Solution-driven bioinspired design: Themes of latch-mediated spring-actuated systems

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Our ability to measure and image biology at small scales has been transformative for developing a new generation of insect-scale robots. Because of their presence in almost all environments known to humans, insects have inspired many small-scale flying, swimming, crawling, and jumping robots. This inspiration has affected all aspects of the robots' design, ranging from gait specification, materials properties, and mechanism design to sensing, actuation, control, and collective behavior schemes. This article highlights how insects have inspired a new class of small and ultrafast robots and mechanisms. These new robots can circumvent motors' force-velocity tradeoffs and achieve high-acceleration jumping, launching, and striking through latch-mediated spring-actuated (LaMSA) movement strategies. In the article, we apply a solution-driven bioinspired design framework to highlight the process for developing LaMSA-inspired robots and systems, starting with understanding the key biological themes, abstracting them to solution-neutral principles, and implementing such principles into engineered systems. Throughout the article, we emphasize the roles of modeling, fabrication, materials, and integration in developing bioinspired LaMSA systems and identify critical future enablers such as integrative design approaches.

Introduction

Over the last few decades, interest and progress in insect-scale robotics have dramatically increased, opening new possibilities to explore environments autonomously.[1–3] When working collectively, insect-scale robots can aid with multiple applications, including search and rescue, surveillance, micro-construction and assembly, manipulation, and medical devices. For example, insect-scale crawling robots have the potential to locomote through the human body and advance medical imaging techniques.[4] In industry, small robots can aid in tasks that require automated handling and assembly of parts with submicron-scale accuracy.[5–7] Not surprisingly, insects and other microscale organisms have inspired these small-scale robots' design, control, and collective behavior concepts.[8–10]

At small scales, biological organisms exhibit movement and manipulation strategies that are far superior to those of most existing robots. Latch-mediated spring-actuated (LaMSA) movement is an example of a biologically inspired strategy that has significantly impacted the design of novel insect-scale robots. Animals from diverse phyla (**Figure 1**) achieve ultrafast movements, such as jumping or striking, by implementing LaMSA strategies and can be collectively referred to as LaMSA systems. In LaMSA systems, muscles or actuators load elastic body elements or springs relatively slowly but forcefully. Once the spring contraction is complete, a latch is disengaged, mediating the release of energy from the spring. When the latch is fully disengaged, the spring recoils quickly, causing an ultrafast motion. Thus, the movement is not directly actuated by the muscles; it is spring-driven. The speeds and accelerations produced by this movement strategy circumvent muscle limitations for these volume-constrained organisms. Several recent studies have reviewed and detailed progress in LaMSA and LaMSA-inspired systems.[11,12]

Rather than offering another review of LaMSA systems, in this article, we apply a solution-driven bioinspired design framework (**Figure 2**)[20,21] to highlight the process for developing LaMSA-inspired robots and systems, starting with understanding the enabling biological themes, abstracting

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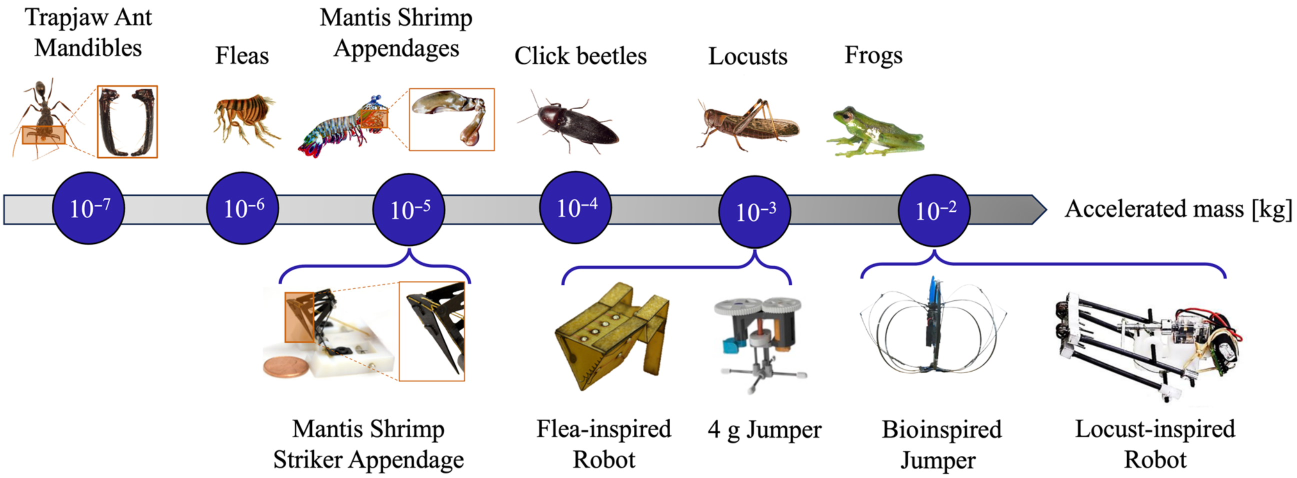

Figure 1. Examples of the diverse organisms that implement latch-mediated spring-actuated (LaMSA) movement strategies and LaMSA-inspired robots and mechanisms. Trap-jaw ant photo adapted from Reference 13 under standard Proceedings of the National Academy of Science (PNAS) license terms. Flea photo credit from public domain. Mantis shrimp photo credit from @dorographie, Unsplash, licensed under CC0. Mantis shrimp dactyl photo credit from Roy Caldwell. Frog photo credit from Jithin Vijayan, licensed under the Creative Commons Attribution 4.0 International License. Locust photo credit from Database Center for Life Science, licensed under the Creative Commons Attribution 4.0 International License. Mantis shrimp striker appendage adapted from Reference 14 under standard PNAS license terms. Flea-inspired robot adapted with permission from Reference 15. © 2012 IEEE. 4 g jumper designed in Reference 16. Bioinspired jumper adapted with permission from Reference 17. © 2022 Nature. Locust-inspired robot adapted with permission from Reference 18. © 2015 IEEE.

