Survey and Introduction to the Focused Section on Bio-Inspired Mechatronics

***Abstract*—Understanding and adapting the underlying principles of biological systems to engineering systems have the promise of enabling many new mechatronic systems that can operate in unstructured and uncertain environments robustly and efficiently. This paper first reports a brief survey of recent studies on bio-inspired mechatronic systems and their biological counterparts in respects of locomotion, actuation, sensing, and control. Next, brief highlights of the 20 papers in this "Focused Section on Bio-Inspired Mechatronics" are given. Finally, current challenges and future trends of bio-inspired mechatronic systems are described.**

***Index Terms*—Actuation, biological inspiration, control, design, locomotion, mechatronics, sensing.**

I. INTRODUCTION

BIOLOGICAL systems have evolved to find just-good-enough solutions to survive in complex, dynamically changing, and uncertain environments. Understanding and adapting the underlying principles of these solutions to engineering systems have the promise of enabling many new mechatronic systems that can operate in unstructured and uncertain environments robustly and efficiently [1].

Biologically inspired (bio-inspired) design is one of the promising methods of solving complex engineering problems where we have limited knowledge. It is not about blindly copying biological systems, but more on understanding the physical principles of their operation and adapting such principles to engineering systems with the available synthetic materials, manufacturing methods, computation, power source, etc. These biological principles are one of the starting points in solving such complex engineering problems where engineering systems can go beyond nature since they could focus on only specific functions and environmental conditions and do not need to have many extra requirements and limitations that biological systems have. In fact, biological systems have evolutionary constraints (e.g., no rotating pin joints can exist in animals except the rotational biomotor of a rotating flagellum of a bacterium at the nanoscale) from their ancestors and they require many vital functions (e.g., mating, respiration, feeding, catching prey, and escaping from predators), which mechatronic systems do not require.

While biological systems inspire new mechatronic systems that can operate in complex and uncertain environments, bio-inspired mechatronic systems could also be used to improve our scientific understanding of their biological counterparts and to validate hypothesis on such biological systems.

II. RECENT WORKS ON BIO-INSPIRED MECHATRONICS

Biological inspiration studies in mechatronic systems can be grouped in respects of locomotion and mechanisms, actuation, sensing, and control. This distinction has been used also for organizing the papers of this "Focused Section on Bio-Inspired Mechatronics" of the IEEE/ASME TRANSACTIONS ON MECHATRONICS, as detailed in Section III.

A. Bio-Inspired Locomotion and Mechanisms

Animals have evolved to develop very agile, maneuverable, power efficient, and robust locomotion on ground, vertical surfaces and water surface, and in air and water. As ground locomotion dynamics, animals can crawl, walk, run, roll, burrow, jump, and hop. Crawling locomotion is very stable on a wide range of complex terrains while its cost of transport is relatively high due to high frictional cost of transport in addition to the inertial cost of transport, which is proportional to the square of the motion speed, in high-speed crawling. The first crawling robotic platform was inspired by snakes [2] by studying their locomotion biomechanics in 1974 since snakes can traverse on a wide range of terrains in a stable manner with large contact area with surfaces, pass through holes or tight spaces, are very redundant, and can be robust against hostile environments with their sealed skin. However, they have drawbacks in respects of high cost of transport due to lost energy to lateral acceleration and friction, difficulty of attaching payloads, and heating issues and limited speeds due to friction. They use lateral undulation, sidewinding, rectilinear, concertina, and some other gaits on different speed, surface type, animal size, and space tightness conditions. They can even swim, jump, and climb using surface friction, and glide. Such advantages and diversity of snake locomotion have attracted researchers to design and build snake-inspired robots [3]–[6]. Such modular robotic snakes are shown to crawl on complex terrains, under water, on ice, and climb where such robots can be used in inspection, exploration, medical surgery, and manufacturing.

