thus, perhaps reduce the necessity of large multidisciplinary research projects.

Organism-driven biomimetics can be subdivided into two approaches: focused and integrative (Fig. 2). The initial stage of the former approach starts with the study of a biological organism or system, which then accidentally or intentionally results in a discovery of an interesting biological solution that could provide inspiration for solving an engineering problem. This approach, which even predates the establishment of biomimetics as a specific field, was used for the most commercially successful biomimetic inventions so far, as mentioned earlier. Recently,

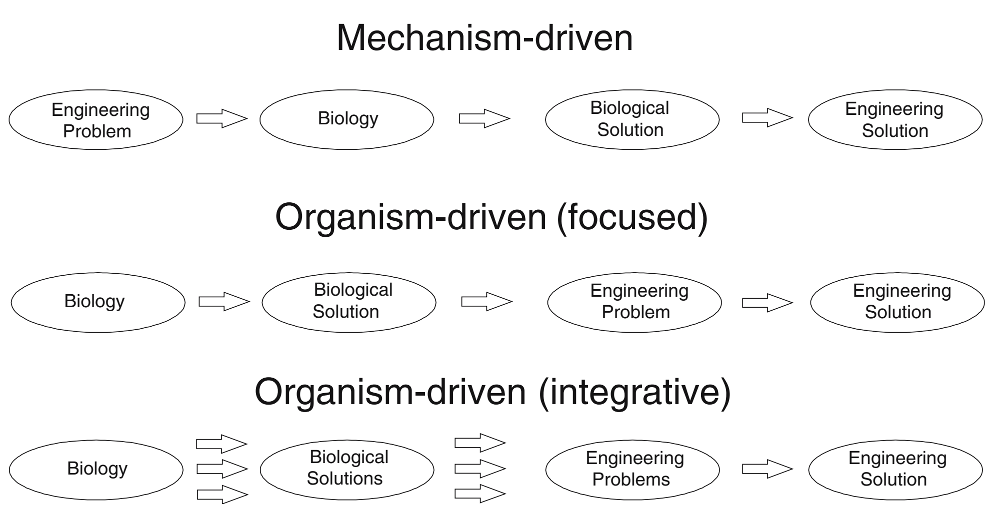

Fig. 2 A schematic diagram of the three different biomimetic approaches: the mechanism-driven and the two organism-driven approaches. See text for further explanation

focused organism-driven biomimetics has started to be used more intentionally. This includes the morphological and biomechanical studies of gecko feet (Autumn et al. 2000), which are undertaken partly for their biological interest, but also partly in the hope of providing inspiration for developing novel attachment mechanisms such as ultra-strong reattachable tape (Geim et al. 2003). In integrative organism-driven biomimetics the same chain of events occurs. An integrative study of several aspects of the morphology or behavior of an organism is undertaken, instead of only focusing on a single aspect. The integrative organism-driven approach has not previously been formalized and not many examples are found in the biomimetic literature. However, there are some that could be grouped under this heading. They include the study of both the sensory system, including locomotion control, and the kinematics of cockroaches to provide inspiration for the development of hexapod biorobots (Delcomyn and Nelson 2000; Delcomyn 1999; Quinn and Ritzmann 1998). Another example is the weakly electric fish, where both the use of an electrosensory system and the use of undulatory ribbon fins for propulsion are of potential biomimetic interest (Bleckmann et al. 2004; MacIver et al. 2004). A disadvantage with the integrative organism-driven approach is that considerable biological knowledge of the studied organism is needed to identify the important aspects of the processes with biomimetic potential and ignore the nonessential. Specific biological knowledge is even more important here than for the focused organism-driven approach and thus integrative organism-driven biomimetics need to be carried out as part of a larger multidisciplinary project. However, the potential rewards are considerable because even common and well-known organism can have significant biomimetic potential. A case study of integrative organism-driven biomimetics in a common group of marine polychaetes, the ragworms, is presented in “The case of the ragworm” section.

