Towards Enduring Autonomous Robots via Embodied Energy

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Preface:

Autonomous robots are comprised of actuation, energy, sensory, and control systems built from materials and structures that are not necessarily designed and integrated for multifunctionality. Yet, humans and other animals that robots strive to emulate contain highly sophisticated and interconnected systems at the cellular, tissue, and organ levels, which allow multiple functions to be performed simultaneously. Here, we examine how nature builds to establish a new paradigm for autonomous robots with Embodied Energy. Currently, most untethered robots use batteries to store energy and power their operation. To extend their operating time, additional battery blocks must be added in tandem with supporting structures, increasing their weight and reducing their efficiency. Recent advancements in energy storage techniques enable chemical or electrical energy sources to be embodied directly within the materials and mechanical systems used to create robots. This perspective highlights emerging examples of Embodied Energy, focusing on the design and fabrication of enduring autonomous robots.

Manuscript Body:

Embodied Energy: a new paradigm for robotics

Power and control remain major barriers to the realization of untethered autonomous robots that can move and adapt on demand for long duration missions. A close synergy between hardware and software design is needed to optimally use the, often limited, onboard energy supply. Recent examples highlight a pathway towards improved operational lifetimes through the co-integration of chemical and electrical energy sources with mechanical systems to imbue robots with high energy and power density[1–5]. By housing this energy supply directly within the robot's architecture and materials, it is readily available for use, can be efficiently converted into useful work and, ideally, can be replenished through onboard energy harvesting mechanisms. We call this design philosophy *Embodied Energy*, where the same mass that is normally used for mechanical or structural systems also contains stored energy that powers at least a portion of the robot or device.

To effectively embody energy in robots, energy sources should not be designed exclusively as external devices that can be affixed to the body of a robot; they should instead permeate both active and structural elements, thus contributing to the multifunctionality of the device. The potential of such Embodied Energy systems can be evaluated through biological analogy. In humans and other animals, energy is primarily stored in the body as fat. However, the functionalities of adipose tissue extend far beyond energy storage to include insulation, the protection of vital organs, waterproofing, and the regulation and production of hormones. Embodied Energy can similarly imbue robotic systems with multifunctionality. Springs, pneumatic and hydraulic actuators, and even the compliant materials used in soft end effectors can be employed in configurations that are reminiscent of biological muscle and tendon, which both store and reuse elastic energy while providing structure to the musculoskeletal system, Just as plants use stored water to maintain turgidity, transport nutrients, and as a reagent in chemical reactions, electrochemical cells can store and transport energy within a device to initiate processes like sensing and actuation, while simultaneously serving an architectural or load bearing function. The merging of materials and faculties to create new multifunctional systems is a delicate balancing act. Robot mass decreases and energy density increases when functions that are normally dispersed between different systems are consolidated within a single part. Auxiliary components, however, may be needed in these merged systems, increasing their complexity and complicating their fabrication and servicing. Hence, we view Embodied Energy as a multi-objective optimization function that enables energy-dense, enduring robots.

In many ways the underlying principles of Embodied Energy parallel those currently employed in robotic artificial intelligence systems. AI-driven robots interact with their environment based on information previously gathered and processed from their surroundings via onboard sensors. This closed sense-decide-response loop is reliant on a continuous synergy between the sensors, processors, actuators, and collected data. The same should be true for the energy harvesting-storage-delivery loop in robots with Embodied Energy. If these systems can fulfill energy and power needs as well as actuation and control functions, we can create robots that more seamlessly interface with their own environments.

Over the past two decades, there has been a small, but growing, effort to improve machine autonomy by developing multifunctional, Embodied Energy systems[4,5]. Most robots, however, still contain isolated power, actuation, sensory, and control *blocks*, each optimized for an individual task (Fig. 1)[1,3,6–8]. In Honda's ASIMO robot, for example, there is a clear division between the actuators in the joints, the control module in the torso, and the batteries in the backpack unit[6]. Such isolated building blocks lack the synergy and efficiency observed in living organisms (e.g., an octopus), which are capable of harvesting, storing, and generating energy either continuously or on demand. By distributing energy sources throughout multifunctional system configurations, as illustrated by the progression of innovative robots and their corresponding block diagrams in Fig. 1, we can expand their range of complex functions while increasing their operational efficiency.

