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Soft Robotics

ROUNDTABLE DISCUSSION

Energy for Biomimetic Robots: Challenges and Solutions

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Animals and autonomous robots need to carry their own fuel (unlike plants, they do not generate usable energy from their surroundings). Animals typically exceed the normal endurance and range of all our current untethered robots. As an obvious example, humans have tremendous burst speed (less than 10 seconds to run 100 meters) and endurance (running a 26-mile marathon), and they can continue to do everyday activities without refueling (eating) for several days. The typical cost of transport for humans is about 0.2. In comparison, most robots operate for less than 1 hour on their carried fuel; the cost of transport is 15 or 20 times more than that for animals. An intriguing insight is that passive dynamic walkers can approach the human cost of transport (the Cornell Ranger can walk nonstop for 65 km), but this is a single optimized task (walking) with none of the versatility of an animal that can step over objects and operate on varied terrain. What it does illustrate is that structures (and by extension, material properties) can be exploited to ‘‘get the most’’ out of a given fuel source. Surely, this is what animals do on a continuous basis. What do we need to do to give our robots similar capabilities? In particular, what are the special demands, advantages, and limitations of fuel storage and usage in soft robots? To begin exploring some of these issues and to also stimulate a larger dialog in the robot community, the following discussion has been compiled from a series of questions posed to the participants.

—*Barry Trimmer*

Soft Robotics: What are the special problems in providing fuel (energy) for biomimetic and soft robots?

William Messner: Biomimetic and soft robots in particular are limited because it is very difficult to convert efficient generators of high-speed rotary motion (e.g., turbines or electric motors) to low-speed/high-force motion with soft components. Are there alternatives such as planetary or harmonic gear trains? While biological muscles are not particularly efficient from a thermodynamic perspective, they do not suffer from the huge losses of miniaturized gear reduction systems, and they are soft!

In addition, heat engines scale very poorly—thermal losses and friction losses reduce their efficiency enormously at small scales. Thus, highly efficient turbines and even modestly efficient reciprocating heat engines do not deliver good performance at centimeter scales and below. Existing batteries on the other hand deliver poor energy density on a per-mass and per-volume basis.

Barry Trimmer: Yes, I can insert here a few numbers that we keep coming back to. The energy density of nuclear fuel such as nuclear uranium is 80,620,000 MJ/kg; by comparison, hydrogen (compressed at 70 MPa) provides 123 MJ/kg and hydrocarbons such as LPG, gas, diesel, and fat range from 35 to 47 MJ/kg. Our best readily available batteries (Li and Li ion) are around 0.3–1.8 MJ/kg. Even if we could get around the safety and security issues associated with radioactivity, capturing that energy requires a lot of physical plant and is unsuitable for soft mobile machines. Clearly, hydrocarbons have the advantage. The obvious drawback is that our conventional use of hydrocarbons involves combustion and the production of extreme heat, pressure, and pollutants. The low-temperature oxidation pathways used by living tissues would seem to make most sense for robots used around humans.

Sangbae Kim: Most of human-made electric energy storage devices are relatively rigid or semirigid (lithium-ion polymer). It will impede compliant behavior if electric energy is required to be part of the structure. Fuel in the form of liquid would be ideal. A possible question to answer is how to deal with the volume change of the liquid as the fuel is consumed. In a rigid robot, like MIT Cheetah, we need better power-density fuel cells. The power density of the current fuel cells is not high enough to use in a robot less than 50 kg.

Robert Shepherd: One of the major benefits that living organisms have over robots is their ability to harvest energy from the environment: eating. While we can develop robots that can go to charging or fuel stations autonomously, these waypoints must be predetermined. Thus, even though the internal combustion engine is more efficient than muscle, a praying mantis can catch prey when it must refuel at many locations.

William Messner: Making structural components out of energy storage devices would be a way to increase the range

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and capability soft robots. Or at least diffusing the fuel storage throughout the device, as biological systems largely do, may make for a more efficient system.

Jamie Paik: Having multiple degrees of freedom and a reconfigurable body, which I also consider to be a soft robot as well, would be able to collect solar radiations by either multiple interactive mirrors and/or solar cells. Multiple micropropellers and generators are also a possibility. Advancement of semiconductive materials, thin film fabrications, and microgenerator designs let us keep the door opened for the ''old'' solutions for use in soft robotics (although scaling and modularization is the key homework).

Soft Robotics: Are current fuel choices ''locked'' by the limited number of actuator options (motors, hydraulics)?