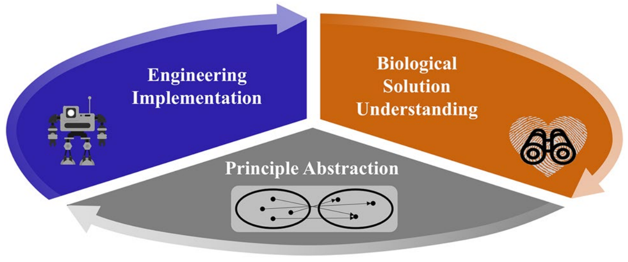

Figure 2. The solution-driven bioinspired design framework used to highlight recent advances in latch-mediated spring-actuated (LaMSA) and LaMSA-inspired systems.

them to solution-neutral principles, and implementing such principles into engineered systems. Thus, we use examples of LaMSA and LaMSA-inspired systems to showcase how biological observations, analytical modeling, novel materials, and advanced fabrication techniques played a critical role in developing diverse robotic systems either inspired by a particular organism or based on generalized themes abstracted from LaMSA movement strategies across various organisms. Throughout the article, we also highlight research opportunities and the gaps and challenges that, if resolved, can revolutionize the next generation of insect-scale robots and answer critical questions about the organisms that inspire them.

Biological themes

Organisms that can move at exceptional speeds can be found throughout various biological kingdoms. However, our relatively recent ability to measure biological movements at small scales and high frame rates has revealed that some of the most rapid and highest acceleration movements in nature are actually observed at smaller scales. Small animals as varied as locusts,[22] froghoppers,[23] fleas,[24] and soft-bodied midges[25] have been noted through the biological literature for their jumping ability, whereas other animals such as snapping shrimp,[26] mantis shrimp,[27] trap-jaw ants,[28] and vampire ants[29] are known for their striking or clubbing ability. These animals are often notable because they can generate higher power density than is possible with muscle alone. Similarly, plants such as witch hazel[30] launch seeds at high speeds, Venus flytraps use fast motions to capture insects,[31] and fungi use high accelerations to disperse spores.[32] The study of these small, fast biological systems has become more accessible with advanced high-speed imaging, enabling scientists to better understand how these organisms can achieve these exceptional feats and establish a number of common themes across these organisms.

A defining feature of the most impressive of these organisms is that their jumps, throws, and strikes are often powered by springs. Several papers have recently outlined the general principles behind these organisms, defined as latch-mediated spring-actuation (LaMSA) systems.[11,12] The key biological themes of LaMSA movement in biology are related to energy transfer and power transmission. As shown in **Figure 3**, these systems are often defined by the energy flow through the system over time. Potential energy is slowly stored in a spring by an actuator or the muscle, and a latch is used to mediate the release of this potential energy to kinetic energy (e.g., kinetic energy in an appendage for a strike). Finally, that kinetic energy is dissipated within the body frame and through interaction with the environment (e.g., a trap-jaw ant mandible