In legged animals on ground, walking, jumping, hopping, and running are the dominant locomotion modes. At slow speeds, biped and quadruped vertebrates walk with an inertial cost of transport as a function of the square of the walking speed. Many passive walking machines have been proposed to use a given downward surface slope to be able to walk with no energy consumption [7]–[10]. As the record, a biped passive walker could walk around 4000 steps on a treadmill [9]. However, such passive walkers are not very robust against disturbances and cannot be steered around. Therefore, animals mostly use passive mechanisms in combination with muscle-actuated active control to be energy efficient while having a controllable and robust system.

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At higher speeds, running utilizes compliance on the legs that enables elastic energy storage and recovery. Energetic study on kangaroo running shows a surprisingly constant (or slightly decreasing) metabolic energy between 7$\sim$20 km/h [1]. Other running metabolic data (from gazelle, cheetah, and goat) show that the metabolic energy consumption is linearly proportional to speed [2]. Legged robotics has been one of the most studied areas of bio-inspired locomotion systems where many researchers proposed biped, quadruped, six-legged, and rotating tri-legged robotic platforms [11]–[17] such as BigDog, RHex, Whegs, and iSprawl. Although wheeled man-made robot designs could be energetically more efficient and faster, legged robots could be superior on traversing rough or uneven terrain and larger obstacles.

Moving from flat terrain to vertical surfaces, many animals can climb on surfaces using a wide range of diverse attachment principles. Such principles could be mechanical interlocking as in the case of human hands and insect or lizard claws, vacuum suction in the case of octopus arms, wet adhesives using liquid coated hairy or smooth feet of insects or tree frogs, and dry micro/nano-fibrillar adhesives in the case of geckos and spiders. Depending on the material type, roughness, porosity, wetness, and contamination of climbed surfaces in a given environment, climbing animals have evolved to have mostly couple of these attachment principles to climb in a stable and robust manner on a wide range of surfaces, e.g., many insects and geckos have both claws in combination with hairy sticky footpads.

Pitch-back moment during climbing upward needs to be balanced by the attachment peel strength of the fore feet of these animals. Most animal attachment materials or mechanisms are directional, which enables more controllability and stability in a given climbing direction. However, due to this directional property, animals need to be able to orient their legs in many different directions when they climb in any given surface orientation. For example, squirrels and geckos rotate their hind feet backward when they climb downward on a vertical surface such as a tree, while domestic cats mostly cannot rotate their hind legs backward and therefore need to jump down instead of climbing down. Many researchers used one of these attachment principles to propose a new climbing robot platform. Related to mechanical interlocking, Spinybot, RiSE, and ROCR are example locomotion platforms using microspines to climb on very rough surfaces [18]–[20]. Waalbot, Stickybot, and Tankbot type of robots used nondirectional or directional elastomer microfiber adhesives to climb on smooth or slightly rough surfaces energy efficiently [21]–[26].

On water surface, many animals stay, walk, jump, or run for different purposes. Insects, such as water striders or fishing spiders, use repulsive surface tension forces to lift their body weight and propel using form drag and surface tension so that they could live on water to feed and survive. Basilisk lizards use hydrostatic and form drag to lift and propel their body by rotating their feet in a specific trajectory at very high speeds (6–10 Hz) to be able to escape from predators or pass through a river quickly. For several bird species such as Grebes and fishes such as dolphins, water surface locomotion is more a mating ceremony or behavioral show. Several researchers proposed legged water surface walking or running platforms toward water surface monitoring or cleaning, security, and nature exploration applications [27]–[29].

In nonpowered flight, many animals use gliding and soaring to lift their body weight with almost no energy consumption. Even some unique animal species of squirrels, frogs, geckos, lizards (Draco lizard), snakes, fishes (flying fish), and monkeys (lemurs) can use gliding for energy efficient traveling among tall and widely spaced rainforests or escaping from predators. These legged animals mostly have a *patagium* type of a skin membrane extending among their legs and tails that behave as a flexible wing for efficient and stable gliding.