The case of the ragworm

The study of locomotion of ragworms formed a part of the biomimetic project BIOLOCH. BIOLOCH was funded under the fifth framework program of the European Commission and ran from May 2002 to October 2005. Its main objective was to use information on perception and locomotion in lower animal forms to inspire the development of mini- and micromachines able to navigate in tortuous and difficult to access cavities, in particular, in the human body. The inspiration for the BIOLOCH project originated from the medical need to develop more powerful and less discomforting devices for endoscopy. The project was carried out by a consortium of six European universities and included engineers, biologists, computer scientists, and surgeons. Although the BIOLOCH project as a whole made use of the mechanism-driven approach to biomimetics, its subobjective of gaining a larger understanding of perception and locomotion in invertebrates gave the freedom to study many aspects of locomotion in ragworms, thus resulting in integrative organism-driven biomimetics.

The ragworms are a group of common and widespread marine worms, although they are seldom seen as they spend the majority of their time in burrows or under stones. They are, however, well known among sport fishermen who use them as bait. The ragworms are errant polychaetes and belong to the family Nereididae. Together with Hirudinea (leeches) and oligochaetes (earthworms), the polychaetes (bristleworms) make up the phylum Annelida (segmented worms). Nereididae is one of the largest families with more than 540 species in 43 genera (Bakken and Wilson 2005). One of the most common species and, together with its larger cousin *Nereis virens*, traditionally the model organism of choice in ragworm studies is *Nereis diversicolor*. It should be noted here that controversy exists on all taxonomic levels in the Annelida, including the genus level (Westheide et al. 1999). Most taxonomists today place *N. diversicolor* in the genus *Hediste*, thus referring to it as *Hediste diversicolor* (Bakken and Wilson 2005).

Like all members of Annelida, the body of errant polychaetes is divided into identical segments, each bearing a pair of lateral appendages called parapodia (Fig. 3). The only exceptions are the two most anterior segments and the most posterior one. The anterior segment is called the prostomium and bears the main sensory structures (antennae, palps, and eyes). The peristomium lies just behind the prostomium and includes the mouth and four head cirri. The last segment is the pygidium, which carries the anus and two pygidial cirri. The jaws are attached to the pharynx and are usually found inside the peristomium; however, the anterior part of the pharynx is eversible (Fig. 3).

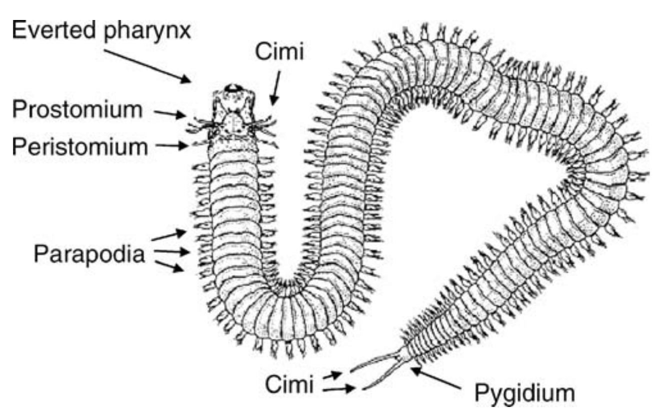

Fig. 3 Drawing of a typical ragworm with its pharynx everted. *Arrows* indicate morphological points of interest

