Robert L. Nagel
e-mail: rlnkc7@mst.edu

Prem A. Midha
e-mail: pamq3f@mst.edu

Andrea Tinsley
e-mail: andrea.tinsley@shawgrp.com

Robert B. Stone
e-mail: rstone@mst.edu

Missouri University of Science and Technology,
Rolla, MO 65409

Daniel A. McAdams
Texas A&M University,
College Station, TX 77843
e-mail: dmcadams@tamu.edu

L. H. Shu
University of Toronto,
Toronto, ON M5S 3G8,
Canada
e-mail: shu@mie.utoronto.ca

Exploring the Use of Functional Models in Biomimetic Conceptual Design

The biological world provides numerous cases for analogy and inspiration. From simple cases such as hook and latch attachments to articulated-wing flying vehicles, nature provides many sources for ideas. Though biological systems provide a wealth of elegant and ingenious approaches to problem solving, there are challenges that prevent designers from leveraging the full insight of the biological world into the designed world. This paper describes how those challenges can be overcome through functional analogy. Through the creation of a function-based repository, designers can find biomimetic solutions by searching the function for which a solution is needed. A biomimetic function-based repository enables learning, practicing, and researching designers to fully leverage the elegance and insight of the biological world. In this paper, we present the initial efforts of functional modeling biological systems and then transferring the principles of the biological system to an engineered system. Four case studies are presented in this paper. These case studies include a biological solution to a problem found in nature and engineered solutions corresponding to the high-level functionality of the biological solution, i.e., a housefly's winged flight and a flapping wing aircraft. The case studies show that unique creative engineered solutions can be generated through functional analogy with nature. [DOI: 10.1115/1.2992062]

1 Introduction

The designs of the biological world allow organisms to survive in nearly all of earth's challenging environments filling niches from under-sea volcanic vents, tundras both frozen and desolate, poisonous salt flats, and deserts rarely seeing rain. Nature's designs are the most elegant, innovative, and robust solution principles and strategies allowing for life to survive many of the earth's challenges. Biomimetic design aims to leverage the insight of the biological world into the engineered world, but because of numerous challenges, biomimetic design is still undeveloped as a method for formal concept generation. Allowing design engineers' formal and full access to the solution principles and strategies of the biological world remains beyond current methods and knowledge.

Many challenges prevent immediate adoption of designing via biological inspiration including (1) a lack of equivalent engineering technologies, (2) a knowledge gap between designers and biologists, and (3) unawareness of analogous biological systems. Significant effort and time are required to become a competent engineering designer, which creates an equally significant obstacle to becoming sufficiently knowledgeable about biological systems to effectively execute biomimetic design. Formal design based on functional modeling and concept generation methods [1–9] provides a unique opportunity to extend biomimetic design to meet the challenges thwarting the adoption into formal engineering design practices. The generation of functional models based on *what* a product must do instead of *how* it will be accomplished provides designers with many benefits such as explicit correlation with customer needs, comprehensive understanding of the design problem, enhanced creativity through abstraction, and innovative concept generation focused on answering what must be done [7,8]. Design based on functional modeling provides designers with the freedom to consider the functionality of analogous biological systems without the burden of technological feasibility, and when applied with automated concept generation techniques based on predefined and expandable knowledge bases such as a design repository, biological systems may be explored without the need for advanced training in biological sciences.

The representation of products by function has enabled the creation of design repositories allowing designers to access solution principles that are outside their personal knowledge or expertise [10–13]. The ability of functional representation to allow designers to access such design information is a key impetus toward the extension of biomimetic design through the method of functional modeling. If biological inspiration requires designers to have extensive knowledge of biological systems, then the insight of the biological world will never be fully accessible to engineering design. The objectives of the research presented in this paper are to functionally explore biological systems to discover the knowledge needed to enable a function-based biomimetic design repository. First, a brief summary of previous work in biomimetic design is provided. Next, the research methodology that was followed to generate the case studies found in Sec. 4 of this paper is discussed. Finally, conclusions reached thus far in this research are discussed as well as a summary of the direction for future work to be completed.

2 Background and Related Work

Numerous biomimetic designs have been developed, where in most cases, the engineered system is a direct emulation of the biological system. For example, prosthetic replacements are a biomimetic design mimicking bone structure. Novel and nonobvious solutions, however, may require the biological system be viewed from a different perspective than an attempt to directly copy nature. The main focus of this research is to provide engineers with a method of learning enough about biological phenomena to inspire novel designs. For example, while plants may be stationary,

Contributed by the Design Theory and Methodology Committee of ASME for publication in the JOURNAL OF MECHANICAL DESIGN. Manuscript received May 16, 2007; final manuscript received September 4, 2008; published online October 28, 2008. Review conducted by John K. Gershenson. Paper presented at the ASME 2007 Design Engineering Technical Conferences and Computers and Information in Engineering Conference (DETC2007), September 4–7, 2007, Las Vegas, NV.

a closer inspection of the process of plant reproduction may give rise to ideas about transportation devices and distribution processes [14]. In a large part, we are looking at nature as an analogy to inspire an innovative design.

Current research in the fields of transformation and reconfiguration finds considerable inspiration from biological systems. Singh et al. at the University of Texas explored transformation principles in biomimetic design [15]. Transformation occurs when a single product has the ability to morph to fulfill other functions. Transformations are used to increase efficiency, reduce cost, and increase weight savings. In the work of Singh et al. [15], a methodology is developed for creating innovative products with broader functionality through the exploration of transformation design principles. The paper details case studies in nature, patents, and products, from which the three transformation principles are deduced including "expand/collapse," "expose/cover," and "fuse/divide."

With reconfiguration, systems are designed to maintain a high level of performance through real-time change in their configuration when operating conditions or requirements change in a predictable or unpredictable way [16]. The research of Ferguson et al. [16] focuses on system optimization for multiple optimization functions allowing reconfiguration to meet known conditions and operations, while the research of de Weck et al. [17] focuses on flexibility in product platform design to allow for customization. The morphing of bird's wings during flight inspires aircraft reconfiguration. Tucker and Parrott [18] and Tucker [19] studied the gliding performance afforded by the adjustable wingspans of birds allowing for changes in drag. Benefits of bird morphing can be afforded to aircraft through morphing aircraft geometry [20]. The research of Martin and Crossley [21] investigates geometric parameters of nonmorphing aircraft to study the benefit of potential geometric changes that a morphing aircraft might undergo, and Weisshaar and Bekey [22] considered reconfiguration applications to space systems where reconfiguration is required functionally, physically, and modularly to allow systems to adapt to meet changing conditions and tasks without having to be redesigned.

The Berkeley Lower Extremity Exoskeleton directly mimics human muscular systems through a wearable robotic exoskeleton for the legs to augment the strength and endurance of the human body through sensory systems and powered linear hydraulic actuators [23]. This system was designed for material transport over rugged terrain where wheeled vehicles may be incapable of navigating. Clinical gait analysis was used to determine the kinematics and dynamics of walking. This form of bioinspired design falls under the category of direct emulation, in which one tries to make an exact copy of the inspiring system.

Mimicking the mobility mechanism of prokaryotic and eukaryotic microorganisms are swimming micro-robots developed to potentially reach currently inaccessible areas of a human body [24]. These micro-robots would allow for minimally invasive surgery, localized drug delivery, and local screening for diseases. Math modeling and analysis of flagella motion in microorganisms led to the design of their mechanical counterparts. These robots were designed using more of a principle emulation level of biomimetic design. The solution is not a direct copy of the biological phenomenon but uses the same principles and strategies.

Others are researching how to bring biological inspiration to a wider range of engineers. The work by Wilson and Rosen [25] focuses on developing a reverse engineering methodology that will allow engineers to understand nature from an engineering perspective [8] and allow engineers to derive a deeper analogy than can be obtained through an informal inspection. Though the concept of function is used to understand nature, Wilson and Rosen [25] do not attempt to represent nature in a repeatable way such that natural solutions can be stored and accessed by engineers with limited knowledge of natural systems. Biomimetic research by Chakrabarti et al. [26] is focused at enabling design engineers to execute biomimetic design. Similar to the efforts of Wilson and Rosen, Chakrabarti et al. [26] used a functional representation of nature. Chakrabarti et al. [26] developed a searchable knowledge base with natural solutions, but the work does not use an established and well-defined functional lexicon; it instead uses overall descriptions of biological systems. Additionally, the research of Chakrabarti et al. [26] is not focused on creating a formal methodology for finding relevant analogy. Rather, it relies on individual expertise to find and recognize the analogy that populates the knowledge base.

Research at the University of Texas by Linsey et al. [27] explores a method of breaking down products into a vocabulary that can then be easily transferred to an analogous system. It does not cover biomimetics per se, but the same concepts can apply to biomimetic design whereby biological systems are represented similarly to engineered systems in a specific semantic form to increase the probability of innovation of novel analogous systems. This semantic representation could be used as an intermediary to open biology-based design to engineers and designers without a need for full understanding of the biological systems.