In powered flight, birds, bats, and insects flap their wings at frequencies varying from 1 Hz up to 1 kHz in a given specific one or two degrees of freedom (DOFs) trajectory to create unsteady aerodynamic airflow for active lift and propulsion generation. Only hummingbirds and insects can hover for long durations since they can produce sufficient flight power density required for hovering, while larger flying animals like birds cannot create enough flight power output for their given heavier weight. Moreover, hummingbirds and insects can create positive lift in both down and up strokes, while birds can produce lift mainly during down stroke. Many researchers developed bird like flapping robots, mainly called as ornithopters, to have controlled forward flight [30]–[32]. As hovering platforms, recent hummingbird or insect-inspired miniature flying robots have showed a significant progress and promise [33]–[40]. Using tiny motors or piezoelectric bending actuators coupled with complex transmission mechanisms and passively rotating wings (mainly underactuated designs), these flappers could create controllable torques on the robot body to enable controlled forward flight and hovering.

In swimming, fish swimming has been studied widely. Methods of slender body theory [41], elongated body theory [42], [43] and waving plate theory [44] have been used to model fish swimming. Till now, the mechanism of momentum transferring between fish and water cannot be clearly described by theory. However, it is commonly accepted that the propulsive force of swimming is highly related to this interaction [42], [43]. Recent experimental work on fish robots and real fish show that fish can enhance its thrust and effectively reduce its drag by manipulating the flow vortex in the wake, which is well explained by the vorticity control theory [45]–[47]. One effective way to understand the mechanism of vorticity control is to examine the vortex by using computational fluid dynamics simulation [48] or by observing it in experiments through particle image velocimetry (PIV) technology [49]–[51]. Given the data obtained from the PIV technology, Anderson argued that the high efficiency of fish benefits from the control of wake vorticity. By using the similar technology, Lauder and his coinvestigators [49], [52], [53] conducted extensive research to explain the function of fish fins and function of biomimetic propellers as an alternative of real fins.

There have been many fish-inspired robotic platforms. Early realization of robotic fish can be traced to the year of 1978 when the small-scaled automatic mechanical fish was developed in Japan. The birth of RoboTuna in 1994 triggered the extensive research interests in bio-inspired swimming robots [54]. Many different fish robots have since been developed over the past 20 years [55]–[70]. Most of them obtain propulsion by simulating the major swimming modes of fish: oscillating, undulating, and flapping. Representative fish robots with oscillating mode include RoboTuna, a body-caudal-fin type robot developed by Hu *et al.* [59], and a robot dolphin by Yu *et al.* [57]. Low and Willy [58] proposed an undulating fins mechanism constructed with rigid sliders and developed several fish robots propelled by these fins [56]. Toda *et al.* proposed a long undulating fin design with flexible fin materials and achieved flexible 3-D locomotion in a robotic squid [70]. While these bio-inspired swimming robots can be used in marine sourcing, seabed charting, surveillance, environmental assessments, sea exploring, and scientific research, etc., they could also help to test and verify the assumptions in biology and hydrodynamics.

In almost all of the aforementioned animals with a tail, the tail dynamics is very crucial for stability and steering during especially highly dynamic and maneuverable locomotion such as high-speed running, flying, and swimming. For example, cheetahs use their tail for high-speed steering, and basilisk lizards use their tail for pitch stability and possibly for steering on water by using it as a rudder. Bio-inspired climbing and water running robotic platforms also used an active or passive tail to stabilize their locomotion in the pitch direction [71], [72]. Next, during climbing or falling from a high surface, it is recently shown that geckos can use their tails to create counterclockwise moment to balance the pitch back moment on a slippery climbing surface by pressing the tail to the surface actively, and to stabilize their body roll and pitch direction in air when they fall [72].

