Underactuated Parallel Robotic Hand with Linear Trajectory Based on the Watt Linkage Mechanism

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ABSTRACT

This study explores an underactuated parallel robotic hand with a linear trajectory based on the watt linkage mechanism. The L-PASA-W hand combines various components to achieve two operational modes: Linear Parallel and Self-adaptive grasping. In the linear parallel grasping mode, the device handles flat-surface objects efficiently. When encountering an obstruction, the device transitions to the self-adaptive grasping mode, adapting to objects of different shapes and sizes with variable grasping forces. The design represents an underactuated finger, using a single motor for multiple joint rotations, ensuring stability, simplified control, and cost-effectiveness. This device is suitable for various robotic applications requiring object grasping.

Keywords: Underactuated robotic hand, Watt linkage mechanism, Linear parallel grasping mode, Self-adaptive grasping mode.

1. INTRODUCTION

In the rapidly advancing field of robotics, the development of intelligent and agile end effectors, capable of intelligent grasping, flexible assembly, and rapid tool replacement, plays a pivotal role. These end effectors cater to a wide range of operational needs and form a crucial component of robotic technology. Among these, the replication of the flexibility, reliability, and adaptability inherent in a human hand has been a key research focus, leading to the development of dexterous hands, such as Gifu hand [1-2] and the Robonaut hand [3]. However, despite their high precision and numerous degrees of active freedom, these devices are encumbered by high costs, intricate structures, and operational complexities, thereby limiting their short-term large-scale adoption.

The advent of underactuated robotic hands addresses these challenges, providing a solution that maximizes joint degrees of freedom while minimizing the number of motors required. This category of robotic hands, including the Robotiq hand [4], and SDM hand [5], has garnered significant attention due to their robust gripping force, simplified control, and cost-effectiveness. In particular, the successful deployment of the SARAH hand [6], an adaptive underactuated hand designed by Laval University, on the International Space Station, underscores the potential of such hands. Laliberté and Gosselin presented a design for underactuated fingers with two degrees of freedom, showcasing its advantages in terms of reduced complexity, diminished cost, and enhanced performance [7,8].

Underactuated hands comprise several subtypes, namely parallel, coupled, and adaptive grippers, and composite types that amalgamate these categories.

Parallel grasping fingers maintain their original posture relative to the base throughout their movement. This trait makes them particularly suitable for grabbing objects placed on a flat surface. Coupled grasping fingers, on the other hand, operate by simultaneously rotating all phalanges when leaning towards an object, making them ideal for holding objects with the distal phalanx on a desktop.

Moreover, self-adaptive grasping fingers offer a different approach. These fingers allow robots to grasp objects of various shapes and sizes with minimal input from the control system. They adjust their movement in response to the shape and size of the object, thereby enhancing the enveloping grasping effect. The self-adaptive grasping mode, using coordinated finger and wrist movements, increases grasp success and reduces object slippage during hand closure [9].

Research efforts have been directed toward the development of compound grasping modes, which amalgamate the strengths of both parallel and self-adaptive fingers. The result is the parallel self-adaptive grasping mode (PASA mode). In the PASA mode, the robotic hand begins with a parallel grasping motion, maintaining the posture of the distal phalanx relative to the base. Upon contact with the object, the hand seamlessly switches to the self-adaptive grasping mode. This adaptability enhances the practicability and versatility of the finger, offering a comprehensive solution to the shortcomings of traditional designs. A unique single-actuator gripper facilitates the lifting of thin objects and passively shifts between different grasping modes [10].

However, traditional parallel adaptive fingers pose specific challenges, such as potential collision due to their circular arc trajectory, and the need to pre-determine the object's size for effective gripping.

Considering these challenges, this paper presents an underactuated parallel robotic hand with linear trajectory based on the watt linkage mechanism (L-PASA-W Hand). This device is characterized by two gripping modes: linear parallel gripping and adaptive gripping. It eliminates the need for intricate real-time detection or planning of the object environment and can adapt to objects of varying shapes and sizes. Driven by a single motor, this novel robotic hand affords a comprehensive gripping range, signaling a step forward in efficient and versatile robotic applications. The research herein delves into the design, development, and evaluation of this underactuated parallel robotic hand based on the Watt Linkage Mechanism.

