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Analysis of Actuator Selection for Low-Cost Bionic Limbs

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Abstract. With the continuous advancement of mechatronics, low-cost bionic hands have been widely used in educational experiments and lightweight robotic research. As the core power components, actuators determine the mechanical output, power consumption and overall practical performance of bionic hands. A small mistake made during the choice making of actuators is fatal, which can result in problems such as insufficient gripping force or exceeding cost. This paper first establishes three evaluation criteria for bionic hand actuators: mechanical performance, electrical power requirements and practical application conditions. Then, the operating principles, hardware characteristics and inherent drawbacks of three mainstream actuators which are massively used in this area are elaborated respectively. A comparison is conducted through a table clearly showing the differences between the three types of actuators, and targeted selection suggestions are provided for different application scenarios. This paper finds that servo motors fit low-difficulty rapid teaching prototypes, geared direct current (DC) motors are suitable for stable long-term laboratory experimental platforms, and shape memory alloy (SMA) actuators are limited to lightweight exploratory research due to power consumption and response speed constraints. This research aims to build systematic hardware reference standards for beginners engaged in low-cost bionic hand design, avoiding biased actuator selection caused by ignoring integrated mechanical and electrical constraints.

Keywords: bionic hands, actuators, robotics, motors

1. Introduction

Bionic hands are a very popular project in the field of robotics and electronic engineering. In the current global robotics research field, most mature bionic hand prototypes rely on high-cost industrial driving modules and customized sensor assemblies, which create high manufacturing thresholds for student teaching and non-commercial amateur research groups [1]. A large number of new designers choose actuators based on fragmented network experience or single sample trials without complete horizontal parameter comparison, which frequently leads to mismatches between driving hardware and expected grabbing functions, resulting in scrapped 3D-printed palm shells and repeated circuit debugging work. It is of great practical value to sort out the performance boundaries of low-cost actuators, which can effectively shorten prototype development cycles and reduce material test costs for educational robotics projects. This paper takes three widely commercialized low-cost actuators as core research objects, adopts literature comparative analysis and horizontal

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quantitative comparison as main research methods, and systematically sorts out their structural principles, performance advantages and inherent hardware limitations. The research outcomes can provide clear hardware selection guidance for learners, and lay basic sorting materials for follow-up optimization research of low-cost multi-finger bionic equipment [1].

2. Requirements for actuator performance

Before analyzing specific driving units, unified evaluation dimensions are formulated to guarantee fair horizontal comparison. Three core assessment modules covering mechanical performance, electrical power demand and practical engineering adaptability are constructed.

2.1. Mechanical performance requirements

Mechanical property parameters form the most fundamental evaluation standard to judge the actual working capacity of each actuator. The index of continuous output torque directly restricts the maximum clamping force that bionic fingers can apply on target objects of different hardness, while overall motion response speed determines the flexibility of continuous daily grabbing actions such as picking up small parts and holding containers [1]. The effective motion stroke of each driving component must match the natural bending angle range of human finger joints; otherwise, the bionic hand cannot complete complete object wrapping movements. Besides instantaneous force output, long-cycle operational stability also cannot be ignored. Qualified low-cost actuators need to maintain stable torque output after thousands of repeated reciprocating grabbing cycles without obvious performance attenuation. If the overall size of the driving unit is excessively large, it will force designers to expand the palm outline, destroying the anthropomorphic appearance of lightweight 3D printed prototypes [1]. Balancing effective mechanical output and compact structural volume is an indispensable core principle in the hardware design of low-cost bionic hands.

2.2. Electrical and power requirements

All electrical characteristic indicators directly constrain the overall peripheral circuit layout scheme and lithium battery endurance of portable bionic prototypes. Rated working voltage and steady-state operating current define the matching range of mainstream single-chip microcontrollers and auxiliary power supply modules commonly used in student labs. Instantaneous current surge will be generated at the moment of finger bending, which easily triggers a sharp voltage drop in the power system and intermittent finger jitter during movement. Therefore, sufficient current margin must be reserved in the early stage of circuit design to avoid unstable motion output [2]. Long-time continuous grabbing tasks will lead to sustained energy consumption, which not only shortens the single-use endurance of wearable bionic hands but also accumulates extra heat inside the palm cavity to interfere with component stability. In addition, developers need to evaluate the matching difficulty of peripheral circuits in advance, including whether independent dedicated drive chips and real-time signal feedback acquisition circuits need to be additionally welded and debugged [2]. Different actuator types bring completely different embedded development workloads for beginners with limited circuit foundation.

