Research on the Design of "Bionic Vascular" Intelligent Prosthetic Arm Based on Multi-modal Sensing and Flexible Drive System

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Abstract: This paper aims to address the core issue that although current intelligent bionic prostheses are powerful in function, they lack the authenticity of life, causing users to experience psychological alienation. This study breaks through the traditional research paradigm of "functional substitution" and innovatively proposes the concept of "bionic blood vessels", dedicated to achieving a paradigm shift from "functional tools" to "living entities" for prostheses. By designing and constructing a system integrating multi-modal sensing, intelligent decision-making, and flexible expression, the mechanical state information of the prosthesis (such as grasping force and environmental temperature) is transformed into human-like vital sign expressions, including vascular pulsation, color changes, and temperature regulation.

Keywords: Bionic Prosthetic Limb; Bionic Blood Vessel; Sense Of Life; Multi-Modal Sensor; Flexible Drive; System Design

1 Introduction: Paradigm Innovation from "Functional Tools" to "Living Entities"

1.1 Research Background and Significance

Currently, robotic arm technology is evolving from industrial automation towards human-robot collaboration and embodied intelligence. However, whether it is high-precision industrial robotic arms or emerging bionic prosthetic arms, their design paradigms are still confined to the category of "functional tools", lacking the emotional interaction and body ownership that living entities possess, which leads to psychological alienation in users during long-term collaboration. This research aims to break through this limitation by taking "lifelikeness" as the core design metric, and by simulating vital signs such as vascular pulsation, color, and temperature, endowing robotic arms with unprecedented emotional interaction capabilities. This is of profound significance for enhancing the human-machine integration of service robots and rehabilitation robots.

1.2 Research Status at Home and Abroad

1.2.1 Current status of sensing technology: "Lifelikeness" absent under the dominance of functionalism

At present, significant progress has been made in the multi-modal sensing technology[1] (force and tactile sensing, temperature sensing, and electromyography sensing) of intelligent bionic arms. However, there is a clear common limitation in their development path: the research paradigm is dominated by "functionalism", and all the sensing information is almost exclusively aimed at improving the precision, stability, and dexterity of grasping operations, while neglecting the use of this information to enhance the "lifelikeness" of the prosthetic arm itself.

Force and tactile sensors are the most mature technology supported by modern science and technology for this research, but they are limited to tasks such as "grasping force control" and "slip prevention". Sensor data is regarded as feedback signals for the control system and has never been attempted to be interpreted as the "physiological state" of the prosthetic arm itself (such as mapping pressure to "blood pressure" changes)[2]. Temperature sensing research is focused on "safety warnings" and "material identification", strictly limiting it to an environmental perception tool, while ignoring its huge potential for dynamically regulating the surface temperature of the prosthetic arm and simulating the thermal response of a biological body[3]. The core role of electromyography signal sensing is as an "input" device for movement intentions, dedicated to more accurately "reading" user instructions, but lacking the "bidirectional closed loop" idea of organically linking the prosthetic arm's state with the user's physiological state (such as force intensity) and externalizing it as vital signs[4]. Existing research views sensors as tools to enhance operational performance rather than as media to endow machines with "lifelikeness".

1.2.2 Current status of flexible technology: Feasibility for "lifelikeness" presentation

On the other hand, the rapid development of flexible electronics and soft robotics provides a solid technical foundation for dynamically presenting vital signs on the surface of prosthetic arms. Flexible electronic skin technology has demonstrated the feasibility of integrating electronic systems on complex curved surfaces[5]; electrochromic polymers and other color-changing materials, with their flexibility, low power consumption, and rapid response, can ideally simulate the dynamic changes in vascular color[6]; and shape memory alloys[7], pneumatic artificial muscles[8], and other flexible actuators can drive vascular models to produce realistic physical pulsations. The current development of flexible display and actuation technologies has cleared the technical obstacles for the physical presentation of "lifelikeness".

1.2.3 Analysis of research gaps: The separation of perception and presentation

In summary, there is a fundamental gap in current research: mature sensing technology and advanced flexible presentation technology are separated, lacking a unified framework to organically integrate the "state information" (such as grip force, temperature) perceived by the internal sensor network of bionic arms with the "vital signs" that the external bionic skin should present.

As shown in Figure 1, this results in the most advanced bionic hands still being experienced as efficient "machines", with the internal sensor network being like a silent "black box", and the rich state data not being used to construct a bionic image that can resonate with the user's emotions. Therefore, this study aims to fill this crucial gap by establishing an innovative mapping model to drive the paradigm shift of bionic prostheses from "functional tools" to "embodied living entities".