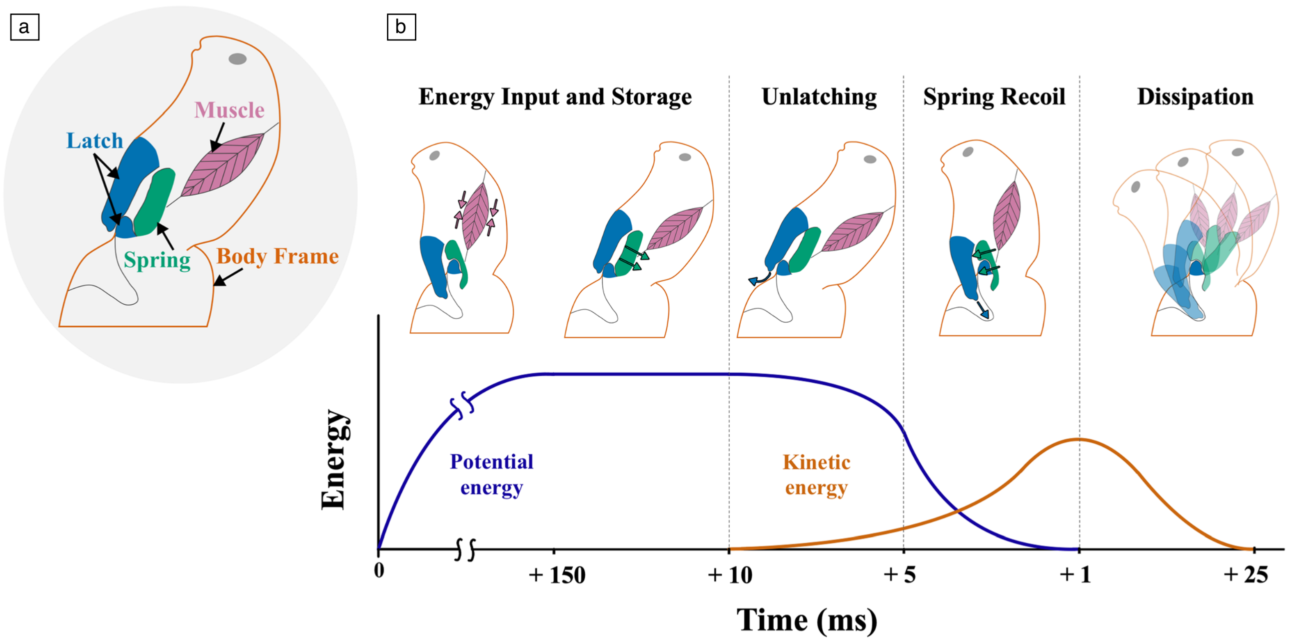

Figure 3. (a) A schematic of a representative latch-mediated spring-actuated (LaMSA) system based on the anatomy of click beetles. (b) LaMSA movements are a result of an exchange between potential and kinetic energies. First, the motor/muscles load spring elements, while a latch is engaged. This stage is represented by an increase in potential energy. Disengaging the latch mediates the energy release and the conversion to kinetic energy. Then, completely removing the latch, or unlatching, initiates the energy exchange and culminates in the spring recoil, where the potential energy is fully converted into kinetic energy, used to move an appendage or an organism. Finally, the kinetic energy is dissipated through internal or external damping mechanisms.

dissipates energy when it strikes prey). The body frame here refers to the exo/endoskeleton for organisms and the overall structure for robots. These movements circumvent the typical force-velocity tradeoff of muscles and effectively amplify their power output. Energy can be released through the elastic recoil of a spring over a much shorter time in comparison to the time taken to store energy in the springs using muscles. These general themes of power transmission tailoring, spring storage and actuation, latch mediation, and energy dissipation can be abstracted for use in various robots and other engineered system designs.

Abstraction themes

In solution-driven bioinspired design, an important step that follows identifying and understanding the biological solution is to extract the key principles that enable the desired function. Proper extraction usually involves identifying the solution-neutral principle, or an abstraction, that the biological system uses and distilling it to the physics that should be exploited and implemented into the engineered system. Several abstraction themes have been derived from LaMSA systems. Here, we categorize these abstractions into three main themes, namely modeling, material design, and mechanism design.

Modeling themes

In addition to developing models to represent specific organisms,[29,33,34] several impactful studies have focused on developing generalized models of biological systems.[11,35] Generalized modeling approaches can aid in uncovering important design principles, such as scaling, component sizing, critical time scales, and required energetics and power. For example, the generalized model presented in Ilton et al. provides a mass upper limit, beyond which spring actuation provides equivalent or reduced power output compared to direct motor actuation, suggesting that only smaller organisms and robotic systems should implement spring actuation as a mechanism for achieving ultrafast movements.[11] Other generalized models focus on representing and abstracting the specific components of a LaMSA system, namely the motor, spring, latch, and structure.[11,26,35,36] The complexity of the abstraction of each component varies significantly among different models. For example, the representation for the spring varies from linear discrete elements to nonlinear, nonideal, and continuous elements.[11,35–37]

In contrast to modeling LaMSA components, some modeling approaches focus more on abstracting the fundamental energetic and power principles.[38] These models aim to answer questions about the energy required for jumping or whether spring-actuated jumps and strikes are more energetically feasible than direct or muscle-actuated jumps and strikes. These models often focus on the various time scales at which energy is stored, transferred, and released.[39] Whether the models are focused on the roles of specific components or the energy time scales within an organism or across organisms, the principles abstracted from these models enable the design of engineered systems with properly sized components and feasible energetics.

Material design themes

The material and structural design is an enabling principle that allows LaMSA organisms to perform rapid movements repeatedly. For example, the ultrafast and potent strike of mantis shrimp dactyl clubs and trap-jaw ant mandibles has inspired scientists to design materials and structures with similar damage tolerance capabilities. Various studies on the mantis shrimp found that the damage tolerance of its dactyl results from its composite fibrous materials, the material microstructure, and the helicoidal organization of such fibers.[40–42] These studies enabled abstractions of the architecture of the mantis shrimp dactyl into several bioinspired materials. Recent studies have introduced engineered materials with properties similar to the mantis shrimp dactyl, and these materials demonstrate superior toughness, crack propagation control, and damage tolerance.[43–45] Similarly, hierarchical springs in biology have inspired novel metamaterials to improve dynamic recoil.[36,46] Although these themes have provided pathways to new materials, these materials have yet to be integrated into LaMSA-inspired mechanisms, devices, or robots.

Mechanism design themes

The final abstraction theme is related to the mechanism design of LaMSA systems. Abstracting the LaMSA mechanism design can be divided into two categories. The first category is focused on abstracting the actuation process or schema. For example, several recent insect-scale robots and systems have implemented latch mediation and spring actuation versus muscle or direct actuation.[16,47] In these designs, the mechanism is not based on a specific organism. Thus, it is still considered solution-neutral. The second category is related to the mechanism design, including not just the actuation process but also some of the geometric features of the organism. This category of abstraction often depends on a specific organism. Thus, the abstraction becomes solution-specific rather than solution-neutral and is better called mechanism transfer rather than mechanism design abstraction.