The most common ragworms, such as *N. diversicolor* and *N. virens*, are found in shallow coastal waters inhabiting a range of substrates, including sand, mud, and clay in which they build Y- or U-shaped burrows (Scaps 2002). The main reason that the ragworms were chosen as model organism for the BIOLOCH project was because of their ability to move in these slippery substrates. The mucous layer lining the inside of the human intestine is similar in consistence to the mud in which *N. diversicolor* is most often found. Another reason is the interesting and diverse way in which the ragworms move. They employ three distinct gaits (Fig. 4). During slow crawling, no (or only very insignificant) lateral undulations of the body are observed and each parapodium functions similarly to a leg in terrestrial animals. It is lifted from the ground and drawn inward and forward in the recovery stroke where after the tip of the parapodium touches the ground and forms a fulcrum (although some slippage is normally observed), around which the parapodium turns during the power stroke and thus advances the segment (Mettam 1967; Gray 1939; Foxon 1936). During fast crawling, the above described parapodial movement is coupled with lateral undulations of the body travelling in a posteroanterior direction. The tip of the parapodium touches the ground as the segment on which it is attached approaches the crest of the body wave, so that the backward power stroke of the parapodium coincides with the crest of the body wave. This means that the force, generated during the power stroke, does not only stem from the parapodial muscles but is amplified by the longitudinal muscles and their resulting body movements (Mettam 1967; Gray 1939). During swimming, the body is no longer in contact with the substrate and the number of body waves along the body decreases and the waves have larger amplitudes (Clark and Tritton 1970). Similar to fast crawling, the body undulations and parapodial movements are coupled during swimming. The undulatory swimming

