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Orimo: Leg-Wheel Transformable Origami Modular Robots

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***Abstract*—This paper presents a novel robot called Orimo that combines the advantages of transformable wheels and modular robots. In addition to enhancing its own mobility, the robot can collaborate with modules to accomplish more complex tasks. The design of the robot utilizes origami mechanisms and printed circuit boards, offering characteristics of low cost and rapid manufacturing, meeting the requirements of extensive usage and quick replacement. The design of the robot in this paper demonstrates good single-module mobility. Through the transformation mechanism, it is able to climb an obstacle whose height is up to 1.6 times its wheel radius, effectively passing through complex terrain. Furthermore, the robot can use module collaboration for assembly, catering to a variety of work requirements and providing a variety of problem-solving strategies.**

Keywords*—*Modular robot, Origami structure, Transformable wheel, Leg-Wheel mechanism.

I. Introduction

With the rapid development in the field of mobile robots, various types of robots have been designed. Developers often aim for robots to reach different locations and overcome challenging terrains. Therefore, rough terrain negotiability is the most crucial indicator. Conventional wheeled vehicles offering basic obstacle climbing capabilities, especially on flat terrain. However, their abilities are limited, driving the development of legged robots to enhance terrain negotiability. Yet, legged robots face challenges in efficient and rapid movement on flat terrain compared to wheeled robots. To meet the need for different movement methods in varying terrains, transformable wheels, an emerging design between wheels and legged robots, have gained attention.

The development of transformable wheels aims to overcome the challenge of employing different movement methods for different terrain transitions. Current transformable wheel designs primarily utilize strategies such as wheel diameter variation [1], leg-wheel transformation [2]-[7], and wheel and track transformation [8]. Some designs also explore the use of origami mechanisms for wheel deformation [9][10], showcasing the practical application potential of origami mechanisms. Deformable wheels endow mobile vehicles with improved terrain negotiability, allowing them to navigate complex terrains and employ different movement strategies in various terrains, enhancing the flexibility of vehicle applications in different scenarios.

However, with current robotic development technologies, it is still challenging to design a robot that can fully adapt to various applications. Specific designs are required for particular tasks. To enhance robotic flexibility, modular robots [11][12] are considered a solution. Utilizing interactions, assembly, and collaboration among modules can bring about more possibilities for robot applications, shifting the design focus from specific tasks to collaborative achievement of diverse task requirements.

This paper aims to design a modular robot with a paper mechanism transformable wheel, merging the advantages of transformable wheels and modular robots to enhance the robot's flexibility in different scenarios. Figure 1. shows Orimo and the demonstration of different configurations through module connections. The wheel of the robot will utilize a paper mechanism for design, offering characteristics of rapid manufacturing, low cost, and easy integration of complex structures. The robot's body will be based on a printed circuit board (PCB), integrating robot control components and attaching power sources and other functional parts onto the circuit board to assemble a complete robot system. The mature processes of printed circuit boards and the characteristics of paper mechanisms will provide manufacturing advantages for the robot, aligning with the requirements of mass production and multi-robot cooperation in modular robots, ultimately leading to greater development efficiency.

(a)
(b)


Fig. 1. (a) Orimo. (b) Configurations through module connections.

II. DESIGN

A. Origami transformable wheel design

The design of the deformable wheel aims to achieve a transformation between wheel and leg configurations. The transformation mechanism was inspired by the origami structure called Origami Moving Cubes [13] shown in Fig. 2. Mechanism design is based on the flipping and body expansion movements induced during the folding and unfolding processes. The transformable wheel in this paper was designed using origami structure, constructing a mechanically functional deformable wheel using flat sheets of paper.

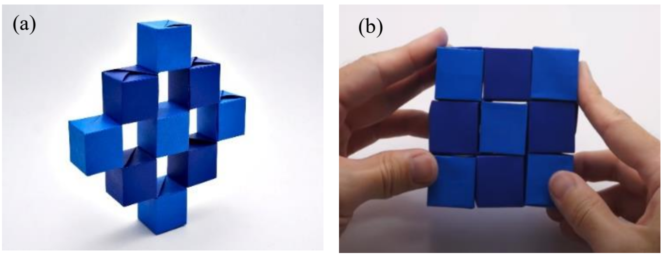

Fig. 2. Origami Moving Cubes. (a) Unfolding status. (b) Folding status.

The mechanism design considers the deformation requirements for transitioning between wheel and leg configurations. The wheel configuration should closely match a circular shape to achieve optimal rolling efficiency, and the leg configuration requires significant deformation for optimal climbing performance. The basic design concept of the mechanism, as illustrated in the skeleton diagram in Figure 3. The outer rim is formed by two semi-circular wheel frames that combine to form a circular wheel configuration. When the semi-circular wheel frames flip outward, the configuration transforms into a leg mode. The internal structure of the rim is based on the deformable structure of the Origami Moving Cubes, with the central cube serving as the axis for the wheel. The axis connects to the drive mechanism of the vehicle, utilizing motor power for rotation and deformation. Surrounding the rotation axis are four flipping cubes, where the one connected to the semi-circular wheel frame is a hinge cube that primarily supports the rotation axis of the wheel frame. It is the main component connecting the wheel frame and the axis. The other type of cube assists in supporting the wheel frame during the wheel configuration, preventing excessive deformation at the end of the wheel frame, which could affect the smooth movement of the robot. Finally, linkages connect the cubes to enable synchronized movement, facilitating the even distribution of force transmission.

