Progress in Robots Driven by SMA Actuators and Their Control

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Abstract. With the popularization of mechanical automation, informatization, and intelligence have become the development direction of future mechanical-related majors, and research related to robots has become a hot topic nowadays. Traditional robots often suffer from shortcomings such as poor adaptability, weak interaction capabilities, and limited functionality. Therefore, some scholars have researched emerging materials represented by Shape Memory Alloy (SMA). The flexibility, high power density, and other characteristics of SMA make it extremely promising for robotic applications. This article primarily introduces the current development status of robots driven by SMA actuators and reviews relevant research in recent years, aiming to explore their future applications. However, most current SMA actuator designs still have significant limitations. This article will summarize some of the more cutting-edge robots driven by SMA actuators and their control methods, analyze the corresponding experimental data in detail, summarize the degree of improvement made to SMA actuators in various studies, and strive to find the optimal solution, providing a plan for the research of SMA actuators.

Keywords: SMA, robots, actuators.

1. Introduction

The pace of industrial automation is accelerating, and traditional processing methods have long been unable to meet the current demand for products. Therefore, in recent decades, researchers have shifted the focus of industrial production to the improvement of automation technology. Automation is often inseparable from robots. Therefore, finding an efficient, precise, and cost-effective robot control technology has become a unanimous pursuit among mechanical researchers. Among them, the memory function of SMA provides new ideas for researchers. Due to its ability to remember shapes, SMA has gained increasing favor among researchers amid the growing demand for intelligent robotic functions.

SMA has a high-power output per unit mass, often with a simple structure, and offers advantages such as low pollution and high precision. However, it is debatable how to integrate SMA into industrial production as a component. Among them, the actuator, as an important component of the robot, can convert energy into mechanical motion. Based on this, actuators composed of SMA provide new ideas for the development of robots, and many researchers have chosen SMA as the actuator to drive robots as a future research direction.

The starfish robot developed by Hu Jin and his team utilizes the phase change characteristics of SMA wires to create SMA actuators, which in turn control the deformation of SMS, thus achieving motion control. The movement speed (body length h-1) of the Starfish Robot developed based on this has reached 1260, which is far higher than that of similar robots [1]. Ji-Hyeong Lee and his team discovered that in traditional methods, embedding SMA wires into a polymer matrix often limited their effective length due to direct contact between the SMA and the matrix. To overcome this limitation, they fixed the lengths of both ends of the SMA wires and applied a certain current. Consequently, the performance of the SMA actuator-driven tendon soft robot and soft gripper they fabricated was significantly improved, achieving a maximum bending angle of 400°, which is much higher than that of similar soft actuators, and a tip force of 0.89 Newton [2]. When designing neuromorphic sensors (NS) for robotic systems, Alexandru and Mircea Hulea chose SMA actuators for their electric actuators. They believed that SMA has a long lifespan and high driving force, but they also have disadvantages such as nonlinearity in contraction and recovery temperature differences, and initial length being affected by the environment. Nevertheless, the spinal accessory muscles they studied still benefit from SMA. It was able to be muted during operation, and in this experiment, it was possible to directly control the SMA driver by controlling the discharge frequency of pulsed neurons, NSFSR (force sensor-based neuromorphous sensor) power consumption was only 0.128 μW, significantly lower than the 3.5 mW of CLC [3].In the past two decades, SMA actuator applications have been extended to include robots and wearable devices, precision drives, manufacturing techniques, and mechanical design, and the range of available SMA materials has been greatly improved [4]. However, SMA actuators have not yet been developed to particularly mature and face many challenges in practical use.

Based on the research on SMA by researchers in recent years, this paper summarizes several cutting-edge robots driven by SMA actuators to improve SMA actuators.

2. Classification of Robots Based on SMA Actuators

2.1. SMA Tendon-driven (Bionic) Robot

Traditional robots are difficult to adapt to complex environments and terrains because their structures are often rigid. Flexible parts can largely solve this defect. The flexibility of SMA makes it a great advantage as a flexible component, and tendon robots have become one of the most common use cases of SMA.