Still, mechanism transfer helps develop new robotic systems and test hypotheses about specific organisms. Examples of mechanism transfer for robotic systems include a mantis shrimp-inspired striking mechanism and a jumping robot inspired by springtails.[14,48] An example of mechanism transfer to test biological hypotheses includes building simplified prototypes to determine how structural and geometric properties affect the jump of click beetles.[49] Mechanism transfer to test biological hypotheses allows us to evaluate a parameter space beyond what is observed in biology because robotic systems do not have the same physiological and evolutionary constraints as their biological counterparts. However, mechanism transfer for developing new robotic systems can also limit engineering implementation. For example, biology uses the work done by a single contraction of a muscle to load energy in a spring, but this work can be amplified in engineering systems, as demonstrated in Hawkes et al.[17]

Engineering implementations

Following understanding the biological solution and extracting the critical physical principles, the next step in the solution-driven bioinspired design framework is implementing or embodying these principles into an engineering design. This section highlights the engineering implementations of LaMSA principles in robotic systems. We present the main fabrication techniques, provide details on components that have been deployed to act as the actuator, spring, and latch, and how they have been integrated into LaMSA-inspired robots, and discuss possible future research avenues.

Fabrication techniques

Fabrication in nature has a bottom-up approach, starting from the cellular and molecular scales all the way to the organism scale. This approach allows for biological composites with localized mechanical properties throughout the body of LaMSA organisms. Localized stiffness is achieved by varying the volume fraction and fiber orientation (where applicable) in exoskeletons, bones, and other structural components. While some biological materials have been utilized as building materials since ancient times (cow tendons were used to store elastic energy by ancient Greeks and Romans[50]), cost and susceptibility to quick decay have prevented their common use for engineering applications. However, it is worth noting that biohybrid robots are currently pushing the barriers of utilizing biological organic materials in robotics thanks to advances in tissue engineering.[51,52]

In contrast, current engineered systems usually rely on a top-down fabrication approach, where systems and components are often designed before considering the fabrication techniques and materials properties. As a result, engineered LaMSA systems combine off-the-shelf and custom components fabricated using a broad range of techniques such as additive manufacturing (AM), microfabrication, and smart materials manufacturing techniques. Most LaMSA systems design is centered around four primary components: (1) the actuator/energy input, (2) the spring/energy-storage system, (3) the latch/energy triggering system, and (4) the body frame and linkage system that enables power transmission between the different components and energy dissipation through the structure and the system's environment. **Table** I details the components used for a range of LaMSA robots and the associated manufacturing techniques.

Shape-memory alloys (SMAs) are broadly used to fabricate actuators and springs in LaMSA systems (Table I). SMA coils are commonly used as temperature-activated artificial muscles in References 53–55, and superelastic SMA wires have been used to prevent permanent deformation due to

Table I. Summary of multiple LaMSA engineered systems, their characteristic lengths and total system mass, LaMSA components, and associated manufacturing techniques.

System	Length, Mass	Energy Flow		
		Function	Component	Manufacturing Technique
Flytrap-inspired robot[53]	150 mm, 121.8 g	Actuator	SMA coil spring	SMA wire winding
		Spring	Bistable composite	Composites manufacturing (prepreg)
		Latch	Geometric (instability)	-
		Body frame	3D printed plastic	Additive manufacturing (technology N/A)
Micro elastomer jumper*[59]	4 mm, 0.008 g	Actuator	External force	–
		Spring	Elastomer tension	Elastomer mixing and molding
		Latch	Contact (silicon body)	Microfabrication
		Body frame	Silicon body with elastomer[60]	
EPFL 7 g robot*[61]	50 mm, 7 g	Actuator	DC motor	Off the shelf
		Spring	Steel torsion	Off the shelf
		Latch	Contact	Additive manufacturing (stereolithography [SLA], fused deposition modeling [FDM]) & off the shelf
		Body frame	Cibatool plates/PEEK	
Steerable MSU jumper[62]	65 mm, 23.5 g	Actuator	DC motor	Off the shelf
		Spring	Steel torsion	Off the shelf
		Latch	Geometric	–
		Body frame	DuraForm HST body	Additive manufacturing (selective laser sintering [SLS])
Locust-inspired robot[19]	130 mm, 23 g	Actuator	DC motor	Off the shelf
		Spring	Steel torsion	Off the shelf
		Latch	Contact	Off the shelf
		Body frame	Acrylonitrile butadiene styrene (ABS) body, carbon rods	Additive manufacturing (fused deposition modeling [FDM]) & off the shelf
Galago-inspired "Salto" robot*[63]	150 mm, 100 g	Actuator	DC motor	Off the shelf
		Spring	Elastomer tension	Off the shelf
		Latch	Geometric	–
		Body frame	Carbon fiber composites (primary)	Milling prefabricated carbon fiber composites and reinforcement using fiberglass sheets (adhesive); molding and casting process to fabricate bushings and shafts (polyurethane)
Water strider-inspired robot*[54]	160 mm, 0.67 g	Actuator	SMA	Custom cut (ultraviolet laser micromachining system) from sheet of nickel titanium SMA
		Spring	SMA sheet + cantilever	Custom cut of SMA sheet + MEMS fabrication
		Latch	Geometric	–
		Body frame	Pop-up MEMS	MEMS fabrication
Flea-inspired robot[55]	20 mm, 1.1 g	Actuator	SMA	SMA wire winding[56]
		Spring	SMA coil	
		Latch	Geometric	
		Body frame	Glass fiber-reinforced composite	Smart composite microstructure (SCM) process (laser machining and lamination of glass fiber composite and polyimide film)[64]
LaMSA air jumper[65]	600 mm, 27.4 g	Actuator	External force	–
		Spring	Latex rubber band	Off the shelf
		Latch	Contact	Off the shelf
		Body frame	Carbon fiber, composite fabric	
Mantis shrimp striker[14]	20 mm, 1.5 g	Actuator	DC motor	Off the shelf
		Spring	Steel torsion	Off the shelf
		Latch	Contact	MEMS fabrication and additive manufacturing (technology N/A)
		Body frame	Pop-up MEMs, 3D printed base	