From a biological science perspective, the Biomimicry Institute has a mission "to naturalize biomimicry in the culture by promoting the transfer of ideas, designs, and strategies from biology to sustainable human systems design" [28,29]. The Biomimicry Institute works to train biologists to better assist engineers in biomimetic design, which includes performing case studies and creating a database of biological solutions searchable by "challenges," "strategies," "organisms," "people," "citations," and "products."

3 Research Methodology

Biomimetic design as a formal method for concept generation is far from a developed science. Additionally, as formally combining functional modeling and the Functional Basis with biomimetic design is new, the basic research approach used here is largely exploratory resulting in the discovery of new knowledge. In general, our approach consists of three steps: (1) identify existing designs, which appear to mimic biology, (2) create functional models for both biological and engineered systems, and (3) explore the similarities, differences, and analogies between the solutions at the subfunction level.

One of the key things explored is the modeling and drawing of analogies at different scales or levels of biological organization. Certain levels of biological organization, particularly organ (e.g., heart and leaf) to organism (e.g., animals and plants), present themselves naturally as potential sources for design inspiration and imitation due to the familiarity with biological phenomena at these levels. Prior research, however, has shown that useful biological phenomena can be found at multiple levels of biological organization [30], and that principles found from molecular to ecosystem can lead to useful engineering solutions. Thus, both functional and process models generated at varying levels of fidelity will be required to fully capture biological analogies. Furthermore, analogous biological phenomena from less familiar levels of organization have the potential to lead to more novel solutions.

Since this work is largely exploratory research on how to apply functional modeling with the Functional Basis to biological systems, only engineered designs with more obvious biological counterparts are considered. The research approach, thus, is the reverse to what the final design approach will be. Rather than start with a design need and the associated required function, as typically a designer would, modeling begins with a biological system, and from that biological system, an analogous engineered system is extracted. First, the researchers arbitrarily identify biological systems that solve problems in an unusual way, and then either a known biomimetic design is paired with the biological system or the research team synthesizes a new connection. Where an existing biomimetic design was identified, the black box and functional models for the biological and engineered system are developed,

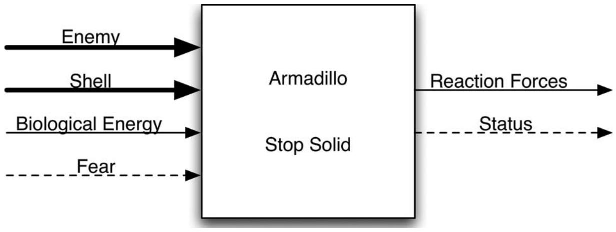

Fig. 1 Armadillo's defense mechanism black box model

and for cases where the synthesis of a connection is required, the research team explores both the black box model and functional model of the biological system in an effort to identify a functionally analogous engineered system. To demonstrate the analogy between the biological and engineered systems, a combined morphological matrix pairing analogous functionalities and solutions is developed.

4 Case Studies

Four case studies are presented in Secs. 4.1–4.4. The first two case studies include the defense mechanisms of an armadillo and a puffer fish. Neither defense mechanism can definitively be paired with a biology inspired design, so for each, the research team has synthesized analogous connections. The latter two case studies of the flight of a housefly and abscission pair biological systems with existing biologically inspired designs. Each case study includes a brief description of a biological system, the biological system's functional model, an overview of engineered systems that share similar functionality with the biological system, the engineered systems' functional models, and combined morphological matrices. After all of these items have been presented, analogous similarities and differences between the biological systems and their corresponding engineered systems are discussed.

4.1 Case Study 1: Armadillo. The defense mechanism of the *Tolypeutes* genus of armadillo has a unique functionality. Upon alarm, the armadillo's defense mechanism provides complete shielding from potential enemies and provides an opportunity for engineers and designers to employ biomimicry to learn from the armadillo's shielding mechanism [15]. The *Tolypeutes* genus of armadillo, which is found in South America, is the only genus of armadillo that can roll itself into a ball when it feels threatened by a predator. This type of armadillo, also called the southern three-banded armadillo, has three bands along its back, which allow it to roll up into a ball only exposing its armor. The armor is made up of plates of dermal bones that are covered in overlapping scales called "scutes." This protective armor covers the biological organism's tail, head, feet, and back. Smaller predators are not able to break the armor of the armadillo when the armadillo is in its defensive position [31].

Engineering and design can take cues from the armadillo's unique defense mechanism through the study of the armadillo's armor reconfiguration and its direct comparison to other embodied designs with similar high-level functionalities. For the armadillo, two engineered systems were studied with the same basic black box functionality as the southern three-banded armadillo. These systems included a retractable stadium roof and the Lexus SC430 convertible. All three systems (armadillo, convertible, and stadium roof) have a black box functionality *stop solid*. All three black box models require energy to propel closure, a shield to protect against foreign elements, and a stimulus to warrant reconfiguration. The black box model for the armadillo's defense system is provided in Fig. 1.

The armadillo's defense mechanism is further decomposed into a functional model, which can be compared directly to each of the similar embodied designs. The functional model, provided in Fig. 2, begins with the armadillo detecting an enemy. A control signal of fear is sent to the brain where it is processed, and a new control signal is generated and routed to *regulate biological energy*. The biological energy, which is internal to the biological system, is converted to mechanical energy. Muscles transfer and change mechanical energy to position the armadillo into its defensive position. This positioning of the biological organism's armor stops the predator from attacking.

Retractable roofs in athletic stadiums are functionally similar to the armadillo's armor reconfiguration and can be modeled and compared with the armadillo as an example of biomimicry. These roofs allow stadium fields to be covered during bad weather to keep the rain, snow, and wind off of the field and the spectators. The Skydome in Toronto was the first stadium to be built with a completely retractable roof. Since then, many others have been built including ones in Phoenix, Seattle, and Houston. These roofs are made up of several panels that are fastened to motorized steel wheel assemblies. When the motors are activated, the panels move across the top of the stadium on steel rails until the stadium is closed off from the inclement weather. The Safeco Field in Seattle, WA, has a retractable roof made up of three panels, which move an average of 0.1524 m/s for a maximum of 152.4 m taking roughly 20 min to close the stadium's roof depending on the wind and weather [32]. Figure 3 provides a functional model of a retractable stadium roof.

The functional model of a retractable stadium roof in Fig. 3, like that of the armadillo, uses a control signal to represent when reconfiguration is required. The processing of the signal is represented by *process control signal*, and the resulting processed signal actuates the flow of electrical energy to the system's motors. Numerous motors convert the electrical energy to mechanical energy. These motors power the wheel assemblies that the roof panels are fastened to, and the panels begin to move along the rails to close off the stadium. The motion of the panels is represented with a *guide solid* and *position solid*. Blocked inclement weather is represented functionally with a *stop material* function-flow block.

The Lexus SC430 has a retractable hardtop convertible roof that is able to automatically fold in half to be stored in the trunk, and like the retractable stadium roof, is functionally similar to the armadillo. The convertible's roof is made up of two panels that

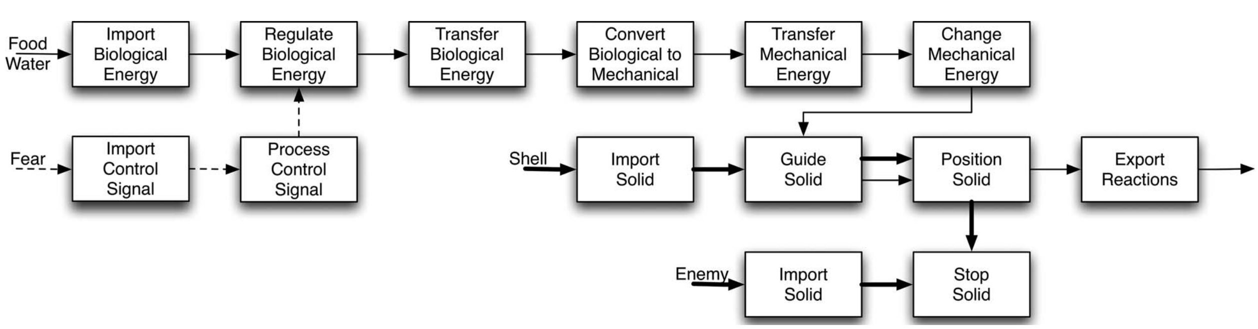

Fig. 2 Functional model of the armadillo's armor reconfiguration

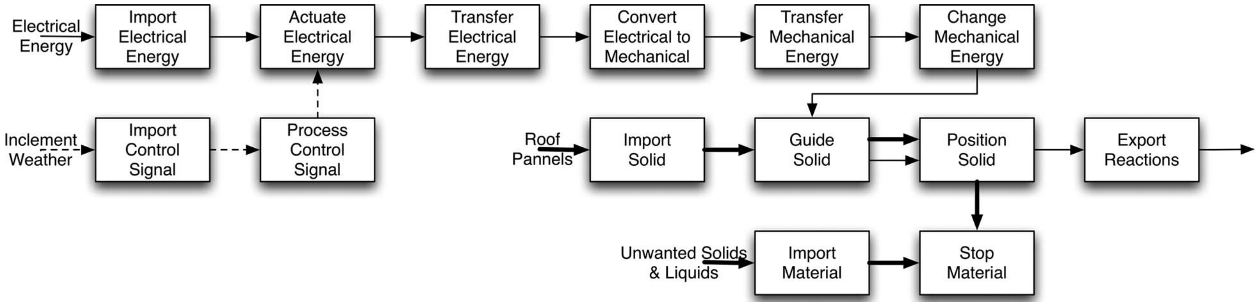

Fig. 3 Functional model of a retractable stadium roof

enable the top to fold as it is being lowered for storage. When the driver pushes a button to lower the convertible's roof, the windows roll down and the trunk opens. The portion of the trunk closest to the driver opens, and the roof folds in half and lowers itself until it is completely inside the trunk. The trunk closes with the convertible roof folded inside [33].

