PREFACE

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PREFACE

Perspectives on biologically inspired hybrid and multi-modal locomotion

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1. Multi-modal locomotion of organisms

In recent years, much attention has been directed to building robots with hybrid and multi-modal locomotion in air, water and on the ground. This rise in interest is due to the enormous requirements of multi-domain earthquake rescue, pollution monitoring, natural species discovery and other applications in which multi-modal locomotion can offer unprecedented advantages to robot mobility. Swimming, crawling, rolling, walking, running, jumping and flying are quite common in the animal kingdom, and such locomotion occurs in very different physical environments. Interestingly, an animal may perform two or more modes of locomotion. For instance, turtles and salamanders can swim underwater and walk on land, while swans can swim and fly effectively. Their often remarkable abilities could inspire innovative designs to improve the way man-made systems operate in and interact with challenging outdoor environments consisting of multiple media.

Modes of locomotion in nature can be decomposed broadly into three categories: terrestrial, aerial and aquatic. There are situations in which the distinction between categories is vague, such as movement on the surface of water or in underground tunneling. However, generally, the types of locomotion used by animals can be categorized into one of these three areas.

The primary venue of locomotion for many animals tends to be mono-modal; the majority of their task-space demands only a singular modality, with minimal need of alternative morphologies for transportation. The fundamental reason for multi-modal animal locomotion is for survival. The need for these multiple modes can arise from different requirements related to survival, including fast escape, fast pursuit, searching for food, breeding, nesting, conserving energy and migration.

Most phylogenetic lineages of organisms are conservative in terms of habitat use, but some groups display major shifts in this trait. Some of the most spectacular examples of such phylogenetic shifts involve the invasion of aquatic (especially marine) habitats by terrestrial taxa. Because of the very different physical properties of air and water, selective pressures for effective locomotion can generate massive morphological divergences. Shine and Shetty \cite{Shine2015} discussed the aquatic and terrestrial locomotion by studying the data gathered on speeds of sea kraits in water and on land. Multiple invasions of oceanic habitats by terrestrial organisms thus provide an excellent opportunity to investigate the process of adaptation in general and the nature and magnitude of trade-offs involved in adaptive transitions between alternative modes of locomotion. As pointed out by Shine \textit{et al} \cite{Shine2013}, amphibious animals may be subjected to strong but conflicting selective pressures to enhance locomotor performance both on land and in water. Biomechanical models suggest that in snakes, adaptations to swimming (e.g. reduction of ventral plates, flattening of tail) will reduce their ability to move on land.

It is impossible to simultaneously optimize performance in two tasks that require mutually incompatible morphologies or physiologies. In addition, conflicting optima can occur for many kinds of traits, but the easiest to study are those in which performance can be easily quantified and optima can be easily identified.

Thus, the most clear-cut examples of trade-offs in locomotor performance involve species that move in highly contrasting ways such as running versus flying or swimming. The results showed that locomotor speeds of amphibious sea snakes vary among species, differ between the sexes within species and change
with body sizes. A snake’s species and sex also affect its relative speed in terrestrial versus aquatic locomotion. In the paper by Shine et al each of these effects was examined with the aim of evaluating conclusions and predictions from an earlier study [1].

As highlighted by Marlene [3], animals’ kinematic changes between air and water can be understood in terms of the mechanical loads characteristic of these different fluid environments. The increased buoyancy and hydrodynamic forces in water compared to those on land can cause a shift in the predominant destabilizing forces an animal experiences. An animal using pedestrian locomotion under water must contend with hydrodynamic forces that can prevent it from locomoting quickly or that can cause it to overturn or wash away. In addition to an animal’s morphology, factors such as posture, behavior and water flow environment dramatically influence the hydrodynamic forces the animal experiences.

In another study of an animal’s multi-modal locomotion, Marlene measured hydrodynamic forces on the amphibious shore crab Grapsus tenuicrustatus in aquatic and terrestrial postures. The amphibious shore crab changes body posture as well as kinematics, using a different locomotory gait on land than in water [4]. The crabs walk on land at slow speeds, but in water at these same speeds, the crabs use a more variable gait (submerged punting), characterized by alternating thrust generation and gliding. Due to the lower hydrodynamic forces in the aquatic posture, a crab could move up to 50% more quickly than it could in the terrestrial posture or through a faster water flow environment [5]. Marlene also found that in slower flow environments, animals can move faster and take advantage of different gaits that are not available to them in faster flow environments.