Table I. (continued)

System	Length, Mass	Energy Flow		
		Function	Component	Manufacturing Technique
JUMPA robots*[47]	20 mm, 1.6 g	Actuator	Nylon coil	Nylon coil wire winding
		Spring	Steel beam	Cut from off-the-shelf steel beams
		Latch	Elastic instability	
		Body frame	E-Partial 3D printed material	Continuous digital light manufacturing (cDLM) additive manufacturing

The asterisk "*" indicates that the system can repeat its LaMSA-powered movement by resetting itself without user input.

repeated use (e.g., legs of the water strider robot in Reference 54). SMA materials are typically purchased and subsequently manufactured to the desired shape to obtain specific force-displacement response profiles. When creating SMA coils, for example, the force-displacement characteristics can be tuned by changing the geometry of the spring: the wire diameter, coil diameter, and number of turns. The manufacturing process itself is a relatively simple, widely adopted SMA wire winding manufacturing method.[56] A similar process is used to create polymer artificial muscles, as in Reference 47. Future LaMSA robots could use SMAs manufactured using AM techniques, thanks to the development of such technologies (4D printing).[57,58] AM SMAs exhibit location-dependent shape-memory effects through precise control of the metal alloy composition and have the potential to enable the manufacturing of functionally graded actuators, springs, and other structural components (e.g., body frame) for LaMSA systems.

Pop-up microelectromechanical systems (MEMS) and composite fabrication processes are other popular manufacturing techniques to manufacture LaMSA systems' frames at the micro- and macroscales. Both techniques involve laminating materials to manufacture relatively stiff structural components. Table I refers to a few traditional composite manufacturing techniques that were employed in LaMSA manufacturing. Pop-up MEMS are flexure hinge-based composites (i.e., three-dimensional [3D] MEMS structures that combine multilayer rigid and flexible laminates), folded into a 3D structure.[66] Pop-up MEMS fabrication techniques avoid complex, time-consuming assembly steps usually required in traditional MEMS manufacturing. However, the design of each pop-up MEMS system involves a custom manufacturing process to achieve the required shapes and materials and structural properties.

Finally, AM has become a very popular manufacturing technique in robotic design to fabricate custom, complex, and/or intricate shapes in a broad range of materials and at different scales. AM's popularity is reflected in LaMSA system design: a majority of LaMSA-inspired systems include several additively manufactured parts, in particular for the robots' body frame (Table I). Most AM parts used in LaMSA systems are manufactured with polymers and commercial printers. For example, fused deposition modeling, stereolithography, and polymer jetting are popular AM technologies. The mechanical performance of these components is driven by the bulk, monolithic materials properties, and overall shape. However, AM has recently emerged as a promising solution to fabricating novel materials with properties unachievable with monolithic materials. More specifically, AM now enables the fabrication of adaptive architected structures with highly tunable materials properties, also known as metamaterials. Although metamaterials have been used in LaMSA system design in a very limited capacity,[36,46] they offer a promising potential avenue to creating lightweight components with locally tuned stiffness, and absorption and dissipation properties.[67–70] It is also worth noting that additive manufacturing allows the creation of microsystems at the micron and submicron scale (e.g., multiphoton lithography additive technology[71]), which provides another promising fabrication solution for small-scale LaMSA systems.

Component implementation

The components of LaMSA-inspired robots can be classified based on their energetic role: energy input, storage, release, and dissipation. The actuators, referred to as motors, are classified as energy-input elements analogous to muscles. Springs and latches are classified as energy storage and mediation elements, respectively. Finally, the moving portions of the systems and the surrounding environment are discussed for their role in energy release and dissipation. **Figure 4** shows examples of the main LaMSA components (i.e., actuator, spring, and latch) implemented in some current LaMSA-inspired systems.

Energy-input components

In LaMSA systems, potential energy is typically input into the system using a high-force, low-speed actuator.[11] In one sense, as long as this actuator can successfully load the spring, its characteristics do not matter: they only determine the initial conditions for unlatching and have no impact on the dynamic behavior. In fact, some engineered systems such as in References 72 and 65 do not use an onboard system for energy input. Instead, energy is input manually into the system. In systems that implement onboard energy input, the actuators could impose autonomy and cycle time constraints, and as such, selecting an appropriate actuator matters. Moreover,