The functional model generated for the opening or unfolding of the Lexus SC430s roof, shown in Fig. 4, is functionally identical to the retractable stadium roof. When inclement weather is detected, a control signal is sent to the circuit board where the signal is processed and used to actuate the flow of electrical energy to the roof's motors. The electrical energy flows to motors, which convert the electrical energy to mechanical energy. The mechanical energy powers the closing of the roof.

The armadillo, the retractable stadium roof, and the Lexus SC430 convertible are functionally similar involving the position solid function-flow and stop solid material function-flow. The models and functional solutions of the armadillo and each embodied solution are directly compared in the morphological matrix provided as Table 1. Armadillos and retractable roofs have much in common from both a function and a solution perspective. From a conceptual perspective, the reconfigurable plates are directly analogous. In the morphological matrix, component dissimilarity arises between the biological world and the engineered world. The

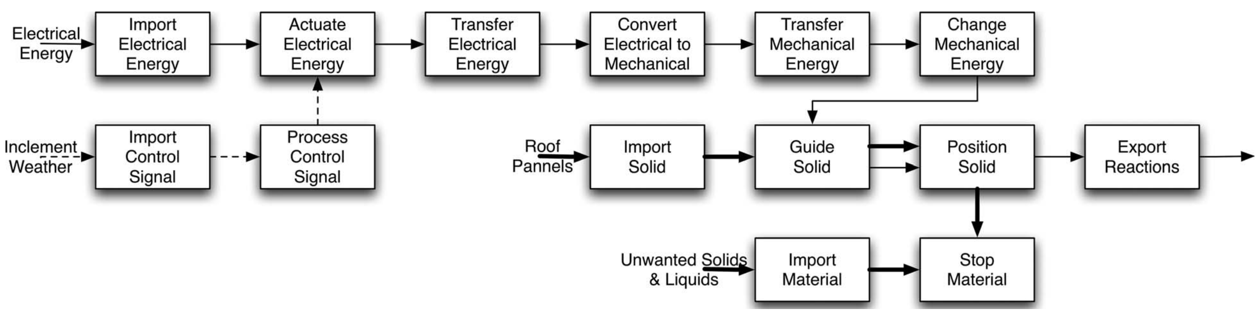

Fig. 4 Functional model of Lexus SC430 convertible

Table 1 Combined morphological matrix for armadillo, stadium roof and convertible

Function-Flow Pairs		**Primary Functionality**	**Components**	
Biological Solution	Engineered Solution		Biological Solution	Engineered Solution
Import Biological Energy	Import Electrical Energy	Import	Blood	Wires
Import Control Signal	Import Control Signal	Import	Brain	Circuit Board
Process Control Signal	Process Control Signal	Process		
Regulate Biological Energy	Actuate Electrical Energy	Control Magnitude		
Transfer Biological Energy	Transfer Electrical Energy	Transfer	Blood	Wires
Convert Biological to Mechanical Energy	Convert Electrical to Mechanical Energy	Convert	Muscles	Motors
Transfer Mechanical Energy	Transfer Mechanical Energy	Transfer		
Change Mechanical Energy	Change Mechanical Energy	Change		
Import Solid	Import Solid	Import	Shell	Roof Panels
Guide Solid	Guide Solid	Guide	Plates – Shells are formed by plates of dermal bone to allow organism to roll up	Roof Panels – Individual panels make up the roof of the stadium and convertible
Position Solid	Position Solid	Position		
Import Solid	Import Material	Import	Enemy	Unwanted Solids and Liquids
Stop Solid	Stop Material	Stop	Scutes – Plates covered by overlapping epidermal scales	Roof
Export Reactions	Export Reactions	Export	Armadillo	Stadium/Car

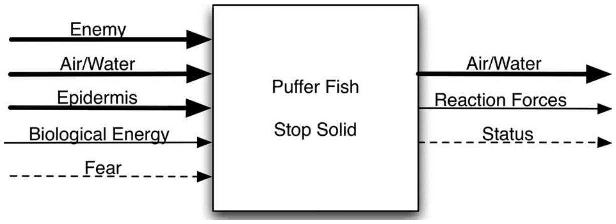

Fig. 5 Puffer fish black box model

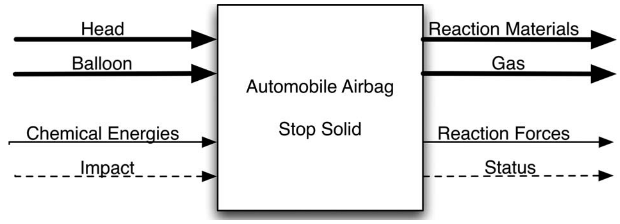

Fig. 6 Automobile airbag black box model

difference is energy. Biological energy is the key energizer of the biological world. Biological energy is converted to mechanical energy instead of the electrical energy, in the engineering world, being converted to mechanical energy.

4.2 Case Study 2: Puffer Fish. The puffer fish defense mechanism, like that of the armadillo, provides engineers with an opportunity to take cues from nature and mimic the expansion of the fish as a functional *stop*. Puffer fish are known for their ability to swallow water or air to inflate their stomachs to frighten predators when threatened. This particular type of fish is not a swift swimmer. Therefore, when the fish expands its stomach to several times its normal size, a predator will find itself faced with a much larger fish and either retreat or pause long enough for the fish to get away. Water or air can be used to inflate the stomach depending on whether the biological organism is in or out of the water at the time of inflation. The puffer fish will continue to remain the expanded size until the threat is no longer present [34]. At this time, the air or water is expelled back out of the fish through the mouth.

At the black box level, the puffer fish's defense mechanism has the functionality of stop solid. The puffer fish black box model, provided in Fig. 5, requires an enemy and its associated fear as inputs, as well as air, water, an epidermis, and biological energy to expand the puffer fish. At the black box level, an automobile airbag exhibits the same overall function, stop solid, as the puffer fish, thus indicating that puffer fish could inspire airbag design. An automobile airbag, however, would have different inputs than the puffer fish. An airbag would input chemical energies, a control signal for expansion, and the body part, in this case a human head, that it is designed to stop. The black box model for the airbag is provided in Fig. 6.

The puffer fish functional model, provided in Fig. 7, requires the control signal stimulus of fear from an enemy to activate its defense mechanism. The control signal is sent to the brain where it is processed and sent as a signal to the muscles. Biological energy is transferred to the muscles where it is converted into mechanical energy. Air or water is imported into the system filling the fish's stomach. The inflation of the stomach fulfills the position solid function in the functional model. This positioning of the biological organism's epidermis stops or deters the predator from attacking.

Automobile airbags were developed for the sole purpose of slowing a passenger's speed to zero with little or no damage during an accident, and at the secondary level of the Functional Basis would have the functionality stop solid. Airbags have become an important part of automobile design and are used in several places including the steering wheel, dashboard, seat, and door. These safety devices are made up of three basic parts: the bag, a sensor, and an inflation system. The bag is made of a thin nylon fabric that is folded into the desired location. The computer, which receives information from an accelerometer, tells the airbag when it needs to inflate. The inflation system that was studied for this model reacts sodium azide (NaN_3) with potassium nitrate (KNO_3) to produce nitrogen gas. Hot blasts of nitrogen gas produced from this reaction are used to inflate the airbag. As soon as the airbag inflates, the deflation process begins. The nitrogen gas escapes through small vents in the fabric. Dustlike particles, which are usually talcum powder or cornstarch, often escape through these vents during deflation as well [35].