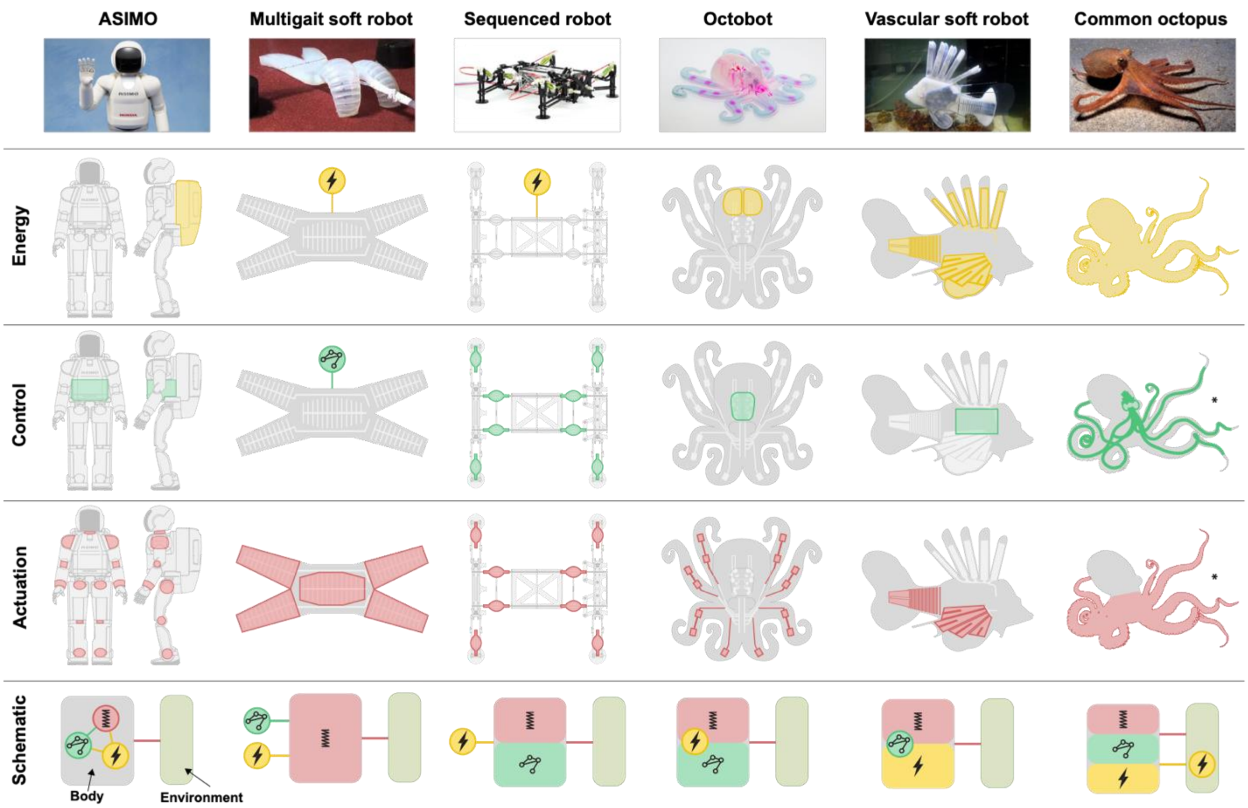

Fig. 1| Energy, control, and actuating systems in modern robots. Energy storage elements are highlighted in yellow, control elements are highlighted in green, and actuators are highlighted in red for each robot. **a**, The ASIMO humanoid robot[6]. **b**, A multigait, quadrupedal soft robot powered by a pneumatic tether[7]. **c**, An 8-degree-of-freedom walking robot with embedded actuator sequencing and a single pneumatic input[8]. **d**, An untethered octopus-inspired robot controlled by microfluidic logic and powered by the decomposition of a monopropellant fuel that produces pneumatic actuation[3]. **e**, An untethered aquatic soft robot with a redox flow battery-inspired vascular system that produces electrical energy and hydraulic actuation[1]. **f**, The common octopus. (*To provide a direct comparison with mobile robots **a–e**, we have highlighted the primary actuators of the octopus: the tentacles. Note: There are secondary actuation and sensory/control capabilities not depicted in this simplistic representation.)

Energy storage and conversion

An important aspect of Embodied Energy is precisely how this energy is harvested, stored, applied, and recovered throughout the robotic system. Most untethered robots generate electrical energy from rigid battery packs that power motors or pumps needed for locomotion. Consequently, these robot designs are guided by a simple tradeoff between size, weight, and power (SWaP). When more electrochemical cells are used, more weight is introduced without the addition of functional benefits beyond operational lifetime. For a robot of fixed size, greater power is needed to provide equivalent mobility as its weight increases. However, one can envision strategies in which energy storage, power generation, and functional outputs are co-designed and integrated to improve SWaP. By broadening the range of functionalities concurrent in a material or subsystem and distributing the mass budgets between them, we can upend the conventional energy budget and design methodology. Power, sensing, computation, and control will be largely native to the mechanical system.

Fig. 2 details strategies and design principles, like SWaP, that are important to consider when designing for Embodied Energy. This diagram shows how exemplary Embodied Energy systems, each representing a specific energy storage and transduction methodology, can be incorporated into different types of robots by applying these principles. Though energy storage can take many forms in mechanical systems, we limit our depiction here to five of the most common types that can be harnessed by autonomous robots: electrical, mechanical, chemical, magnetic, and thermal. Several of these categories overlap in conventional systems (e.g., electrochemical batteries, thermochemical heat storage), a property that can be leveraged when merging different energy storage and transduction technologies. Systems that store energy can vary wildly in their efficiency (see Table 1), material composition, and even the states of matter they interface with (e.g., solid state batteries, liquid redox flow batteries, and gaseous hydrogen fuel cells). Similarly, the landscape of energy transduction mechanisms (e.g., electromagnetic motors, combustion engines, hydraulic pistons, etc.) is vast, complicating design decision making.

The intersection of energy storage and transduction will form the framework of our discussion, as Embodied Energy seeks to accomplish these tasks collectively. Generally speaking, Embodied Energy is best discussed in the context of robotics by examining its conversion to mechanical work (i.e., actuation and locomotion). In the sections that follow, we will present existing technologies that can transduce different types of stored energy into mechanical actuation in robots. We will describe how these technologies can be implemented in multifunctional Embodied Energy systems, citing existing examples, and discuss future developments for each energy transduction category, before culminating in an exploration of influential Embodied Energy design principles (Fig. 2).