B. Scaling Laws in Locomotion

In biological and robotic locomotion systems, it is crucial to understand how the structure of animals or robots and their patterns of movement depend on body size, to make generalizations about the movements of animals or robots of different sizes, and to study the animal locomotion dynamics in a scaled up or scaled down dynamically similar robotic systems. Therefore, scale-independent nondimensional parameters are crucial to define for different locomotion systems. Using the Newton's second law, one can derive three major nondimensional parameters [73]: Froude number ($= v^2/gh$ where v is the body speed, g is the gravitational acceleration, and h is the hip height from ground) for ground locomotion, Reynolds number (ratio of inertial forces to viscous forces) for motion in air and fluids, and Strauhal number for any oscillatory movement. Such numbers can be used to compare different size scale animals to see if they are dynamically similar or not, and to quantify when gaits or fluidic flow behavior change. Robofly used same Reynolds and Strauhal numbers with flies to study insect flight with a scaled up actuated wing system in a large oil tank [74]. Weber (ratio of inertial forces to surface tension) and Bond (ratio of buoyancy to surface tension) numbers are other nondimensional parameters for water surface locomotion [75]. Nature of physics favors small animals such that insects are very well adapted [76]: they can walk on water using very skinny and wax-coated hairy legs that repel water, be very fast relative to their body length, can carry much heavier weights relative to their body weight, can jump very high relative to their body size, and can cool down and heat up very fast. Finally, we need to understand which physical forces become dominant in different length scales to be able to design robots and understand animals correctly. For example, at large scales, volumetric (bulk) forces such as inertial and gravitational forces and buoyancy dominate surface forces such as friction, drag, and adhesion and circumferential forces such as surface tension. Inversely, surface area and circumference-based forces dominate the animal and robot locomotion physics at very small length scales down to micro/nanoscale.

C. Bio-Inspired Actuation

Skeletal muscles as the soft contractile actuators (motors) of vertebrates have advanced properties such as high power density (up to 100 W/kg), high strain (up to 40%), high stresses (up to 0.35 N/mm^2), high efficiency (up to 35%), stiffness tuning capability (up to five times stiffness change), high strain rates (up to 5 lengths/s), multifunctionality (e.g., can be used also as a brake), high durability (up to billions of cycles), self-sensing capability, and self-repairing capability [1]. Muscles are highly hierarchical fibrillar structures with parallel and distributed actuation architecture. Developing soft muscle-like actuators with similar properties has been a dream for many researchers. Electroactive polymer actuators, conductive or ionic polymer actuators, shape memory alloys (SMAs), and piezoelectric actuator-based systems have been proposed as muscle-inspired actuator systems [77]–[80].

D. Bio-Inspired Sensing

Animals use a large number of distributed and diverse sensors on or inside their body for their vital functions such as locomotion control, catching a prey, escaping from a predator, mating, etc. As an example, a fly has around 30 different types of sensors on their body. Visual sensing is enabled by single-lens eyes (vertebrates, reptiles, etc.) or compound eyes (insects) consisting of hundreds or thousands of lenslets. While the former eyes enable actively focused and high-resolution (in human: around 60 μm linear resolution and 37 cycles per degree angular resolution) images, their speed is limited to around 30 frames/s and their field of view is limited to up to 180°. On the other hand, compound eyes that are much smaller in size and simpler can only give unfocused and low-resolution images while they are optimized for high-speed imaging up to 200 frames/s, high motion sensitivity, and wide field of view up to 360° imaging. Even many insects (and snails) have a third eye called *ocelli*, which is just a photoreceptor to detect light intensity (no direction information) with very high speed and high sensitivity for flight stabilization or other sun light or horizon detection related functions. There have been some studies to create bio-inspired single-lens spherical eyes [81], compound eyes [82], [83], and *ocelli* [84]. Moreover, many groups have been studying the optical flow-based visual motion sensing of flying insects [85]–[87], and implementing such sensors and their image processing to flying robots [88].