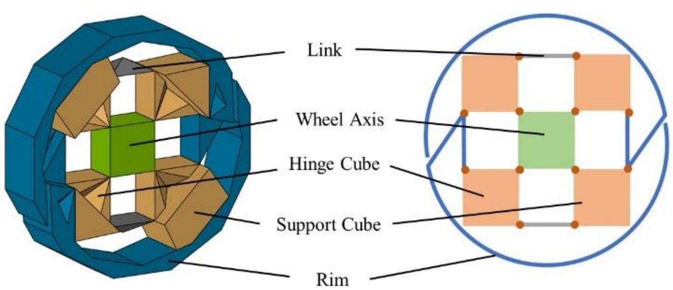

Fig. 3. Transformable wheel skeleton diagram.

Figure 4 illustrates the deformation process of the transformable wheel. To deform the wheel, power is applied to flip the cubes around the axis. To achieve this effect, a control plate and four spokes are employed for coordinated deformation. When the control plate and the wheel axis have relative motion, the plate drives the spokes, causing the cubes to flip and achieve the desired deformation. When there is no relative motion between the plate and the wheel axis, the wheel configuration remains unchanged. Therefore, the phase difference between the plate and the wheel axis controls the transformation between wheel and leg configurations.

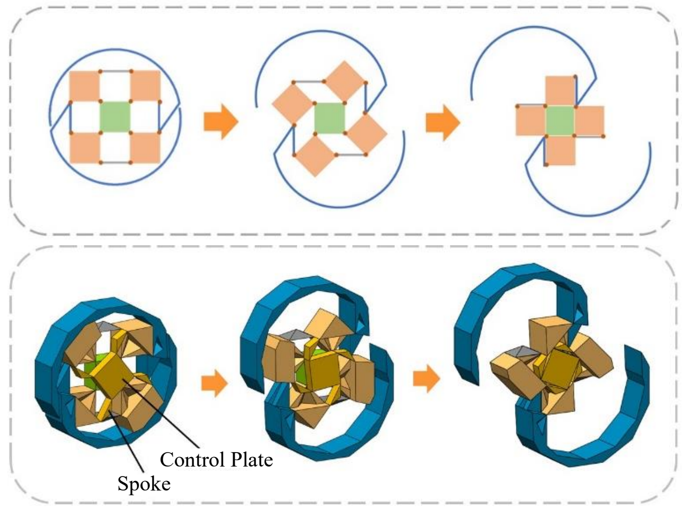

Fig. 4. Deformation process of the wheel.

In addition to the deformable mechanism, the design of the transformable wheel incorporates an energy-absorbing structure utilizing energy absorption to further enhance its functionality. The distinctive feature of paper mechanisms lies in their utilization of folded planar sheets, enabling the integration of diverse structures without the need for extensive machining parts, as observed in Figure 3 and Figure 4. In the wheel configuration, the supporting cubes outside the axis make contact with the outer wheel frame. Therefore, this wheel design in this paper integrates an energy-absorbing origami mechanism, resembling a spring, as the picture shown in Figure 5. Through the elastic properties of paper and the collapse and rebound of the structure, an energy absorption effect is created. Additionally, extensible structure is applied to the hinge cubes, as depicted in Figure 6, reinforcing the strength of the hinge support. By integrating these special structures, the design of the transformable wheel in this paper distinguishes itself from other literature, breaking away from the established perception of deformable wheels as having a singular functionality.

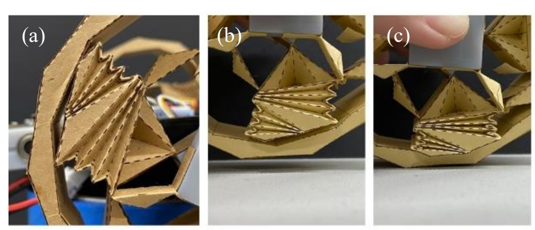

Fig. 5. Energy-absorbing structure. (a) The origami structure. (b) The collapse of the structure. (c) The rebound of the structure.

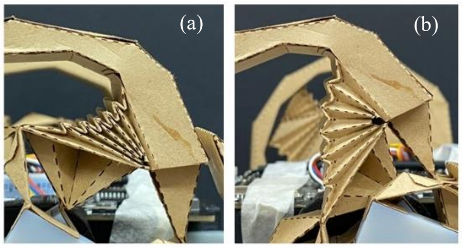

Fig. 6. Reinforcing structure. (a) Compression of the structure. (b) Extension of the structure.