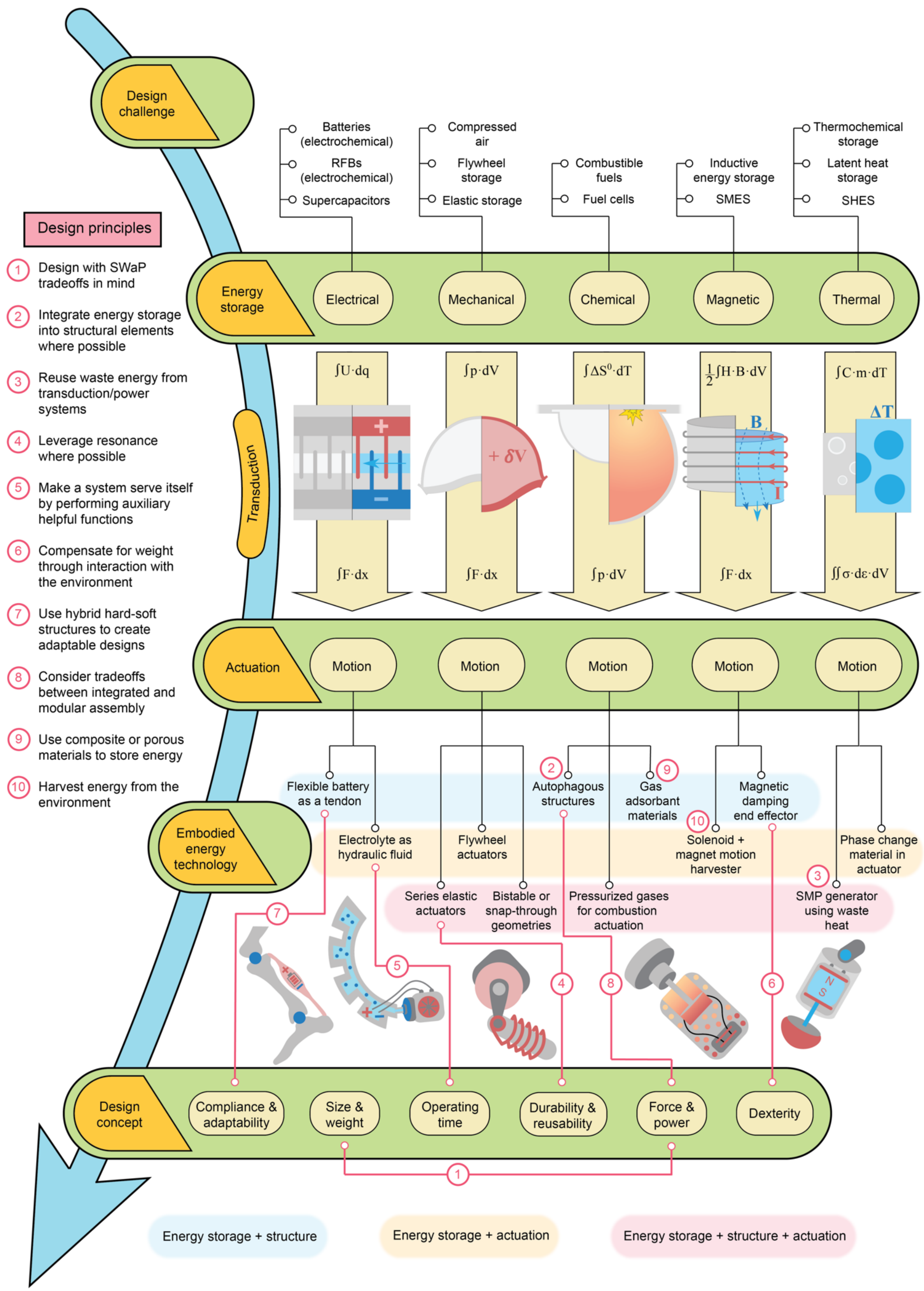
Design challenge
Batteries (electrochemical)
RFBs (electrochemical)
Supercapacitors
Compressed air
Flywheel storage
Elastic storage
Combustible fuels
Fuel cells
Inductive energy storage
SMES
Thermochemical storage
Latent heat storage
SHES
Design principles
1 Design with SWaP tradeoffs in mind
2 Integrate energy storage into structural elements where possible
3 Reuse waste energy from transduction/power systems
4 Leverage resonance where possible
5 Make a system serve itself by performing auxiliary helpful functions
6 Compensate for weight through interaction with the environment
7 Use hybrid hard-soft structures to create adaptable designs
8 Consider tradeoffs between integrated and modular assembly
9 Use composite or porous materials to store energy
10 Harvest energy from the environment
Energy storage
Electrical
Mechanical
Chemical
Magnetic
Thermal
Transduction
∫U·dq
∫p·dV
∫ΔS⁰·dT
½∫H·B·dV
∫C·m·dT
+ δV
B
I
ΔT
∫F·dx
∫F·dx
∫p·dV
∫F·dx
∬σ·dε·dV
Actuation
Motion
Motion
Motion
Motion
Motion
Flexible battery as a tendon
Electrolyte as hydraulic fluid
Flywheel actuators
Autophagous structures
Gas adsorbant materials
Magnetic damping end effector
Solenoid + magnet motion harvester
Phase change material in actuator
Series elastic actuators
Bistable or snap-through geometries
Pressurized gases for combustion actuation
SMP generator using waste heat
Embodied energy technology
Design concept
Compliance & adaptability
Size & weight
Operating time
Durability & reusability
Force & power
Dexterity
Energy storage + structure
Energy storage + actuation
Energy storage + structure + actuation

Fig 2| Energy storage and transduction form the framework of the Embodied Energy design process. The Embodied Energy technologies shown are created by storing a specific type of energy into the structural or energy transduction components of a system. The images in the transduction pathway depict, from left to right, an electric comb drive, a bistable mechanical actuator, a soft combustion actuator, a magnetic solenoid actuator, and a thermally responsive gel. The variable definitions are as follows: U = voltage, q = charge, H = magnetic field strength, B = magnetic flux density, V = volume, S^0 = standard entropy, T = temperature, C = specific heat capacity, m = mass, p = pressure, F = force, x = displacement, σ = mechanical stress, ε = strain. The acronyms are: RFBs = redox flow batteries, SMES = superconducting magnetic energy storage, SHES = sensible heat energy storage.

1. Electrical to mechanical transduction:

Untethered robots and their mechanical actuators are predominantly powered by rigid rechargeable batteries (e.g., lithium-ion, lithium-polymer, nickel-metal hydride, etc.). Some of the earliest notable cases of multifunctional energy storage involve structural power sources[5,9,10], where static, load-bearing components of machinery also supply electrical energy. A simple example is the use of lead-acid batteries in forklifts as counterbalance for lifting heavy loads[11]. More sophisticated Embodied Energy examples include structural batteries in satellites[12], spacecraft[13] and electric vehicles[4,14], lithium-polymer batteries that function as wings in unmanned aerial vehicles (UAVs)[9], pliable, biomorphic zinc-air batteries that can serve as protective covers for robots[15], and flexible galvanic thin-film batteries in flapping wing aerial vehicles (FWAVs)[16]. In the latter example, the use of embodied electrical energy sources increased the operating time of an FWAV by 250% relative to designs using standard batteries and conventional wing materials.

The conversion of electrical energy to mechanical actuation is most commonly accomplished in robots by electric motors, though they do not store their own onboard energy. Electroactive polymers (EAPs), so-called because they change size or shape in response to electric stimulus, are a class of materials that are capable of multifunctional energy storage. They have the capacity to quickly ($t \sim 10^{-3}$–10^{-4} s) undergo large reversible strains ($\varepsilon_{ult} > 300\%$)[17,18] making them an attractive option for robots with muscle-like actuators[17–19] and sensing capabilities[20,21]. EAPs can broadly be classified as either electronic (e.g., electrostatic, electrostrictive, and ferroelectric polymers) or ionic (e.g., gels and ionic polymer-based composites) depending on their mode of action[18].