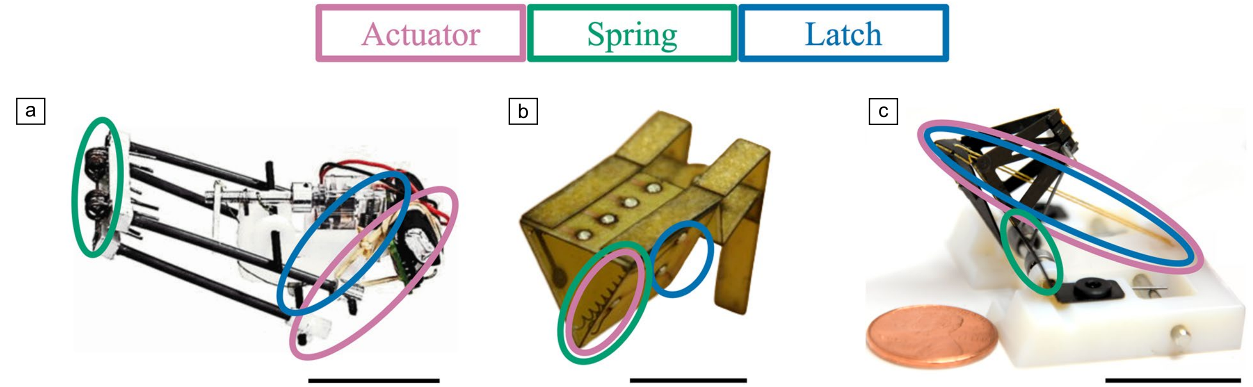

Figure 4. Examples of modern engineering implementations of latch-mediated spring-actuated (LaMSA) systems. The LaMSA-inspired components circled are the actuator (pink), spring (green), and latch (blue). (a) Adapted with permission from Reference 18. © 2015 IEEE. (b) Adapted with permission from Reference 15. © 2012 IEEE. (c) Adapted from Reference 14 under standard PNAS license terms (scale bar = 20 mm).

energy stored in the system is fundamentally limited by the work done by these components, which in turn, limits the energy that can be recovered during elastic recoil.

Currently, when energy input is accomplished onboard in engineered systems, it is most often by means of an electromagnetic DC motor.[11,14,17,19,73,74] These motors are usually commercial off-the-shelf components that are mounted onto the system. They are usually slow and have a low bandwidth, but this does not usually limit performance, as typical LaMSA strategies do not call for extremely fast resets. Other engineered systems use shape-memory alloy (SMA) springs for energy input[15,54] or other forms of artificial muscles.[47] SMA actuators and artificial muscles are more laborious to design and manufacture and are harder to control, but they also provide major advantages in mass and integration over electric motors. These advantages are important because, in many engineered LaMSA systems where energy input is accomplished onboard, the actuator weight is usually a significant fraction of the total weight.[19,75]

Compared to biological actuators or muscles, engineering implementations of actuators tend to be bulkier and heavier. The actuators also substantially constrain both the design space (because the mechanical design must accommodate the motor) and the performance space (because the motor force determines maximum energy storage). Thus, there is a need for lightweight, high-strength, and small-scale actuators that can achieve repeatable loading while freeing up space for other design elements.

Energy-storage components

The elastic storage component in engineered LaMSA systems is typically a discrete spring or a system of springs. However, animals that employ LaMSA movement strategies more typically form an integrated elastic mechanism that includes their exoskeleton, sclerites, and tissue to store energy.[34,76] In general, spring properties determine how the potential energy is stored and converted to kinetic energy upon release of the latch.[36] Current spring implementations in engineered LaMSA systems include rubber bands, carbon fiber strips, torsion springs, linear springs, including SMA coils, and other materials that can store strain energy when deformed, such as spring steel.[14,17,65,73,75,77] Of particular note are SMAs that combine the roles of actuation and energy storage in the same structure.[15,54]

Mechanical springs have known performance limits, which, in turn, limit the performance of engineered LaMSA systems.[78] There is some literature on the problem of tuning these springs for better energy storage in LaMSA systems, but there are still significant gaps.[35,79] It is difficult to simply look to biology for these answers, as the energy stored in biological systems is extremely challenging to quantify (and in some cases, the elements composing the spring are difficult to identify as well). It is rare to find robotic systems that use the elasticity of their structural members for energy storage (e.g., Reference 17), and we are not aware of any robotic LaMSA systems that use the saddle-shape geometry of springs found in several biological systems.[80–82] Moreover, the internal damping properties of the engineered springs need improvement. These types of design improvements in spring mechanism, shape, and force-displacement relationship could enable faster, better, and more controlled energy storage and release.

Energy-release components

The latch in LaMSA systems is the mechanism that mediates the recoil of the elastic element. In engineered systems, the most common type of latch is a simple contact latch,[11,17,19,72,75] in which a physical barrier impedes the recoil of the spring. The process by which this barrier is removed, along with a number of analogous processes that allow the release of stored energy for other types of latch, is referred to as "unlatching," and is usually characterized by a distinct dynamic regime during which work done by a constraint force dominates the behavior of the system. For a contact latch, this occurs by withdrawing the constraint, allowing the spring to recoil partially under a time-varying position constraint. Some current literature examines how elastic recoil can be controlled via the latch dynamics.[36,72,73] Tailoring the elastic recoil can enable control over the robot's trajectory during jumping or striking.[36,72,73]

Although the contact latch is most common in engineered systems, in recent years, engineered LaMSA systems have begun to take more inspiration from the diversity of latches seen in biology. Animals and plants exhibit many different types of latches (e.g., geometric, antagonistic, contact, and fluidic).[11,14,26] Each type of latch, in turn, enables different dynamic regimes in the unlatching phase of actuation, ranging from quasistatic behaviors as in Reference 72 to highly dynamically coupled behaviors as in Reference 73. Some current work also uses muscle-based latches, although they are limited in their performance.[83]

At present, there are large open questions around the control of unlatching. First, it is not known if most biological latching systems implement any feedback. The engineered systems typically operate as open-loop systems because the large internal forces and short time scales involved make feedback control difficult. There is a need for smaller and better-integrated internal force sensors to provide needed data for calibration and modeling of the unlatching system. Additionally, most engineered systems simply replicate unlatching mechanisms seen in biology. Although these mechanisms work, there is room for greater abstraction and novel mechanical linkage development, which can make better use of the capabilities of engineered actuators used to move the latch.