William Messner: At the moment, actuation and fuel-to-useful-energy conversion are largely decoupled. For example, a typical approach is chemical energy to electricity (battery or fuel cell) and then electricity to mechanical work (electric motor magnetic, electrostatic, or piezoelectric). The actuator and the energy extractor are physically separated. The conversion of fuel to mechanical work is direct in biological systems. Direct chemical to mechanical energy conversion at the millimeter scale is a holy grail for biomimetic system.

Barry Trimmer: That is a very good point. In muscle, the exchange of high-energy phosphate bonds (in adenosine triphosphate or ATP) is translated directly into a molecular conformational change. Of course, all of these molecular-level movements have to be highly coordinated. That is one of the remarkable features of biological systems: they can organize themselves into massively parallel systems and then stack the systems hierarchically so that the tiny protein transitions emerge as concerted muscular force.

Sangbae Kim: Either we choose electric motors or hydraulic actuators, it is desirable to have electric energy source.

Jamie Paik: I agree. Electric energy source is highly preferable not only because of the ''conventions'' used for the actuators, sensors, and controllers, but also because of ease of characterization and modeling. However, as we are already searching for unconventional solutions to various components of soft robots, there no longer is a boundary. What we need would be a great ''transformer,'' whatever the fuel may be.

Robert Shepherd: Fuel is a method of providing force to an actuator; there are many ways to transmit that force, regardless of the source. The question is how efficient is the method of transmission and the energetic output of the fuel source.

Soft Robotics: Are there creative avenues we can explore instead (e.g., gas production as an actuator)?

Barry Trimmer: I am not sure if actuator efficiency is the most important problem. Muscle is not particularly efficient (overall less than 30% mechanical output to total metabolic cost calculated from oxygen consumption); electric motors are typically 50–75%, and internal combustion engines can be between 25% (gas) and 40% (diesel). What about pneumatics, hydraulics, and electroactive materials?

Sangbae Kim: It could be desirable to generate pressure directly from fuel (e.g., microdirect combustion) to minimize required rigid hardware that converts fuel to mechanical work.

William Messner: Gas production from chemical actuators can produce high pressures and thus high forces. How efficient can this production be? Decomposition of hydrogen peroxide generates one molecule of oxygen for every two molecules of H_2O_2. At standard pressure and temperature, this corresponds to a volume increase of approximately 160 and 16 J/g (0.05 MJ/kg) of mechanical work alone (compared with about 0.8 MJ/kg of heat!) for a 30% solution. The mechanical work alone is comparable to that stored in a supercapacitor but less than a lead acid battery on a per-kilogram basis.

However, advantages with respect to mechanical losses and the opportunity to effectively capture some of the heat might make this approach worthwhile. For example, using such an actuator for jumping might be a good way to utilize the heat produced to increase pressures, greatly improving efficiency.

Robert Shepherd: The decomposition of azides provides a rapid method for producing pressurized gas (e.g., an air bag deploying). Liquid azides are an attractive opportunity for high energy density sources of pressurized gas that can be transported like arterial blood; however, they are potentially explosive and typically have toxic degradation products.

Jamie Paik: Apart from chemical actuators, smart material-based actuators are still an interesting and valid option. Unfortunately, in practice, they are not as widely used in robotics as other actuation methods. However, having unique mechanical properties (reactive to magnetic field, pH level, UV, and temperature) and material properties (fluid, metal, colloid, and gel), smart material actuators could create specific solutions in combination with chemical/combustion actuators acting as one of the ''mechanical'' components (e.g., catalyst, container, switch, and transmission).

Soft Robotics: Should biorobots use different fuels for different purposes (range, power, etc.)?

Robert Shepherd: The question is whether we wish to replicate organisms entirely, or simply learn from their attractive features (hopping, climbing, swimming, etc.). The primary source of fuel for a horse, for example, is glucose whether it is trotting or galloping. In human technology, however, the direct conversion of solar energy into electric current is an excellent method of powering machines that require low wattage, or that can be operated intermittently at higher power using battery storage. In cases where high-power output is required, with or without a charged battery (e.g., escape maneuvers), then hydrocarbon combustion may be desirable. So, I think we should definitely consider different energy sources for a particular purpose, and even mix modes of fuel for a single biorobot.

William Messner: High forces/high power = gas actuator. Long-distance low-power travel = battery.

Sangbae Kim: Chemical compatibility could be important considering that the available material is limited to soft materials (no stainless steel).

Jamie Paik: Another factor to consider is the longevity of the system/function. If only a single shot movement that does not need to be repeated is required, fuel choices could be more diverse. However, for longer running systems where the locomotion pattern becomes important, it would need a sustainable and self-sufficient quantity/methods to restock the fuel.