A brief survey on the recent application works of hybrid and multi-modal locomotion is presented in the following sections.

2. Hybrid air-water mobility

Current Unmanned Aerial Vehicles (UAVs) are greatly limited by being able to operate in air only, preventing them from moving effectively on the ground or in water. Developing robots with hybrid air-water mobility would address the need for remote water sampling in inaccessible areas during disasters. Of particularly high importance is the detection of chemicals and biological contaminations in the sea, in coastal regions or in urban areas where humans are in contact with water. This is of paramount interest in disaster scenarios such as flooding situations, after chemical or nuclear accidents and during oil spills. Recent examples, such as the BP Deepwater Horizon Oil spill in 2010 or the Fukushima nuclear accident in 2011, show the urgent need for remote sensing capability in hazardous situations to better react to emergencies and coordinate manned interventions.

While some UAVs can land on water, no technology is available that would allow them to both dive and fly due to dramatic design trade-offs that have to be solved for movement in both air and water and due to the absence of high-power propulsion systems that would allow a transition from underwater to air. However, in nature a variety of animals are able to move in both air and water such as diving birds, flying squid and jumping fish. In the following sections, existing concepts of air-water mobility in robotics will be reviewed, and a summary of the design principles for the next generation of flying robots with hybrid mobility capabilities will be provided.

3. Air-Water mobility in robotics

One of the main challenges in the design of aerial-aquatic vehicles includes the design of the mission profile. A variety of approaches can be taken to achieve aerial water sampling (figure 1). For example, a water sampling probe can be descended from a hovering UAV (figure 1(A)) or a simple floating UAV (figures 1(B) and (C)) might be used to land on the water surface and take a water sample. However, these concepts are inherently limited by either very short flight times or susceptibility to surface movement and by waves that can be detrimental to the operation of the UAV. Other concepts include dropping an underwater vehicle from the UAV (figure 1(D)) for single-use missions or using the propellers to move underwater (figure 1(E)), although the propellers that are used for flight are not adapted for underwater operation due to the different fluid properties. Looking at nature, a variety of solutions for air-water mobility has evolved, with several animals executing a plunge dive maneuver, i.e. drop-diving from air to water and transitioning back to flight directly from under the water’s surface. This approach of dynamic air-water-air locomotion (figure 1(F)), although a technically challenging solution, is very promising for high-frequency water sampling in cluttered and unpredictable terrain, with a high robustness to water waves and an avoidance of floating obstacles that would prevent hydroplane style landing and take-off.

The challenges in the design of such aerial-aquatic robots or Aquatic Micro Aerial Vehicles (AquaMAVs) include platform design, high power density propulsion systems and control across the air-water interface. Novel robotic technologies, fluid structure interaction principles and control methods need to be developed to enable the implementation of AquaMAVs. In efforts toward implementing AquaMAVs, studies have been conducted on the implementation of plunge diving capability in a flying vehicle [5–7], and Liang et al [7] have developed a testing platform able to fold its wings before diving into the water. However, these systems are currently experimental platforms and are not able to fully transition between air and water.

Propulsion in both air and water has been studied in [8–10] using a flapping wing approach for diving-bird-
inspired flapping flight. Using a hydroplane style surface landing approach, many existing robotic aerial vehicles use the water’s surface as an extended runway. While none of these robots are able to operate beneath the surface, some systems deploy underwater vehicles from the air but are usually reliant on single-use, disposable equipment such as parachutes, airbags and disposable wings. However, the existence of demand for air launched underwater vehicles [11] is important nonetheless, and several military programs have attempted to create manned submersible aircraft [12, 13]. A fully integrated AquaMAV would have the ability to be launched from underwater from an autonomous surface vessel as well as from the air, offering added mission capability to existing unmanned vehicle frameworks.

Although several different approaches have been taken in the design of an aerial-aquatic vehicle, a fully functional AquaMAV has yet to be presented. Inspiration from biology, in combination with the best of robotic engineering and a thorough understanding of the fluid dynamics involved in the process, will be a key to achieving this objective and developing this next generation of UAV.

