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Design and Grasping Performance Experimental Research of a Variable Stiffness Compliant Gripper for Flexible Materials

Bin Zhou[1], Tiesheng Liu[1], Zongwang Cai[1], Shufeng Zhang[2*]

[1]Jingwei Systemtechnik Ltd., Ningbo, Zhejiang, China

[2]Ningbo City College of Vocational Technology, Ningbo, Zhejiang, China

[*]Corresponding author

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Abstract: To address the issues of material damage, poor shape adaptability, and insufficient grasping stability during the automated transfer process of flexible materials, this paper designs a novel variable stiffness compliant gripper based on a project technical report. The gripper is based on a novel VSFPM (Variable Stiffness Flexible Parallel Mechanism) mechanism, achieving independent control of stiffness adjustment and opening/closing motion. The variable stiffness range is from 0.2064 N/mm to 13.0014 N/mm, with a stiffness ratio of 62. By detailing the gripper's configuration design, stiffness adjustment module, opening/closing motion module, and tooling support system, a corresponding control scheme is formulated. Experiments grasping 11 objects with different properties, including brittle, soft, and hard objects, were conducted, verifying the gripper's excellent compliance and grasping ability in its lowest stiffness state. Meanwhile, stiffness adjustment experiments demonstrated its continuity and stability in grasping fragile objects (such as peeled grapes) under low, medium, and high stiffness states. The results show that this variable stiffness compliant gripper effectively solves the grasping problems of flexible materials, providing a reliable solution for the end-effector design of high-speed precise transfer equipment.

Introduction

In the automated cutting and transfer process of flexible materials (such as fabrics, films, optical materials, etc.), achieving high-speed, precise, and damage-free grasping is a core challenge faced by the industry. Unlike rigid materials, flexible materials possess characteristics such as softness, susceptibility to wrinkling, and strong extensibility. Traditional rigid manipulators are difficult to adapt directly and easily cause material damage or grasping failure. Therefore, the research and development of a compliant end-effector capable of dynamically adjusting the clamping force according to material properties has become one of the key technologies to break through the "last mile" problem in smart unmanned factories for flexible materials[1]. Targeting the above pain points, this project conducted design and experimental research on a variable stiffness compliant gripper for flexible materials. Section 3.2 of this report details the design process of the gripper prototype based on a novel VSFPM (Variable Stiffness Flexible Parallel Mechanism), including the system configuration, stiffness adjustment module, opening/closing motion module, tooling design, and exhaustive grasping performance experiments. Building upon this, the present paper summarizes and analyzes the design principles and experimental results of the gripper to verify its effectiveness in practical applications.

1. Structural Design of the Variable Stiffness Compliant Gripper

The core of the variable stiffness gripper's design lies in its ability to dynamically adjust its clamping stiffness based on the properties of the grasped object, adapting to objects of different shapes, weights, and materials while avoiding damage to fragile flexible materials[2].

1.1 Overall Configuration and Working Principle

The variable stiffness gripper designed in this project is based on the integration of a novel VSFPM mechanism. The overall dimensions of the gripper are 213mm×120mm×264.5mm, and its mass is approximately 3.5kg. The variable stiffness range is from 0.2064 N/mm to 13.0014 N/mm, with a stiffness ratio reaching 62. The innovation of this mechanism lies in designing the stiffness adjustment and the opening/closing motion as two mutually independent sub-systems, driven separately by two independent stepper motors without interfering with each other (see Figure 1).

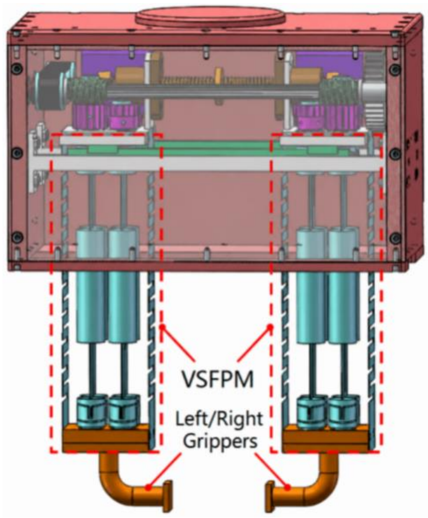

Figure 1: integration of the Novel VSFPM Mechanism

1.2 Core Module Design

(1)Stiffness Adjustment Module: Stiffness adjustment is the key to achieving compliance in the gripper. This module is driven by a stiffness adjustment motor, and the power is sequentially transmitted through a synchronous belt, worm gear, and gear train, ultimately driving the four flexible branches of the VSFPM mechanism into symmetric rotation. By changing the rotation angle of the flexible branches, the equivalent stiffness of the gripper in the opening and closing direction can be altered, enabling passive adaptation to different material properties. This design cleverly utilizes the reverse self-locking characteristic of the worm gear. This ensures that after the gripper is adjusted to the target stiffness, it does not require continuous power to maintain its state, effectively reducing energy consumption and improving stability (see Figure 2).