The functional model that was generated for the inflation and implementation of an automobile airbag is shown in Fig. 8. Two potential chemical energies are imported and stored in the system, NaN_3 and KNO_3. Like the puffer fish, a control signal is required to tell the system when inflation is required. In the case of the airbag, the control signal is imported after the accelerometer has indicated extreme deceleration. The control signal is processed and routed to two *supply chemical energy* function-flow blocks, which supply the chemical energies for mixing. Nitrogen gas is produced upon mixing of the chemical energies. The nitrogen gas is routed to a balloon type enclosure, which inflates and stops the human head before it hits the steering wheel or dashboard during an accident. After the airbag has been inflated, the nitrogen gas and dust particles begin to escape through vents in the airbag's balloon enclosure. This escape of reactionary elements is shown functionally with the export reactions and gas function-flow blocks.

At the high-level, both the functional models for the puffer fish and the automobile airbag have the same functionality, to stop

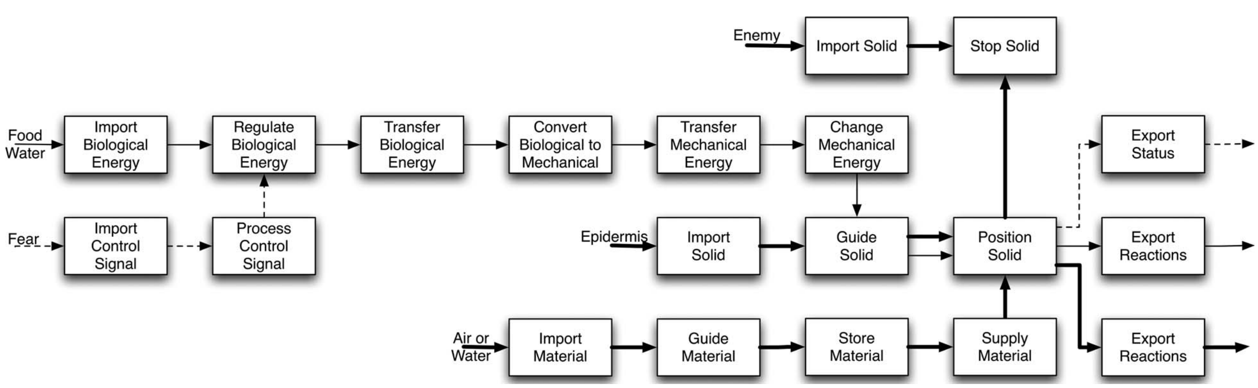

Fig. 7 Functional model of puffer fish

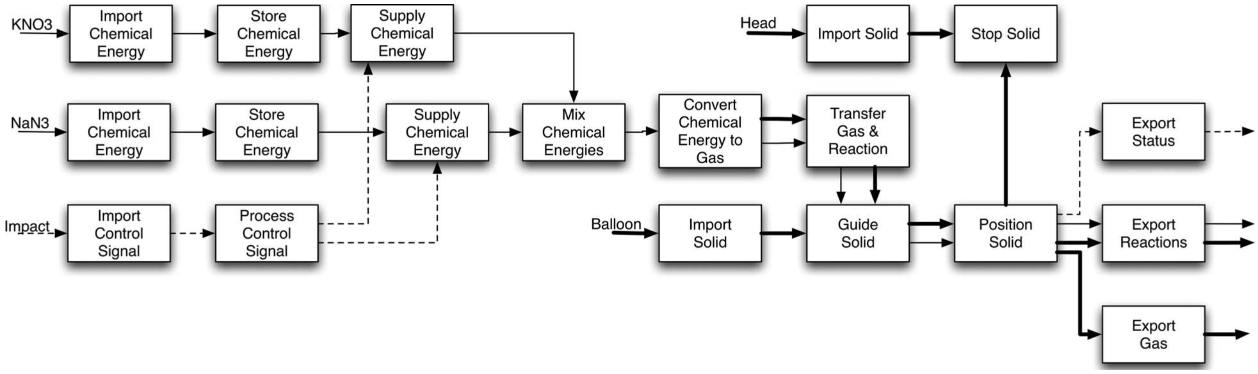

Fig. 8 Functional model of automobile airbag

solid. However, at the subfunctional level, each performs the overall goal differently. The puffer fish, like other biological systems, requires biological energy and external air or water to perform its inflation. The automobile airbag, however, being an engineered system, cannot practically rely on biological energy. Instead, the airbag converts chemical energy to the gas required to inflate the airbag. Thus, the airbag does not have to import any type of material into the system because the chemical reaction inside of the airbag creates all of the gas required to inflate the system. Table 2 provides a combined morphological matrix for the puffer fish and the automobile airbag summarizing the differences between the biological and engineered solutions for stopping a solid.

4.3 Case Study 3: Housefly. Since at least 500 B.C. in ancient Greece, humans have been fascinated with birds and other flapping wing creatures. Fascination has spawned not only myths and fairy tails but also the imagination of designers and engineers to mimic biology. During the 1400s, Leonardo da Vinci studied the flight of birds and became one of the first to sketch out a man-powered ornithopter, but it took until 1870 for the first successful ornithoper to be flown 70 m by its builder Gustave Trouvé [36]. Today, biomimicry of flapping flight continues to fascinate engineers and designers who continue to try to fully capture the gracefulness and efficiency of the biological world.

Microair vehicles (MAVs) used for military reconnaissance have spawned a keen interest in ornithopters. Microair vehicles, being considerably smaller than previously designed ornithopters, have spawned interest in the biomimicry of common houseflies. Houseflies have an incredible range of maneuverability making six full turns per second and recovering lift within a few microseconds of impacting a solid surface. Houseflies have numerous

Table 2 Combined morphological matrix for puffer fish and automobile airbag

Function-Flow Pairs		Primary Functionality	Components	
Biological Solution	Engineered Solution		Biological Solution	Engineered Solution
Import Biological Energy	Import Chemical Energy	Import	Blood	KNO_3
	Store Chemical Energy	Store		KNO_3
	Supply Chemical Energy	Supply		KNO_3
	Import Chemical Energy	Import		NaN_3
	Store Chemical Energy	Store		NaN_3
	Supply Chemical Energy	Supply		NaN_3
Import Control Signal	Import Control Signal	Import	Brain	Circuit Board
Process Control Signal	Process Control Signal	Process		
Regulate Biological Energy	Mix Chemical Energies			
Transfer Biological Energy		Transfer	Blood	
Convert Biological to Mechanical Energy	Convert Chemical Energy to Gas	Convert	Muscles	Chemical Reaction – Sodium azide reacts with potassium nitrate producing nitrogen gas
Transfer Mechanical Energy	Transfer Gas and Reaction	Transfer		
Change Mechanical Energy				
Import Solid	Import Solid	Import	Epidermis	Bag
Guide Solid	Guide Solid	Guide	Air/Water	Nitrogen Gas – Inflates airbag
Position Solid	Position Solid	Position		
Guide Material			Esophagus	
Store Material			Stomach	
Supply Material			Stomach	
Import Solid	Import Solid	Import	Enemy	Human
Stop Solid	Stop Solid	Stop		
Export Status	Export Status	Export	Puffer Fish	Airbag system
Export Reactions	Export Reactions	Export	Puffer Fish	Airbag system
Export Material	Export Material	Export	Mouth	Vents
Import Material			Mouth	