Figure 1. Design Sketch of a Lifelike Bionic Mechanical Arm

2. "Bionic Vascular" System Overall Design

2.1 System Requirements Analysis and Design Goals

The core function of this system is to simulate the essential life characteristics of the body surface blood vessels. Therefore, the functional requirements focus on the dynamic visual, tactile, and thermal manifestations of the blood vessels.

Firstly, in the simulation of vascular pulsation, the system should be able to simulate the periodic pulsation of the blood vessels, and its frequency can be dynamically adjusted according to different physiological or interactive states. At the controllable intensity level, the system should be able to simulate the changes in pulsation intensity, such as from a weak pulsation in a calm state to a strong pulsation during movement or tension. In terms of realistic waveform, the pulsation form should be as close as possible to the waveform characteristics of the human pulse, avoiding simple sine waves or square waves to enhance the realism.

Secondly, in the color change function of the blood vessels, the system should be able to simulate the color changes related to blood oxygen saturation, with the core range covering from the cyan-blue color in an oxygen-deficient state to the bright red color in an oxygen-rich state. Moreover, the process of the "blood" color change should be smooth and continuous, rather than abrupt jumps, to conform to the continuity of physiological responses.

Finally, in the local temperature simulation function, the system should be able to actively adjust the surface temperature in the local area of the "blood vessels". The temperature should be able to adaptively change according to the perceived external environmental temperature or the temperature of the interacting object, simulating the thermal regulation mechanism of the biological body.

2.2 System Overall Architecture

The first layer is the perception layer, acting as the "nerve endings" of the system, responsible for collecting raw physical signals from the prosthesis itself and the external environment[9]. It consists of four parts: force sensors, temperature sensors, electromyography sensors, and signal conditioning circuits. The force sensors detect contact pressure and simulate the input of "blood pressure" changes, as well as monitor the grasping force; the temperature sensors monitor the temperature of the environment and the objects in contact, serving as the triggering conditions for changes in vascular color and temperature; the electromyography sensors detect the user's muscle activity level, which can be mapped to the overall physiological arousal; the signal conditioning circuits amplify and filter the analog signals from the sensors, improving the signal quality and preparing for digital processing.