Dielectric elastomer actuators (DEAs), a class of soft electrostatic transducers belonging to the electronic group, have been performing multifunctional electrical to mechanical energy conversion for decades[22]. During operation, DEAs store energy throughout their structure, with elastomer layers functioning as deformable capacitors. Consequently, DEAs can serve simultaneously as actuators, sensors, and energy harvesters[23]. DEAs have been implemented in crawling[24,25], gripping[26], swimming[27–29], and even flying robots[30], while more recently introduced soft electrostatic transducers (e.g., hydraulically amplified self-healing electrostatic (HASEL) actuators[31,32]) have combined solid and liquid dielectrics to produce additional functionalities, including hydraulic and pneumatic[33] actuation modes. Unlike conventional electric motors, soft electrostatic transducers inherently store electrical energy and can assume “catch states”, where negligible power is consumed while holding a position. When used in a multifunctional manner, soft electrostatic transducers provide a rich opportunity for Embodied Energy in robots, and have already been used for high frequency, high amplitude actuators[32,34,35]

Ionic polymer-metal composites (IPMCs) have also been used in the creation of mobile robots[36–38]. Composed of a thin conductive polymeric material placed between two metal electrodes, IPMCs use the transport of ions into and out of the polymer for actuation. Though they generally produce lower actuation forces compared to soft electrostatic transducers, their ability to operate at low voltage (V_{in} ~ 1-5 V, vs V_{in} > 100 V for DEAs) and also generate a small voltage in response to deformation has made IPMCs both useful actuators and sensors in biomedical and engineering applications[21,39–41].

We anticipate future improvements not just in the energy density of batteries, but also in the materials used in their composition[42]. Batteries with tunable mechanical properties could serve a variety of functions outside of traditional energy storage, expanding the benefits of Embodied Energy to a wider array of robot designs. As exemplified in Figure 2, a stretchable battery can theoretically be used as an extensible tendon in a walking robot or a wearable exosuit, thus combining electrical and elastic energy storage into a structural element that connects different system components. Fluidic energy storage using flow battery technologies is also a key innovation in this domain. For example, in 2019, a soft robotic fish was created with an embedded "electrolytic vascular system[1]." This design was inspired by redox flow batteries and consisted of a distributed liquid electrolyte that also served as a hydraulic fluid. This multifunctional use of electrochemical energy storage enabled simultaneous power generation and fluidic actuation, which allowed the fish to swim for long durations (>36 h).

2. Mechanical to mechanical transduction:

There are many methods for converting stored mechanical energy into motion, including springs, linkages, gear trains, cams and followers, etc. However, multifunctional and embodied applications are far less common in modern machinery. One use case that has been explored is the inclusion of flywheels in spacecraft to both store energy and provide torque for attitude and control[43–45].

For robots, the potential for improvements through Embodied Energy lies not in the creation of exotic mechanisms, but in advancements in high energy density materials, composites, and interfacial chemistry that can replace or supplement existing mechanisms. The field of soft robotics has provided a platform for the latest innovations in Embodied Energy due to the vast design space offered by the high strain capabilities (ε_{ult} > 1,000%), range of stiffnesses ($E \approx 1 - 10^5$ kPa), and durability of soft matter, such as silicone elastomers, hydrogels, and polyurethane rubbers[46]. Other characteristics of soft robots, including their ability to be fabricated via additive manufacturing methods (e.g., 3D printing and soft lithography)[47], the existence of well-established actuation techniques (e.g., fluidic, electrostatic)[46–48], adaptability, and human compatibility, all motivate synergistic applications for multifunctional and efficient power conversion technologies.

As robots continue to emulate biology and evolve towards hybrid hard-soft structures, there will be additional opportunities to generate unified musculoskeletal systems that provide energy storage, power, and structural functionality. Series elastic actuators (SEA), where a spring-like element is placed between an actuator and the end effector, is perhaps the simplest example of this concept. Figure 2 highlights how this approach to Embodied Energy can be used to improve the adaptability and durability of terrestrial robots. Integrating compliant elements like SEAs into robot architectures could lead to greater shock tolerance, more accurate and stable force control, lower reflected inertia, and decrease inadvertent damage to the environment, all while storing energy[49].

Soft robotics has historically embraced the storage or tuning of elastic energy in elastomeric structures for improved efficiencies and high-power actuation. Recent work has pushed this further by harnessing materials and geometric nonlinearities to discretize the actuator response. Some nonlinear soft actuators, for example, are characterized by instabilities that cause the actuator to undergo a snap-through response, where a fast motion with a large stroke follows from a small external input. During the snapping phase, the elastic energy stored in the actuator structure is suddenly released and can be redirected towards the external world. This principle was recently exploited in the fabrication of bistable hybrid soft actuators inspired by the spinal flection of mammalian quadrupeds[50]. In another example, stored pressure-volume mechanical work was harnessed to create a jumping robot consisting of spherical caps that leveraged a volumetric instability[51]. Embedded actuator sequencing has been achieved by connecting multiple nonlinear balloon actuators, adding passive control to the energy conversion process[8,52]. We see this snap-through behavior in nature as well; a classic example is that of the venus flytrap[53].

Advancements in manufacturing techniques will inform future designs for hybrid hard-soft robots that can structurally store mechanical energy. Multi-material additive manufacturing represents a clear step towards this approach. An idealized process would be able to dynamically tune the chemical and mechanical properties of a part during synthesis to produce functionally graded composites. Monolithic robots with specific operational domains are made feasible through this approach. Just as humans capture and reuse elastic energy with their muscles and tendons, we also expect future robots to more commonly harvest, store, and reuse energy from inertial forces. A variation of this approach can be seen with regenerative braking in electric vehicles. Here, kinetic energy from braking is captured by the motor, functioning as a generator during deceleration, and fed back into the vehicle battery, where it can again be used to power mechanical actuation[54]. MIT's cheetah robot incorporates this energy harvesting technique into its design[55]. Hydraulic hybrid drives represent another evolving technology that could be adapted to robots[56]. In hydraulic vehicles, a working fluid is pressurized during braking, thereby capturing kinetic energy that is returned to the pump or motor during acceleration. More than 70% of the vehicle's deceleration energy can be stored and reused in this way[57].

3. Chemical to mechanical transduction:

Humans and other animals rely on chemical fuels like glucose and fat to serve as their primary energy source for mechanical work. Similarly, combustion engines convert energy-dense hydrocarbons into power for transportation, but the high temperatures required necessitate the use of rigid and dense metal bodies (or frameworks) in most applications. Compressed, gaseous hydrocarbon fuels have now been used for both variable compliance[58], as well as, when combusted, high power density actuation in soft elastomeric robots[2]. While the efficiency is not yet high, the large energy density of these hydrocarbon fuels, along with their multifunctional capabilities, can increase the high power performance and adaptability of these robots compared to inert gases[58,59]. More recently, liquid fuels have been implemented in multifunctional power-structure-actuation systems to achieve cyclic movement in untethered robots[60]. The "octobot", unveiled in 2016, employed a distributed chemical energy system (platinum-catalyzed H_2O_2 decomposition) coupled with a microfluidic logic circuit to autonomously achieve mechanical actuation of the tentacles of a 3D printed octopus[3].

