Flexible Robotic Arms Under Multiple Driving Methods and Their Application Environments

Yihuan Feng

{ maping@njfu.edu.cn}

College of Mechanical and Electronic Engineering, Nanjing Forestry University, Nanjing, China

Abstract. This paper focuses on the field of flexible robotic arms, systematically analyzing the principles, advantages, and disadvantages of five driving methods: rope-driven, shape memory alloy-driven, and pneumatic-driven. Pneumatic drive uses compressed air as power, with a simple structure, good compliance, and safe human-machine interaction, but it has limited output force and insufficient control precision. Hydraulic drive relies on liquid pressure transmission, providing high drive force, control accuracy, and stability, yet it suffers from complex systems, leakage risks, and heavy equipment. Shape memory alloys drive through material deformation, offering compact structure and good concealment, but with low energy conversion efficiency and limited driving stroke. A cable-driven system uses cable stretching and slack to transmit the motion, which allows use over distance and a large range of motion, however, elastic actuation and slack may affect accuracy. The needs in the medical, industrial, deep-sea exploration and home service applications of the driving methods are also mentioned in the paper and the flexibility of each driving approach elucidated. The findings can bring references to the rational use of the flexible robotic arm and these designs can be used to promote the technological development.

Keywords: Flexible Robotic Arm, Driving Method, Application Environment.

1 Introduction

Compared to the traditional rigid robotic arms, flexible robotic arms are flexible and safe because their core is made of flexible material or structure which can change depending on the nature of working conditions. Their main strengths are safer human-robot contact, greater environmental flexibility, and greater precision of their work. They have found extensive use in medical care, industrial production, special detection and domestic services. Even now, their development is still challenged by such aspects as lack of perception accuracy, inadequate force control, and performance adaptation. Being one of the fundamental considerations, the driving mode directly defines their working principles, area of application and performance characteristics. The article based on different driving modes as initial point to examine the characteristics of mainstream driving technologies including pneumatic, hydraulic and motor driven systems and their adaptation patterns to application environments and offers reference

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point in the optimized design of flexible robotic arms and facilitating the smooth application of the arms in the cross environments referred to multiple fields.

2 Drive Methods of Flexible Robotic Arms

Mainly driving methods of flexible robotic arms comprise three categories: cable-driven, shape memory alloy drive and pneumatic drive, each possessing its own features, and suitable in various application conditions including where only light loads are needed, heavy loads needed and precision control is necessary.

2.1 Cable-driven

Another approach to automated driving of soft robotic arms is cable-driven actuation. It consists of the application of a set or sets of strong cables (high strength) (such as).

steel cables or synthetic fiber ropes) placed along the axis in order to produce actuation [1]. This is normally achieved with 3-4 sets of drive cables and with some control over the length of each cable, the robotic arm will be able to bend or twist. More complex multi-segmenting procedures and motions in the three-dimensional range can be realized by connecting several cable-controlled modules to each other in series to gain new degrees of freedom, thus allowing high-degree-of-freedom movements. This mode of driving offers a lot of provisional force and a powerful load-bearing capacity that results in it being used in grasping heavy objects [2] intuitive control. The control strategy is intuitive: the arm configuration and end-effector pose can be directly controlled by changing the cable length.

Additionally, the power source (mostly motors) can be positioned externally, reducing the moving mass and improving response speed and energy efficiency [3].

YE Han, BIAN Guibin, and others designed a multi-degree-of-freedom cable-driven micro-manipulation wrist gripper for microsurgery [4], as shown in Figure 1. This wrist gripper has three degrees of freedom, and modeling with a generalized coordinate system has verified its high precision, smooth motion, and ability to sense contact forces, allowing safe operation on delicate human tissues and improving surgical success rates. WANG Changhui, YUAN Gang, and others developed a pneumatically variable-stiffness cable-driven soft robotic arm [5], composed of five pneumatic variable-stiffness joint modules alternately connected with rigid links. Each joint has two degrees of freedom, and 15 high-strength cables are independently controlled (three per joint). The pneumatic-cable hybrid actuation allows rapid switching between high-stiffness load-bearing and high-flexibility motion states, suitable for post-disaster rescue, aircraft engine maintenance, and similar scenarios. The results of static and stiffness model verification are satisfactory.