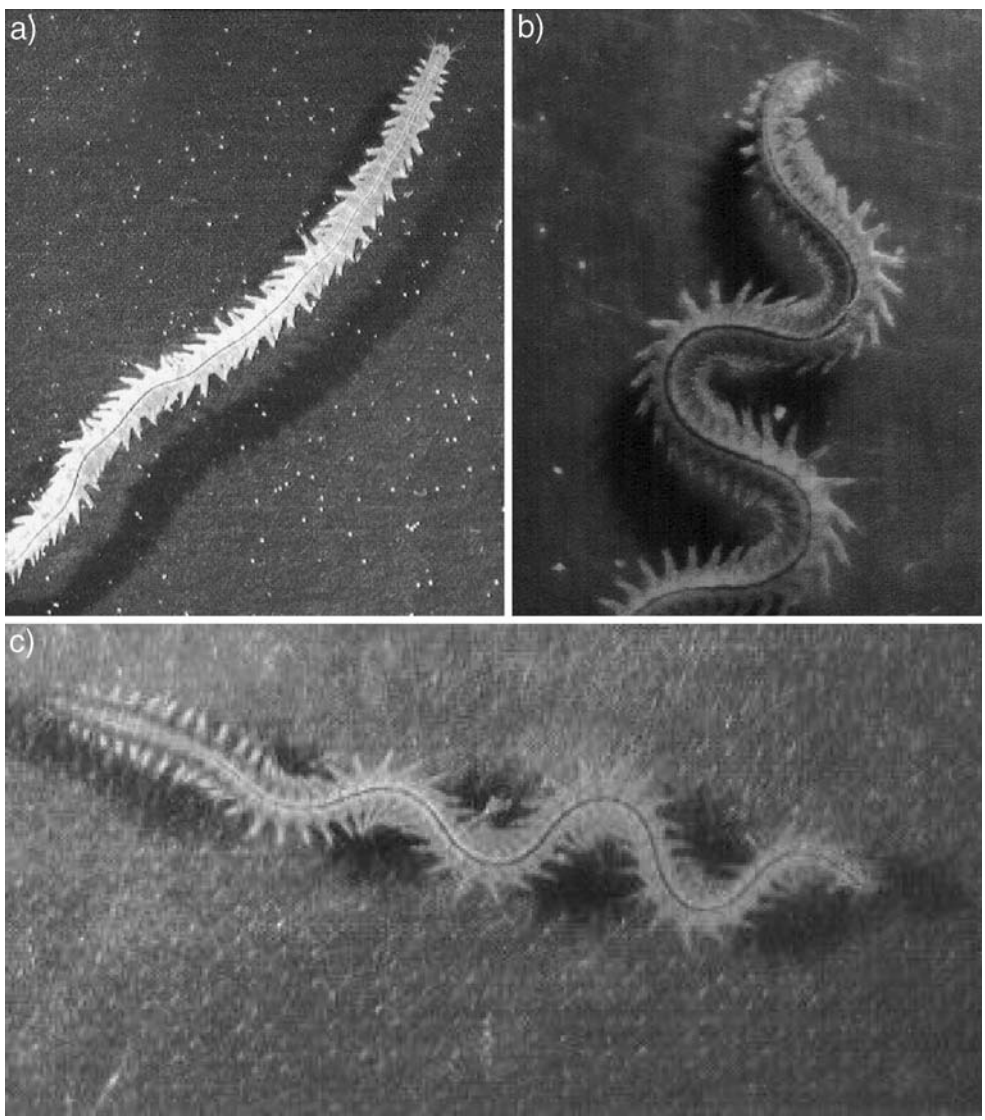

Fig. 4 The three gaits found in errant polychaetes. All photos here are of *N. diversicolor*. **a** Slow crawling. **b** Swimming. **c** Fast crawling

found in errant polychaetes is unusual because the body waves are moving in an anterior direction from tail to head, contrary to what is found in most other elongate undulatory swimmers, such as eels and snakes, where the body waves move from head to tail (Tytell and Lauder 2004; Gillis 1998). It was shown theoretically that thrust can be produced in the same direction as the wave travels if the elongate body possesses a certain roughness (Taylor 1952). However, in ragworms the thrust is produced by the parapodia, which function as paddles during swimming (Hesselberg et al., in preparation; Clark and Tritton 1970).

The primary interest of the BIOLOCH project in ragworm locomotion was, besides the general application of the overall locomotion in undulatory robots and in an undulatory simulation environment (Tsakiris et al. 2005; Sfakiotakis and Tsakiris 2004), the worms' ability to crawl in slippery substrates. How do the ragworms generate sufficient friction? An indication is given by the many small hairs, the so-called setae, which are protruding in bundles distally from the parapodia (Fig. 5). The parapodium consists of two parts of soft fleshy lobes, the dorsal one is called the notopodium and the ventral one is called the neuropodium. Each part has an internal semirigid chitinous structure, the aciculum, on which the bundles are attached; one bundle in the notopodium and two in the neuropodium (Fig. 5). The seta bundles consist of numerous individual setae of primarily three types differing in length and joint morphology (Hesselberg and Vincent 2006a). However, all setae found in the errant polychaetes are compound setae, which consist of two parts: a shaft and a blade. The joint between these allows independent movement of the blade relative to the shaft, although a boss and a ligament restrict the degrees of freedom (Fig. 6). There are no muscles in the seta, so the blade has no intrinsic power and all movement occurs passively in response to external forces (Gustus and Cloney 1973). This elaborate structure and the presence of fine teeth on the blade (Fig. 6) suggest that setae are the primary structure used to generate friction by passively adapting to the substrate. This is further corroborated by experimental studies showing that ablation of setae results in slower crawling (Hesselberg and Vincent 2006b; Merz and Edwards 1998). Preliminary results with simple artificial setae mounted on a mechanical robot show that setae can enhance thrust compared to a similar-sized plate on certain substrates (La Spina et al. 2005). The real setae, however, are more multifunctional in nature. Both comparative and experimental studies show that setae are not adapted to a specific substrate but function equally well in many substrates (Hesselberg and Vincent 2006a,b). Furthermore, setae probably function as hooks in adhering the worm to the burrow walls (Woodin et al. 2003; Woodin and Merz 1987) and may play a role during swimming (Merz and Edwards 1998, but see Hesselberg and Vincent 2006b).

