Analysis of the Efficient Use of Energy Based on Soft Robots

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Abstract. Soft robots have advantages in simulation and non-structural environments, and the problem of energy "provision" is one of the bottlenecks in the development of soft robots. This article reports the progress in the effective technology for the provision and use of soft robot energy, including the progress of core key technologies such as self-power actuation of soft robots, energy efficiency optimization of gas-driven systems, and intelligent energy management systems. The article focuses on the research progress of environmental mechanical energy collection and self-actuation possibilities of Triboelectric nanogenerator (TENG). Besides, it analyzes the advantages of exhaust gas energy consumption and use provided by Internal Exhaust Air Recirculation (IEAR) technology and bidirectional pneumatic actuators in gas-driven systems. Lastly, it outlines the energy management system method of soft robots based on "mechanical intelligence" or "adaptive" algorithm. The article emphasizes the shortcomings of soft robots in terms of energy density, integration and environmental adaptability. If the problems of energy integration, intelligent energy scheduling and system integration can be solved, the long-term autonomous operation of soft robots in complex environments can be realized.

Keywords: Soft robot, Energy, Triboelectric nanogenerator, Pneumatic soft actuator.

1 Introduction

At present, soft robots have achieved a large number of simulations and research in the areas of biological simulation and scientific applications. Compared with traditional robots, soft robots are safer, more adaptable and more efficient in non-structured environments. For example, Soft Jellyfish Robot, Frog-inspired swimming robot, etc., can further imitate biological forms and movements [1,2]. However, there is a problem facing most soft robots in the laboratory. When the robot is disconnected from the fixed power supply, it is necessary to ensure an adequate energy supply by equipping it with an independent power source or other energy sources, without affecting its original application functions. Making reasonable plans and appropriate control is also a method for reducing energy consumption.

For these problems, generating or collecting new energy from the surrounding environment and working methods is a way to achieve energy supply. For example, Triboelectric self-

ICMEEA 2026, April 24-26, Singapore, Singapore

DOI 10.4108/eai.24-4-2026.2364845

powered soft robotics, which can convert some mechanical energy into electrical energy, and then this electrical energy can directly or indirectly drive the soft robot. This technology expands the application of traditional robots in driving and human-computer interaction, etc., and provides technical support for the development of untethered soft robots. In addition, for gas-driven soft robots, Internal Exhaust Air Recirculation technology can improve the energy utilization efficiency of gas-driven soft robots. At the same time, through intelligent data operation, the data model can also be applied to the energy consumption of soft robots to solve the energy planning problem.

This article will review the existing TENG soft robots, gas-driven robots and exhaust gas recirculation, the planning of untethered soft robot energy by AI algorithms and the energy utilization and consumption of soft robots. It summarizes the current situation of the development of these technologies, analyzes their difficulties and breakthrough directions, and the prospects of further research.

2 The core technology to realize the efficient use of energy

2.1 Self-powered actuation technology

Self-powered actuation technology means turning the energy of the surrounding environment into usable energy. This technology alleviates the pressure on the energy supply. For untethered soft robots in the experiment, the Triboelectric nanogenerator (TENG) will be an emerging technology that can replace the continuous consumption of energy.

Triboelectric Nanogenerator (TENG) Technology and Soft Robot Fit Point. Soft robots face many challenges, like reliance on rigid batteries, requirement for high voltages, and limited battery life, so Triboelectric nanogenerators (TENG) and other technologies can solve them one by one. Specifically, based on electrostatic induction and the triboelectric effect, TENG converts some of the extra mechanical energy generated in the robot's movement into electrical energy. Then the machine collects the electricity and uses it again. Wang's team successfully invented TENG in 2012. They pointed out that the core of the technology is to use environmental mechanical energy such as vibration, friction and water flow to couple the triboelectric effect with Electrospray Ionization (ESI) [3-5].

And TENG can be made of a variety of flexible and stretchable materials (such as polymers, hydrogels, fabrics), which are highly matched with the ontological material system of soft robots. In addition to energy supply, TENG can also be used as a sensor, actuator, etc.