4. Design principles for effective air-water mobility

In the animal kingdom, the combination of aerial with underwater locomotion is very prevalent, with several species able to transition between the two medium very effectively. Examples include flying fish, flying squid, diving birds and diving insects (figure 2) [15]. We have summarised the advantages and limitations of several animals and robots with aerial-aquatic capabilities in table 1 [15].

Taking inspiration from these animals, we can extract the key design principles that make their mobility effective. In this process of biological inspiration it is important to adopt only the principles and not copy the exact morphology of the animals. To this end, we adopt the Inspire-Abstract-Implement paradigm for bioinspired robot design (figure 3) [14] that outlines how the successful robots can be built based on principles from biology.

While each animal has a distinct set of locomotion modes, several recurring principles can still be extracted. Based on the analysis in table 1, the most important principles are: (i) using jet propulsion, (ii) employing a wing folding mechanism and (iii) performing a plunge diving approach for the transition from air to water by using the flight momentum to move underwater.

The main challenge for the propulsion unit is achieving the very high power density required for take-off. For example, flying fish reach a speed underwater of around 20 body lengths per second. This performance is one order of magnitude higher than what has been achieved with swimming robots so far [15]. Moreover, miniaturisation of the mechanism would make it very difficult to build a vehicle at a very small size.
size that requires a propulsion choice that can be fabricated across the range of AquaMAV sizes. An alternative and easily scalable propulsion approach is offered by water jet propulsion. Using pre-charged or locally generated pressure, scalable mechanisms can be designed to eject water, allowing for thrust in both water and air. In the animal kingdom, water jet propulsion is used by flying squid that can range from several centimeters to several meters in size, proving the utility and effectiveness of the approach. The first robotic implementations of the high-power water jet propulsion mechanisms are presented in \[15, 16\].

Most animals have a folding wing mechanism that offers protection for their often fragile wing structures. Folding wings are also used by many birds to actively modulate the wing shape to initiate and guide dynamic flight behaviours. All aerial-aquatic animals use some kind of folding wings. Most notably, flying fish and flying squid use them to sustain lift in air while having them shaped differently in water for efficient swimming. Gannets also fold their wings to reduce the impact forces on their body when diving through the water’s surface, allowing them to reach depths easily. For AquaMAVs, using folding wings is likely a preferred choice to protect the wings from mechanical damage on impact, to use the flight momentum to dive deeply without needing underwater buoyancy control and to potentially use the folding wings for efficient dynamics in both air and water.

Aerial-aquatic mobility is the next step for flying robots to enable applications such as water sampling, oil spill response and underwater inspection. The challenges that need to be addressed in the development of these AquaMAVs include propulsion methods and wing folding principles and their integration with novel control approaches for operation in both air and water. Building on principles found in nature by diving birds and flying sea animals, we can develop AquaMAVs and advance the fields of mobile robotics.

5. Recent works on land-water locomotion

In the field of hybrid or multi-modal locomotion, biologists and robotists have collaborated and achieved meaningful results. On one hand, biological emulation and investigation have inspired engineers and have been fused into implementing novel mechanisms and/or improving pre-existing prototype performance [40–42]. On the other hand, robotic prototypes have been developed to understand hybrid locomotion principles [10, 43–57]. Experimental observation on multi-modal locomotion is often limited to the behaviors voluntarily executed by amphibious animals. Moreover, the measurement of biomechanics and dynamics on free locomotion is also a challenging task.

Typical cases of multi-modal locomotion include swimming robots with walking and/or flying abilities within amphibious behaviors. Low et al [43] proposed and developed swimming and crawling gait and action patterns of an amphibious land-water robot inspired by sea turtles, as depicted in figure 4. Ijspeert et al
Table 1. Key design principles of aerial-aquatic locomotion in nature and robotics reproduced with permission from [15], copyright IOP Publishing.