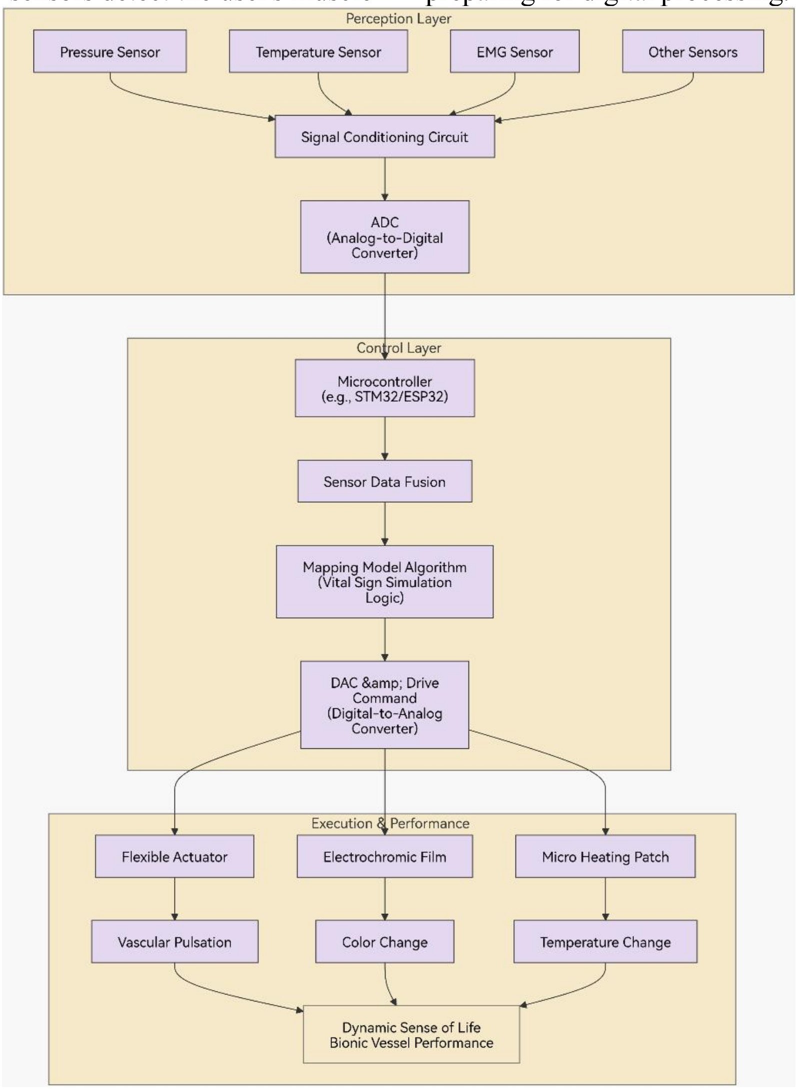

Figure 2. "Bionic Blood Vessel" System Overall Architecture Diagram

The second layer is the control layer, acting as the "brain" of the system, responsible for information processing, decision-making, and coordination[10]. It consists of three parts: microcontrollers, sensor data fusion, and mapping model algorithms. Microcontrollers such as STM32 or ESP32 are the computing core of the system, executing all algorithm logic; sensor data fusion integrates information from different sensors to obtain a unified understanding of the current state (such as "grasping a cold object with great force"); the mapping model algorithm is the core intelligence that realizes the "sense of life", based on the fused sensor data, using preset bionic rules (for example, "if the grasping force increases, the pulse frequency accelerates"), calculating the instructions to be sent to the execution layer[11].

The third layer is the execution and performance layer, acting as the "muscles and appearance" of the system, responsible for converting control instructions into dynamic manifestations in the physical world. It consists of four parts: flexible actuators, electrochromic films, micro-heating elements[12], and final output. The flexible actuators receive instructions, drive the vascular model to deform, simulating the pulsation; the electrochromic films receive instructions, changing their optical properties, simulating the color change of the blood vessels between blue and bright red; the micro-heating elements receive instructions, adjusting the local temperature, simulating temperature changes. As shown in

Figure 2, the three layers work together, presenting a realistic and dynamically associated "sense of life" vascular manifestation on the surface of the prosthesis.

3. Multimodal Sensor System Design and Implementation

3.1 System Requirements Analysis and Design Objectives

Based on the overall system requirements of this research, the sensor system of the "vascular bionic arm" needs to meet specific goals in multiple aspects. In terms of functional requirements, the sensors should be able to simultaneously collect various physical quantities such as pressure, temperature, and electromyographic signals; in terms of accuracy, the measured values should have high signal-to-noise ratio and low non-linear error; in terms of real-time performance, the data acquisition and processing speed should meet the response time requirements for vascular dynamic changes (such as pulse frequency response); in terms of integration, the sensors should have flexible and small volume characteristics, facilitating conformal adhesion to the prosthetic surface without affecting the normal movement and appearance of the prosthetic limb. In terms of reliability requirements, this sensor should be able to withstand mechanical impacts, wear, and environmental changes during daily use.

3.2 Selection, Layout, and Signal Processing of Multimodal Sensor System

3.2.1 Sensor selection: Precise matching based on function and integration

The force-tactile sensor uses the Interlink Electronics FSR402 thin-film piezoresistive sensor. Its core advantage is a thickness of only 0.3mm and good flexibility, allowing for seamless adhesion to the prosthetic surface. Its force sensing range of 0.1N to 10N is sufficient to capture dynamic changes from gentle touch to forceful grasping, and the characteristic that the resistance value decreases as the pressure increases facilitates signal conversion[13].

The temperature sensor uses the DS18B20 digital temperature sensor. Its ±0.5°C high accuracy and single-bus interface simplify the circuit design, and multiple sensors can be connected in parallel to the same bus, significantly saving the I/O resources of the microcontroller, making it suitable for integrated scenarios requiring multi-point temperature measurement[14].

The electromyographic signal sensor uses embedded modules such as MyoWare AT-04. Its innovation lies in integrating electrodes, amplification, filtering, and rectification circuits, directly outputting standardized analog voltage signals, significantly reducing the difficulty of collecting weak sEMG signals and system noise.

3.2.2 Layout strategy: Functional distribution based on bionics principles

The force sensors are mainly distributed on the fingertips (for fine grasping force) and the palm (for overall grip force), comprehensively monitoring grasping actions, and their signals serve as the main input for driving the vascular pulsation intensity.

The temperature sensors are mainly placed on the back of the hand (for monitoring environmental temperature) and the fingertips and palm (for monitoring contact temperature), providing data for achieving the "physiological response" of vascular color and temperature.

As shown in Figure 3, the electromyography sensor is placed in the medial muscle group of the forearm. The amplitude of the sEMG signal collected can be used to map the user's physiological arousal level, serving as an input for adjusting the base pulse frequency.