Use TENG to directly power actuation. The power supply actuation of TENG is mainly in several modes. The first model is to collect energy from the external environment to collect and actuate, that the robot is equipped with a TENG to collect external energy to supply energy for the actuation device. For example, the TENG, which collects biomechanical energy researched by the Y.Wu team, these research results can collect the conductive solution of energy through the sole of the sole during human movement [6]. There is also the high-efficiency wind energy collection TENG researched by the Q.Mu team, or the honeycomb structure TENG of the X.Xiao team, which can realize the monitoring and collection of vibration energy [7][8]. However, this actuation method still faces some major challenges, such as how to store a small amount of energy and sensing information through micro capacitors, or how to store energy sources.

The second mode is to recover the excessive mechanical energy generated by some movements. Specifically, it uses the deformation generated by the compression and elongation of some soft robots to recover electrical energy. These energy supplies power for subsequent actuation to achieve high-efficiency utilization of energy. For example, Jonghyun Ha and others realize the expansion and contraction of the hygrobot by changing the humidity, which can collect the trace energy generated by it in the swing bending movement [9]. Obviously, though this method has improved the efficiency of energy utilization, the energy density it recovers still needs to be improved.

The third mode is directly driven by TENG, which uses the instantaneous voltage generated by it to directly release the pulse signal to stimulate some materials. Dielectric elastomer (DEA) requires a one-way regular current to achieve its expansion and contraction, and thus its direct actuation can achieve DEA's free movement and expansion in an unstructured environment. Meanwhile, TENG's high-voltage characteristic is well-suited to DEA-actuation soft robots. This actuation method gives full play to the advantages of fast DEA response and large strain. Therefore, TENG can free some soft robots using DEA from the shackles of wires.

2.2 Energy efficiency optimization of pneumatic system

Pneumatic actuation has the advantages of high power density, flexibility and low cost. These advantages make pneumatic actuation one of the mainstream actuation methods of soft robots. The energy released by the pressure of the pneumatic actuator after compressing the air is not only kinetic energy, so in the exhaust process, the pneumatic actuation will waste some energy converted into sound energy and heat energy. In addition, in the process of continuous compression and exhaust movement, some exhaust losses also reduce the efficiency of the overall system. Therefore, the first way to solve the problem is to recycle the wasted gas energy, and the second is to use a new design to reduce exhaust loss.

Internal Exhaust Gas Recirculation Technology (IEAR).IEAR is a bionic concept inspired by internal combustion engine technology. Its core is to guide the "exhaust gas" , the air still with a certain pressure, generated when venting one chamber of the actuator to another chamber that needs to be inflated for reuse, rather than directly discharged into the atmosphere. Specifically, Multichamber soft pneumatic actuators (m-SPAs) use the mechanism of 'direct actuation', that is, compressed air enters the actuator and directly reaches the outlet discharge chamber. The IEAR technology compresses the released exhaust gas to another chamber, thus reducing the system pressure and making the movement more stable. In addition, due to the reduction of the process of high-speed exhaust to the atmosphere, the operating noise of the system is significantly reduced.

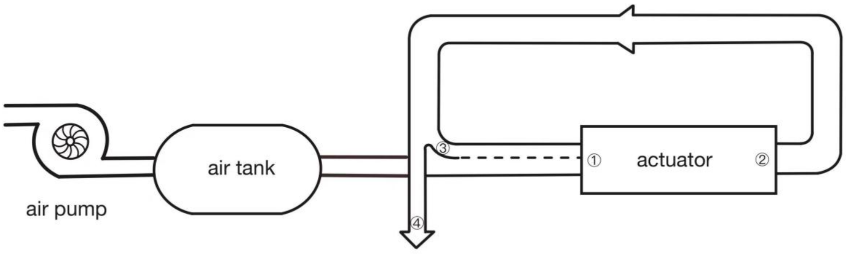

Fig.1. Internal Exhaust Gas Recirculation Sketch Map

As shown in figure 1 the entrance inflates the gas into the chamber of actuator. The gas exits to vent the chamber. The branch is a recirculation channel for the exhaust gas within the system . The branch direct exhaust gas into the atmosphere. Tips:It is characterized by storing part of the exhaust gas as an actuator pre-inflated, while the air pump only needs to replenish the insufficient pressure.