Importantly, we anticipate further advances by storing convertible fuel sources within intelligent structural and machine elements. Autophagous systems are one such approach, wherein physical loads are borne by structural components that also provide energy in a "self-consuming" process. Prior work in this area has been explored for use in aerospace applications[5,61]. The structural requirements for launching vehicles into space greatly exceed those needed for normal operation; with the components consequently sized for launch, the lifetime and efficiency of these vehicles would increase by breaking down and harvesting energy from their excess materials. This same strategy could be implemented in robots, and is supported by research involving autophagous metal-air batteries[62], structural beams pressurized with gaseous fuels[61], and thermoplastic matrix composites that can be converted to fuel and burned with liquid oxidizers[63].

Naturally, end-use applications must be carefully considered when designing autophagous structure-power systems. The large energy density of solid fuels comes at the expense of ease-of-servicing and long-term durability as the structure is depleted. Recyclable, biodegradable, and single-use devices do show promise in applications including surveillance, exploration, and medicine, but more traditional robots will need to prioritize refueling capabilities, possibly through the use of modular designs, energy harvesting, and secondary or emergency means of power generation to ensure perpetual functionality. One difficult challenge that can be envisioned is the nonhomogeneous consumption of materials in autophagous systems. Using the autophagous metal-air battery as an example, a localized catastrophic failure could incapacitate the system, leaving a fraction of the remaining energy inaccessible. A solution to this problem is the use of materials and configurations that leave behind residual structures that can still function in their intended roles. Bimetallic shells could be used in configurations where only one of the two compounds is consumed. Porous structures containing internalized liquid or adsorbed gaseous fuels are another promising solution, as shown in Fig 2. Chen et al. recently reported an ultraporous (7,310 $m^2\ g^{-1}$) metal-organic framework that can store large volumes of methane and hydrogen gases that could be used to power vehicles, aircraft, and even robots[64].

4. Magnetic to mechanical transduction:

The coupling of electricity and magnetism leads to a fair degree of overlap when discussing energy storage applications. Energy can be stored in the magnetic field of an inductor or a superconducting coil (a process called superconducting magnetic energy storage, or SMES), for example, but current flow is required. Many robotic components and actuators, including motors, valves, pumps, solenoids, switches, and relays all leverage this same basic electromagnetic principle: a conducting coil produces a magnetic field when energized by an electric current, which in turn induces movement in a magnetic body. Movement mechanisms differ according to device configuration; the shaft of a conventional motor rotates when a current-carrying armature and an orthogonal magnetic field interact to produce a torque, while a linear solenoid actuator applies an axial force to a metallic rod contained within an electromagnetically inductive coil.

Many improvements to magnetic actuators have been realized over the past few decades, most recently with regard to smaller size scales and the adoption of different substrate materials[65–68]. While these designs can be more readily integrated into a wider array of robots, these innovations are primarily undertaken at the component level. Magnetic microrobots, in which the body and magnet are mostly one and the same, represent an entirely new set of capabilities, especially in the biomedical or *in vivo* realms[69–71]. Constructing the robot from magnetic materials allows the transduction of magnetic energy into mechanical motion to be embodied at the structural level. While remote power generation eliminates the need for an integrated energy storage system, external control via bulky, stationary magnetic coils restricts the scope of these robots to some degree.

Though examples are limited, magnetic actuation presents an excellent opportunity for Embodied Energy technologies, as the coil and magnet configurations used for actuation can also be used for energy harvesting (a magnet traveling through a coil will induce an electromotive force). One example is the use of electromagnetic dampers[55,72] within end effectors for proprioceptive force control, energy generation, and locomotion, as demonstrated in Figure 2. Another example is the Moball robot, which contains moveable, permanent magnets that can provide steering and enable rolling movements by changing the device's center of mass, in addition to generating energy by passively oscillating within solenoids[73].

Improvements in offboard magnetic control will be required for future robots to maximize the potential of Embodied Energy in this domain. We can envision coupling magnetic actuation and energy harvesting/delivery with the existing electrical systems in larger robots to achieve higher efficiencies and a wider range of functionalities. Additionally, we anticipate the expansion of magnetic actuator technologies in robots by implementing and innovating with non-rigid materials. Interesting applications include stretchable inductors for compliant power electronics[74,75] and the transport of ferrofluids through hydraulic and microfluidic devices without the use of movable parts. The incorporation of ionic or magnetic nanoparticles into elastomers and hydrogels also presents possibilities for an emerging suite of compliant and adaptable magnetic actuators at different length scales.

5. Thermal to Mechanical transduction:

Thermal to mechanical energy conversion is commonly accomplished by combustion engines, which are ubiquitous in modern machinery. Combustion engines present a number of challenges when designing with Embodied Energy in mind. The mechanical complexity, weight, size, and scaling limitations of engines (smaller, "micro" engines suffer from stiction, leaking, and fabrication difficulties), in addition to the supplementary components required by their system infrastructures (e.g., fuel reservoirs, engine control units) complicate integration into other energy-power systems and typically restrict them to larger applications in industry and transportation. Heat engines make up for their lower efficiencies (efficiency η ~ 25–40%)[76] relative to other energy transducers by consuming high energy density reactants.

At smaller size scales, bimetallic strips are among the simplest technologies used for thermal actuation. Heating a pair of thin, bonded metal parts with different coefficients of thermal expansion will cause the strip to bend. This phenomenon is leveraged everywhere from household appliances to MEMS devices. More recently, this technique of coupling materials with different thermal properties has been extended to soft matter to create fiber-based muscle-like actuators capable of producing large stroke cycles and withstanding high strain (in some cases >1,000%)[77,78].

Shape memory polymers (SMPs) are a promising, though less common class of materials/actuators that can be engineered to react to both thermal and magnetic stimuli. As their name suggests, SMPs are capable of undergoing a shape transformation—the entropy-driven restoration of a prior mechanical deformation—that is fast, reversible (t_{recovery} < 1 sec to minutes), and reprogrammable[79]. The favorable mechanical properties of SMPs, including high ultimate strains (ε_{ult} < 800%), tunable stiffnesses (E = 10^{-4}–3 GPa), and a wide range of transition temperatures (T_{crit} = -10–100 ˚C)[80] have seen them used in medical devices[81,82], fabrics and wearables[83], sensors[84], robots[85,86], and aerospace technologies[87]. Additionally, the multifunctionality associated with storing several different shape configurations within a single or composite material[79,88,89] , which can serve as both a structure and an actuator[86], makes SMPs an attractive option for Embodied Energy technologies. Shape memory alloys (SMAs) comprise a similar group of smart materials that can return to their original forms when subjected to changes in temperature or magnetic field strength. SMAs are typically stiffer than SMPs (E ~ 28–83 GPa, with generally similar moments of inertia)[80] and while they possess limited strain capabilities (ε_{ult} < 8%)[90] their high power densities ($\Gamma = 10^3$–10^5 kW m^{-3})[48] have contributed to their use in a wide array of robots and actuators[90–95].