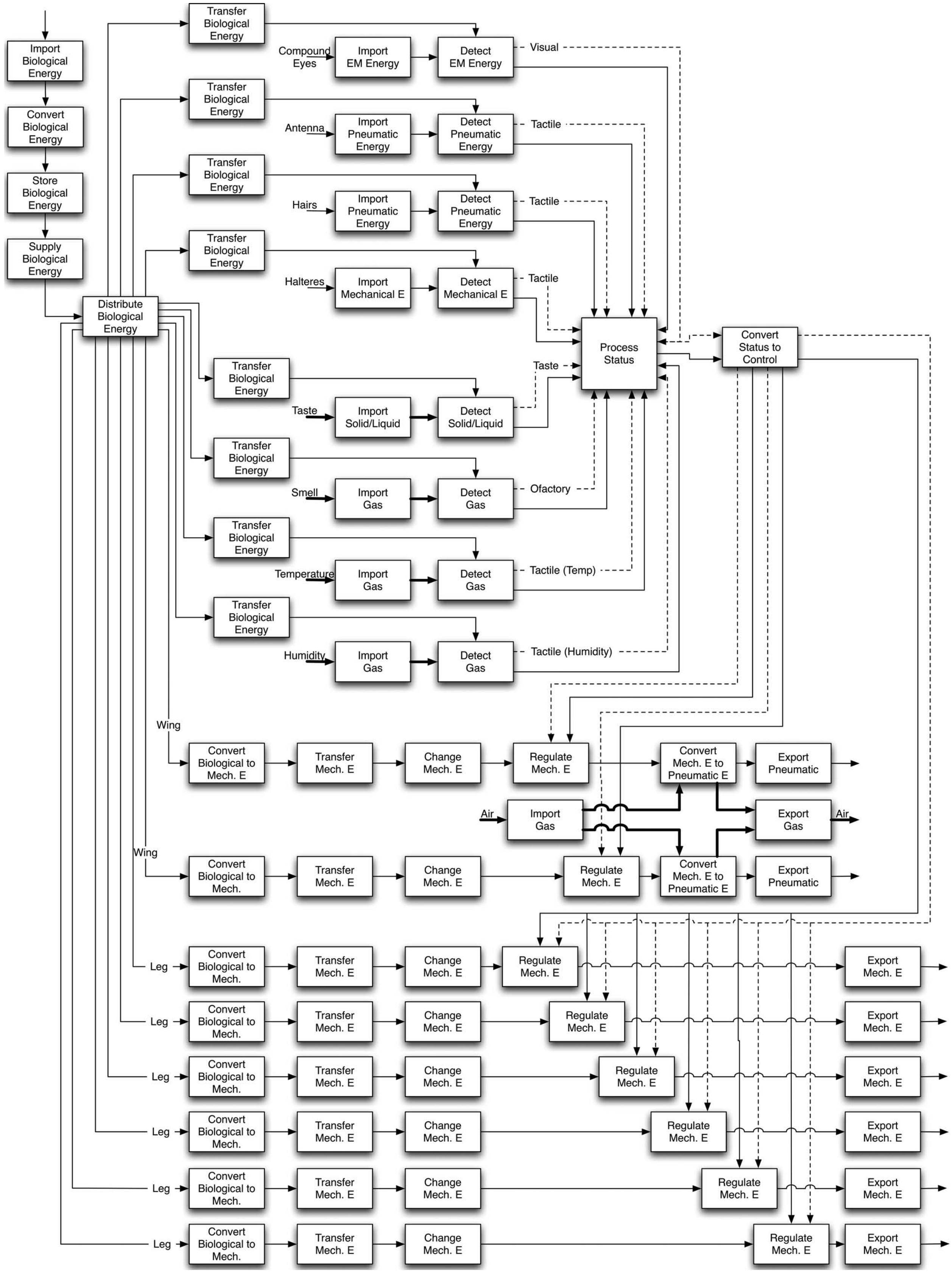

Fig. 9 Housefly functional model

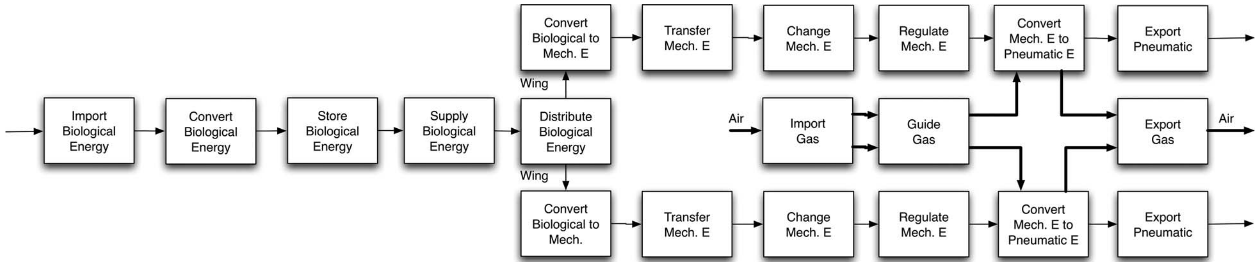

Fig. 10 Flight mobility from the housefly functional model

sensors allowing for their quick reflexes and instinctive motion. A common housefly has been modeled functionally for a MAV project at the Missouri University of Science and Technology (Missouri S&T) following the details of a housefly's flight and sensory abilities found in Ref. [37]. The housefly functional model used for the MAV project, provided in Fig. 9, captures the housefly's sensory abilities as well as its winged and pedal motion. The housefly functional model considers the housefly as a system, which can be reverse engineered. Through functional analysis of the housefly system, the researchers searched for analogies that could be transferred to the engineering solution during the conceptual design phases for insight into how to mimic a housefly during the development of a MAV.

MAV researchers were interested in gaining an understanding of the sensory and mobility aspects that would be required to mimic nature's design with engineering solutions. The functional model imports biological energy, which is converted into a usable form, stored, supplied, and distributed throughout the housefly. Sensory abilities modeled use the *detect* function and include compound eyes, antennae, hairs, halteres (used in aerial balance and guidance), taste, smell, temperature, and humidity. A *process status* function-flow block models the housefly's processing of status signal information from each of the detect function blocks. The status signals are converted to controls and routed to the housefly's mobility. Mobility aspects modeled include both of the housefly's wings and six legs. A detailed discussion of insect flight including the complexities of housefly aerodynamics can be found in the work of Dickinson et al. [38].

Due to the complexities of sensor and mobility design, the Missouri S&T MAV and many other MAVs are not mature enough to compare with the complete housefly at a function-form (morphological) level. For this reason, the flight mobility was extracted from the housefly functional model and compared with a simpler MAV, which provides an engineering solution for only the flight aspect of the housefly.

The Sparrow Flapping Wing Microair Vehicle (FWMAV) developed at the University of Delaware mimics the flight aspect of a common housefly [39]. The simplicity of this model is the result of the exclusion of all sensors and navigational control. It consists solely of a power source, power train, wings, and chassis, thus allowing it to fly freely in circular paths. The wings of the FWMAV are directly analogous to nature with their optimization of weight, local and overall stiffness, and fluid dynamics properties.

The extracted housefly wing mobility functional model can be directly compared with a functional model of the Sparrow FWMAV. The extracted housefly wing functional model in Fig. 10 imports biological energy into the system. The biological energy is converted to a usable form and stored. Once needed by the housefly, it is supplied and distributed to each of the housefly's wings. The biological energy is converted to mechanical energy, which is transferred and changed through muscle cells. The energy is regulated to control the housefly's velocity and converted to pneumatic energy representing the housefly's flight. Surrounding air is imported into the system and acted upon by the pneumatic energy as a result of the wings overall motion.

The functional model of the Sparrow FWMAV, provided in Fig. 11, is largely the same as the common housefly wing functional model provided in Fig. 10. The FWMAV, like the housefly, imports energy to fuel the system. The energy used by the FWMAV, however, is electrical energy. The electrical energy is stored in the system and supplied as needed. Once supplied, the electrical energy, like the biological energy in the housefly, must be converted to mechanical energy. Where the housefly uses muscles for this conversion, the FWMAV uses an electric motor. Through a type of gear train, the mechanical energy is changed and transferred to actuate the wings. The FWMAV's wings, just like those of the housefly, import air and convert mechanical energy to pneumatic energy resulting in the overall motion of the FWMAV. The combined morphological matrix of the housefly and FWMAV functional models is provided as Table 3.

4.4 Case Study 4: Abscission. Abscission is a biological survival mechanism through which plants separate leaves, fruits, flowers, and seeds from the main body of the plant. Auxin, a hormone released by plants to stimulate and direct growth, is the key to abscission. When a leaf has been damaged or the plant detects that leaves are no longer supplying a sufficient amount of energy through photosynthesis (as in winter), the release of auxin is slowed. This in turn allows abscisic acid and ethylene to mani-

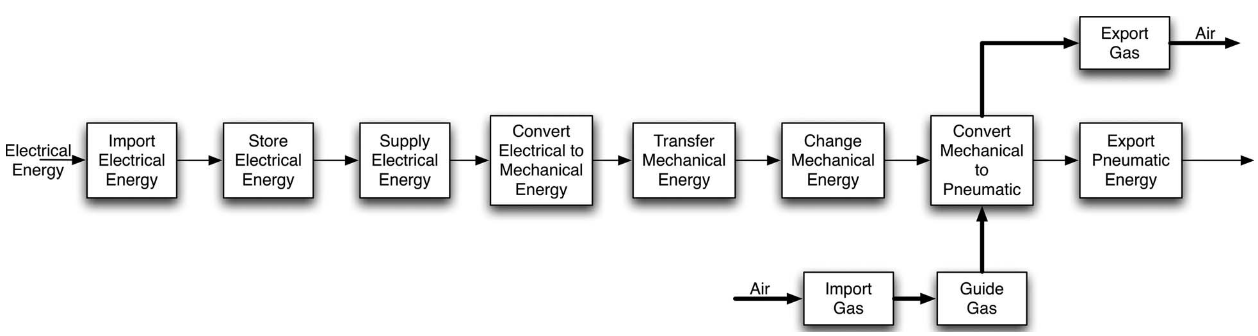

Fig. 11 Functional model of Sparrow flapping wing microair vehicle

Table 3 Combined morphological matrix for housefly and Sparrow FWMAV

Function-Flow Pairs		Primary Functionality	Components	
Biological Solution	Engineered Solution		Biological Solution	Engineered Solution
Import Biological Energy	Import Electrical Energy	Import	Mouth	Battery
Convert Biological Energy		Convert	Digestive Enzymes	
Store Biological Energy	Store Electrical Energy	Store	Lipids	Battery
Distribute Biological Energy		Distribute	Blood	
	Supply Electrical Energy	Supply		Battery
Convert Biological to Mechanical Energy	Convert Electrical to Mechanical Energy	Convert	Muscles	Motor
Transfer Mechanical Energy	Transfer Mechanical Energy	Transfer	Muscles	Gear train
Change Mechanical Energy	Change Mechanical Energy	Change	Muscles	Gear train
Regulate Mechanical Energy		Regulate	Brain	
Convert Mechanical to Pneumatic Energy	Convert Mechanical to Pneumatic Energy	Convert	Wings	Wings
Export Pneumatic Energy	Export Pneumatic Energy	Export	Wings	Wings
Import Gas	Import Gas	Import	Air	Air
Guide Gas	Guide Gas	Guide	Wings	Wings
Export Gas	Export Gas	Export	Air	Air