Jewel beetles' pit organs can also sense IR light very sensitively so that they can detect fires up to 50 km away because burned trees provide the environment for their larvae to develop and hatch into adults. Several groups investigated the reversible conformational change in the IR sensitive protein of these pit organs and proposed a bio-inspired miniature and low-cost IR sensor that does not need any cooling [89].

For motion sensing, flying insects use halteres, a tiny oscillating beam under the wing with a spherical and larger tip end, or their antennae. Their working principle is the same: linearly driven oscillating structures bend due to coriolis force when the animal's body rotates with a given rotational speed, and by detecting such bending stresses, rotational speeds can be induced in roll, pitch, and yaw directions. A synthetic haltere was proposed by Wu *et al*. [90] for insect-inspired flying robots.

Some electric fishes produce weak (less than 1 V) electric fields around their body using their electric organs discharges (EOD) to detect objects in dark or blurred waters. Objects within this field alter the EOD-induced current at epidermal electroreceptor organs distributed over their entire body surface. These electroreceptor cells are voltage sensors. Using such sensing modality, they can detect, localize, and analyze object types (living or dead) by monitoring self-produced electric signals. Similar electrical sensing function was implemented and integrated to an electric fish-inspired swimming robot [91]. Also, sharks and some other marine fishes use their *Lorenzini ampullae* on their head to have very high sensitivity electrical sensing down to 1 nV/cm to detect their prey fast when they are in very close vicinity and understand the stress level of their prey. Such detection is enabled by the induced voltages due to angular swimming movements of their prey in earth's geomagnetic field; so, there is no active electric field generation in this case.

For force or air/fluid flow sensing, insects use many mechanoreceptors such as hairs for flow and contact detection throughout their body, flex receptors called *campaniform sensilla* as strain sensors on their articulated joints, stretch receptors for muscle position sensing, and chortodonal organs for vibration detection. Rodents and seals use whiskers for contact, surface texture, or turbulent fluid flow detection. Many bio-inspired whisker sensors have been proposed for beating heart position detection and mobile robot obstacle avoidance and surface texture recognition [92]–[94]. Flying insect antennae are used both as odor and gyroscopic sensing. Cockroach antennae can detect and help tracking walls dynamically with their segmented strain sensors providing distributed contact detection. Cockroach-inspired six-legged robots used synthetic flexible antennae with distributed strain gage sensors for wall following applications [95]. Such tactile sensors become crucial under low light or high air-particle content conditions where visual sensors cannot be used. Moreover, tactile sensing provides much faster feedback for dynamic motion control while visual sensors are computationally more expensive and slower.

Additionally, sonar is used as an ecolocation sensor under water or in air by dolphins and bats, which inspired current sonars and radars.

E. Bio-Inspired Control

Animals are capable of dealing with complex unstructured outdoor environments, noisy sensors, and highly redundant mechanical systems to exhibit motor skills that are impressive in terms of agility and efficiency. These skills are still far better than those observed in robots. One simply has to observe a cat jumping, hunting, running, and climbing trees, to see that we are yet far to replicate these impressive motor control abilities in robots.

Experiments on decerebrated and spinalized animals have shown that many of those motor behaviors are implemented at a low level in the vertebrate central nervous system, namely in the brainstem and the spinal cord [96]–[98]. The (vertebrate) locomotor system is organized such that the spinal circuits are responsible for producing the basic rhythmic patterns, and that higher level centers (the motor cortex, cerebellum, and basal ganglia) are responsible for modulating these patterns according to environmental conditions [99]. A key element in the locomotor system is the *central pattern generators* (CPGs) located in the spinal cord. CPGs are neural networks that 1) are capable of producing coordinated patterns of rhythmic activity without any rhythmic inputs from sensory feedback and (2) can be activated and modulated by relative simple signals from higher control centers [98], [100]. These circuits represent the basic building blocks, the *motor primitives*, out of which movements are created (i.e., the "vocabulary" of movement generation). A nice conceptual image of these spinal cord circuits is that of a marionette puppet on strings as proposed by [101] where a pulling a few strings (i.e., activating a few descending pathways) can generate complex coordinated movements of whole limbs.