Thermophoresis, a phenomenon where temperature gradients cause particles to experience a net force that may induce flow, represents another instance of thermal to mechanical energy transduction. Over the past few decades there has been growing interest in using thermal gradients to manipulate and propel micro/nano scale objects. Recent achievements in the medical field include the creation of thermophoretic nanomotors that can target and penetrate cancer cells[96], and the development of a micro-rocket robot that can be optically actuated through a bloodstream[97].

One established technique for improving the efficiency of combustion engines is the capture and reuse of waste heat (e.g., through the use of exhaust gas heat recovery, organic Rankine cycle units, or thermoelectric devices)[76,98]. Another approach is to leverage an alternative fuel source shared by another onboard, power-generating device. Hybrid electric vehicles represent a simple example where an electric and thermal system can operate synergistically through the addition of an optimizing control element. A related technology is combined heat and power (CHP), wherein fuel is used in the concurrent production of electricity and thermal energy, the latter of which is efficiency captured and used in processes like heating and cooling. Future robots could all stand to benefit through the incorporation of similar processes. With waste heat being a significant byproduct of many mechanical systems, it is easy to visualize how SMAs and SMPs could be integrated and embodied within existing machine architectures to improve energy efficiency, weight, or device performance. Both materials, for example, could be used as structural or skin-like elements that actuate to allow thermoregulation in different machines. Shape memory actuators could also be configured to respond to the waste heat of solar energy harvesters or heat engines, or used in concert with thermoelectric or pyroelectric devices[99,100] (Fig. 2). A recent report detailed the creation of an insect-scale, autonomous crawling robot containing a platinum-coated SMA artificial muscle that was powered via catalytic combustion with an onboard methanol fuel supply[101]. Another publication by Kim et al. demonstrated how low-grade waste thermal energy could be converted into electrical energy through the use of artificial polymer muscles.[102] More than 120 W of electrical energy per kilogram of muscle were successfully produced, which could be used in powering autonomous sensors.

Table 1: Energy and power density of common energy storage and actuator technologies

Energy storage technology	Energy density (Wh kg^{-1})	Efficiency (%)	Actuator technology	Power density (W kg^{-1})	Efficiency (%)
Lithium ion	75–200[122], 30–300[123], 120–200[124]	70–100[123], 85[124]	AC/DC motor	100–300[117], ~300–10000[128]	60–90[127]
Lead acid	30–50[122], 10–50[123], 25–50[124]	63–90[123], 85[124]	Hydraulics	50[119], 2000[118], ~50–20000[128]	21–50[136] 90–98[134]
NiCd	50–75[122], 10–80[123], 45–80[124]	59–90[123], 85[124]	DEAs	400–5000[126], 3600[117]	25–30 (max 80–90)[126], 80[117]
Ni metal hydride	30–90[123], ~70–140[9], 50–80[125]	50–80[123]	Piezoelectric	<600[118], <800[120], ~25000[134]	90–99[134]
Fuel cell	100–450[123], 150–1500[124]	22–85[123], 59[124]	SMAs	15000[134], 1000–50000[126], >10000[120], 50000[117]	1–2[134], <5[126], 1.5[120], 10[117]
RFBs	10–50[122], 10–90[123], 10–80[124]	60–88[123], 60–82[124]	Combustion engine/turbine	~300–10000[128], ~1200–4000[120], 4000–10000[138]	~15–30[120] ~30–47[129]
Hydrocarbon fuels	~4000–15000[130]	>98[137], ~92–100[139]	Pneumatic	40[119], 300[118], 1500–10000[121], 10000[117]	<30[119], 30–40[134], 49[117]
Latent heat	150–250[123]	75–90[123]	Pump	~10–1000[131], <5000[128]	~50–90[132]
Flywheels	10–30[122], 5–100[124], 10–30[135]	70–96[123], 87[124], 93–95[135]	Human Muscle	50[119], 50–284[126]	20–25[134], 30[119], 40[126]
Body fat	~10500[130]	41[133]			

Embodied Energy design principles:

Creating efficient robots that effectively embody energy can be accomplished by optimizing for endurance and operating time while overcoming key design contradictions (e.g., increasing the energy content of a robot while maintaining its volume.). To that end, we have identified several key design principles that can be acted upon to improve the Embodied Energy potential of future robots. Fig. 2 depicts how these design principles can be used in both existing and hypothetical Embodied Energy technologies.

1. *Design with SWaP tradeoffs in mind*. Generally, while power density is inversely proportional to weight and volume, operating time scales proportionally with size in untethered robots. Smaller, lighter devices by definition carry less onboard energy, and so compromises must be made when designing at different length scales. Using embedded, high energy density fuels is one approach to optimizing for high power at smaller sizes.

2. *Integrate energy storage into structural elements where possible*. Using batteries as structural elements can eliminate the need for certain load bearing components, thereby reducing the total mass of a device and increasing energy density. Additionally, mass or volume elements that would normally bear loads can consequently be reassigned to perform functions unrelated to energy storage.

3. *Reuse waste energy*. Recovered energy can be reconverted into onboard power, as in exhaust gas heat recovery systems, or repurposed for a secondary function, such as heating and cooling in CHP systems.

4. *Leverage resonance where possible*. The efficiency of a system can be increased by carefully selecting materials and geometries during the design phase, and subsequently driving the system with parameters that lead to high amplitude outputs. Further, operating actuators at resonance will require less energy input (e.g., a pneumatically powered actuator may need to be inflated fewer times and endure less stress for an equivalent distance traversed).

5. *Make a system serve itself by performing auxiliary helpful functions*. Halogen lamps are a simple example of this phenomenon—they regenerate their own filament when in use through the redeposition of evaporated metal[103]. The redox flow battery inspired electrolytic vascular system also epitomizes this principle[1]. The same liquid used for hydraulic actuation is also used for energy storage, and the pumping of this liquid recirculates the soluble ions to improve the rate of charge transfer.