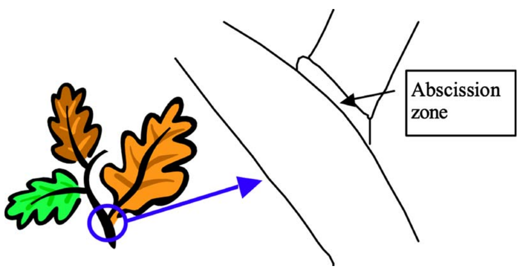

Fig. 12 Abscission zone [40]

fest, which advances the process of abscission by breaking down portions of the stem at the junctions where leaves are attached. The abscission zone, shown in Fig. 12, is comprised of a layer of cells, which swell and cut off the supply of nutrients in the absence of auxin [40]. Auxin is synthesized in plant cells and allows for reactions to environmental changes without the need of a central nervous system. The cells adjust the rate of auxin synthesis based on energy efficiency. When photosynthetic efficiency decreases, a hormonal imbalance is created, triggering the process of abscission. These chemicals are responsible for the breakdown of plant matter in the abscission zone, and gravity and wind carry away the unwanted leaves [41].

The biological process of abscission is modeled functionally

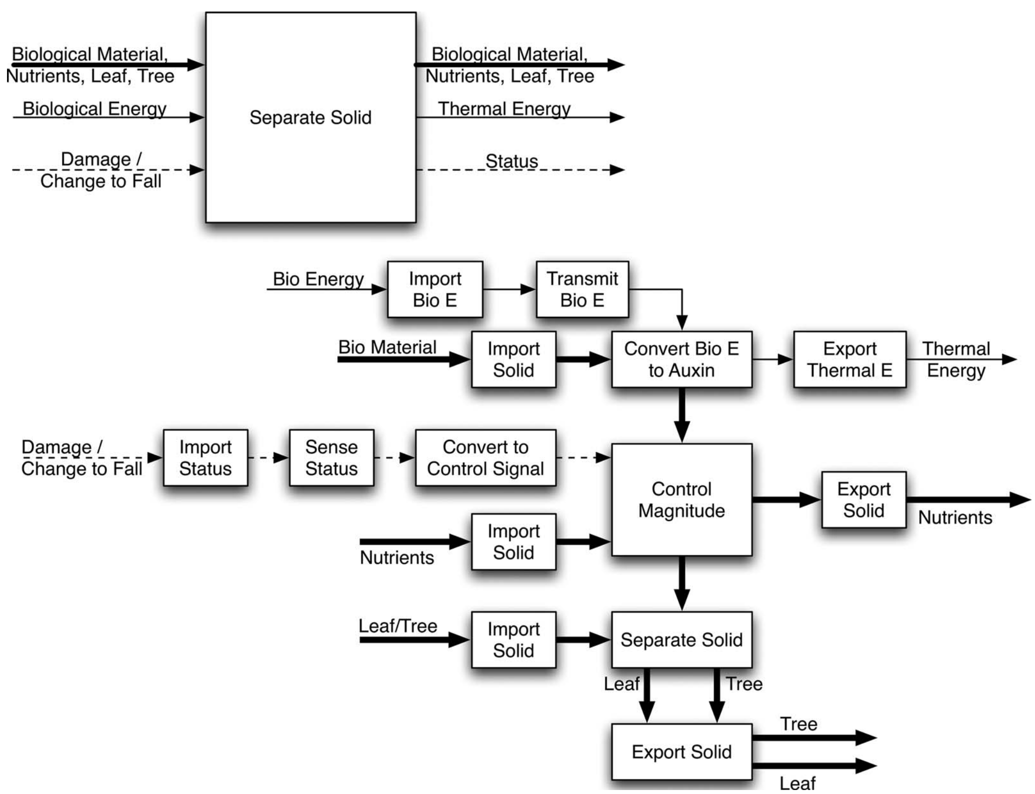

Fig. 13 Functional model of abscission

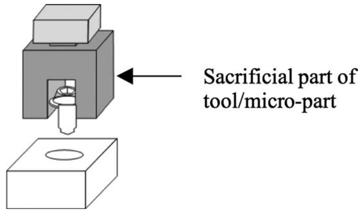

Fig. 14 Example of microassembly with sacrificial part [40]

with the Functional Basis and is shown in Fig. 13. The model shows how the process of separation of a damaged or unwanted leaf from a plant is initiated by a status signal representing the detection of damage, the changing of seasons, or impending burden. The status signal is converted to a control signal as the plant regulates the release of auxin. Auxin is the result of a conversion of biological energy and material, and a decrease in its levels triggers the separation of the leaves from the tree.

The strategy that can be derived from the process of abscission is the utilization for an intermediate abscission zone to facilitate the separation of disposable parts. Disposable parts attached to a recyclable tool fixture via abscission zones provide the potential for easier maintenance, shorter down times, and cheaper life cycle costs. More expensive fixtures would be separated from the disposable work ends similar to how disposable blades are separated from a razor.

An analogous engineered system that was analyzed for comparison was a proposed method of microassembly abscission [40] where an intermediate zone is broken down to enable separation. The proposed method of microassembly abscission was designed based on insight from the aforementioned abscission zones in plants. A tool, such as a robot arm end-effecter, can be positioned so that a postprocess can chemically or thermally remove the sacrificial part of the tool. This saves time and money on tool replacement and limits opportunities for damage to occur to the significantly more expensive robotic arm. The proposed tool is shown in Fig. 14. The sacrificial part of the tool is released with the working object. The significant size and weight of the sacrificial part allow the object to be easily oriented and released. The gripper, sacrificial part, and micro-object are analogous to the plant, abscission zone, and leaf, respectively.

An interpretation of this process was implemented and tested at the Technical University of Denmark and is shown in Fig. 15. The specific microassembly process was that of mating a 0.6 mm microscrew with a plastic counterpart. A polypropylene rod is melted locally at the tip and is then placed in contact with the microscrew. Upon contact, the plastic solidifies and creates a firm connection. The microscrew is inserted into the plastic counterpart and rotated until the torque increase breaks it free of the polypropylene rod.

The functional model of the microassembly process implemented at the Technical University of Demark, shown in Fig. 16, models the connection and subsequent abscission of the disposable microscrew. A processor sends control signals via data cables to the robotic arm, which controls the grabbing of the screw, the screw and rod placement, and the turning of the screw and rod. A heating plate is used as the source of thermal energy to secure the screw into the polypropylene rod. To secure the connection, the rod comes in direct contact with the heating plate transmitting thermal energy to the polypropylene rod. Then as the rod cools, its solidification causes the mating of the rod and the screw. Once the screw and polypropylene rod are to be disconnected, the torque is increased to overcome the bond, which results in the release of the modeled reaction forces and thermal energy. Following the sacrifice of the screw, the polypropylene rod is removed by the robotic arm.

Based on a direct function-to-function comparison, the microassembly process is different from the biological phenomenon that inspired it. The analogy, instead, exists from a process or strategic

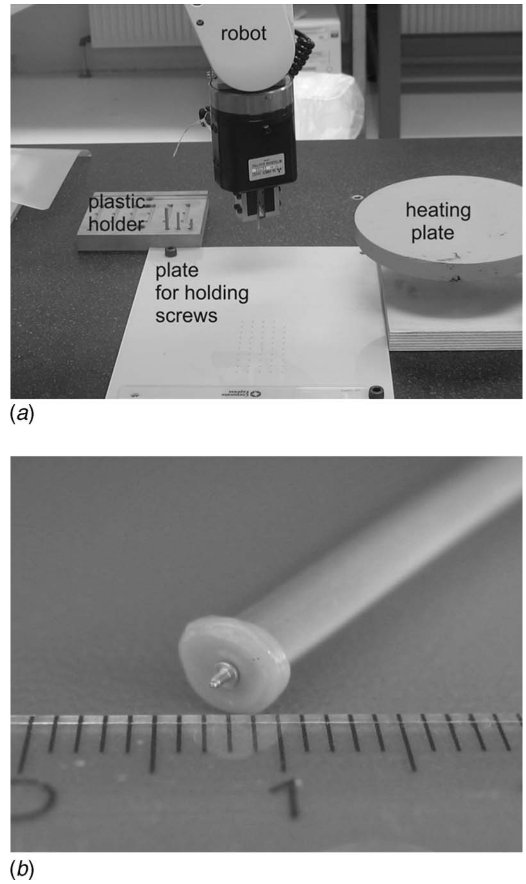

Fig. 15 Experimental setup for abscission-based release of microparts (*a*) and microscrew embedded into a polypropylene rod (*b*) [40]

perspective. At the black box level, abscission with plant's leaves is functionally the same as abscission with the microassembly process; however, strategy is implemented quite differently at a subfunctional level. Both the biological and engineered systems share the objective of separating two objects when the usefulness has diminished. In plants, the removal of the unwanted parts occurs from a chemical reactions while in the engineered solution, there is no chemical reaction to release the *used* part; instead, mechanical energy in the form of rotation is used to position, tighten, and ultimately release the screw through with an increase in torque. To show how the two strategies differ functionally, a combined morphological matrix of the biological and engineered models is shown in Table 4.