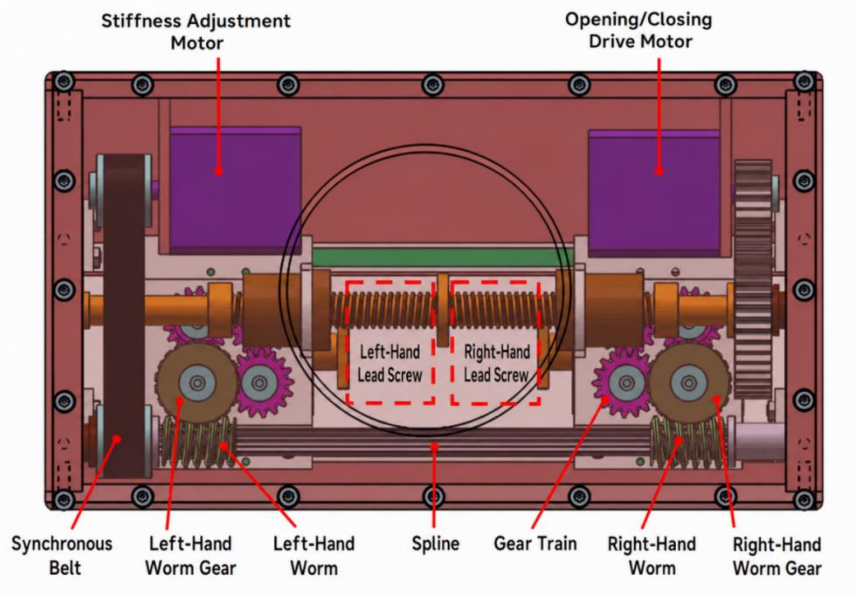

Figure 2: Stiffness Adjustment Module

(2)Opening and Closing Motion Module: The opening/closing module is used to adapt to the geometric size of the grasped object. Driven by the opening/closing motor, gear transmission rotates a ball screw with left and right threads. The nuts on the left and right threaded sections are fixedly connected to the sliders of the left and right grippers, respectively. When the screw rotates, it drives the grippers to move towards or away from each other along dual linear guide rails, achieving opening and closing. The reduction ratio of the gear transmission in this design is 17:47 (see Figure 3).

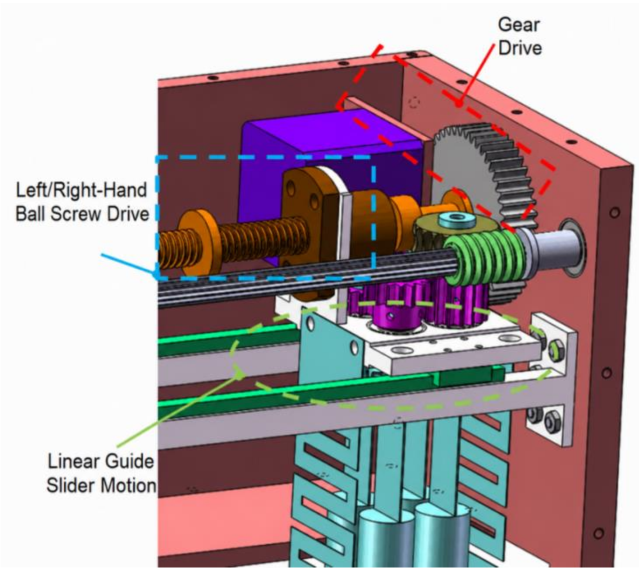

Figure 3: Opening and Closing Motion Module

(3)Tooling Support Design: To ensure the assembly precision and long-term operational stability of the gripper, the project designed multiple pieces of tooling: a intensifying device for adjusting synchronous belt tension; a 0° tooling adjustment device to ensure consistent initial installation states of the four flexible branches of the VSFPM mechanism; and limit devices to prevent over-deformation of the VSFPM mechanism in non-opening/closing directions or to limit its stroke in the opening/closing direction to avoid reaching fatigue limits (see Section 3.2.1 of the report). The final Performance Indicators of the Variable Stiffness Gripper are shown in Table 1, demonstrating its excellent performance indicators[3].