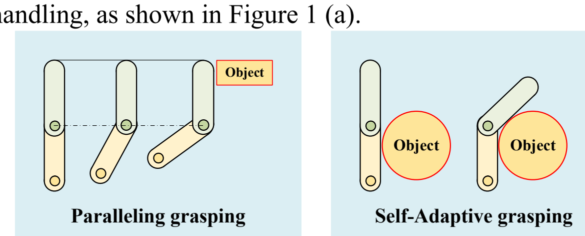
2. DESIGN OF L-PASA-W HAND

2.1 Design Concept

The L-PASA-W hand possesses two distinct modes of operation: the linear parallel grasping mode, and the self-adaptive grasping mode and their combination.

1. Linear parallel grasping mode (L-PA Mode)

In the Linear Parallel Grasping Mode, the proximal phalanx undergoes a rotational motion, while the distal phalanx retains a static position relative to the base, executing a translational movement. This results in the motion trajectory of the distal joint axis approximating a straight line. This method of grasping is particularly beneficial for the precise handling of objects. It is an optimal strategy for holding flat or rigid objects that require equal pressure across all contact points for secure handling, as shown in Figure 1 (a).



(a) (b)

Figure 1: (a) Paralleling grasping mode and (b) Self-adaptive grasping mode

2. Self-adaptive grasping mode (SA Mode)

Self-Adaptive Grasping Mode initiates upon the initial contact of the proximal or middle phalanxes with an object. While the proximal and middle phalanxes remain fixed upon contact, the distal phalanx continues to articulate and rotate until they also contact the object. This process results in an enveloping grasp, essentially conforming to the shape and surface of the object. This method is particularly advantageous when handling irregularly shaped or delicate objects, as the adaptive nature of this grasp modulates the applied forces, preventing potential damage, as shown in Figure 1 (b).

3. Linear parallel and self-adaptive grasping mode

The hybrid mode of operation involves maintaining a linear grasping state with the distal phalanx before object interaction. Upon the first contact of the proximal or middle phalanx with the object, these phalanxes are held static while the distal phalanx undergoes rotational movement until it too makes contact. This fusion of the two modes allows the L-PASA-W hand to adapt to a variety of grasping situations, enhancing its versatility in handling diverse objects.

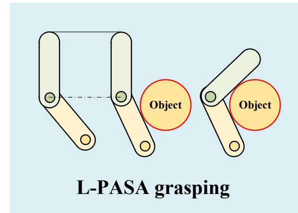


Figure 2: The L-PASA grasping mode

2.2 Structure of L-PASA-W Finger

The L-PASA-W Hand incorporates a unique linear trajectory based on the Watt Linkage Mechanism, shown in Figure 3. It's constructed with several phalanxes and mechanisms, all operating in sync to deliver adaptive and versatile grasping.

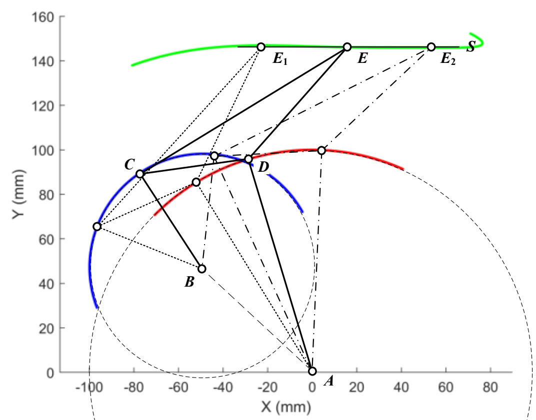


Figure 3: Schematic diagram of the Watt mechanism

The relationships of lengths among these links are carefully calibrated to a ratio of AB : BC : CD : DE : CE : AD = 68:51:49:68:110:100. By maintaining the fixed positions of shaft A and shaft B, the rotation of link AD, with A as the pivot point, induces the rotation of link BC around point B. Consequently, this causes point E to travel along a linear path, denoted as trajectory S. The center point E of the distal joint shaft oscillates between points E1 and E2, tracing an almost linear trajectory.