Soft Robotics: How far can we get by concentrating on efficiency of motion (passive dynamics, energy storage, and release) rather than the fuel itself?

Barry Trimmer: To my way of thinking, the key issues in order of importance are (1) the energy density of fuel, (2) the efficiency of supplying and using energy in the actuators, and (3) the overall fuel energy conversion into mechanical actions (with compliance matching).

Sangbae Kim: It depends a lot on the system details. However, I can describe in terms of a legged robot's case based on my experience. The actual mechanical power required for locomotion is actually not much. In our MIT Cheetah robot's case, the overall cost of transport is similar to animals of a similar scale, and the mechanical power was only 20% of the total power consumption. Seventy percent of the power consumption is dissipated through heat (this is directly related to torque not power) in the process of converting energy to mechanical work. According to some literature, this is not too different from animals. One study[1] shows that the 70% of the energy is used in producing force in human running.

This high cost of force production might be true in other actuation techniques, such as piezo-electric devices.

If the robot and the controller are well-designed, I'm confident that the robot can equal or exceed the performance of the animal in terms of efficiency. Not necessarily because we have better mechanisms or computation, but because we have more choices in energy storage and power conversion mechanism.

William Messner: Trickle ''charge''/fast release (energy storage) for jumping or jump-glide systems may be a good way to harness energy from light energy from the environment or highly ratchet-type actuators and internally powered actuators.

Jamie Paik: Adding on William's comment, although it may not be so common in nature, for example, we can maximize the energy usage via introducing multilocomotion methods for a single robot (e.g., bats would fly and crawl, and flying fishes would swim and fly) that can change its method of locomotion via reconfiguration of the body shape (rolling, crawling, and hopping).

Soft Robotics: How important are regenerative mechanisms (e.g., piezo systems) likely to be?

William Messner: Regenerative mechanisms work best with high-inertia systems. Small-scale soft robots or biomimetic systems will not be suitable for such mechanisms because of friction and other dissipative losses, in my opinion.

Sangbae Kim: Regenerative mechanisms could save a nontrivial amount of energy depending on the detail. The negative work in a cycle is not big (10% in the MIT Cheetah). However, if the regenerative system is not well-designed, the impedance control can't be great. Simply saying, the energy flow should be bidirectional.

Robert Shepherd: I think the most important regenerative mechanism is elastic energy storage, for example, ligaments. Some elastomers are extremely resilient and can return most of the energy stored in them during stretching; simply by incorporating strands of these rubbers so that they engage at particular moments during programmed gaits, we could reduce the amount of fuel required for locomotion.

Soft Robotics: What about fuel safety? Animals ''burn'' fat, sugars, and proteins safely (even indoors in crowded rooms). Surely we can engineer something similar for our soft biorobots!

Sangbae Kim: I am certain that we can design a safe storage technique for a given system.

Jamie Paik: First of all, not all fuel solutions need to combusted. Endo- and exothermic reactions under triple/critical point could be used. In any case, the safety issue requires addressing both the pressure and temperature change of the fuel: as long as the ''container'' is well-designed, the safety issues could be well-characterized.

Robert Shepherd: Fuel cells (perhaps ideally methanol) are an opportunity that I have not seen used, yet would operate similarly to the ''burning'' seen in animals without the safety hazards of igniting gasoline.

William Messner: Fats and/or solutions of simple sugars are safe fuels—they do not readily burn with flame, and even then burn slowly. However, the cellular machinery that biological systems use to extract their energy is remarkably complex but also remarkably robust. Teaming with lab-on-a-chip people to create complex plants, which might still be thousands of times larger than the nanometer-scale machinery of cells, seems like something we should pursue. Can we make millimeter-sized fuel cells employing glucose, for example? Can we make these fuel cells mechanically active? That is to use the reaction to power a mechanical mechanism that is part of the fuel cell?

Barry Trimmer: I like that idea. We do not have to copy the living system itself but instead engineer a scalable solution based on the mechanisms that work so well in living systems. The fixation of electromagnetic radiation into hydrocarbons (photosynthesis) requires highly organized and polarized arrays of molecules, as does the production, and use, of ATP. Fuel cells and modern batteries are beginning to emulate these approaches.

In closing, I would like to thank you all for your contributions. We have just touched the surface of some major issues. Solving these challenges will require significant and coordinated advances in materials sciences and robot engineering. We will be exploring all these areas in more detail in future articles and discussions in *Soft Robotics*.

Reference

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