Because the biomimicry is based on strategy, there is difference in the function-flow pairs between the two systems. Instead of seeing an analogy with the subfunctions of the systems, the analogy exists at the black box level, separate solid. The functional models for the biological and engineered processes suggest the possibility of alternative approaches to similar problems. The process, method, functionality, and form of abscission could also lead to other innovative concepts, which more closely mimic abscission at the subfunctional level. For example, abscission could lead to the development of a bonding agent and gas that work in a similar manner. Products joined with this bonding agent could be exposed to the codeveloped gas at the end of the product's useful life to facilitate disassembly for disposal or repair.

5 Discussion of Results

From the case studies, a number of useful results can be reported. Through the use of the Functional Basis, biological sys-

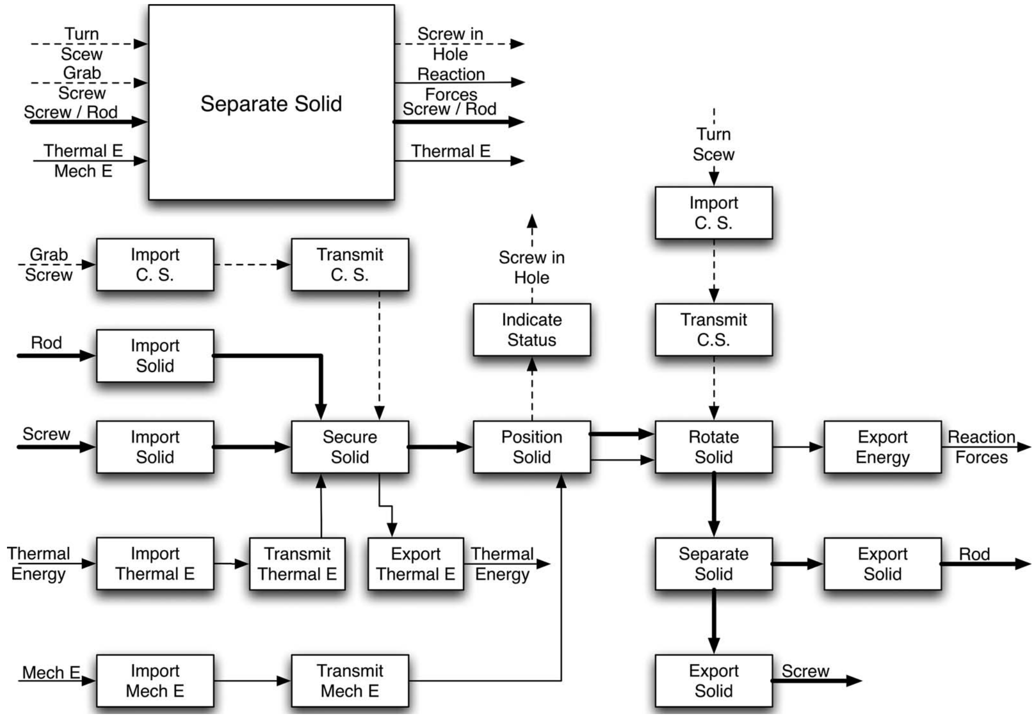

Fig. 16 Functional model of microassembly abscission

tems can be functionally modeled as if they were engineered systems. Also, given a functional model, engineered systems with similar functionality to the biological system can adapt solution principles and strategies from the biological system. Functional analogies can also occur at different levels of fidelity. For instance, in the case of abscission, the analogy provided with the microassembly process occurs with the strategy. This strategic analogy is drawn at the black box level indicating similarity with the functionality of the system as a whole; this analogy, however, is not continued at the subfunction level. With the model of the housefly, the analogy with the MAV exists at a high fidelity subfunctional model capturing the mechanics of flapping wing flight. Unlike abscission, this analogy of flapping wing flight would be more difficult to spot as a black box model that is all inclusive of the functionalities of the housefly than it is at the subfunctional model. From the case studies of the puffer fish and the armadillo, analogies exist with the high-level models provided; however, as the models increase in fidelity, the similarity of the functional correlation would also diminish. To capitalize on the potential for analogy at varying levels, functional fidelity and functional decompositions of biological systems must be performed and cataloged at multiple levels of fidelity such that each level may be simultaneously quarried for solution principles.

Another observation of this research is that a crucial difference

Table 4 Combined morphological matrix for abscission and microassembly abscission

Function-Flow Pairs		Primary Functionality	Components	
Biological Solution	Engineered Solution		Biological Solution	Engineered Solution
Import Biological Energy	Import Mechanical Energy	Import	Roots and Leaves	Motor
	Import Thermal Energy			Heating Plate
Transmit Biological Energy	Transmit Thermal Energy	Transmit	Xylem and Phloem	Heating Plate
	Transmit Mechanical Energy			Robotic Actuators
Import Solid	Import Solid	Import	Roots	Robotic Actuators
Convert Biological Energy to Auxin		Convert	Plant Cells	
Export Thermal Energy	Export Thermal Energy	Export	Plant Cells	Polypropylene Rod Cooling
	Export Energy			Reaction Forces
Import Status	Import Control Signal	Import	Plant Cells	Processor
Sense Status	Indicate Status	Signal	Plant Cells	Sensors
Convert Status to Control Signal		Convert	Plant Cells	
Control Magnitude		Control Magnitude	Plant Cells	
	Transmit Control Signal	Transmit		Data Cables
	Secure Solid	Secure		Polypropylene Rod Cooling
	Position Solid	Position		Robotic Actuators
	Rotate Solid	Rotate		Robotic Actuators
Separate Solid	Separate Solid	Separate	Abscisic Acid and Ethylene	Robotic Actuators
Export Solid	Export Solid	Export	Gravity and Wind	Robotic Actuators

between biological and engineered systems is the energy source. In nature, energy was modeled as biological. In the engineered systems, it was modeled according to its engineering specification. While this observation is not surprising, it is important to the application of biomimetic design in automated concept generation. When biological systems are quarried as a potential analogous solution to an engineering design problem, the flows must not be considered as a locked pair to functionality. Thus to find analogy, the search is by function alone, not function and flow. Future work will explore the modeling of effort-flow pairs to see if this yields more innovative results.

Correlations have also been observed between biological systems and engineered systems ranging from broad processes and strategies to more focused mechanics of system operation. Traditionally, biomimetic designs have tended to mimic the observable aspects of biological systems. In the case of the abscission example, the analogy with the microassembly process exists at the strategic level where the analogy occurs at the black box level mimicking only the observable biological process of leaves abscising with the seasons and does not try to copy the mechanism with which plants abscise. More detailed information about the functionality behind the process of abscission reveals further opportunity for inspiration with a direct analogy at the subfunctional level. For example, a bonding agent could be designed to react to a specific release agent in the form of a gas. Once the release agent is applied to the bonding agent, a chemical reaction results in the breakdown of the bonding agent. As previously mentioned, to make these levels of inspiration and analogy accessible to a designer, a repository must contain information on the biological systems at multiple levels of fidelity.

6 Conclusions

Biomimetic design can provide new inspiration and increased efficiency in engineering by bringing about clever and novel design solutions. This research proves the feasibility of using functional modeling and the Functional Basis as a means to capture the biological world. Case study examples including functional models and morphological matrices demonstrate that relationships can be made at the functional level between embodied engineered solutions and those found in nature. The comparison of both the biological and engineered solutions shows that the elegance, simplicity, and efficiency of biological solutions can lead to innovative engineered systems through direct imitation, as in the case of flapping winged flight, or broader strategic methods, as in the case of abscission and micromanufacturing.