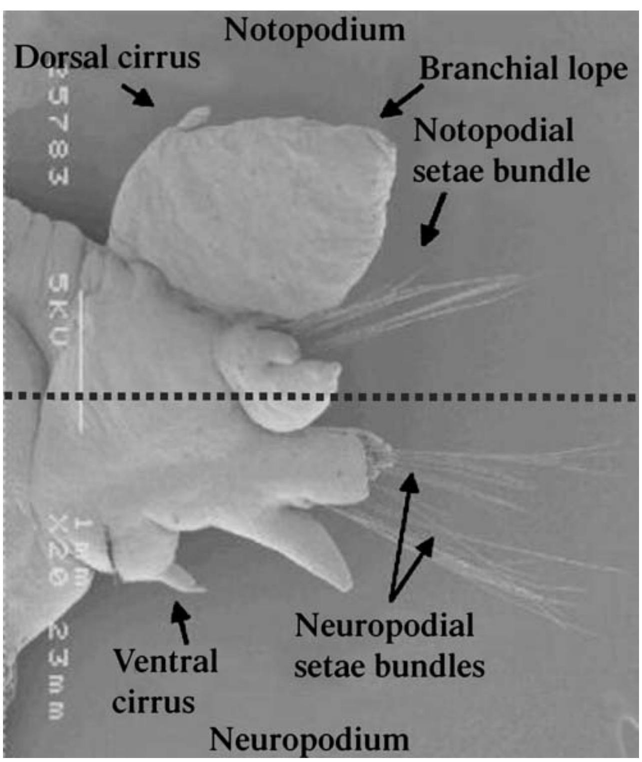

Fig. 5 A SEM photograph of a posterior parapodium in *N. virens*. The *dashed line* shows the approximate delimitation between the notopodium and neuropodium. *Arrows* point to interesting morphological structures

Aside from the overall locomotion and the function of the setae mentioned above, which were actively studied during the BIOLOCH project, the ragworm offers other biomimetic aspects. A digital particle image velocimetry study of swimming ragworms revealed that they generate distinct jets in their wake and utilize a novel form of continuous jet-like propulsion where the action of the parapodia can be likened to a conveyor belt moving water backward (Hesselberg et al., in preparation). Besides a propulsion system for a swimming undulatory robot this mechanism also has biomimetic potential as a pump. Such a pump would work well with viscous fluids or mixtures of liquid and particulate matter. In an undergraduate project at the Centre for Biomimetic and Natural Technologies at the University of Bath, Bath, UK, it was shown theoretically that a system with multiple artificial parapodia would generate flow rates comparable to other displacement pumps (Cummings 2004). Another interesting aspect is the burrowing abilities of the ragworm. The worm burrows using the everted pharynx and the hydrostatic skeleton (Trevor 1977). A recent study show that the larger *N. virens* uses it everted pharynx to propagate cracks in muddy cohesive sediments (Dorgan et al. 2005). This is, incidentally, a method, which in itself, is worth investigating in more detail from a biomimetic perspective. With an extra