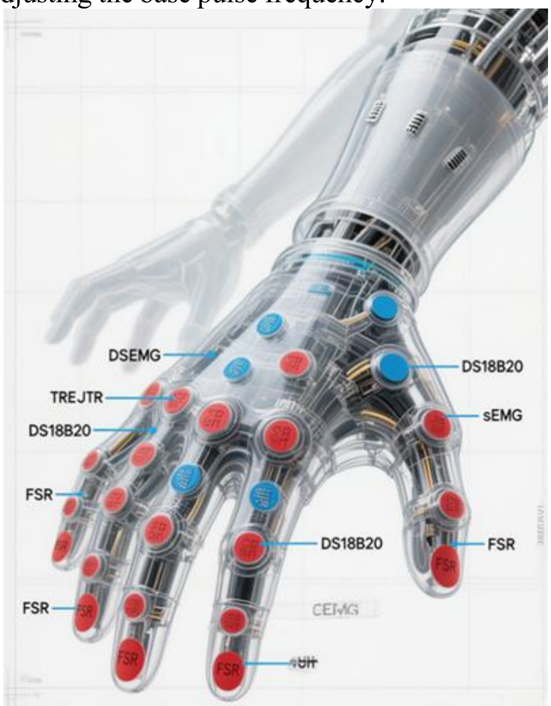

Figure 3. Layout Design Diagram of Multi-modal Sensors on the Bionic Arm

3.2.3 Signal acquisition and processing: The foundation for accurate and reliable data

The signal conditioning circuit for FSR employs a simple voltage divider circuit to convert the resistance change of FSR into a voltage signal that can be read by the microcontroller's ADC[15]. The DS18B20 is a digital signal, and MyoWare outputs are standardized, requiring no additional complex conditioning.

When the microcontroller and ADC collect data, the core main controller selects the STM32F4 series microcontroller, which utilizes its high-performance Cortex-M4 core and multiple high-precision ADC channels. A sampling rate of 1kHz is set for force signals and sEMG signals to capture dynamic changes, while a sampling rate of 10Hz is set for slowly changing temperature signals. The computing resources are reasonably allocated.

During data preprocessing, software digital filtering (such as moving average filtering) is implemented in the microcontroller to further purify the signals and extract key features (such as the real-time value of force, the average absolute value of sEMG signals) from the preprocessed data, providing pure and effective input for the subsequent intelligent mapping model.

4. Vascular Morphology Flexibility Drive and Visualization Technology Implementation

4.1 Vascular Pulse Flexibility Drive Scheme

4.1.1 Scheme selection argumentation and design

To achieve the physical pulsation of blood vessels, various flexible drive technologies need to be considered and compared for selection.

Scheme One: Aerodynamic Drive. Its principle involves using a micro air pump[16] and an electromagnetic valve to pump air into the elastic silicone vascular model, causing it to expand; when the air is exhausted, the model contracts under its own elasticity. Its advantages include very soft and realistic pulsation, and high output force; its disadvantages are the need for air pumps, storage tanks, valves, etc., making the system complex, large in size, and with air flow noise and delay.

Scheme Two: Shape Memory Alloy (SMA) Wire Drive. Its principle is that SMA wires undergo an austenite phase transformation when heated by electricity, shortening in length (up to 5%), generating a huge contraction force; when cooled after disconnection, they return to their original length. Its advantages are that the driving unit is just a thin wire, with a compact structure, silent operation, and extremely light weight; its disadvantages are that the response speed is limited by the cooling time, and the cycle life is relatively short, requiring thermal management[17].

Scheme Three: Servo Motor + Linkage Mechanism[18]. Its principle is to use a micro servo motor to periodically squeeze the vascular model through a cam or linkage mechanism. Its advantages are precise control and fast response. However, the mechanism is complex, with mechanical noise and vibration, and it is difficult to achieve fully flexible integration.

Based on the extremely high requirements for integration, silence, and flexibility of the bionic arm, this research ultimately selects shape memory alloy (SMA) wire drive as the core scheme, and optimizes its thermal management through design to improve the response speed.

The detailed design is to select 0.15mm diameter nickel-titanium nitride wires with a transformation temperature of 70°C for SMA wires; in the mechanical structure design, the SMA wires are arranged parallel to the hollow elastic silicone vascular model, and when energized and contracted, they exert radial compression to simulate pulsation; the driving circuit uses a H-bridge circuit, precisely controlling the heating power and contraction force through PWM signals; in thermal management, the first prototype uses passive cooling, optimizing the space layout to ensure air circulation.

4.2 Vascular Color Visualization Scheme

In terms of technology selection, electrochromic polymer (ECP) is chosen due to its uniform, soft, low power consumption, and the ability to be made into a flexible film, far superior to the LED point light source scheme, making it an ideal choice for simulating vascular color lines. In system design, purchase or customize strip-shaped flexible ECP films (such as switchable between blue or transparent states). The driving circuit needs to convert the single-polarity DAC output of the MCU into a bipolar voltage of -3.3V to +3.3V to drive ECP to change color.