The concept of CPGs is interesting for robotics [102]. CPGs implemented as coupled nonlinear oscillators can exhibit limit cycle behavior, i.e., stable rhythmic patterns that can recover from transient perturbations, e.g., from the environment. When coupled to a robot (e.g., a dynamic walker), this can lead to robust mutual entrainment between the CPG and the mechanical body [103]–[105]. Also, CPGs are well suited for distributed implementation, which might be interesting for modular robots, such as snake robots and reconfigurable robots. Finally, because CPG models typically have only a few control parameters (e.g., drive signals) to modulate locomotion, they facilitate control and learning by reducing the dimensionality of the control problem.

III. HIGHLIGHTS OF THIS FOCUSED SECTION

We had around 100 papers submitted to the Focused Section while we could accept only 20 papers due to the given page length limit. After a rigorous review process, the following papers were accepted for publication while we could not accept many solid papers unfortunately.

The Focused Section is organized to group the publications in areas of bio-inspired locomotion dynamics and mechanisms, sensing, actuation, and control, respectively.

In bio-inspired locomotion dynamics and mechanisms topics, first, Koh and Cho propose an omega-shaped inchworm-inspired crawling robot with large-index-and-pitch SMA spring actuators. The distinguishing features of the robot are mainly related to the compact design, thus not requiring difficult assembly steps, and to a novel concept for using SMAs, thus allowing to increase the efficiency and the frequency which the actuator can reach. The experimental tests show the potential of the system in terms of locomotion performance, thus providing hints for developing miniature robots with similar technologies.

An approach close to the aforementioned one is proposed by Onal *et al*., who report a worm-type compliant crawling robot manufactured by laser machining of origami patterns and allowing us to obtain in an easy, cheap, and fast way, 3-D robotic systems from 2-D microfabricated foils. By combining this fabrication technology with SMA-actuated hinges, the authors present a working worm-like robot whose performances make visible the potentials of "printable robotics," especially for applications where large payloads are not requested, but hazardous operations are frequent.

A powerful approach to simple control in bio-inspired robots is presented by Boyle *et al*. The authors contribute to the field of snake-like robots for rescue applications by developing a novel robot design based on the mechanisms and neural control of locomotion of a tiny nematode worm. Thanks to the simple yet high-performance decentralized control system, the robot is able to find a path without any form of external sensory capability.

As the legged ground locomotion example, Hutter *et al*. demonstrate an efficient and versatile locomotion platform with highly compliant legs. They report the design and control of a couple of leg prototypes able to perform precise joint torque and position control, adaptation in a passive way to the environment, and exploitation of dynamic motions. These intriguing results are achieved by an integrated design incorporating novel hardware and active damping control. Both legs are intended to be included in robust and highly versatile quadruped robots.

Related to underground locomotion, Omori *et al*. propose a bio-inspired planetary subsurface explorer where they showed preliminary experimental results of a prototype excavator with propulsion and excavation units. The propulsion unit of the system is based on peristaltic crawling and it is able to maintain the body position and orientation during excavation, which is normally extremely challenging. In addition, the excavation performance is really good: they range between 430 and 650 mm, without any slowing, thus opening interesting opportunities for the exploitation of the proposed technology in planetary applications.

As aquatic locomotion systems, a fish-inspired robotic platform is presented by Kopman and Porfiri for research and education in bio-inspired swimming locomotion studies. The robotic fish takes advantages of widely available, low-cost, and resilient off-the-shelf components, thus making the system ideal for education purposes and even for a limited production. The very low fabrication cost (less than 100 USD) allows an easy customization of the device, which can be used also as a basis for further investigations.