Soft robots have unique potential in biomimetic robotics because they can emulate the natural mechanics, deformability, and mobility of soft biological organisms [5]. Hu Jin's team developed a starfish soft tendon robot inspired by various kinds of mollusks in the biological world. The design uses SMS (smart modular structure), which can move flexibly and simulate the regeneration capacity of the starfish. The structure consists of a mechanical arm skeleton composed of a plurality of SMA conductors and a PCB circuit board embedded in a PDMS and a PVC sheet.

When heated, SMS can recover its shape during cooling by the energy stored in PVC. In order to control the movement of their limbs, the team used AR (adaptive regulation) heating to regulate the heating process of SMS.AR sends a heating signal to the transistor switch, compares the target sampling voltage with the reference resistance sampling voltage, and determines the resistance change of the SMA lead, so as to accurately control the bending range based on AR.

Thermodynamic modeling results in Table 1:

Table 1. Numerical values of parameters in the thermodynamic model. Where λ is the thermal conductivity coefficient, Cp represents the specific heat capacity of PDMS, A0 represents the equivalent heat transfer area, and Af represents the final austenitic temperature of SMA wire in SMS [1]

Parameter	n	$\lambda(Wm^{-1}k^{-1}))$	C_p(J/kg℃))	A(W/(m^2℃))	A_0(mm^2)	A_f(℃)
Value	8	0.205	1.553*106	15	4π	130

2.2. Robot Actuated by SMA Spring

2.2.1 SMA spring-driven medical surgical robot

To manufacture a neurosurgical robot of sufficient precision, the Mingyen Ho team adopts the tendinous sheath transmission structure, which has the advantages of high flexibility and small space occupation. It transmits tension through the hollow cannula mechanism and the tendon through the cannula.MINIR's drive mechanism has been redesigned, and the orthogonal arrangement of four swivel joints ensures that the robot arm can move out of plane, while the adopted sleeve structure is more rigid than the tendon[6]. For control, in the experiments, the team modeled SMA springs and developed temperature feedback control algorithms based on this. The recovery length of the SMA spring can be controlled, so as to precisely control the motion of the MINIR joint. In the force experiment, record the corresponding force reading after SMA is heated to a specific temperature, and calculate R2 as 0.9948, which proves that the theoretical model is in good agreement with the actual application, and proves the accuracy of control [6]. Fig. 1 shows the team's envisioned MINIR (minimally invasive neurosurgical intracranial robot) overall system.

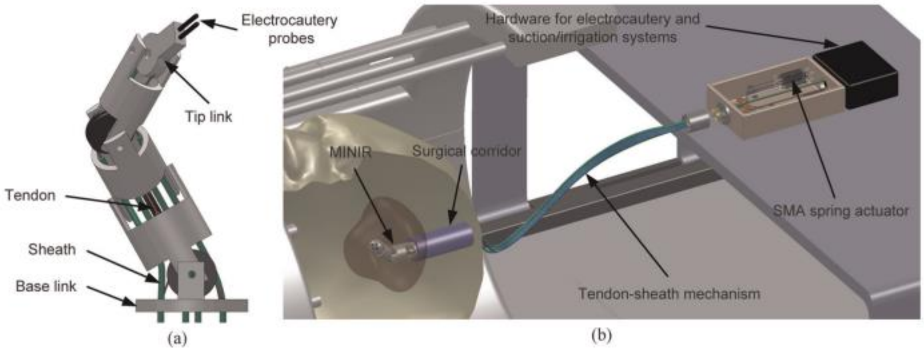

Fig. 1 Minir Integral System Image consisting of a four-DOF robot, tendon sheath mechanism, actuation box including SMA spring actuator, and hardware box with cautery and suction, and irrigation hardware [6]

2.2.2 Soft wearable robot driven by SMA (spring) fabric

A textile made up of fibers can adjust its mechanical properties, such as strength and flexibility, by changing the arrangement of fibers. In particular, in the case of a smart textile comprising a reactive material, various deformations can be generated according to the fiber pattern that determines the directivity of the reactive material [7].