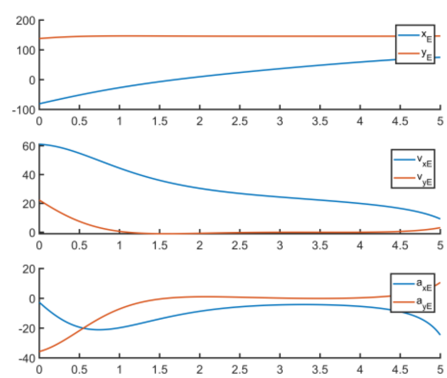
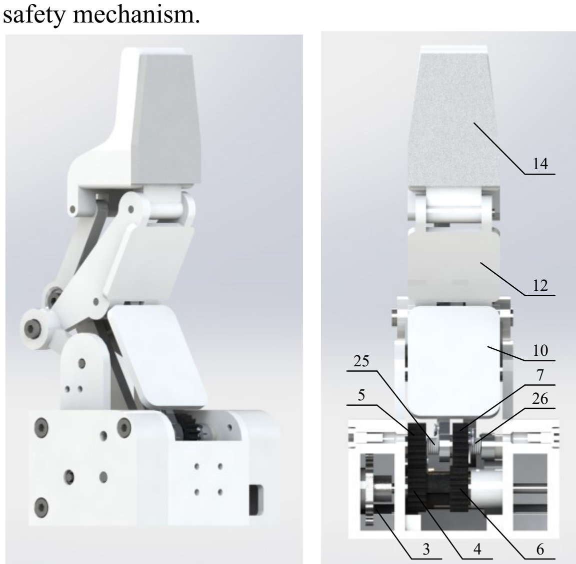


Figure 4: Simulation of Watt Linkage Trajectory

The simulation result of the displacement, velocity, and acceleration of the Watt linkage trajectory are shown in Figure 4. Through trajectory simulation results, it can be concluded that the angle between AB and the horizontal direction α=44 °. Within a certain range, the displacement, velocity, and acceleration in the y-direction are all approximately zero, exhibiting the linear characteristics of the Watt linkage mechanism.

The L-PASA-W finger consists of three phalanxes: proximal, medial, and distal phalanx, connected by joint shafts, as shown in Figure 5. Each phalanx is attached to a corresponding joint shaft. The proximal phalanx is connected to the proximal shaft, the middle phalanx to the middle shaft, and the distal phalanx to the distal shaft. This arrangement allows for independent yet coordinated movement of the phalanxes, shown in Figure 5 (a).

The L-PASA-W finger possesses nine shafts, five linkages, two ratchets, three springs, and a limit block, making up the L-PASA-W finger that gives the hand its special adaptive gripping capabilities. The springs allow the hand to adapt its grasping depending on the object, providing a versatile grip that can handle objects of various sizes and shapes. The limit block ensures that the grip does not exceed its operational range, providing a safety mechanism.



(b)

Figure 5: (a) Side view and (b) Main view of L-PASA-W finger. 1-base, 2-3-1st - 2nd transmission gear, 4-7-1st – 4nd gear, 8-transmission shaft, 9-proximal shaft, 10-proximal phalanx, 11-middle shaft, 12-middle phalanx, 13-distal shaft, 14-distal phalanx, 15-19-1st – 5th shaft, 20-24-1st – 5th linkage, 25-27-1st – 3rd spring.

The gears in the finger work in concert to control the motion and force applied by the actuator. The first gear is connected to the output end of the transmission mechanism, with subsequent gears meshing to transfer the motor's motion to the phalanxes.