Nowadays, although IEAR technology is still in the experimental development stage, there are still many teams that combine IEAR with soft robot movement. For example, the robot fin designed by M.Feng's team has a better swing frequency and average propulsion force than the original gas actuator [10].

Bidirectional pneumatic actuator. In addition to the above method, a bidirectional pneumatic actuator can also be a solution. When two or more chambers are properly pressed, the SPA can be reciprocal. This method facilitates the deformation of the actuator in two directions of movement. Bidirectionality is through the combination of pleated membranes that expand and contract when pressurized, and make the bellows expand when inflated. In simple terms, by using pleated membranes and bellows, the bidirectional pneumatic actuator is a new actuator that can realize the linear movement of pushing and pulling in two directions at the same time. The advantage of the bidirectional pneumatic actuator is that it uses exhaust energy to compress the bellows and then releases it in the next cycle. In this way, the internal recirculation and reuse of energy can be achieved. In addition, compared with traditional actuators, two independent air chambers to control bidirectional movement, bidirectional pneumatic actuators do not consume new compressed air in half a movement cycle, which greatly reduces the total gas consumption. Therefore, its high energy efficiency and compact structure make it suitable for scenes that require efficient reciprocating linear motion. For example, the BiSoft.QA grippin studied by the N team is grasped by a two-way gas actuator [11].

2.3 Intelligent energy management system

Although the basic new actuator and energy harvesting technology can solve some energy problems, the energy challenges in soft robots have not been completely solved. Untethered soft robots lack energy management and distribution,so they are often considered unable to accurately complete long-term tasks. Therefore, it is necessary for a mainframe computer to simulate the energy consumption of soft robots in advance, or to generate planning and temporarily schedule energy through a simple simulation of a minicomputer, in the form of physical intelligence. However, the unconditioned reflex of surplus energy is not enough to complete energy planning, such as the low power mode of mobile phones. Therefore, the intelligent energy management system allows soft robots to carry actuators and sensors. In doing so, the passive energy supply of the laboratory's bound soft robot is turned into an intelligent energy management soft robot.

Mechanical Energy-Harvesting Self-Powered Control System. Specifically, the self-driving control system belongs to the transformation of complex control methods into physical intelligence. This means that the mechanical stimulus will be directly converted into a control signal from a functional material, and then the actuator will be driven to generate a response model, which realizes this 'sensing-power supply-actuation' architecture. For example, the dual-mode dielectric elastomer system proposed by the Z. Zhang team shows how to integrate energy collection and actuation functions into one to realize the closed loop of "sensing-energy supply-actuation" [12]. The innovation of this system is that the actuator can perceive and judge its own mechanical energy state. Then, through the small electrical energy to regulate the release timing and direction of the mechanical energy stored internally, the large output can be controlled with minimal energy. Chong Chan Kim and others derived the idea of integrating energy storage, sensing and actuation functions into the ontological structure of the robot, which is highly consistent with the research direction of "body energy" and aims to reduce dependence on complex external control through physical intelligence [13].

Low-power Adaptive Control Algorithm. The low-power adaptive control algorithm estimates the remaining energy and task priorities through pre-simulation, and then adjusts the behavioral strategy. For instance, Edamana, B and others proposed optimal switching control and partial charge recovery strategies for piezoelectric microrobots, which significantly reduced the energy consumption of the system through algorithm-level optimization [14]. In the general non-working environment, the algorithm robot is in a low-power sleep state. In environmental interaction, it makes robots learn and use the most energy-efficient learning strategies. Another idea is that Caasenbrood, Team B is based on the energy shaping control of the port Hamilton model. This method provides theoretically strict passive controllers for soft robotic arms and other systems by shaping the total energy flow of the system, so as to achieve efficient utilization of energy and natural stability of the system while ensuring motion performance. When the robot has multiple actuators, it coordinates the use of different actuators to actively reduce energy consumption [15].