2.3. Practical application requirements

Practical engineering indicators convert abstract theoretical parameter data into operable experimental prototype performance. The complexity of control programming logic greatly affects

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the total development cycle of classroom demonstration projects. Simple standard Pulse-Width Modulation (PWM) signal driving logic can drastically shorten hardware assembly and software debugging time for students without advanced programming skills. Reasonable tendon transmission structural design allows actuators to be arranged remotely in the forearm area instead of being embedded inside narrow palm cavities, effectively reducing palm thickness and improving anthropomorphic simulation effect [1]. Frequent impact generated by repeated grabbing will accelerate abrasion of gear sets and metal connecting parts. Actuators with easily replaceable vulnerable components are more suitable for long-term repeated teaching experiments. Meanwhile, heat dissipation performance under continuous operation also determines the long-term service stability of the whole set of bionic equipment [3]. For low-budget open-source robotic projects, post-maintenance cost brought by component loss is an easily overlooked restrictive factor in actuator selection.

3. Three representative low-cost actuators used in bionic hands

Combined with the structural schemes and test data recorded in collected IEEE and MDPI papers, this section elaborates on the working principle, structural characteristics, advantages and inherent defects of servo motors, geared direct-current (DC) motors and shape memory alloy (SMA) actuators respectively.

3.1. Servo motor actuator

Integrated hobby servo motors are the most widely adopted driving components for entry-level low-cost bionic hand prototypes. A complete commercial servo integrates miniature DC motor, multi-stage plastic reduction gear set, potentiometer position feedback sensor and built-in closed-loop control circuit inside a unified compact plastic shell. Developers only need to send standard PWM pulse width modulation signals from the main control chip to realize accurate fixed-angle positioning of the output shaft without additional closed-loop programming [1, 4]. Two mainstream layout modes are summarized from existing research literature: direct built-in palm installation and remote steel wire tendon transmission layout. The built-in layout simplifies mechanical transmission structures but increases palm thickness; the tendon transmission scheme separates driving units from fingers to realize slimmer human-like hand outlines [1]. Mass-produced miniature servo modules represented by SG90 and MG996R have complete global supply chains with low unit price, simple wiring operation and low assembly difficulty [4]. However, servo motors have obvious inherent defects under long-cycle working conditions. Plastic gear structures wear rapidly under frequent impact loads generated by heavy object grabbing. Continuous static clamping for a long time will trigger gradual torque attenuation, making servos unable to maintain a stable object holding state for hours, so they are only suitable for rapid teaching prototype verification rather than long-term continuous mechanical testing platforms [1].

3.2. Geared DC motor actuator

Different from the integrated closed-loop design of servo motors, miniature geared DC motors adopt a fully split modular structural layout. The motor main body, metal reduction gearbox and independent position encoder are mutually separated components without pre-installed control logic circuits. External H-bridge driving chips such as DRV8833 must be matched to realize forward and reverse rotation control, and developers need to independently compile position closed-loop

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programs according to real-time encoder feedback signals [5]. The most prominent core advantage of geared DC motors lies in outstanding continuous load performance. Stable output torque can be maintained for dozens of minutes of uninterrupted clamping without obvious attenuation, and unlimited positive and negative continuous rotation functions can be realized to meet multi-angle repeated grabbing test demands. The optimized multi-stage reduction gear ratio greatly amplifies output force, which can fully satisfy the heavy object grabbing test requirements of formal laboratory experimental prototypes [5]. The most obvious disadvantage of this driving scheme is the sharp rise in overall system complexity. Developers need to finish complete circuit wiring, drive parameter calibration and control algorithm writing simultaneously, which puts forward high requirements for comprehensive embedded hardware and software capabilities. A large number of matched peripheral electronic components will also slightly increase the overall volume of the driving system [5]. Geared DC motors are more suitable for professional experimental platforms with sufficient development time and technical reserves.