Again on aquatic locomotion, Serchi *et al*. report a soft underwater robot inspired by octopus and using vortex propulsion. Although several authors developed underwater machines propelling thanks to streams of fluids ejected through a nozzle and moving in the vortices, the main feature of the proposed device is the true biomimesis, achieved by using silicone molds of a real octopus and replicating all details of the animal. The experimental results demonstrate good potential of the system as a soft unmanned underwater vehicle.

Related to multimodal locomotion mechanisms, Dickson and Clark propose a design of a multimodal climbing and gliding robotic platform called ICAROS. More specifically, the ICAROS platform has demonstrated optimal performance in the combination of these two locomotion modalities and an extraordinary versatility, even if there are other robots able, separately, to climb faster or to fly more agilely. Another relevant feature of this platform is related to the size, which is the smallest available in the state of the art to date.

Doyle *et al*. propose a new avian-inspired passive mechanism for perching quadrotors. The design of the flying robot takes inspiration from songbirds, able to sleep in trees without any active muscle control, and it holds promises for innovative systems for reconnaissance missions. Combination of compliant and underactuated feet and collapsing leg mechanisms is the distinguish feature of the robot. Tests demonstrate an effective robot perching and a reliable stability also under disturbance.

Related to gecko-inspired climbing robots, Hawkes *et al*. present scaling issues of directional adhesives for climbing applications. Interestingly, the authors present a bio-inspired mechanism allowing large patches of directional dry adhesives to reach adhesion levels previously seen only for small samples in controlled conditions. The key considerations in scaling climbing adhesives to large robots (and even humans) are to maintain alignment and uniform load distribution as contact areas increase, despite imprecision in foot placement and loading.

Finally, Hatakeyama and Mochiyama present an original chameleon tongue-inspired shooting mechanism to catch objects in a highly dynamic manner. Two systems are presented with slightly different actuation mechanisms for shooting an end-effector attached to a flexible string on relatively long distances. The system is even capable of catching objects that are behind obstacles.

In bio-inspired actuation topics, Pierce and Mascaro propose an interesting bio-inspired wet SMA-actuated robotic pump. The purpose of such a pump is to manage the flow of a fluid for heating and cooling a series of wet SMAs (i.e., SMAs that are surrounded by fluids for faster actuation thanks to faster heat transfer). The prototype is capable of pumping 2.1 times more fluid than is required for its own actuation, and can therefore provide a net positive thermofluidic output to a system of wet SMAs, therefore paving the way for untethered robots actuated solely by SMAs.

Chang and Kim use ionic polymer-metal composite (IPMC) actuators to develop an insect-inspired aquatic legged robot. The article explores the effect of different levels of wetness of the anode surfaces on the bending properties of the IPMC strips. It also investigates effects of the surface conductivity in an aquatic environment using different types of input signals. Thanks to its 2 DOFs per leg, the hexapod robot can perform a tripod gait in water.

As a new bio-inspired sensing demonstration, Duhamel *et al*. report an innovative bio-inspired optical flow sensing system for altitude control of insect-inspired flying microrobots. The sensor is light enough to be mounted on a very light (68 mg) microrobot with flapping wings. The bio-inspired sensor and control algorithm were successfully used to control altitude online.

In bio-inspired controls topics, we have six papers. Rombokas *et al*. develop a reinforcement-based learning and control method for a tendon-driven hand robot, the ACT Hand. Their control method is inspired by the biological concept of muscle synergies which is a useful way of reducing the dimensionality of the control and learning problem. Using path-integral reinforcement learning, they successfully manage to learn movements such as sliding a switch and turning a knob despite the complex physical properties of the tendon-driven robot.

Brunete *et al*. propose an offline genetic algorithm-based optimization method for heterogeneous modular multiconfigurable chained microrobots. The method is used for determining optimal heterogeneous multiunit structures as well as for designing gaits that can handle different situations such as pipes and uneven terrain.