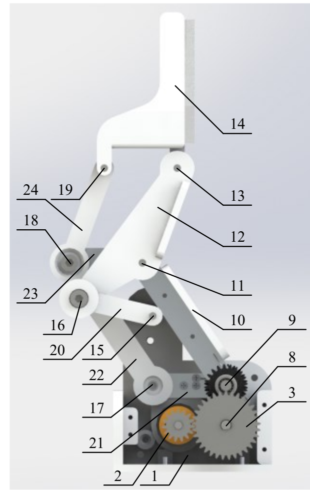


Figure 6: (a) Side view of L-PASA-W finger

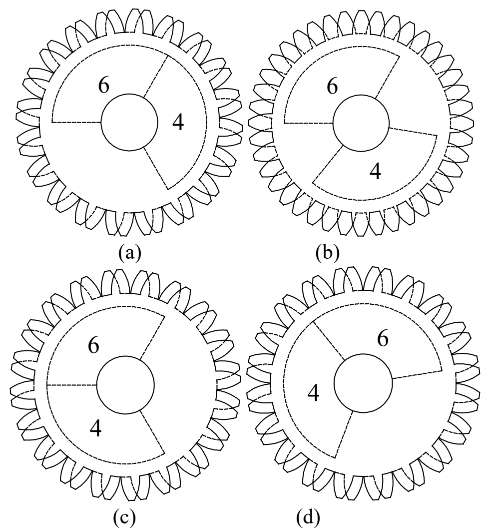
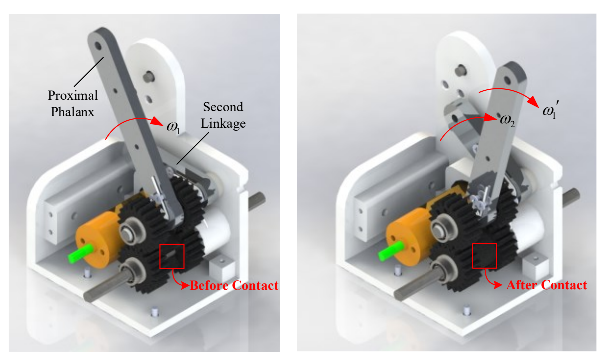


Figure 7: (a) Initial state, (b) L-PA grasping mode grasping period, (c) Switching point from L-PA grasping mode to SA grasping mode, and (d) SA grasping mode period, 4-first gear, 6-third gear.



(a) (b)

Figure 8: (a) Position of the proximal phalanx and third linkage before contact during PA grasping mode, and (b) after contact during SA grasping mode.

Both the first and third gears have protrusion. In the initial state, the protrusions are in contact. When the first gear 4 rotates clockwise, the first gear leaves the third gear 6. After 120 degrees of rotation, the first gear contacts the third gear again, and then the first gear will drive the third gear to rotate together, shown in Figure 7 (a-d). Due to the fact that the first gear and the third gear control the movement of the proximal phalanx and the second through the second and fourth gears respectively, this idle transmission mechanism allows the proximal phalanx of the L-PASA-W finger to move independently for a period of time before automatically switching to the operation of the proximal phalanx and second linkage, thus achieving automatic switching between the L-PA grasping mode and the SA grasping mode, shown in Figure 8.

Overall, the L-PASA-W finger is a complex, yet efficient mechanism designed for versatility and adaptability. Its unique design allows it to grip a variety of objects with different shapes and sizes, making it a promising tool in the field of robotics.

3.2 The Grasping Process of L-PASA-W Finger

The L-PASA-W hand begins in an initial state with a specific configuration of its base, proximal phalanx, middle phalanx, distal phalanx, and various linkages, shafts, and gears. This allows the center point of the distal joint shaft to move along an approximate straight-linear trajectory.

In operation, the L-PASA-W hand has two primary modes of action: L-PA grasping mode and Self-adaptive grasping mode.

3.2.1 L-PA grasping mode of L-PASA-W finger

In Linear Planar Grasping, the motor rotates and initiates a series of movements. The proximal and middle phalanxes, along with the first linkage, move in an approximately straight-line due Watt linkage mechanism, maintaining their orientation relative to the base, as shown in Figure 9. This results in an effective linear parallel grasping.

3.2.2 SA grasping mode of L-PASA-W finger

In the Self-adaptive grasping mode, if the proximal or medial phalange contacts an object, their rotation is blocked, but the first and second gears continue to rotate, stretching the first and second springs. After a time, this leads to the rotation of the third gear and the fourth gear, which in turn causes the distal phalanx to rotate and envelop the object, as shown in Figure 10. This mode exhibits adaptability to objects of different shapes and sizes.

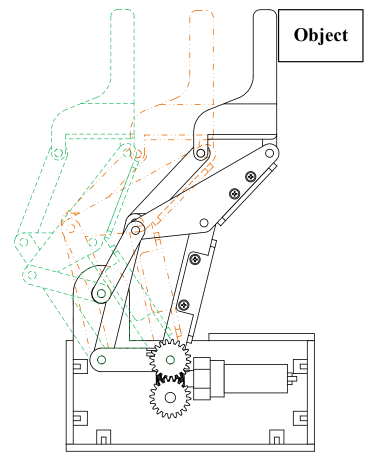


Figure 9: Parallel grasping mode of L-PASA-W finger

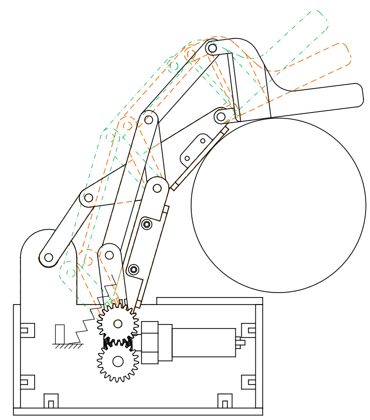


Figure 10: Self-adaptive grasping mode of L-PASA-W finger

The process of releasing an object is essentially the reverse of these described processes. Overall, the L-PASA-W hand offers versatile and adaptive robotic manipulation through a sophisticated arrangement of mechanical components.