<table>
<thead>
<tr>
<th>Animal</th>
<th>Dry Flight</th>
<th>Water Entry</th>
<th>Submerged Movement</th>
<th>Water Exit</th>
<th>Wet Flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flying Fish (Exocoetidae)</td>
<td>Flight in ground effect to reduce drag [17]. Thin, flexible wings for stall performance and stability [18, 19].</td>
<td>Wings lie flat against the body [20].</td>
<td>Oscillating tail fin propulsion; swim bladder allows changes in buoyancy [21].</td>
<td>Taxing acceleration with only propulsive fin submerged [20].</td>
<td>Hydrophobic mucus helps shed water. Intermittent taxiing to increase speed.</td>
</tr>
<tr>
<td>Flying Squid (Ommastrephidae)</td>
<td>Water jet propulsion provides thrust [22]. Elliptical wing to reduce wing tension [23].</td>
<td>Fore wings lie flat against the body. Hind wings streamlined backward [24].</td>
<td>Water jet propulsion [25] or flapping wings/fins [26]. Intermittent locomotion used to conserve energy [27].</td>
<td>High-speed leap, followed by water jet thrust to accelerate [24].</td>
<td>Flying time limited by muscle tension and oxygen; flight is ended deliberately by air braking and diving [28].</td>
</tr>
<tr>
<td>Ganne (plunge diving) (Sulidae)</td>
<td>High-aspect ratio wings for efficient loitering [29]. Feathered wings adapt to wind perturbations [18].</td>
<td>Wings swept to 90°; air sacs cushion impact [30]. Flight into wind for low-groundspeed and fast-dive response [29].</td>
<td>Little swimming [31], depth gained by dive momentum; buoyancy used for ascent [32].</td>
<td>Hydroplaning taxiing by flapping and foot propulsion.</td>
<td>Water-repellent feathers shed moisture. Foraging upwind of nest, so tailwind aids return flight when food and water add to weight.</td>
</tr>
<tr>
<td>Cormorant (foot propelled) (Phalacrocoracidae)</td>
<td>Relatively high weight compensated for by large wings [33]. Feathered wings.</td>
<td>Slowed descent and soft, floating landing. Short dive-initiating leap from the surface.</td>
<td>Foot propulsion with wings folded. Depth compresses air to reduce buoyancy [34]. Intermittent kicking/gliding for efficiency [35].</td>
<td>Hydroplaning taxiing by flapping and foot propulsion.</td>
<td>Drying period on land [36]. Foraging upwind of nest for efficient return flight.</td>
</tr>
<tr>
<td>Guillemot (wing propelled) (Alcidae)</td>
<td>Small wings adapted for swimming [21], compensated for by fast flapping and short flights [29]. Feathered wings.</td>
<td>Slowed descent and soft, floating landing. Dive begins from standstill.</td>
<td>Flapping propulsion, with wings morphed shorter [7]. Depth compresses air to reduce buoyancy.</td>
<td>Hydroplaning taxiing by flapping and foot propulsion.</td>
<td>Drying period on land [37]. Foraging upwind of nest for efficient return flight.</td>
</tr>
<tr>
<td>Diving Beetle (Dytiscidae)</td>
<td>Insect flight by rapid flapping of hind wings.</td>
<td>Dive begins from standstill. Wings fold beneath forewings/shell [38].</td>
<td>Kicking foot propulsion with wings folded. Air trapped beneath wings for breathing.</td>
<td>Flight from standstill on land.</td>
<td>Drying period on land.</td>
</tr>
<tr>
<td>Robot US NRL 'Sea Robin'</td>
<td>Dry Flight Fuel-cell-powered propeller thrust.</td>
<td>Water Entry Landing is final; craft not designed to relaunch.</td>
<td>Submerged Movement Not possible</td>
<td>Water Exit Discardable torpedo and deployable wings.</td>
<td>Wet Flight Not possible</td>
</tr>
<tr>
<td>Beihang U'Bionic Gannet'</td>
<td>Currently a non-flying test platform.</td>
<td>Plunge diving, impact reduced by variable wing sweep.</td>
<td>Passive plunge dive</td>
<td>Not yet possible</td>
<td>Currently a non-flying test platform.</td>
</tr>
</tbody>
</table>
Figure 3. Inspire-Abstract-Implement bioinspired design paradigm [14] in which the bioinspired design process can be separated in three distinctive phases which integrate the abstraction of biological design principles with modern engineering tools. Reproduced with permission from [14], copyright Soft Robotics.

Figure 4. Land-Water amphibian robot inspired by turtles [43]: (A) swimming and crawling turtles, (B) Crawling gait of a sea turtle, (C) Crawling gait of a turtle-inspired robot and (D) Swimming gait of a turtle-inspired robot. Reproduced with permission from [43], copyright 2007 IEEE.