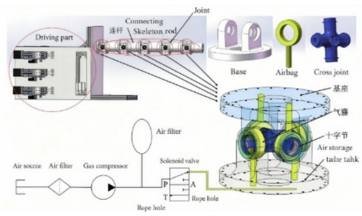

Fig.1. Schematic Diagram of Pneumatic - Driven Multi - Joint Mechanism and Its Air Supply System [4]

2.2 Shape Memory Alloy Drive

Shape Memory Alloys (SMA) are smart materials that can change their shape and mechanical properties under thermal, light, or electrical stimuli, exhibiting shape memory effect and superelasticity. They are often made into wires or thin sheets embedded in flexible matrices. When electrically heated, SMA generates driving stress and strain due to Joule heating-induced phase transformation; when cooled, it transforms from austenite to martensite, becoming easily deformable. Heating above the critical temperature triggers the reverse phase transformation, restoring the preset shape. Controlled deformation is achieved through phase transformation cycles.

WANG Yangwei and others designed an SMA wire-driven bio-inspired flexible manipulator imitating an octopus arm, featuring a cylindrical continuum structure [6]. A silicone matrix simulates the supporting structure of the octopus arm, and three sets of SMA wires are symmetrically arranged along the axis. When electrified, they pull the manipulator to bend flexibly [7]. Experiments verified that the theoretical model matches the actual performance, addressing the long-standing issue of insufficient underwater flexibility in traditional manipulators and laying the foundation for precise control.

2.3 Pneumatic Drive

Pneumatic actuation uses gas as the medium, typically consisting of an inflatable elastic sealed cavity (e.g., rubber, silicone) and an external high-strength fiber braided mesh [8]. When compressed air is introduced, the radial expansion of the cavity is constrained by the angle of the braided mesh (commonly 54.7° or 60°), converting it into axial contraction to produce force and displacement, and the cavity elastically recovers after exhaust [9].

The modular pneumatic soft robotic arm Paul, developed by García-Samartín [10], as shown in Figure 2, consists of segments each containing three inflatable air bladders (three degrees of freedom per module), manufactured using tin-cured silicone and wax casting, along with 3D printed molds. Its open-loop control system drives motion by adjusting the inflation time, and experiments demonstrate its excellent flexibility and load-bearing capacity.

Fig.2. PAUL and its working environment. [10]

3 Flexible Robotic Arm Application Environment

Flexible robotic arms are applicable in a variety of tasks, including medical, industry, deep-sea exploration, space exploration, domestic services and each case places a performance value in the sub-millimeter positioning control and sterile and antibacterial properties [11]. In the health industry, they have been used in the context of minimally invasive surgeries precision: surgical operations are interested in accuracy in sub-millimeter positioning and sterile and antibacterial qualities, and other tasks.

rehabilitation scenarios have the opportunity of utilizing sensor feedback to dynamically control assistance forces, which can be used to assist patients to recover their functions. In the manufacturing industry, micrometer accuracy and controlled force is needed during assembly, high strength is needed in heavy-duty environments with high availability, where force is needed and high operational efficiency and safety are balancing criteria. At sea, they are dependent on special materials and sealing and heating solutions to support high pressure and low temperatures as well as corrosion, as well as intelligent autonomous operation systems [12].

Domestic service applications are aimed at safeguarding, easy control and less noises besides learning and independent decision making abilities to support various tasks at home [13].