3. PROTOTYPE AND EXPERIMENT

3.1 Design of L-PASA-W Hand

The L-PASA-W robotic hand comprises two identical L-PASA-W fingers, each manipulated by a separate actuator, shown in Figure 11. This design allows the robotic hand to achieve both linear parallel grasping and self-adaptive grasping. Currently, the L-PASA-W finger prototype is under development. The structures of individual phalanxes and the palm are manufactured using 3D printing technology. Components such as the motor, joint shafts, bearings, and springs are standard, commercially available parts. These components are assembled using fasteners such as screws.

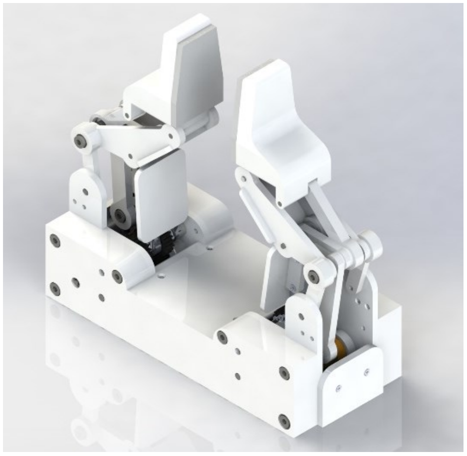


Figure 11: Simulation of L-PASA-W hand

3.2 Grasping experiments

Based on the design of the L-PASA-W hand, we have made a prototype. The L-PASA-W hand is composed of two identical L-PASA-W fingers, each controlled by an independent actuator.

The outcome of the grasping experiments reveals that the L-PASA-W hand showcases an impressive grasping strength, with the ability to perform both linear PA grasping mode and SA grasping mode effectively, as shown in Figure 12. Its distal trajectory approximates a straight line, eliminating the need for further displacement adjustments during object manipulation. These attributes highlight the superior gripping performance of the L-PASA-W hand.

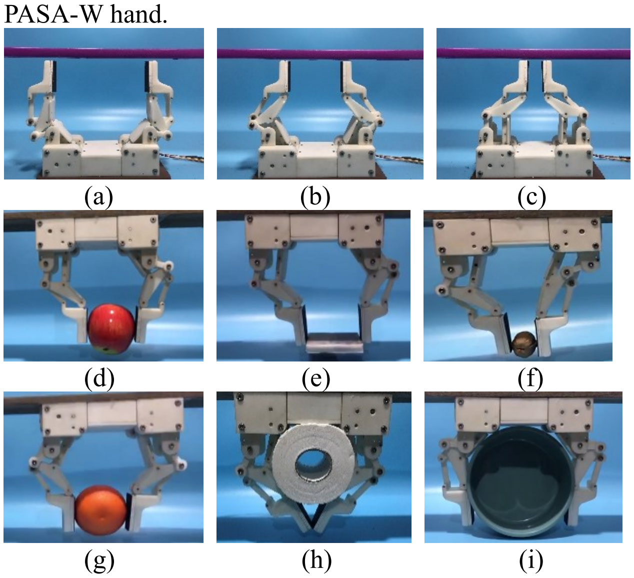


Figure 12: The grasping experiments of the L-PASA Hand

4. CONCLUSION

This paper presents a underactuated parallel robotic hand with linear trajectory based on the watt linkage mechanism (L-PASA-W hand), proficient in both linear parallel grasping mode and self-adaptive grasping mode. Utilizing a single motor to manipulate multiple joints, it maintains a low-cost, straightforward control system, and minimizes manufacturing and maintenance expenses. The dual functionality allows the device to adeptly handle objects of diverse shapes and sizes. When unobstructed, it utilizes direct parallel gripping, ideal for holding flat objects without vertical compensation. Conversely, upon obstruction, it transitions to adaptive enveloping grasping, where the distal phalanx rotates around its joint until contact is established. The device exhibits adaptable grip strength, contributing to its versatility, and rendering it an optimal solution for various robotic applications.

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