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Research of Grasping Strategy of Bionic Manipulator

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Abstract: This article reviews the research progress of bionic manipulator grabbing strategies in recent years, subsequently, the classification of existing bionic manipulator grabbing strategies was sorted out in detail, including crawling strategies based on the principle of biological inspiration, crawling strategies based on mechanical models and crawling strategies based on intelligent algorithms. First, the paper outlines the structural design and control methods of bionic manipulators. Next, the classification and characteristics of existing crawling strategies are summarized. These include strategies based on biological mechanisms, those guided by intelligent optimization algorithms, and data-driven learning methods. On this basis, the advantages and disadvantages of various crawling strategies and their performance in practical applications are compared and analyzed. Finally, the paper discusses the flexibility of bionic manipulator grabbing strategies, challenges and future development trends in adaptability and intelligence. This review not only provides a comprehensive theoretical reference for researchers in the field of bionic manipulator grasping strategies but also identifies key areas for future technological development.

Keywords: Grab strategy, Manipulator, AI.

1. Introduction

Since the development of the Stanford/JPL Hand and the Utah/MIT Hand, the dextrous manipulation of objects has emerged as a new field in robotics. Work done in this area can be devided into three groups: the development of robotic hands, the control of robotic hands, and the design of grasp strategies [1]. In recent years, China has witnessed a surge in the development and application of robotics technology, revolutionizing various sectors of the economy. As a key component of this technological revolution, robots are playing increasingly crucial roles in diverse fields, from industrial production to medical rehabilitation and domestic services. As an important branch of the field of manipulator, bionic manipulator has become a hot topic of current research with its simple structure, flexible control and strong environmental adaptability. Among them, the research on the grasping strategy of bionic robots is of great significance to improve the intelligence level of the robot and broaden its application scope.

After hundreds of millions of years of evolution, organisms in nature have formed their own unique grasping methods to adapt to complex and changeable environments. For instance, the human hand, with its intricate structure, is capable of performing precise and delicate operations, while the octopus's tentacles, soft and pliable, can effortlessly grasp objects of various shapes and sizes. Inspired by these creatures, the researchers began to explore the design and control strategies of bionic

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robots. Studying bionic manipulator grasping strategies helps uncover the principles of biological grasping and informs innovative manipulator designs.

Recent advancements in bionic manipulator grasping strategies by domestic and international scholars have yielded significant achievements, yet current approaches face several limitations. The existing crawling strategies demonstrate poor universality, primarily focusing on specific object types or shapes and struggling to adapt to complex environments. Additionally, the intelligence level of the crawling process requires enhancement, as current strategies heavily rely on preset parameters without adequate adaptive adjustment capabilities. Moreover, a disconnect exists between grasping strategies and manipulator structural design, with many studies overlooking the impact of structural elements on grasping performance. To address these challenges, this research explores a bionic manipulator grasping strategy emphasizing high universality, intelligence, and structural adaptability. The study analyzes biological capture mechanisms, extracts key parameters for theoretical foundation, implements machine learning algorithms for object recognition and adaptive strategy adjustment, and optimizes grasping performance through integrated structural design considerations. Following an introduction to biological grabbing mechanisms and bionic manipulator development status, the research presents the proposed grasping strategy, validates its effectiveness through experimental results, and concludes with future research directions. The study aims to provide valuable theoretical support for advancing robotic technology in China, promoting cross-field applications, and contributing to the development of efficient and stable manipulator operations in complex environments within China's intelligent equipment industry.

2. Classification of grasping strategies for bionic manipulators

2.1. Bionic claw

As a crucial component of Handling Robots, mechanical claws inspired by biological structures excel at manipulating objects with irregular shapes and substantial sizes. These bionic fingers, developed for specific operational requirements, employ a rope-driven mechanism that combines simplicity, cost-effectiveness, and energy conservation. The dimensional parameters and structural configuration of these fingers are carefully determined by considering both the target material characteristics and anthropometric measurements of human digits. Following the D-H methodology, this research encompasses the calculation of spatial coordinate representation, derivation of three-chain kinematic equations, and analysis of differential static mechanics [2]. Furthermore, the study addresses the optimization of gripping envelopes and structural dimensions, thereby establishing valuable parameters for grip control implementation.