Figure 5. Hybrid land-water locomotion of biological and robotic systems within amphibious behaviors. (A) Salamandra robotica I driven by a spinal cord CPG model [56], (B) Salamandra robotica II, a salamander robot that can swim and walk, was designed to test hypotheses about the organization of salamander spinal circuits and the mechanisms of gait transition [48]. Images used with permission courtesy Biorobotics Laboratory EPFL.
focused on using robotic models to understand behaviors of amphibious salamanders, as shown in figure 5. The transition from aquatic to terrestrial locomotion was implemented and further understood using a neural central pattern generator (CPG) control scheme in the vertebrate multi-modal robotic prototype. Furthermore, a CPG control architecture was developed for controlling the hybrid locomotion of an amphibious snake/lamprey robot capable of swimming and serpentine locomotion. Yu et al [46] proposed and implemented a versatile amphibious robot, AmphiRobot-II, inspired by various amphibian principles in the animal kingdom. A novel hybrid propulsive mechanism coupled with wheel-propeller-fin movements was proposed that integrates fish- or dolphin-like swimming and wheel-based crawling. The robot is not only able to implement flexible wheel-based movements on land but is also able to perform steady and efficient fish- or dolphin-like swimming under water. Furthermore, it can switch between these two patterns via a specialized swivel device.

Extensive works on bioinspired legged robotics have produced robots that have been suggested to perform a variety of tasks in dynamically changing environments. Some of these robots achieve these tasks through multiple locomotion modes as shown by animals [49, 56, 58, 59]. Multi-modal locomotion, particularly that of the multi-legged robotics, has recently gained increasing interest due to its ability to achieve natural interaction between the mechanical dynamics of the robot and the environment. Locomotion dynamics are the result of interactions between a particular internal control structure, the mechanical dynamics of the robot’s body and the environment [60, 61]. In addition to low-power systems and portability, which are vital challenges that substantially limit any successful biorobotic-based application, the proposed paradigms should also take into account issues related to scalability and security.

6. Works related to air-ground locomotion

In nature, many animals that can fly can also move on ground effectively by either walking, crawling or jumping. Walking birds or insects are examples of this faculty, offering precise ground locomotion to the animal in addition to its flying capacity. There are some animals that use their ground mobility as a way to transition from ground to air, e.g. by jumping, which is then followed by gliding flight. Examples of such jump-gliding animals include gliding lizards, locusts, gliding geckos, gliding ants, spiders, gliding frogs, jumping bats, gliding mammals, gliding snakes and many birds (figure 6) [62]. Jumping and gliding can also be found amongst extinct species, such as the Sharovipteryx, and amongst some lizard-like reptiles with similar wings to that of the Draco lizard. Although all of these animals have very different body morphologies, they have converged in their evolution by adopting a hybrid jumping and gliding locomotion strategy. As the focus of this article is of a technological nature, the reader may refer to [63–65] for in-depth reviews of jump-gliding animals, with detailed descriptions of morphology and behavior.

In robotics, jump-gliding robots have recently gained attention, and several groups have developed prototypes (figures 7(A)–(D)) [49, 66–71] with the motivation to reduce the energy cost of transport and
extend flying robots with locomotion on ground. A related class of mobile robots includes propeller or flapping-wing-propelled vehicles that have added ground mobility [66, 68] using legs or whegs (figures 7(E) and (F)). These hybrid robots offer proof-of-concept implementation of multi-modal mobility for aerial vehicles, and they demonstrate the potential of combining ground and aerial locomotion. However, the field on multi-modal mobility is still at its early stages, and there are many unexplored avenues on how to combine aerial with ground and aquatic locomotion. Challenges include actuation, materials, propulsion, control and system integration. Thus, this field offers a wide range of possible research topics. Biological inspiration and creative design beyond the commonly employed airframes and control schemes will be a key in the development of these next-generation multi-modal robots.

7. Relevant IROS 2013 workshop and special issue

Biologically inspired concepts for hybrid and multi-modal locomotion have revealed new challenges regarding mechanism design, sensor integration, control theory, robustness, adaptability, etc. These challenges must be overcome if we are to reduce the performance gap that exists between biological and robotic systems. Recent advances in biorobotics have helped bridge the gap between robotists and biologists; thus, recent mechatronic systems and robots are controlled in a way that reflects better understanding of complex living organisms.