Energy-dissipation components

Once the spring has begun recoiling, LaMSA systems can produce very large accelerations. Such accelerations require energy dissipation mechanisms to reduce damage to the system as a whole.[28] Compared to the damage tolerance exhibited by biological systems, engineered LaMSA systems fail more frequently, although the failure modes and lifetime of these systems have not been reported. Damage tolerance studies have been done on individual materials used in LaMSA system construction, particularly springs, but little has been done to analyze the damage tolerance of the full mechanical structure.

The dissipation of kinetic energy can be thought of primarily in terms of damping forces and the system's total energy, with the two most significant internal dissipation modes in these systems being viscous and Coulomb friction. For example, click beetles have been reported to rely on nonlinear damping mechanisms to dissipate the energy release.[37] Externally, the environment can provide numerous other pathways to dissipate energy from the LaMSA system, including fluid viscosity or drag and energy transfer through impact.The mantis shrimp is an example of an organism that dissipates energy to its environment (water) through viscous damping and impact with prey. In contrast, engineered LaMSA systems assume linear linkage and joint damping, as well as external viscous friction.[14,73] In general, there is a need for a more systematic characterization of energy dissipation mechanisms in biology and the implementation of some of these strategies in mechanical systems to mitigate damage and enhance repeatability.

Integration strategies

As discussed in the "Fabrication techniques" section, LaMSA systems are often assembled from combinations of off-the-shelf components and mechanisms fabricated using various manufacturing approaches. For example, many jumping robots, especially those with larger sizes, have separate actuators that load energy into a spring, separate springs to store energy, and separate latches to release that energy.[61,62,84,85] Even one of the very highest jumping robots recently demonstrated by Hawkes et al.[17] uses this approach to assemble separate components. However, interfaces between components are often a limiting factor in the robot; it is not uncommon to see robots assembled from various components supplemented with significant glue or duct tape at the interfaces between components.

Biology generally integrates functionality and components in a much more robust manner, and in fact, many components often serve more than one purpose. For example, the dracula ant mandibles both store energy through bending and provide the latch through their curvature.[29] Trap-jaw ants and snapping shrimp use their exoskeletons to both support and protect the organism, but also as part of the spring that drives their fast motion.[26,28] Many of the novel fabrication processes from the previous section can be used to design mechanisms or integrate materials that further integrate engineered components in clever ways, especially when trying to scale robots down closer to the size of biological jumpers such as insects. It is often useful to combine LaMSA functionality into fewer components to help reduce the robot's size, mass, and number of moving parts.

When designing robots with similar LaMSA capabilities, there is a need to use some of these same integrative design principles found in biology, including using singular fabricated components for multiple purposes. Several jumping robots use mechanical design to integrate various LaMSA themes into a single component (**Figure 5**). A multistable beam provides both spring functionality and latch functionality in previous work by Wang et. al.[47] The spring design in Hawkes et. al. also serves to support the robot and reset it for a jump, much like an exoskeleton.[17] The ratchet used as part of the actuator to do more work and store more energy in the spring can also be used as a latch.[59,89]

Smart materials add another design element that can further enhance these integrative design principles in engineered LaMSA systems. Beyond the mechanical designs previously discussed, the properties of the material itself allow it to serve more than one purpose. For example, shape-memory alloys have frequently been used as both actuator and spring in small, lightweight jumping robots due to their phase change and superelastic properties.[15,54,55] Dielectric