2.2. Bionic finger

The capability to handle delicate, small, or pliable objects through soft grasping represents a key application of bionic finger technology. Drawing inspiration from human hand functionality, this remains a complex challenge in robotic manipulation systems. Through CT scanning technology, this research examined the internal finger architecture, introducing a soft contact mechanical index 'a' to quantify finger region pliability during precise gripping operations. The research investigated the relationship between tissue mechanics, structural properties (illustrated in Figure 1), and this newly defined index using finite element analysis combined with multiple linear regression techniques. Through hierarchical cluster analysis, the study categorized 14 distinct finger regions into 6 classification groups. Each classification received a dedicated mathematical framework connecting tissue mechanics and structure to the soft contact mechanical index [3]. Statistical analysis ($p < 0.05$) revealed that the majority of finger regions displayed significant correlations between their

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mechanical index and several key parameters: skin elastic modulus (E skin), subcutaneous tissue elasticity (E tissue), Poisson's ratio (υ tissue), and subcutaneous tissue thickness (T tissue) [4].

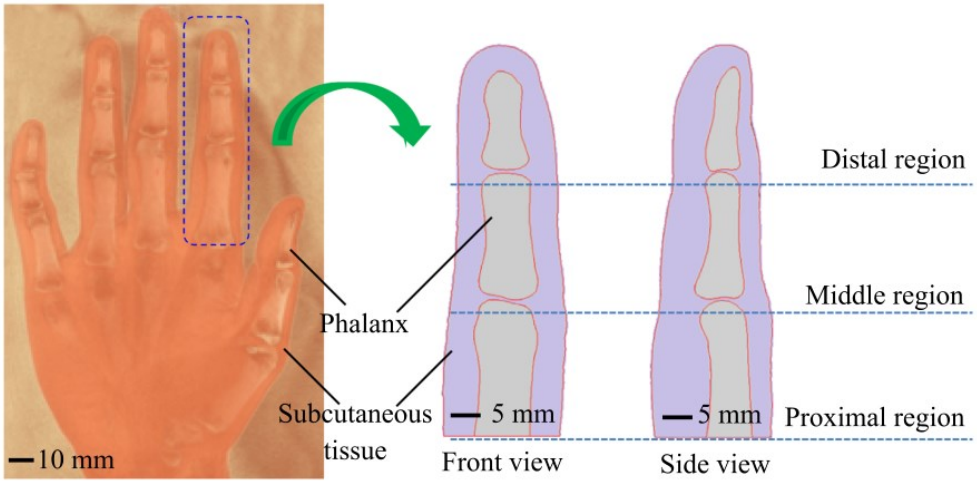


Figure 1: The effects of mechanics and structure of finger [3]

3. Bionic grasping strategy based on biological behavior

3.1. Dynamic grab

Coordinating dual-arm movements and rapidly adapting to moving, perturbed targets presents significant challenges in robotic manipulation. Addressing these complexities, this research introduces a data-driven methodology for automated pre-grasp manipulation. The approach enables robots to relocate objects from initial positions to designated target zones through calculated pre-grasp strategies [5]. Recent research has explored control frameworks enabling dual-arm robotic systems to execute precise object tossing toward moving targets. The current study presents an innovative hybrid learning-optimization framework for computing optimal tossing parameters. This system incorporates an inverse throwing map, providing closed-form solutions to complex non-linear throwing calculations, determining minimal object release velocities for specific release positions [6]. This mapping integrates with a kinematics-based bi-level optimization process to establish feasible dual-arm release configurations.

The research introduces a novel closed-form modeling approach for defining the robot's tossable workspace, predicting optimal interception points for maximizing success rates. Dynamic system principles generate synchronized dual-arm movements, while adaptive strategies ensure robust performance despite target perturbations. Implementation validation occurred using two 7-DoF robotic systems. Robotic throwing represents a sophisticated manipulation technique offering extended object placement capabilities beyond physical workspace limitations, while optimizing time and energy efficiency compared to traditional methods. The process encompasses three critical phases: acceleration, release, and free-flight. Robot control directly influences the initial phases, managing object transport and release parameters, while projectile dynamics govern the final phase.