Bliss *et al*. present a swimmer robot prototype that is constructed as a tensegrity structure composed of bars, cables, springs, and motors that provides a first approximation of the musculoskeletal structure of fish. The control is based on the concept of CPGs, which are bidirectionally coupled to the tensegrity structure such as to obtain mutual entrainment and robust limit cycle behavior. The robustness of the periodic behavior is tested by applying perturbations to the mechanical system as well as variations in the controller parameter selection and observing that the closed-loop system can handle significant perturbations and variations compared to open-loop control.

Huang *et al*. report their study on step length and velocity control of a dynamic bipedal walking robot with adaptable compliant joints. The robot uses the MACCEPA actuator that allows one to control compliance and set position independently. The control scheme leads to energy efficient locomotion with controllable speed and stride length.

Karnati *et al*. propose a novel method of motion planning for an anthropomorphic arm based on movement primitives. They address the complex task of unscrewing and screwing objects with a dexterous anthropomorphic robotic hand in two cases: with the first finger and thumb and also with the little finger and thumb. The sinusoidal trajectories are implemented using a proportional-integral-derivative sliding mode controller for a dexterous artificial hand to ensure overall system stability.

Finally, Ding and Fang present a novel three-level motion-planning framework "joint space–movement primitive space–task space" for an anthropomorphic arm by introducing movement primitives as the bridge connecting the task space and joint space. The proposed method does not only control the motion process of an anthropomorphic arm, but also simplifies the motion planning of complicated operation tasks. The validation and feasibility of the proposed method are verified by simulations and experiments.

IV. Future Trends of Bio-Inspired Mechatronics

Although there have been many progresses on bio-inspired mechatronic systems, many major research challenges still remain unsolved. First, design, actuation, and control of bio-inspired robotic mechanisms for high-speed locomotion with high maneuverability are very challenging such as in the case of flapping wing-based flight, high-speed legged running on ground or on water, and high-speed climbing. Exploiting the passive dynamics of compliant motion mechanisms and soft materials is a crucial aspect of dynamic and soft robots where modeling, design, manufacturing, and control of such underactuated soft/compliant systems remain as a significant challenge. Many groups are investigating these challenges as one of the exciting future trends.

Most of the current works have focused on single locomotion systems while animals could have multimodal locomotion to operate in uncertain environments. Therefore, design, actuation, and control of multimodal locomotion systems with multifunctional or highly integrated mechanisms, actuators, and sensors are promising research directions.

Animals can operate on a wide range of terrains, and bio-inspired robotic counterparts are not that multiterrain yet. By understanding the multiterrain locomotion dynamics, actuation, and transitioning control methods in detail, we could have multiterrain robots that could operate on solid ground, sand, mud, water, and rocks.

Automated high- and low-level control of dynamic bio-inspired robotic platforms is still an important challenge, and many people are studying such control methods coupled with the given robot's mechanical, actuation, and sensing design. On the other hand, computational modeling and experimental characterization of fluid–structure interactions in compliant systems are essential for our detailed understanding of animal and robotic locomotion systems, and more advanced and fast computational methods, which could be also used in design of robotic platforms, are a significant trend in theoretical and experimental mechanics studies.

Finally, it is important to have advanced new bio-inspired or other man-made materials, which enable high performance and robust locomotion functions of animals, with limited power consumption. Such materials include high strength-to-weight ratio composite materials as in the case of bones, shells, tooth enamel, and silk, repeatable adhesives as in the case of geckos and insects, stiffness tunable materials and structures as in the case of muscles and sea cucumbers, reduced drag surfaces as in the case of shark, dolphin and other fish skin, superhydrophobic and mechanically robust self-cleaning coatings for wet environment operation and easy cleaning, new robotic soft skins and actuators with embedded and distributed sensing, and self-healing materials that are robust against mechanical failure in robot mechanisms.

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