The IEEE Robotics and Automation Society Technical Advisory Committee on BioRobotics organized a workshop on ‘Biologically inspired based strategies for hybrid and multi-modal locomotion’, in conjunction with the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) that was held at Tokyo Big Sight, Japan on November 3–7, 2013. The aim of the workshop was to explore and tackle the challenges of applying biologically-based concepts to robots in order to improve the robotic capabilities. The specific focus was on hybrid and multi-modal locomotion in air, water and/or on land.

The IROS 2013 Workshop consisted of four sessions: multi-modal ground robots, multi-modal locomotion dynamics, swimming and amphibian robots and multi-modal aerial robots. Four keynote speakers and several others were invited to present their work on the relevant fields. All scientists who presented their work at the workshop were invited to submit their work for review and possible publication in Bioinspiration & Biomimetics.

In this special issue, seven distinguished research teams with biology and engineering backgrounds present their ideas and works to fuse biological inspirations into robotic hybrid locomotion. Among the seven papers, one paper is concerned with the flapping wings inspired by bat and bird morphology, another paper focuses on a bioinspired underwater robot, four papers consider bioinspired land robots in different locomotion modalities and modes and one paper is devoted to the formulation schemes of bioinspired locomotion by virtue of multibody systems dynamics.

In the first paper, Stowers and Lentink present a new mechanism for passive wing morphing of flapping wings inspired by bats and birds. The mechanism
consists of an unactuated hand wing connected to the arm wing with a wrist joint. To better understand the passive dynamics, a computer model of the unfolding process was constructed using rigid body dynamics, contact models and aerodynamic correlations. This model predicts the measured passive unfolding within about one flap and shows that unfolding is driven by centrifugal acceleration induced by flapping. These simulations indicate that unfolding is dominated by centrifugal accelerations induced by wing flapping rather than aerodynamic or gravitational forces. Finally, it is experimentally shown that passive unfolding wings can withstand impact with a branch by first folding and then unfolding passively. This mechanism enables flapping robots to squeeze through clutter without complex control. Experiments suggest that friction in the hinge should be minimized to the largest extent possible. The predicted unfold time based solely on centrifugal acceleration is on the order of one wingbeat and can be as short as half a wingbeat. This insight, corroborated from the theoretical, numerical and physical analysis of a flapping folding wing, provides new research avenues for the functional interpretation of the muscle groups that control vertebrate hand and arm wings.

Bioinspired sensing modalities enhance the ability of autonomous vehicles to characterize and respond to their environment. The paper by DeVries et al describes the design and implementation of a multimodal artificial lateral line for flow sensing and feedback control of an underwater vehicle. By employing an artificial lateral line, the performance of underwater sensing and navigation strategies is improved in dark, cluttered or murky environments where traditional sensing modalities may be hindered. The estimation and control strategies enable an airfoil-shaped unmanned underwater vehicle to assimilate measurements from a bioinspired, multi-modal artificial lateral line and to estimate flow properties for feedback control. The robotic prototype outfitted with a multimodal artificial lateral line composed of an ionic polymer metal composite and of embedded pressure sensors experimentally demonstrates the distributed flow sensing and closed-loop control strategies.

Inspired by observations from a biological runner, the paper by Park and Kim presents a bioinspired quadruped controller that allows variable-speed galloping. The developed controller estimates the required vertical impulse at each stride by applying the linear momentum conservation principle in the vertical direction and prescribes the ground reaction forces at each stride. Based on a biological observation, a new control design scheme is proposed for high-speed galloping in the MIT Cheetah 2 robot. A stable 3D galloping controller is currently applied to the MIT Cheetah 2 robot and will be implemented in indoor running of the robot.