The methodology incorporates deep neural networks for learning residual physics in control spaces, considering grasping-tossing interactions, successfully demonstrated with various small objects. Regarding interception mechanics, the research builds upon existing dual-arm robotic interception studies. Previous research established coordinated motion generation using dynamical systems and virtual object concepts. Intercept point determination utilized forward modeling for object trajectory prediction, with feasible interception zones identified through GMM-modeled robot workspace intersection analysis. Kinematic principles provide spatial positioning framework.

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The manipulator kinematics establishes the relationship between joint space ($q \in R^{n\times1}$, n = DoF) and task space ($x \in R^{6\times1}$), encompassing four types of links with 1 DoF each, despite potentially containing multiple dependent joints. These links include prismatic links allowing translation along z-direction, revolute links with a single revolute joint, flexible links comprising multiple dependent joints with identical direction and amount of in-plane bending, and constant curvature links characterized by flexible elements with high (approximating infinite) number of dependent joints [7].

3.2. Bionic claw

The flexible manipulator has the characteristics of high degree of automation and strong adaptability, which can effectively reduce the damage of objects in the process of grasping. It has been widely used in many fields such as agricultural product picking, precision manufacturing and medical care. In the research of flexible claws, many scholars globally have adopted a flexible material chamber structure, which achieves grasping through lumen inflation-induced deformation. For example, Wehner has developed a six-finger soft manipulator with fingers made of silicone. These fingers deform when internal air pressure is applied, allowing smooth grasping of objects with various shapes. While this design demonstrates strong adaptability, it has drawbacks such as complicated production and limited gripping force. Deimel et al. have developed a pneumatic manipulator that imitates human hands. The fingers are made of silicone material and fiber composite, which can grasp objects of different shapes. However, the dexterous hand control is complex and has high requirements for the perception system. It is easy to be interfered and unstable in control and perception when grasping. Jia Jiangming et al. designed a soft pneumatic gripper with inflatable and spiral movement to achieve damage-free picking of slender fruits and vegetables. However, this type of claw suffers from problems such as easy deformation and limited clamping force. To address the challenges in grasping four-corner dumplings, which arise from significant bending deflection and poor fingertip contact performance of flexible gripping fingers, a novel enhanced fingertip-type flexible gripper was designed. The flexible fingers and fixing assembly were fabricated using 3D printing and casting forming technology. The material constants of second order Yeoh model for translucent silica gel (SJ3113) were determined, and the finger bending deformation was predicted by finite element simulation and verified by experiments. And the experimental research on grasping of rice dumplings and clamping force was also conducted. The results show that the flexible finger has good bending deformation characteristics, and the simulation results are basically consistent with the experimental results. When the air pressure of the flexible gripper is 60~80 kPa and its clamping force is 2.1~3.9 N, the clamping performance of the flexible gripper is the best. The current flexible gripper, with its simple structure and reliable grasping performance, shows promising application potential in the automatic sorting and packing of rice dumplings by manipulators.

3.3. Multi-fingered collaborative grasping

As robots find more and more applications in unstructured environments, the need for grippers able to grasp and manipulate a large variety of objects has brought consistent attention to the use of multi-finger hands. The hardware development and the control of these devices have become one of the most active research subjects in the field of grasping and dexterous manipulation. This paper made some perceptual evaluation as follow: the study evaluated participant response to the pre-grasp manipulation plans and direct grasping plans. In survey, 21 participants viewed pairs of simulation videos showing the humanoid agent using, in a random order, either pre-grasp manipulation or direct grasping. Participants selected the preferred video in each pair. A chi-square test on the number of participants preferring pre-grasp manipulation or direct grasping for at least 3 of the 5 video pairs rejected that the ratio was balanced 50-50 ($p(X^2 = 5.76, df = 1) = 0.02$) [5].

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4. Realization of grasping strategy of bionic manipulator

4.1. Structure design of bionic manipulator

The innovative design of this biomimetic robotic system centers around high-precision conductive plastic potentiometers. These components are integrated into a biomechanical framework that mirrors human arm mechanisms, with strategic placement at joint locations to achieve naturalistic movement patterns. Signal processing occurs through wireless transmission modules, where joint potentiometer variations are detected and transmitted. The receiving module interprets these signals, enabling the control board to regulate servo motor rotations accordingly.