3 Technical challenges and future development

3.1 Energy density and output power limitation

Whether it is TENG open source technology or exhaust gas recovery technology in pneumatics. Their energy reserves have problems such as low energy conversion efficiency and limited output power. As a result, it is difficult for soft robots to meet the problem of long-term high-intensity use. Soft robots are increasingly miniaturized and integrated. Thus, the most concerning issue for materials and structures is to determine the need to achieve greater energy density in a limited internal space in the future.

3.2 System integration and long-term stability

Soft robots are generally composed of sensors, actuators, and controllers. Many modules of soft robots together to form a whole will make the stability and reliability of the system have high requirements. At present, many cases of soft robot research are still in the original prototype stage of the laboratory. Therefore, the durability, variable environment and long-term feasibility of the robot cannot be effectively tested.

3.3 Adaptability and intelligent decision-making ability in complex environments

Soft robots need online real-time perception and response to deal with problems in complex outdoor environments. The existing energy management methods have pre-compiled strategies or are realized under offline learning, which cannot meet sudden tasks and solve the unknown environment of standby dynamic changes. In the future, it is necessary to develop methods with online learning and online adaptive energy control capabilities in combination with the idea of "body intelligence".

3.4 Multi-energy integration and collaborative management

A single energy source cannot meet the various complex tasks of soft robots. In the future, it is also necessary for machines to explore mechanical energy, thermal energy, light energy and other diverse environmental energy sources for complementary collection and cooperative coordination. Therefore, the emergence of some hybrid power supply systems can also increase the flexibility of the overall energy supply.

In table 1, the efficient utilization of energy supply of soft robots is developing in the direction of the trinity of "open source-Reduce expenditure-dispatch".

Table 1. Summary of difficulties and development.

Core strategy	Technical path	Current challenges	Focus of future development
Open source (Environmental energy harvesting)	Environmental energy collection technologies such as Triboelectric nanogenerator(TENG)	Low energy density, output power, and unstable energy source	Research of efficient conversion materials, and development of composite energy fusion technologies such as light, heat and mechanical energy
Reduce expenditure (Internal optimization)	Pneumatic system optimization (such as IEAR, bidirectional pneumatic actuator)	High wasted exhaust energy, high energy consumption of the system, and low work efficiency of the structure	Innovative design ideas for actuation structure, improved the efficiency of energy recovery and reuse, and reduced

Core strategy	Technical path	Current challenges	Focus of future development
			overall gas consumption.
Dispatch (Smart management)	Mechanical intelligence and adaptive algorithms	Rigid preset model and the lacks of ability to make independent decision-making and dynamic distribution to cope with complex environments.	Intelligent and online learning algorithms, realization real-time, intelligent scheduling and task adaptation of energy.

4 Conclusion

This article summarizes the three main technologies that soft robots are committed to saving energy: self-powered driving technology, driving energy saving of air pressure system and intelligent management system of robot energy scheduling. TENG is an emerging technology to drive robots with the energy absorbed by the environment, which allows soft robots to obtain electrical energy from movement; and various structural optimizations of the air pressure system, IEAR and bidirectional linear actuators, etc. have achieved better energy recovery and output use efficiency; and related mechanical intelligence and The energy utilization problem of the adaptive mechanism provides the possibility for robots to use energy intelligently in complex environmental situations in the future. The current research on these problems has limitations such as low energy density, adaptability of the whole system, environmental compatibility, etc., but the combination of multiple energy, intelligent energy scheduling, and combined with machine structural optimization can promote soft robots to further break through energy restrictions, in the detection, medical treatment and rescue scenarios of complex environments. Long-term, intelligent and efficient operation, future research needs to make leapfrog integration to promote soft robots from laboratory prototypes to practical applications.

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