Seong Jun Park's team has created a new fabric muscle with textile fabric covering SMA springs, providing soft, lightweight properties. The team conducted heat treatment on the SMA guidewire after winding to meet the required shape memory effect, measured the performance data of SMA spring (Table 2), respectively using (20×1), (10×2), (5×4), (4×5), (2×10), (1×20) methods for connection (Table 3), and finally selected (5 × 4) method to synthesize the required SFM (spring-based fabric muscle) with 20 SMA springs [8].

Table 2. Specification of shape memory alloy spring [8]

Item	Unit	Value
SMA wire diameter, d	mm	0.5
SMA spring diameter, D	mm	2.5
No. Of spring turn, n	turn	52
Spring index	—	5
Mass of SMA spring	g	0.5
Transition temperature	℃	40

Table 3. Current and voltage values required by the connection method of shape memory alloy springs, where Np is the number of springs in a group connected in parallel, and Ns is the number of springs in series [8]

Connection method(Np×Ns)	Combined resistance(Ω)	Required current(A)	Required voltage(V)
20×1	0.09	40.8	3.67
10×2	0.36	20.4	7.34
5×4	1.44	10.2	14.69
4×5	2.25	8.16	18.37
2×10	9	4.08	36.74
1×20	36	2.04	73.48

In the load test, at a 5kg load, the shrinkage strain of the SFM decreased by only 10% compared with no load, and the SFM maintained a level of more than 40% at all heating temperatures of 40℃ and above [8]. Shrinkage strain increased to 59% when heated to 60℃. At 70℃, the shrinkage property tends to be saturated, and the shrinkage strain reaches 60% [8]. The shrinkage strain measured at 40℃ at 10 kg load is only 6% [8]. However, when the temperature rises to 50℃ and above, the shrinkage strain increases significantly to more than 38% [8]. Shrinkage strain energy up to 50% at 70 ℃ [8]. This experiment demonstrated that the SFM heated to 60℃ and above met the force index of more than 100 N required by the team and verified the possibility of achieving shrinkage strains of more than 50% when applying a 100 N force. Demonstrated superior contractility to human muscle, helping workers in the field of wearable robots [8].

Modifications to SMA actuators

Although the advantages of robots driven by SMA actuators are numerous, their effective length is greatly limited. To improve the driving tendons made by SMA, the Ji-Hyeong Lee team chose to embed them into the polymer body, thereby magnifying their original small deformations and significantly increasing their effective length [2]. At the same time, both ends of the SMA wire are fixed, and a certain current is applied so that it is not limited to the matrix, and this problem is solved to a certain extent [2].

See Fig. 2 for details:

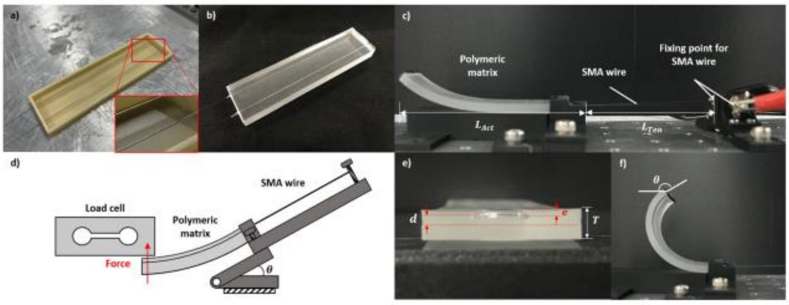

Fig. 2 (a) Mold with SMA wire located inside silicone rubber tube, (b) Actuator manufactured, (c) Fixing point and length dimensions of the actuator, (d) Fixture for measuring the force at the tip of the actuator, (e) Cross-section of the actuator, and (f) Bending deformation of the actuator [2]

SMA is favored by researchers in aviation and biomedical fields due to its unique advantages. This type of spring is usually made by SMA winding and annealing.