6. *Compensate for weight through interaction with the environment*. Hydrofoils are used to lift ships out of the water to reduce drag, and vortex strips are implemented in aircraft wing designs to improve lift[103]. Many aquatic animals achieve buoyancy due to their energy storing fat reserves.

7. *Use hybrid hard-soft structures to create adaptable designs*. Using compliant, muscle-like materials can lead to durable robots that can dampen or even absorb and redistribute forces, traverse difficult terrains, and operate with many degrees of freedom.

8. *Consider tradeoffs between integrated and modular assembly*. Modular designs can be easier to assemble, service, and reuse. A complex and heavily integrated design can likely achieve higher performance and should execute an array of self-sustaining functions, at the cost of simplicity in maintenance.

9. *Use composite or porous materials to store energy*. Composites can contain both structural and energy storing domains. Similarly, porous materials, as in the example of gas adsorbent metal lattices[64], can form lightweight structures that house fuel or energy in their pores.

10. *Harvest energy from the environment*. To achieve fully autonomous robots that do not require regular refueling, we must equip them with the technology to extract energy from their surroundings.

<u>*Energy harvesting:*</u>

Energy harvesting in robots, itself a burgeoning area of research, warrants additional consideration in the context of Embodied Energy. The state of the art in energy harvesting methods (e.g., thermal, solar, vibration/kinetic, radio waves) is well established in the literature[42,61,104–107], but existing technologies fall far short in producing enough power to independently operate a typical robot (maximum length, $l > 10^{-1}$ m). Even in smaller systems, harvesting the minimum energy required for actuation can impose specific positioning and alignment conditions within the environment, which can constrain device utility and control[108]. Many researchers instead see energy harvesters as being valuable in complementary applications where the microwatt to milliwatt power outputs can reliably operate low-power sensors. These sensors could, for example, enable advanced levels of control in robot swarms, or spatial sensing in robotic exosuits.

Vibration or motion-driven microgenerators, such as piezoelectric generators, and photovoltaic cells are among the most mature energy harvesting technologies[109], making them obvious choices to complement robotic Embodied Energy systems. Solar energy in particular has been used to power an assortment of semi-autonomous machinery, including agricultural robots, UAVs[16], microrobots[110], and spacecraft, but environmental variability and limitations in power density and efficiency (typically, efficiency α ~ 8–35%[62]) do restrict this application space. Triboelectric generators,[111] have demonstrated impressive power densities (Γ = 490 kW m^{-3})[112], and produce high voltages that can power electrically responsive materials with large internal impedances, like DEAs[113]. Ryu et al. highlights several hybrid energy harvesting designs, including mechanical-photovoltaic, mechanical-thermal, and thermal-photovoltaic harvesters.[107] Finally, interest in wearable tech has led to the creation of flexible energy harvesting devices with thin or thread-like form factors that easily contour to most geometries.[114,115] These technologies could potentially replace or augment the exterior of different robot designs for the purposes of extracting energy and information from the environment.

Challenges and future advancements

A universal methodology for characterizing and evaluating Embodied Energy systems in a design context has yet to be established. However, techniques for characterizing the advantages of multifunctional systems, in general, have been proposed. Johannisson et al. introduced a "residual performance methodology," that involves comparing the specific properties (e.g., mass, shear strength, specific energy) of a multifunctional block with those of two or more monofunctional systems (e.g., structure, energy storage)[116]. By subtracting known properties of one monofunctional system from those of the multifunctional system, we can obtain the properties that would be required of the accompanying single function systems to achieve performance metrics that match or exceed those of the multifunctional one. Other approaches include establishing a multifunctional efficiency metric or directly calculating the change in a value of interest as a function of different design variables. In the latter case, this relationship may not always be known. Thomas et al. demonstrated this in their work by modeling the flight endurance time of a hypothetical, electrically powered UAV in terms of the relative masses of the onboard batteries, solar cells, and structure to draw conclusions about the most effective multifunctional configurations[61].

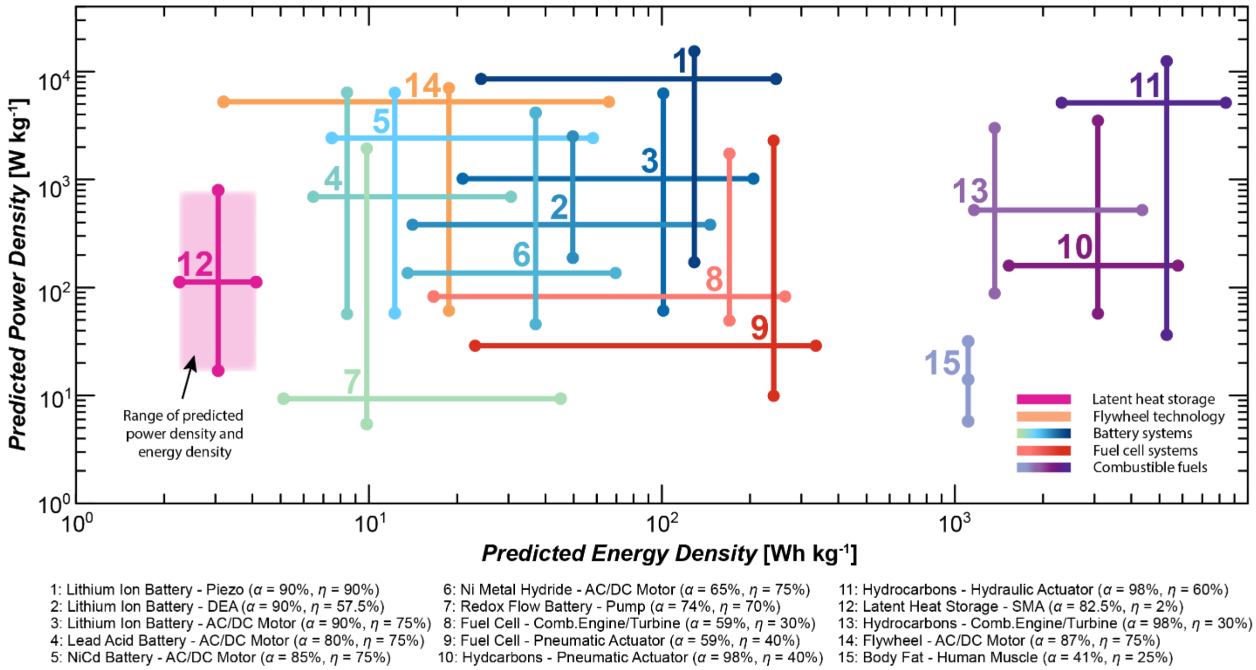

Fig 3| Multifunctional Ragone plot of Embodied Energy storage and energy transducer combinations. Each pair of intersecting line segments (corresponding to a specific number and color) represents the range of predicted energy density and predicted power density values for a given energy storage and actuator combination, based on existing products and prototype devices[4,9,48,117–139]. Predicted energy density is the product of an energy source's energy density Z, efficiency α, and the efficiency η of the energy transducer where it is embodied. Predicted power density is the product of an energy transducer's power density Γ, efficiency η, and the efficiency α of the energy storage system in which it is embodied. [The intersection points of the line segment pairs are arbitrarily chosen for visibility.]