The application of functional models to biological systems provides engineers with a translation of biological solutions from the biological domain into the engineering domain, thus allowing novel biological solutions, which would otherwise go unrecognized, to be provided in engineering terms ready for design application. However, for functional models of the biological world to be useful to design engineers, they must be translated with a functional lexicon and made accessible to design engineers. To make the biological world accessible, biological systems must continue to be modeled functionally and at varying levels of fidelity. The functional models of biological systems must be stored in a biomimetic library searchable by design engineers using terminology from the engineering domain. The researchers are developing such a biomimetic library as a part of the Missouri S&T Design Repository [42] for storing the translated functional information of nature's designs, thus allowing the information to be accessible from around the world. Implementation of a biomimetic library in the Missouri S&T Design Repository will allow designers to access biological solutions during conceptual design using the repository's online concept generation tools [43]. Through the knowledge based concept generation afforded by the Missouri S&T Design, the functionalities of a single concept would be matched with the functionalities of many biological systems allowing a designer to potentially utilize multiple analogies for multiple different biological systems in a single products design.

Further work will include the investigation of modeling nature at varying levels of fidelity. One of the discoveries of this research is that modeling different aspects of a biological system leads to different functional models and different analogies. In the case studies, the biomimetic designs and analogous biological systems were identified before creating the functional models. The goal was to discover if functional modeling would serve as an appropriate representation for biomimetic design. Thus, as future work, different aspects of biological systems will be modeled prior to identifying an analogous engineered system. Models will be generated at varying levels of fidelity and will capture processes, state changes, and functionalities of biological systems to explore the potential impact on innovation in engineering design. The application of process analysis will allow models to be generated, which capture the events (e.g., metamorphosis) that a system encounters and the various state changes (e.g., happiness, fear, hunger, and anger) that a system undergoes. The modeling possibilities are limitless and can include entire cellular interactions, complete organisms, herding, ecosystems, aging, and seasons.

Acknowledgment

This work was supported in part by the National Science Foundation under Grant Nos. CMMI-0636411 and CMMI-0737657.

References

[1] Miles, L., 1961, *Techniques of Value Analysis and Engineering*, McGraw-Hill, New York.
[2] Cutherell, D., 1996, *The PDMA Handbook of New Product Development*, M. Rosenau, Jr., ed., Wiley, New York, Chap. 16.
[3] Fenves, S., 2001, *A Core Product Model for Representing Design Information*, National Institute of Standards and Technology, Gaithersburg, MD.
[4] Dieter, G., 1991, *Engineering Design: A Materials and Processing Approach*, 2nd ed., McGraw-Hill, New York.
[5] Cross, N., 2000, *Engineering Design Methods: Strategies for Product Design*, Wiley, Chichester.
[6] Ulrich, K. T., and Eppinger, S. D., 2004, *Product Design and Development*, 3rd ed., McGraw-Hill, New York/Irwin, Boston, MA.
[7] Ullman, D. G., 2002, *The Mechanical Design Process*, 3rd ed., McGraw-Hill, New York.
[8] Otto, K., and Wood, K., 2001, *Product Design: Techniques in Reverse Engineering, Systematic Design, and New Product Development*, Prentice-Hall, New York.
[9] Pahl, G., Beitz, W., Feldhusen, J., and Grote, K. H., 2007, *Engineering Design: A Systematic Approach*, 3rd ed., Springer-Verlag, Berlin.
[10] Bohm, M., 2004, "Design Engineering Lab: Design Repository Login," available from http://function2.device.mst.edu:8080/view/
[11] Bohm, M., and Stone, R., 2004, "Representing Product Functionality to Support Reuse: Conceptual and Supporting Functions," Proceedings of the DETC2004, Salt Lake City, UT, Paper No. DETC2004-57693.
[12] Bohm, M., and Stone, R., 2004, "Product Design Support: Exploring a Design Repository System," Proceedings of the ASME International Mechanical Engineering Congress, Anaheim, CA, Paper No. IMECE2004-61746.
[13] Bohm, M., Stone, R., and Szykman, S., 2005, "Enhancing Virtual Product Representations for Advanced Design Repository Systems," ASME J. Comput. Inf. Sci. Eng., **5**(4), pp. 360–372.
[14] Paturi, F., 1976, *Nature, Mother of Invention: The Engineering of Plant Life*, Thames and Hudson, London.
[15] Singh, L. H., Hansen, H. N., Gegeckaite, A., Moon, J., and Chan, C., 2006, "Case Study in Biomimetic Design: Handling and Assembly of Microparts," Proceedings of the ASME IDETC/CIE, Philadelphia, PA, Paper No. DETC2006-99398.
[16] Ferguson, S. M., and Kemper, L., 2006, "Effective Development of Reconfigurable Systems Using Linear State-Feedback Control," AIAA J., **44**(4), pp. 868–878.
[17] de Weck, O. L., and Suh, E. S., 2006, "Flexible Product Platforms: Framework and Case Study," Proceedings of the ASME International Design Engineering Technical Conferences, Philadelphia, PA, Paper No. DETC2006-99163.
[18] Tucker, V. A., and Parrott, G. C., 1970, "Aerodynamics of Gliding Flight in a Falcon and Other Birds," J. Exp. Biol., **52**, pp. 345–367.
[19] Tucker, V. A., 1987, "Gliding Birds: The Effect of Variable Wing Span," J. Exp. Biol., **133**, pp. 33–58.
[20] Bowman, J., Sanders, B., and Weisshaar, T., 2002, "Evaluating the Impact of Morphing Technologies on Aircraft Performance," Proceedings of the AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Denver, CO, Paper No. AIAA-2002-1631.
[21] Martin, E. T., and Crossley, W. A., 2002, "Multiobjective Aircraft Design to Investigate Potential Geometric Morphing Features," Proceedings of the

AIAA's Aircraft Technology, Integration, and Operations (ATIO) 2002 Technical, Los Angeles, CA, Paper No. AIAA-2002-5859.
[22] Weisshaar, T., and Bekey, I., 2005, "Operationally Responsive, Persistent Space Systems," Proceedings of the Responsive Space Conference, Los Angeles, CA, Paper No. RS3-2005-2005.
[23] Chu, A., Kazerooni, H., and Zoss, A., 2005, "On the Biomimetic Design of the Berkley Lower Extremity Exoskeleton (BLEEX)," Proceedings of the IEEE, Barcelona, Spain.
[24] Behkam, B., and Sitti, M., 2006, "Design Methodology for Biomimetic Propulsion of Miniature Swimming Robots," ASME J. Dyn. Syst., Meas., Control, **128**(1), pp. 36–43.
[25] Wilson, J., and Rosen, D., 2007, "Systematic Reverse Engineering of Biological Systems," Proceedings of the DETC2007, Las Vegas, NV, Paper No. DETC2007-35395.
[26] Chakrabarti, A., Sarkar, P., Leelavathamma, B., and Nataraju, B. S., 2005, "A Functional Representation for Aiding Biomimetic and Artificial Inspiration of New Ideas," Artif. Intell. Eng. Des. Anal. Manuf., **19**(2), pp. 113–132.
[27] Linsey, J. S., Murphy, J. T., Markman, A. B., Wood, K. L., and Kurtogula, T., 2006, *Representing Analogies: Increasing the Probability of Innovation. IDETC/CIE*, ASME, Philadelphia, PA.
[28] Biomimicry Institute, 2006, available from http://www.biomimicryinstitute.org/
[29] Biomimicry Institute, 2006, "Biomimicry: Nature as Model, Measure and Mentor," available from http://www.biomimicry.net/
[30] Hacco, E., and Shu, L. H., 2002, *Biomimetic Concept Generation Applied to Design for Remanufacture. DETC*, ASME, Montreal, Canada.
[31] Nixon, J., 2006, "Armadillo Online!," available from http://www.msu.edu/~nixonjos/armadillo/
[32] Safeco Field, 1999, available from http://www.djc.com/special/safeco/10053886.htm
[33] 2007, "How Convertibles Work," available from http://auto.howstuffworks.com/convertible.htm
[34] UCI Biomechanics, 2005, available from http://www.biomechanics.bio.uci.edu/
[35] 2007, "How Airbags Work," available from http://auto.howstuffworks.com/airbag.htm
[36] Ornithopter Zone, 2007, "Nathan Chronister, Ornithopter Media Collection," available from http://www.ornithopter.org
[37] Zbikowski, R., 2005, "Fly Like," IEEE Spectrum, **42**(11), pp. 46–51.
[38] Dickinson, M., Lehmann, F., and Sane, S., 1999, "Wing Rotation and the Aerodynamic Basis of Insect Flight," Science, **284**(5422), pp. 1954–1960.
[39] Agrawal, S. K., 2007, "Sparrow Flapping Wing Micro Air Vehicle," available from http://mechsys4.me.udel.edu/research/birdproject/
[40] Shu, L. H., Hansen, H. N., Gegeckaite, A., Moon, J., and Chan, C., 2006, *Case Study in Biomimetic Design: Handling and Assembly of Microparts*, Proceedings of the ASME IDETC/CIE, ASME, Philadelphia, PA.
[41] 2007, "Abscission," available from http://en.wikipedia.org/wiki/Abscission
[42] 2007, Missouri S&T Design Repository, available from http://repository.designengineeringlab.org
[43] 2007, Missouri S&T Design Repository, available from http://function2.device.mst.edu:8080/view/conceptgeneration.jsp