The TPSMA springs (torsionally prestrained SMA) manufactured by the Yoon Seop Chung team improve the performance of conventional SMA springs. In the manufacturing process of TPSMA, SMA is vertically suspended on the clamp with the motor connected at the top end, and the bottom end is fixed on the vertically movable guide rail with a counterweight only. The wire is annealed after winding, and the clamp is installed at both ends after the wire is removed, so that most of the initial torsional prestrain can be maintained after the wire is removed from the clamp. The shrinkage of this TPSMA spring is increased by 8% - 15% compared to conventional SMA springs [9].

3. Discussion and Analysis

The above robots solve the practical application of SMA to some extent, but there are also some limitations. The starfish robot driven by SMA tendons developed by HuJin's team solved the problems of slow response and difficult heat dissipation of SMA, but still had some defects, such as limited driving force caused by low SMA tension change, and performance degradation and life caused by repeated heating and cooling [1].

Mingyan Ho's team focuses on detailed modeling and analysis of SMA springs, and it can be seen that they are pursuing accurate regulation of SMA springs [4]. To study the performance of the SMA spring actuator, the theoretical model of the SMA spring actuator shall be established. However, when SMA materials undergo martensite phase change or reverse martensite phase change when temperature and stress change, the relationship between output force and output displacement of the SMA actuator is nonlinear, which brings great difficulty to the description of the constitutive relationship [10]. Therefore, it is not easy to establish the theoretical model of the SMA spring actuator.

Seong Jun Park's novel textile muscle-driven soft wearable robot made from SMA springs is highly flexible (human), lightweight, and adaptive; however, the article also shows that it has high temperature requirements (it must operate at low temperature if conditions permit) and poor endurance (frequent charging is required) [8].

4. Conclusion

This paper describes the structure and control of the robot controlled by SMA actuators, which are more advanced nowadays. The SMA tendons developed by the HuJin team, as one of the common uses of SMA, offer new ideas for biomimetic manipulators driven by SMA actuators. The Mingyan Ho team and the Seong Jun Park team also demonstrated the feasibility of SMA springs as actuators. The HuJin team still has some problems to solve, such as the need to optimize the design and manufacturing process of the software robot. Mingyen Ho's team found that SMA materials cooled more slowly in the antagonistic configuration, resulting in slower actuation speeds. Seong Jun Park's team only proposed the basic concept of the mechanical arm and verified its performance in their paper, and the insulation and shrinkage maintenance devices are not discussed in this paper and need to be improved through further research.

SMA still has some limitations. The common SMA material is Nickel-Titanium Alloy, which is expensive and limits its wide application. The cost can be reduced by developing low-cost alloys. The fatigue life of SMA is usually short, and the fatigue life can be improved through technologies such as nano-crystallization.SMA response is often insufficient and can be improved by binding to other materials such as electrically active polymers. With more development and research of SMA materials and corresponding control methods, SMA may become a new star among scientific researchers in the future.

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Please expand on any weak areas in the checklist and offer specific advice as to how the author(s) may improve the paper.
This paper provides a systematic review of robots driven by shape memory alloys (SMAs), analyzing their advantages in flexibility and high power density, as well as the problems of poor adaptability, weak interaction capabilities, and functional limitations found in traditional robots. The authors introduce the current status of SMA-driven robot development, summarize relevant research results in recent years, outline typical robot designs and control methods, and analyze the effects of various studies on improving the performance of SMA actuators based on experimental data. The paper discusses optimization schemes for SMA actuators, providing a reference for future robot design and applications. With a clear overall structure, comprehensive content, and thorough analysis, this paper possesses certain forward-looking and reference value, and is recommended for direct acceptance.