To predict the efficacy of different embodied energy storage and energy transduction systems, we created a graphical tool in the form of a multifunctional version of the classic Ragone plot[140] (Fig. 3). Each of the intersecting line segments, designated by a unique number and color, depicts the range of *predicted energy density* (x-axis) and *predicted power density* (y-axis) values for a paired energy storage and energy transducer (actuator) combination (e.g., 9: a fuel cell and a pneumatic actuator). We define predicted energy density here as the product of the gravimetric energy density of a given energy storage system, the efficiency α of that energy storage system, and the efficiency η of the energy transducer in which it is embodied. Predicted power density is calculated in the same way. The energy sources in these hypothetical combinations can be thought of as fully embodied within their assigned energy transducer, where they will serve multiple functions. Combination 13, for example, implies an engine or turbine configuration that takes energy from the burning of its hydrocarbon support structure, rather than a traditional fuel reservoir that serves a single energy storage function. The efficiency, energy density, and power density data for Figure 3 was acquired from several publications and existing products[4,9,48,117-139], and is compiled in Table 1.

The energy storage and energy transducer pairs shown in Fig. 3 were selected based on complementary features or their usage in previously reported prototypes. While the full scope of possible systems and combinations is impossible to sample, this data does allow for a direct comparison of the energy content and output of different hypothetical Embodied Energy arrangements. For example, combinations 10, 11, and 13 store energy as a hydrocarbon fuel and are akin to autophagous power systems; however, despite possessing greater energy densities than many of the other systems, the upper bound of their power density range is not significantly different from several battery and motor driven designs due to the low efficiencies involved. This graph does not take into account the mass budgets and efficiency penalties of supplementary systems that may be necessary for the construction or operation of these hypothetical systems, as these could take any number of forms. Similarly, the plot does not capture the additional functionalities or non-energy storage characteristics that may be beneficial in certain designs (e.g., material compatibility, scalability, or cost). All Embodied Energy technologies, along with their inherent characteristics and design tradeoffs, must necessarily be evaluated in the context of their intended environment and applications. Hence, we see this multifunctional Ragone plot as a useful tool for exploring different robot designs when energy and power requirements are known.

Embodied Energy both presents and promises to solve future challenges. SWaP tradeoffs, for example, will always present difficulties to robotics researchers, particularly as smaller robots and personal devices, each possessing significant payload restrictions and energy requirements, are pursued. Microrobots present an extreme case, with many of the latest innovative designs requiring an electric tether to deliver power[141]. Several are limited to specialized environments,[141] and most also forego conventional actuators (i.e., DC motors) due to fabrication limitations as well as the unfavorable scaling of friction and electromagnetic forces[142]. If the advantages promised by microrobot technologies (e.g., swarm capabilities, exploration, search and rescue, medical intervention) are to be realized, multifunctional design strategies employing Embodied Energy must be pursued.

Other challenges must be overcome as well, including the need for new, compatible materials that operate synergistically with existing technologies, as well as yet unimagined ones. Examples include conductive and corrosion-resistant materials that could function as battery electrodes and ion exchange membranes, energy-dense solid polymer fuels for autophagous systems, controllable shape-morphing materials[143], and biocompatible materials that can be assembled into lightweight composites composed of organic, inorganic, and even living matter. Advancements in additive fabrication techniques across multiple scales, coupled with predictive (inverse) design will be necessary to increase both the compositional and structural complexity of robots, and to realize new levels of multifunctionality.

The tighter integration of sensing, actuation, control, and power towards biological size scales (i.e., organs and tissue) will realize first order improvements in robot autonomy. While synthetic systems are striving to achieve tissue level autonomy, biohybrid ones already do. Consequently, we expect research in this area to be fervently pursued in the immediate future. 3D printing will also be an increasingly used tool; Direct Ink Writing,[144] PolyJet,[145] and Digital Light Processing[146,147] have all been used to create complex robots with intricate internal networks out of soft materials. The use of new, more energy dense materials will also provide new design tools for directly printing robots. Finally, the direct chemical to mechanical conversion of energy, as demonstrated with hydrocarbon fuels, will likely become increasingly used to provide the greater energy densities and efficiencies required for biological magnitudes of endurance and adaptability.

Finally, the multifunctional energy storage paradigm we are attempting to codify can be further separated into passive and active control. Within these logic mechanisms there is further opportunity for multifunctionality; the structures themselves provide control (e.g., origami[148], bistable beams[149,150], and elastomeric actuators[151–154]). In this context, information processing becomes another material property embodied in the physics of the soft, architected structure; enabling local computations that seamlessly integrate the sense-decide-response chain[155,156]. For example, networks of elastomeric light guides have demonstrated the information density and sufficient sampling rates to classify deformation states through offboard neural network training[157]. Remarkably, the mechanical nonlinearity of elastomeric materials is even capable of embodying recurrent neural network behavior; as demonstrated in the dynamics of a silicone octopus arm[158]. Embedded computation has the added benefit of requiring less energy, as the information processing is inherently coupled to, or a by-product of, the deformation and environmental loading. Embodied Energy and Embedded Computation, therefore, will be intricately linked in the future of advanced robotics research.

The conjoined aspects of harvesting, storing, transforming, and releasing energy provide a unique lens through which to view the evolution of autonomy and intelligence. Such considerations similarly challenge roboticists to rethink how to design, program, and deploy their creations into the world. The design principles that result from the proposed Embodied Energy paradigm have the potential to yield new multifunctional energy storage systems that improve the multi-objective optimization of robot endurance and adaptability. The frontier of this research lies in integrating advancements in predictive multiscale design, multifunctional materials, digital manufacturing, and robotics.

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