4 Analysis of Drive Modes and Application Environment Adaptation

4.1 Medical Environment Adaptation Drive Mode

In medical surgical scenarios, pneumatic actuation is more suitable. The compliance of pneumatic actuation can ensure safe contact between robotic arms and human tissues, avoiding excessive compression. For rehabilitation therapy, pneumatic actuation, with its good compliance and adjustable output force, can provide personalized rehabilitation training assistance according to patient needs.

Pneumatic muscle actuators (PMAs), as a type of soft actuator [14], are highly suitable as compliant actuators for rehabilitation robots, elbow exoskeletons, medical care devices, and manipulators due to their compliance and high power-to-weight ratio. However, the irregularity and asymmetry of the PMA's hysteresis loops limit the modeling accuracy of existing models. Mazxin et al. proposed an improved asymmetric generalized Prandtl–Ishlinskii (MAGPI) model [15] for describing the irregular and asymmetric hysteresis characteristics of PMAs. Experimental results show that the MAGPI model has better modeling capability in describing the complex hysteresis loops of PMAs, and this advantage becomes more evident when the hysteresis loops become irregular.

4.2 Drive Methods Adapted to Industrial Environments

Shape memory alloy-driven flexible robotic arms, with their compact structure free of redundant components, low-noise and quiet operation, and deformation control accuracy at the micron level, demonstrate unique adaptability in industrial environments. They are particularly suitable for precision assembly of electronic components, plugging and bonding operations of miniature machinery, as well as inspection, cleaning, and minor fault repair in confined spaces within equipment. They can efficiently perform delicate tasks that traditional robotic arms struggle to cover, without disturbing the production environment or damaging workpieces.

Zhang Linfei, Xu Yong, Yang Hao, and Jin Hu designed and developed a new type of flexible drive module, using SMA springs as the key driving source to construct a four-joint flexible robotic arm [16]. As shown in Figure 3, by utilizing the property of SMA resistance changing with temperature, they established an SMA resistance self-feedback control system to achieve precise control. In addition, a multi-modal motion control system was developed, enabling the flexible robotic arm to perform complex movements such as spatial curling and grasping. Experiments confirmed that the designed flexible robotic arm can perform tasks flexibly in various spatial environments, demonstrating its potential application value in fields such as industrial automation.

Fig.3. Flexible drive module bending prototype [16]

4.3 Deep Sea Exploration Environmental Adaptation Drive Mode

Rope-driven and hydraulic-driven systems are suitable for deep-sea exploration environments. Rope-driven systems can place the drive units in relatively safe locations, reducing the direct impact of the deep-sea environment on the drive system; hydraulic-driven systems, with their high drive force and stability, can ensure that robotic arms complete complex exploration and sampling tasks under deep-sea high pressure. At the same time, the hydraulic system needs to be specially designed to enhance its sealing and pressure resistance.

The team led by Associate Professor QU Juntian at the Shenzhen International Graduate School of Tsinghua University proposed a rope-driven flexible arm based on deep reinforcement learning in this paper [17]. As shown in Figure 4, This flexible arm is designed based on an elephant trunk shape and consists of 10 pulleys, 1 silicone rod, and 8 drive ropes, driven by 4 servos. The research team used a whale optimization algorithm neural network to fit an approximate dynamic model of the flexible arm, employed a twin-delayed deterministic policy gradient as the control strategy, and combined it with a long short-term memory neural network, allowing the deep reinforcement learning control strategy to more accurately control the end position of the flexible arm. Experiments showed that this flexible arm can not only achieve precise tasks such as grasping and placing 6 mm diameter small balls on land, but also perform underwater sampling in narrow confined spaces, L-shaped pipe inspection, and grasping targets.