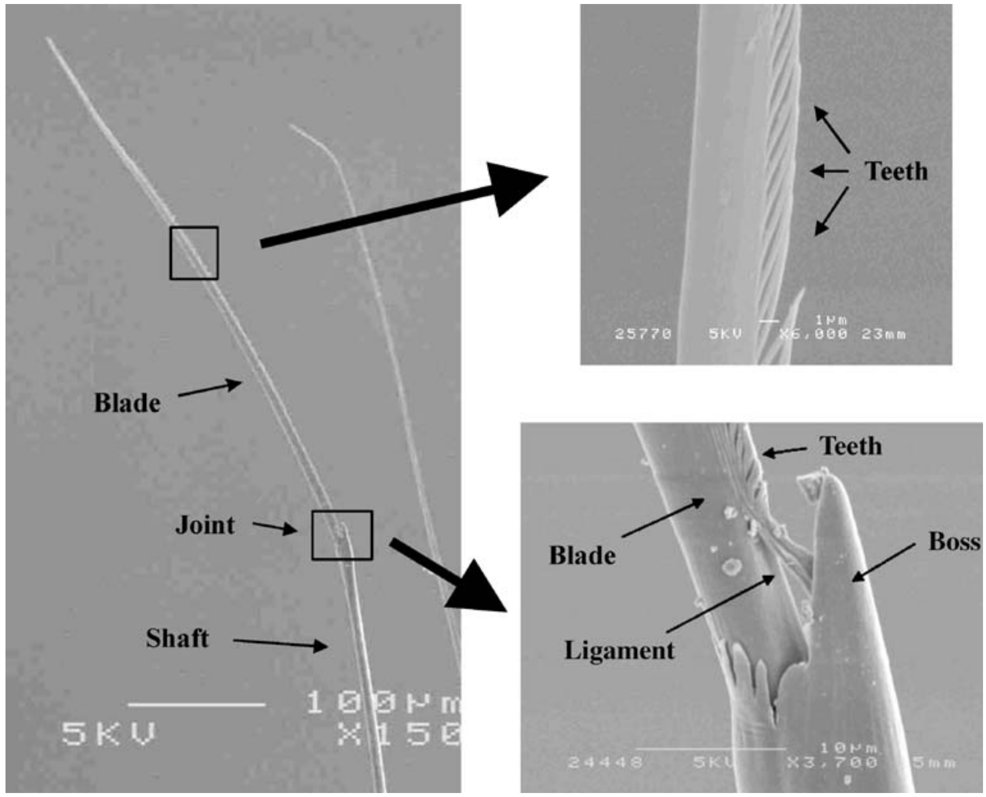

Fig. 6 SEM photo of a seta (a heterogomph spiniger) from *N. virens*. The blade and joint are shown in magnification on the right with arrows referring to points of interest

layer of morphological detail (such as an artificial eversible pharynx or a hydrostatical skeleton) a robot based on the nereidid design would be able to burrow, crawl, and swim in a wide range of habitats requiring relatively simple control mechanisms.

Discussion

That a relatively common but overlooked group of organisms like the ragworms can provide inspiration for robotics, by suggesting a design for a biomimetic endoscope and a multifunctional robot, shows the potential of the integrative organism-driven approach to biomimetics. This is slowly being realized by the biomimetic community and a good example is the Micromechanical Flying Insect project at the University of California, Berkeley, USA. The aim is to build a biomimetic microair vehicle based on inspiration from the fly. They use not only the overall design of the fly, but also use kinematics (Deng et al. 2006), control (Schenato et al. 2001), and sensory systems (Wu et al. 2002) of the real fly as inspiration. However, although the integrative organism-driven approach is superior for some types of biomimetic projects, it is by no means generally superior to the other two approaches. As stressed in the "Introduction," biomimetics shows significant growth in these years and all three approaches to biomimetics are important for this increased research output to result in commercially viable products. However, for biomimetics to result in more successful products, such as Velcro and Lotusan, more knowledge of the field and how to conduct it is needed among young scientists. Fortunately, more and more engineering schools now offer biomimetic courses to their undergraduate students; but it is of vital importance, especially for the success of the organism-driven approaches, that it will be taught more in the future to biology undergraduates and postgraduates.

However, before we uncritically praise the biomimetic approaches, some caution is required. As the biologist Vogel (1992) points outs, natural technology has evolved under several major constraints, which should not limit our technology. Nature, for instance, uses only a very limited number of materials, where our technology has a far greater variety available (Vincent 2000). Furthermore, designs in nature are usually not optimized for any single function, but instead have multiple functions. For example, the spider web's primary function is to detain prey long enough for the spider to catch it (Eberhard 1990). However, it also functions as a communication channel during courtship behavior and in camouflage by blurring the outline of the spider. Therefore uncritical copying of biological structures will often not give useful results. Instead a careful analysis and assessment of the functions in nature is required before potential aspects can be identified and attempts made to imitate them. This will often be a complex process and it is here that cooperation between biologists and engineers is of vital importance for a successful outcome.

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