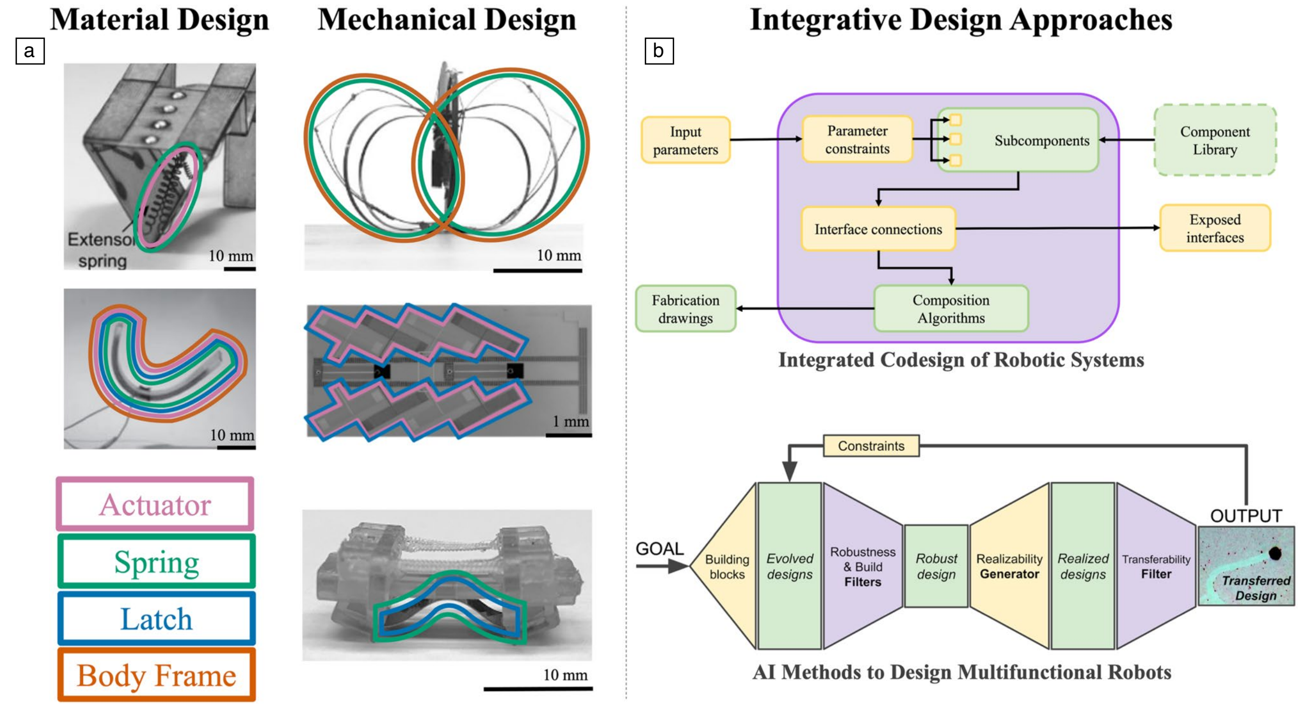

Figure 5. (a) Examples of systems that use integrated design through the use of materials as well as mechanical design. (b) Multiple methods for integrated design approaches, including codesign and artificial intelligence (AI) methods for robot design. Flea-inspired robot adapted with permission from Reference 15. © 2012 IEEE. Elastomer jumper adapted with permission from Reference 86. © 2019 IOP Publishing Ltd. Bioinspired jumper adapted with permission from Reference 17. © 2022 Nature. Compliant elastomer designed in Reference 59. Insect-scale buckling robot photo credit from Qiong Wang. Integrated codesign schematic based on Reference 87. AI methods schematic adapted from Reference 88 under standard Proceedings of the National Academy of Science license terms.

elastomer actuators have been used as the actuator, spring, and latch.[86] Mechanical design and liquid-crystal elastomers (LCEs) have been combined to achieve actuation, energy storage, and unlatching in a clever way.[90]

Despite the importance of integrative design for small robots that are naturally resource-constrained due to their size, integrative design is still exceptionally challenging. Previous work in biology has shown that minor mechanical design changes can evolve an organism from a non-LaMSA organism (e.g., a snapping shrimp closing its claw with muscle power) to a LaMSA organism (closing its claw with a spring).[26] In engineered robots, many of these integrated designs come from the mind of a clever student. A significant gap remains to improve exploration of the mechanical and material design spaces to optimize designs for desired robot outcomes, given the energy and size constraints. Although there are several codesign techniques that could be applied to this realm of bioinspired robotics,[87,91–93] machine learning approaches may prove to be a particularly effective pathway for further optimizing robot designs at small scales and getting closer to the metrics that are achieved in biological organisms (Figure 5).[88,94,95]

Integrating functionality into fewer mechanisms and materials can also provide a pathway for energy dissipation and damage mitigation. LaMSA systems typically achieve very high accelerations and often large energies relative to the system size, which can easily lead to damage during operation. Biology solves this problem to some degree with molting (e.g., replacing exoskeletons that could undergo damage) along with novel material architectures designed to dissipate energy in safer ways upon impact.[40,43,96] More work is needed to integrate more robust materials and mechanisms into our robotic systems through novel mechanical design or choice of materials and manufacturing processes. The vast majority of the LaMSA research to date has focused on energy storage and release, and design for the final phase of the LaMSA energy cycle (energy dissipation) is an important further area for study and design.

Concluding remarks

This article presented LaMSA-inspired systems through the well-developed framework of solution-driven bioinspired design to provide a scaffold for designing and fabricating novel and small-scale robots. Discovering and understanding LaMSA systems in biology has already enabled a new class of robots that relies on elastic recoil to achieve high acceleration movements and circumvent actuator power limitations. These robots have been designed and evaluated across scales ranging from a millimeter to tens of centimeters (Table I). LaMSA design principles are especially appealing for insect-scale robots because they provide a pathway toward integrating multiple functional elements to tailor movement energetics. The impressive effort dedicated to abstracting organism-neutral physical principles enabled the implementation of LaMSA movement strategies in such a wide range of robotic solutions. Such abstractions in modeling, materials design, and mechanism description and transfer allowed for the development of robotic systems, some based on specific organisms and others generally inspired by the strategy itself. Finally, examining the engineered implementations reveals that there is a diversity in the types of LaMSA-inspired components (i.e., the actuators, springs, and latches) and their fabrication methods.

Still, there are numerous research gaps and opportunities for LaMSA-inspired systems related to their component integration and multifunctionality, their design for damage tolerance and energy dissipation, and the development of formal codesign methods that involve material and structural design as well as control and autonomy. The study of LaMSA and LaMSA-inspired systems is new relative to other biological fields that sparked new classes of robots (e.g., flapping flight or running). Nonetheless, the proliferation of studies focusing on LaMSA and LaMSA-inspired systems results from the conscious effort to simultaneously advance biological understanding, principle abstraction, and engineering implementation and the iterations to improve them all.

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Author contributions

All authors reviewed and approved the final version of the manuscript. T.M. and L.V. wrote, edited, and reviewed the paper and created figures. O.B. wrote sections in the paper, created the table, and edited and reviewed the paper. S.B. and A.W. conceived and designed the paper outline, provided funding, and edited and reviewed the paper.

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Conflict of interest

The authors declare no conflicts of interest.

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Publisher's note

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