3.3. SMA actuator

SMA wire actuators rely on the solid-state martensite-austenite phase transformation of nickel-titanium alloy materials to generate a pulling driving force. After current passes through thin SMA wires, Joule heat accumulates to trigger material contraction to pull finger joints to complete the bending movement; after power cut off and natural heat dissipation, the alloy wire restores its original length to realize finger opening action [6]. Differential pulley amplification structures are usually matched to compensate the limited linear strain range of single-section SMA wires and expand the effective rotation angle of bionic joints [6]. The unique irreplaceable superiority of SMA driving lies in ultra-lightweight and ultra-miniaturization characteristics. Extremely thin alloy wires occupy almost no internal palm space, which can realize ultra-thin bionic hand outlines that electromagnetic motor driving schemes cannot achieve at present [7]. Nevertheless, multiple hardware bottlenecks restrict the large-scale popularization of SMA actuators in low-cost teaching projects. SMA wires generate extremely high instantaneous power consumption during heating contraction; movement response speed is strictly limited by natural cooling efficiency without auxiliary heat dissipation structures. Precise angle adjustment requires complex multi-channel temperature closed-loop control circuits, and repeated heating-cooling thermal cycles will cause metal fatigue damage to alloy wires and greatly shorten service life [3]. At the current research stage, SMA actuators are only applied to lightweight exploratory miniature prototypes rather than general-purpose teaching bionic hands [7].

4. Decision on the selection of three types of actuators

After integrating all mechanical characteristics, electrical parameters and practical use restrictions summarized in the above chapters, a unified horizontal comprehensive judgment and selection analysis are carried out under consistent evaluation standards. Obvious differentiated performance gaps exist among the three types of driving units, and no single actuator can fully meet all types of design requirements at the same time [8]. Servo motors rely on factory pre-integrated closed-loop control modules to greatly lower the overall hardware development threshold, which is extremely friendly to student designers without abundant embedded programming experience [1]. Geared DC motors sacrifice simple operation logic in exchange for durable and stable long-time clamping torque, which perfectly matches long-cycle repeated mechanical grabbing experiments [5]. SMA actuators possess unparalleled advantages in lightweight miniaturization design, while excessive

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instantaneous power consumption, slow movement response and limited cycle service life make them unable to adapt to conventional daily object grabbing tasks [6]. Before formal hardware purchasing and prototype assembly, designers must clarify core development objectives as the primary premise. If the project is oriented to classroom teaching demonstration and rapid prototype effect verification, servo motors are the optimal choice. If the core design demand is to build a stable experimental platform requiring long-time continuous clamping work, geared DC motors should be given priority selection. Only when ultra-small volume and ultra-light weight are set as the primary pursuit and battery endurance restrictions are relatively loose can SMA actuators be adopted for lightweight wearable exploratory research [1]. Blind selection of mismatched actuators will lead to excessive manufacturing cost waste or insufficient functional performance of the finished bionic hand prototype.

Table 1. Performance comparison of three low-cost bionic hand actuators

	Servo Motor	Geared DC Motor	SMA actuator
Programming difficulty	very low	medium	high
Continuous gripping torque	medium	High and stable	poor
Response speed	fast	medium	slow
Overall power consumption	medium	medium	Extremely high
Size and weight	Medium size and weight	Slightly larger and heavier	Can be very small and light
Life cycle	long	Very long	short

As shown in Table 1, the six standardized evaluation dimensions intuitively reflect the respective strengths and inherent defects of each driving scheme, providing quantitative data support for subsequent scene-oriented targeted actuator selection.

5. Conclusion

This paper systematically sorts out the complete actuator selection analysis workflow for low-cost anthropomorphic bionic hands based on verified academic research literature. Three complete evaluation frameworks including mechanical performance, electrical power characteristics and practical engineering adaptability are constructed as unified screening benchmarks for driving hardware selection. The internal structural principles, prominent performance merits and inherent hardware limitations of servo motors, miniature geared DC motors and SMA thermal actuators are fully analyzed through comparative research. It can be concluded that servo motors fit low-difficulty rapid teaching prototypes, geared DC motors are suitable for stable long-term laboratory experimental platforms, and SMA actuators are limited to lightweight exploratory research due to power consumption and response speed constraints. This paper only carries out qualitative comparative sorting analysis without supplementing measured quantitative data from physical prototype grabbing experiments. Subsequent related research can add actual force and response time test data of self-made bionic hands to realize quantitative calibration of each actuator's performance parameters. Future research directions can focus on hybrid composite driving schemes combining

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two or more actuators to balance lightweight appearance and stable load capacity of low-cost bionic manipulators.

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