To enhance remote manipulation capabilities and environmental awareness, the system incorporates real-time image acquisition through WIFI connectivity and router infrastructure. The comprehensive architecture consists of four integrated subsystems: the biomimetic arm mechanism, wireless visual data transmission components, voice-based control interface, and an Arduino-powered mobile platform serving as the primary control unit.

4.2. Design of control system for bionic manipulator

Mathematical modeling serves as the foundation for robotic arm control systems, as system controllability analysis requires accurate mathematical representations. Following successful modeling, various control simulation approaches become applicable. The D-H (Denavit-Hartenberg) methodology stands as the standard approach for robotic arm modeling. This technique involves sequential coordinate frame establishment at each joint position, followed by determination of homogeneous transformation matrices describing inter-joint relationships.

The implementation of D-H modeling utilizes "teach function" capabilities to generate kinematic representations. Within this framework, individual control elements correspond to specific joints, enabling motion control through interactive slider manipulation. The comprehensive robotic arm control architecture follows a three-tier structure: initial D-H arm modeling, followed by biomimetic control implementation, culminating in mobile platform management.

4.3. Vision feedback control system

The machine vision processing adopts a Point Grey Bumblebee2 stereo camera with IEEE-1394 Firewire connection. The Point Grey Bumblebee2 stereo camera is a 2 sensor progressive scan CCD camera with fixed alignment between the sensors. Video is captured at a rate of 20 frames/s with a resolution of 640 × 480 to produce dense colored depth maps to assist in tracking and a viable pose estimation of the object. The resolution-speed tradeoff has to be managed concisely as an increased frame speed gives a smooth robot trajectory whereas enhances the processing time. And an increased resolution provides a denser, more accurate point cloud for feature extraction but with increased latency. In this paper, the adopted projection model is shown in Figure 2 [8].

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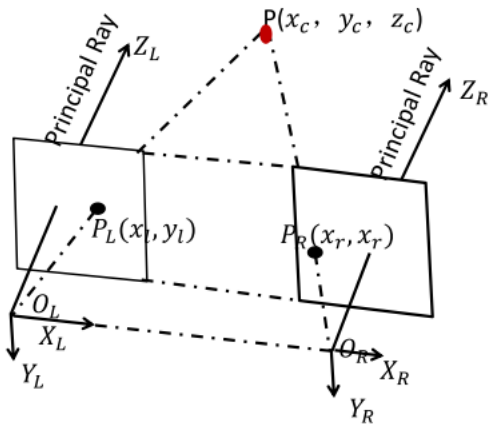


Figure 2: Front view of vision localization [8]

5. Application of grasping strategy of bionic manipulator

The robotic arm grasping strategy demonstrates extensive applications across various sectors. In industrial production, robotic arms execute precise assembly operations through programmed instructions, handling tasks such as electronic component placement on circuit boards and automotive part assembly, while simultaneously performing multiple assembly operations to enhance production efficiency. Within the medical field, robotic arms facilitate raw material handling by transporting pharmaceutical materials to production lines, conduct material sorting for subsequent mixing and reactions, and perform content inspection through techniques like spectral analysis for drug composition detection. The service industry represents another significant domain for robotic arm applications, encompassing catering services, household assistance, educational training, and logistics distribution. These diverse applications highlight the broad prospects and transformative potential of robotic arm grasping strategies in revolutionizing service delivery methods and operational efficiency across multiple sectors.

6. Conclusion

Through in-depth discussion of the grasping strategy of bionic manipulators, this study has achieved significant results. First, the design principles of bionic manipulators have been clarified. Additionally, crawling control based on biological mechanisms has been successfully realized. Second, the advantages and disadvantages of different crawling strategies have been compared and analyzed. The intelligent optimization algorithm and data-driven learning method have proven effective in improving crawling performance. Finally, the experimental results show that the proposed crawling strategy has significant advantages in flexibility, adaptability and intelligence. Despite these significant advancements, there are still areas that require further research and development. Future research will focus on the following aspects: further optimize the structure of the manipulator and improve the universality and adaptability of the grasping strategy; explore more efficient learning algorithms to realize the real-time adjustment of the crawling strategy; and expand the application research of bionic manipulators in more fields.

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