One of the most significant challenges in bioinspired robotics is determining how to make use of multi-modal locomotion to help robots perform a variety of tasks adaptively in different environments. In order to address the challenge properly, it is important to understand that locomotion dynamics are the result of interactions between a particular internal control structure, the mechanical dynamics and the environment. The fourth paper by Nurzaman, Kim and Lida presents an approach to enable a robot to take advantage of its multiple locomotion modes by coupling the mechanical dynamics of the robot with an internal control structure known as an attractor selection model. The robot considered is a curved-beam hopping robot that possesses rich and complex mechanical dynamics that are dependent on its interactions with the environment. Through dynamical coupling, the robot performs goal-directed locomotion by gracefully shifting between different locomotion modes regulated by sensory input, the robot’s mechanical dynamics and an internally generated perturbation. The coupling between the mechanical dynamics and the attractor selection mechanism enables the robot to take advantage of the different locomotion modes to bring itself toward the goal. The approach was also implemented in a real robot, enabling it to perform goal-directed locomotion based on the same principle.

Animals have demonstrated the ability to move through, across and over some of the most daunting environments on earth. This versatility and adaptability stems from their capacity to alter their locomotion dynamics and employ disparate locomotion modalities to suit various terrains. Dynamic climbing captures the underlying pendular motion observed in studies of cockroaches and geckos running on vertical substrates. The paper by Miller et al presents a biologically-inspired model for dynamic climbing that captures the underlying pendular motion observed in studies of cockroaches and geckos running on vertical surfaces. This model was inspired from observations of similar gait characteristics in the dynamics of rapidly climbing cockroaches and geckos. This paper investigated several of these factors and proposed policies and methodologies to improve performance and reliability on both dedicated climbers and multi-modal systems.

Recent works suggest that jumping locomotion in combination with a gliding phase can be used as an effective mobility principle in robotics. The paper by Vidyasagar et al evaluated the performance of jump-gliding locomotion and provides models for the relevant dynamics of flight. It also defines a jump-gliding envelope that encompasses the range that can be
achieved with jump-gliding mobility and that can then be used to evaluate the performance and improvement potential of jump-gliding robots. In order to validate the prediction of these models, a jump-gliding robot, named the ‘EPFL jump-glider’, has been tested in experiments to perform jumps from elevated positions, to perform steered gliding flight, to land safely from considerable heights and to move on ground by repetitive jumping.

The last article of the special issue by Boyer and Perez developed a set of generic tools for multibody systems dynamics devoted to the study of bioinspired locomotion in robotics. In considering a general problem of locomotion, they progressively drew a unified geometric picture of locomotion dynamics, starting from the model of discrete mobile multibody systems, followed by the case of continuous and finally soft systems. Starting from animals before moving on to robots, it is shown that there is a need to develop methodological tools for designing, modeling, control and motion planning of a new generation of robots with multi-degrees of freedom. The paper also addresses the practical problem of the efficient computation of these models by proposing a Newton-Euler-based approach to efficient locomotion dynamics, with a few illustrations of creeping, swimming and flying. The authors discovered that behind their apparent diversity, many locomotion modes share common geometric structures.

8. Concluding remarks

As discussed in this article and covered by the papers in this special issue, various modes of locomotion that can be adopted by different genus groups in multiple media are investigated to understand the compromise in ability adopted by the animals when achieving multi-modal locomotion. Considering all of the natural examples shown for aerial, aquatic and/or terrestrial operations, it would appear that using distinct locomotive mechanisms for multi-modal operations of this type is advantageous. This is true for both birds and insects, with birds having the advantage of higher feasible scalability of functions. More experimental works would be required to determine if the terrestrial ability has led to a decrease in aerial ability within a specific species.

Many different types of locomotion are used across the biological classes, but it should be noted that each has a varying level of competence within the substrate, and as such, careful consideration must be given before assuming that mimicking the animal’s techniques will provide the most suitable combination for real-world engineering problems [40, 48, 60, 72–74].

In the near future, much closer biologist-and-robotist collaboration will still be an important step for developing multi-modal locomotion. More innovative biorobots are to be developed to emulate and investigate hybrid locomotion since man-made prototypes outperform repetitive behaviors and influential factor isolation when compared to animals. Biomechanics on transition among jumping, walking, running, rolling, crawling, swimming and/or flying should be focused on. Agile movements of animals should be further understood in principles of their central and peripheral nervous systems as well as their musculoskeletal system. Certainly, their adaptation to varying environments is also a really interesting and inspiring component. Furthermore, inspiration from emulating or understanding multi-modal locomotion should promote robotics performance and enable more practical applications. Smart materials, flexible mechanisms and advanced control strategies are essential to realize the enormous potentials in industrial, educational, common-health, security-related, home-service and special fields of robotics.

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