4.3 Local Temperature Simulation Scheme

In terms of temperature control, this design research adopts flexible polyimide heating film[19], with a thickness of only 0.1mm, which can be adhered to the bottom of the vascular. The temperature system design is controlled by MOSFETs by the PWM of the MCU to control the heating power. The system integrates a DS18B20 temperature sensor, using a PID control algorithm to achieve rapid and high-precision closed-loop temperature control, ensuring the temperature is stably adjustable within the range of 30°C to 37°C.

5. System Feasibility Analysis: Based on the Examination of Contemporary Technology Development

5.1 Technical Foundation: Multi-disciplinary Integration as the Base

The current technological development provides a solid foundation for the realization of the system. The maturity of flexible hybrid electronics[20] (such as flexible printed circuits FPC) enables sensors and actuators to be seamlessly integrated into the complex surfaces of prostheses; the trend of miniaturization and low power consumption driven by the Internet of Things and wearable devices has solved the problem of embedding computing cores and power supply systems in limited spaces; advanced manufacturing technologies such as high-precision 3D printing have significantly reduced the production costs of customized "bionic skin" and vascular models, clearing the hardware obstacles for system integration.

5.2 Core Enabling Technologies: Key Bottlenecks Have Been Broken Through

The realization of the three core functions of the system relies on mature key technologies. In terms of intelligent perception and decision-making, the edge computing power based on the ARM Cortex-M series microcontroller is sufficient to run multi-sensor data fusion and the lightweight mapping model algorithms required by the system, ensuring real-time interaction[21]. Its logical paradigm of "perception - mapping - performance" also highly aligns with the cutting-edge embodied intelligence research ideas; in the flexible drive and performance layer, this design study is the most powerful proof of the feasibility of this design, enabling the realization of vascular pulsation by using a shape memory alloy (SMA) drive scheme, although the response speed is limited by heat management; through material optimization (such as reducing the phase transition temperature) and efficient drive circuit design, it can meet the physiological pulsation frequency requirements; while new soft actuators such as dielectric elastomer actuators (DEA)[22] provide better options for future iterations. In the design of vascular color transformation, this study uses electrochromic polymers (ECP), which is a key breakthrough. Its response time has reached sub-millisecond level (seconds), has a long cycle life, and possesses flexibility and low power consumption characteristics, perfectly matching the application scenarios of prostheses. For the control of local temperature, the design focus in this study is based on the flexible heating film and PID control algorithm for precise temperature control, which is a highly mature technology and has no significant obstacles in achieving precise regulation of 30°C to 37°C today.

5.3 Forward-looking Paradigm: Deep Integration with Future Technology Waves

The feasibility of this design study lies not only in the technical implementation, but also in its forward-looking nature. It elevates prostheses from tools to "living entities", is a practical implementation of the concept of emotional computing, providing an emotional carrier for the deep integration with future brain-computer interfaces and artificial intelligence. Its modular architecture also has high openness, facilitating seamless integration of new materials and algorithms in the future.

6. Summary and Outlook

This research focuses on the core goal of "endowing intelligent prostheses with a sense of life", successfully designing an intelligent prosthetic system integrating "bionic blood vessels". Conceptually, it innovatively proposed the "bionic blood vessel" concept, promoting the paradigm upgrade of bionic prostheses from "function simulation" to "life-sign simulation"; at the system design level, it completed the systematic top-level design and engineering implementation of a system integrating "perception - decision - performance", constructing a complete technical chain. However, this research still has shortcomings. Firstly, the vascular morphology is relatively simple; secondly, the system weight and power consumption need to be optimized; thirdly, the upper limit of SMA drive frequency is limited by cooling; fourthly, there is a lack of long-term clinical data.

Future research work will focus on building more complex three-dimensional vascular networks based on microfluidic technology, developing faster-response and lower-energy consumption new flexible materials, linking the "life signs" of the prostheses with the real physiological signals of the user, achieving deeper human-machine integration, and conducting long-term clinical research to quantify its real impact on quality of life.

7. Conclusion

This paper, through the innovative concept of "biological-like blood vessels", successfully transformed the intelligent prosthetic limb from a silent "tool" to a "living entity" with intrinsic vitality. The research not only completed a systematic design from theory to practice, but also infused the "emotional computing" spirit into the development of the next generation of embodied bionic devices, pointing out an innovative path towards true human-machine integration.

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