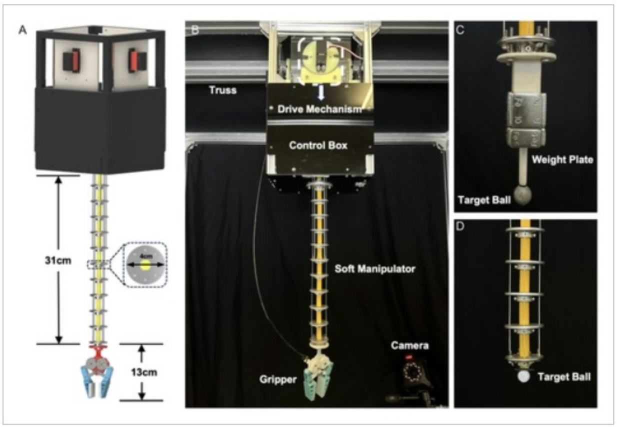

Fig.4. Cable-driven flexible robotic arm model [17]

4.4 Home Service Environment

Adaptation to Drive Methods Pneumatic drive and cable drive would be better adapted to domestic service requirements. Pneumatic drives are less dangerous and noisy in contact with members of a family because of their compliance properties and low noise; cable drives also leave drive units more easily, which is why they can be used to more actively move robotic arms in residential settings [18]. Meanwhile, the incorporation of smart control systems may advance the interaction ease and the intelligence of robot arms on their operation.

The SUN Fengxin team created a pneumatic soft robot built on the fabric engineering design by the use of industrial weaving technology [19]. The intelligence deformation of the robot is based on the dual system weaving process of warp and weft yarns. It will have a more flexible and comfortable appearance by playing with the tension of the yarn in certain sections to create the differences in the elasticity of the various parts. This pneumatic soft robot of the woven type has wide areas of application in domestic services including medical service, and can serve to help patients during rehabilitation training, among other tasks.

5 Conclusion and Outlook

The application areas and the driving methods of the flexible robotic arms closely resemble one another with their own characteristics and constrained by their environment: pneumatic drives operate fast and with compliance but their output force is limited; hydraulic drives have high-force and stability but can be easily compromised by leakage; motor drives allow preciseness of control and eliminate adhesiveness; shape memory alloy drives are small, yet respond sluggishly; cable drives allow a vast range of motion but control accuracy can be readily affected. Various application environments have their own needs: medical use requires high safety, precision, and cleanliness; industrial apps and search under the sea need high-pressure resistance, low temperatures, and corrosion; household use emphasizes on safety, low noise, and easy maintenance, as Table 1. Having determined how far the driving methods and applications are compatible, it is possible to find reasonable matches. An example is use of medical surgery that can be used in a combination of pneumatic and motor drives, using heavy industrial operation that can have hydraulic drives, and implementing assembly operations that can be used in motor drives avoiding resource wastage and inadequate performance. In the future as the corresponding technologies evolve, driving techniques will also be optimized, increasing new use cases, and introducing new prospects to all industries.

Table 1. Pneumatic soft robotic wearable device.

Application environment	Drive mode	Principle	Advantage	Disadvantages / Limitations	Specific use case scenarios	Future Outlook
Medical environment	Pneumatic drive	Driven by gas pressure, using the compliance of pneumatic muscle actuators (PMAs) to achieve movement.	Good flexibility, can safely contact human tissue; adjustable output force, capable of providing personalized rehabilitation assistance.	PMA has problems with irregular and asymmetric hysteresis loops, limiting the modeling accuracy of existing models.	Avoid excessive tissue compression during surgical procedures; assist patients in rehabilitation training, such as with elbow exoskeletons and medical care equipment.	Optimize models such as MAGPI to enhance the accuracy of PMA hysteresis characteristic descriptions and expand applications in precision surgery and personalized rehabilitation.
Industrial environment	Shape Memory Alloy Drive	Under temperature changes or stress, SMA transforms from the martensite phase to the austenite phase, generating recoverable elastic deformation and driving force.	The structure is compact with no redundant components, operates silently without disturbing the production environment, and achieves micron-level deformatio	The output load is relatively small, and the response speed is affected by temperature, requiring a matching temperature control system.	Precision component assembly Pipeline inspection and maintenance Automotive parts manufacturing Food packagingBionic robot manufacturing	Material performance optimizationControl precision upgrade Application scenario expansionStructural and integration innovation