Table 1: Performance Indicators of the Variable Stiffness Gripper

Performance Indicator	Value
Minimum Stiffness (N/mm)	0.21
Maximum Stiffness (N/mm)	12.7
Stiffness Ratio	62
Stiffness Adjustment Time (s)	1
Stiffness Adjustment Precision (N/mm)	0.62
Gripper Mass (kg)	3.5

2. Control System Scheme

2.1 Control Architecture

Given the independent nature of the gripper's stiffness adjustment and opening/closing motion, the project designed a dual-channel control scheme. The system transmits grasping commands and stiffness commands from the host computer to an Arduino UNO R3 controller via USB communication. The controller uses two independent PID closed-loop circuits (Tr1 and Tr2) to actuate the opening/closing motor and the stiffness adjustment motor, respectively.

2.2 Operation Control Modes

To accommodate different task requirements, two grasping control modes were designed:

●Mode 1 (Precision Clamping): First, perform micro-adjustment of stiffness so the gripper's stiffness adapts to the geometric and material characteristics of the object; then, perform macro-motion opening/closing to generate sufficient clamping force. This mode is suitable for the precision clamping of objects with known properties[4].

●Mode 2 (Unstructured Environment Grasping): First, quickly adjust the gripper's position in the lowest stiffness state to adapt to the object's geometric size; then, micro-adjust the stiffness from small to large to achieve a reliable grasp. This mode is suitable for grasping objects with unknown properties.

3. Grasping Performance Experiments and Result Analysis

To comprehensively evaluate the gripper's performance, the project designed a series of grasping experiments, testing 11 types of objects with vastly different properties, including brittle potato chips, soft pudding, easily broken grapes and cherry tomatoes, raw eggs, peeled soft bananas, hard utility knives, smooth fixtures, triangular erasers, and staplers.

3.1 Grasping Capability in the Lowest Stiffness State

Experimental results showed that the gripper successfully grasped all 11 types of objects purely in its lowest stiffness state (0.21 N/mm). This result fully proves the outstanding performance of the gripper in terms of compliance; its flexible mechanism can passively adapt to objects of different shapes and materials, accomplishing grasping without the need for complex, extra online adjustments.

3.2 Opening and Closing Adaptability Experiment

The gripper is capable of grasping different sides (narrow side and wide side) of the same object (such as a stapler) by adjusting its opening and closing angle. This demonstrates the gripper's flexible operation modes, adapting to spatial grasping constraints or varying object poses.

3.3 Stiffness Adjustment Continuity and Compliance Test

Online testing best demonstrates the gripper's core advantage—dynamic stiffness adjustment capability.

●Experiment 1 (Grasping Peeled Grapes): The gripper successfully grasped soft, peeled grapes without damaging them in low, medium, and high stiffness states. This verified that through the dual-flexible universal joint transmission mechanism design, the gripper maintained precise control over the finger tip position during the stiffness adjustment process, ensuring continuity and compliance in grasping.

●Experiment 2 (Grasping an Eraser): Under both low and high stiffness states, the gripper stably picked up a triangular eraser[5]. This confirmed high stability during the stiffness adjustment process, further proving the reliability of the mechanism's design.

4. Conclusion

This project designed and verified a novel variable stiffness compliant gripper based on the VSFPM mechanism and conducted extensive experimental research on grasping performance. The main conclusions drawn are as follows:

●Rational structural design and excellent performance: The gripper achieves complete decoupling and independent control of stiffness adjustment and opening/closing motion. It boasts a high stiffness ratio of 62, fast adjustment capabilities, a compact design, and light weight.

●Outstanding compliance and strong universality: Operating at its lowest stiffness state, it successfully grasps objects with diverse properties-including brittle, soft, hard, and fragile items—demonstrating profound passive adaptability.

●Flexible control and stable grasping: The designed control scheme and dual operation modes accommodate both precision clamping and unstructured environment grasping needs. The stiffness adjustment process is continuous and stable, capable of non-destructively grasping fragile items (such as peeled grapes) under varying stiffness settings. The successful development of this variable stiffness compliant gripper effectively solves the most critical end-effector grasping challenges in the transfer of flexible materials. It significantly enhances equipment adaptability to different materials and lays a solid actuator foundation for building smart unmanned factories for flexible material cutting, presenting broad application prospects.

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