			n accuracy.			
Deep-sea exploration environment	Tendon Drive	Power is transmitted through ropes, allowing the drive unit to be positioned away from harsh environments.	The drive unit can be placed in a safe position to reduce direct impacts from the deep-sea environment; the structure is relatively flexible.	Precise control of rope tension is required, and it is easily affected by interference in complex environments; relies on intelligent control strategies to improve positioning accuracy.	Deep-sea exploration and sample collection; sampling in narrow and confined spaces (such as probing L-shaped pipes), and small ball grabbing.	Combine intelligent algorithms such as deep reinforcement learning to improve end-point positioning accuracy and autonomous operation capabilities.
Home service environment	Pneumatic drive	Driven by gas pressure, utilizing fabric engineering design to achieve flexible movement	Good flexibility, safe interaction; low noise, suitable for home environments; can achieve intelligent feedback when combined with strain sensing.	The range and strength of movements are limited, making it difficult to perform heavy household tasks; a gas supply system is required, and some scenarios are restricted in setup.	Home care (such as assisting with rehabilitation exercises); light household chores (wiping windows, arranging items)	Optimize fabric structure and drive system to enhance range of motion and strength, combined with intelligent interaction to improve ease of use.
Home service environment	Tendon Drive	Transmit power through ropes and flexibly	The drive unit layout is flexible, adapting to complex	Ropes are prone to wear and tear, and long-term	Moving and organizing household items; performing	Develop wear-resistant, low-maintenance rope materials, and combine

	arrange drive units to achieve diverse movements.	home spaces; it has a high variety of actions and can perform multiple household chores.	reliability needs improvement; control accuracy can be easily affected during complex movements.	household tasks in complex spaces (such as cleaning in narrow areas)	intelligent control to enhance the precision of complex movements, making them suitable for more home scenarios.

6 Conclusion

The present status of flexible robots arm technology allowed applying the current development status as the basis to conduct a systematic review of the logic of adapting the drive methods and application environments and the systemic analysis of the essence of mainstream drive technology, including pneumatic, hydraulic, and motor drives. Simultaneously, it defined the special needs of the situation with medical, industrial, deep-sea exploration, space exploration, and home services which provided a strong theoretical background of the accurate choice and effective utilization of articulate robotic arms in various industries. At the present, the flexible robotic arms have started appearing in a variety of spheres, becoming a significant technical assistance to the industry modernization. Nevertheless, because of technological advancement and the constant increase in application cases, they continue to develop. But numerous bottlenecks which have to be broken. In materials science, available materials have a tough time being lightweight, strong, and able to adapt to extreme conditions and while robots can be utilized specifically to deep space and deep sea challenges. Control technology wise, control over dynamically complex environments is too little in terms of autonomy and accuracy of response, which influences the stability and efficiency of operation. As far as the introduction of artificial intelligence is concerned, it is possible to continue enhancing the completeness of the process of environmental perception and adaptability of intelligent choices and cannot completely adapt to the scope of requirements of various and dynamic tasks. The future direction should be on core technological innovation: in materials, new materials that are lightweight, have high strength, and are resistant to extreme temperatures, humidity and corrosion; in control technology, the optimization of the algorithm architecture to increase the adaptability of robotic arms and their responsiveness to extreme working conditions; in artificial intelligence, the enhancement of multi-sensor fusion perception and deep learning processes so as to be able to make more accurate judgments of the environment and decide independently. It is arguable that with multidisciplinary innovative cooperation, the breakthrough in the technology of flexible robotic arm driving will eliminate the existing bottlenecks, integrate deeply into the emerging scenarios like smart manufacturing, smart healthcare, and deep space and deep-sea exploration, and bring the radically new changes in different industries and offer the prospects of the technological application and forthcoming industrial development.

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