The issue of strength in origami mechanisms has always been a challenge. Common structural reinforcement techniques in the field of paper folding include gluing and curing, increasing paper thickness, and creating ribs or triangular structures through folding. In the design of the deformable wheel presented in this paper, which features numerous box-like structures, structural reinforcement is a crucial consideration.

For the outer wheel frame section, the design requires the folding of flat sheets of paper into a circular structure. Inspired by the Yoshimura Pattern, shown in Figure 7 [14]-[16], a paper structure that forms a circular polygon is employed to approximate a circular wheel frame, enhancing rolling efficiency. This structure creates multiple rows of peaks and valleys, resembling the corrugated layers in a corrugated cardboard sheet, thereby increasing the strength of the outer wheel frame. This effectively withstands the forces exerted on the robot during rolling and climbing.

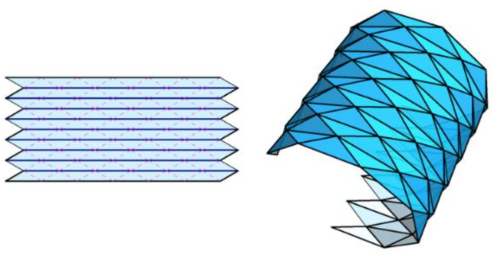

Fig. 7. Yoshimura pattern.

Within the wheel frame, box structures support the outer rim. This internal structure features collapsible deformation when subjected to external forces. Drawing inspiration from the effectiveness of triangles in supporting weight, as demonstrated in [17], and considering the relationship between the angle of triangles and the magnitude of supporting force, a design concept similar to Figure 8 (b) is employed. Concave triangular cones are strategically placed at the primary load-bearing locations, creating multiple triangular structures within the box. This design significantly improves the transmission of force and support effectiveness within the structure.

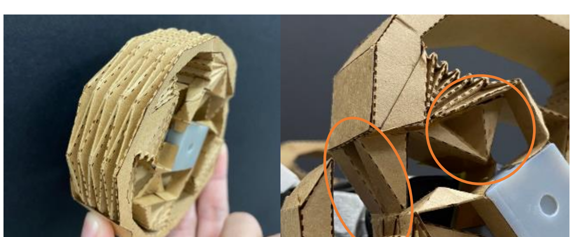

Fig. 8. (a) Wheel frame design. (b) Reinforcement of box-like structure.

The manufacturing process of the deformable wheel involves laser cutting the paper to create folding patterns, as illustrated in Figure 9. Through the folding and adhesive bonding of scored lines, a 3D mechanism is constructed from flat sheets of paper. For the central axis, considering the need for motor and gear connections and accounting for strength and manufacturing limitations, the axis is fabricated using SLA (Stereolithography Appearance) 3D printing. The final design of the deformable wheel is depicted in Figure 10, with an outer diameter of 100 mm in the wheel configuration and transforming into a leg configuration with a height of 160 mm after deformation.

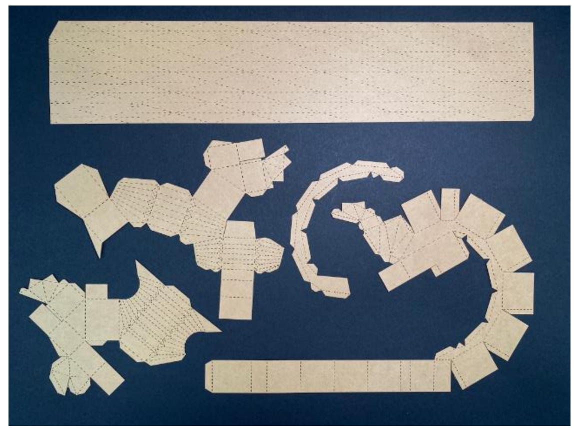

Fig. 9. Laser cutting patterns.

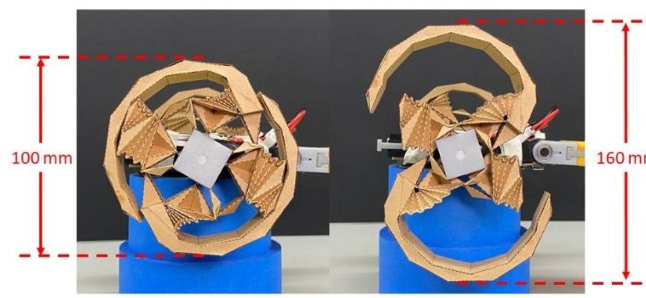

Fig. 10. Final design of the origami transformable wheel.

B. *Chassis design*

The design of the robot chassis primarily considers the dimensions of the robot, the placement of motors, and the mechanical interference and configuration requirements when connecting modules. The chassis design, as shown in Figure 11, utilizes a printed circuit board (PCB) as the base, where motors and other power sources, as well as the outer shell, are attached. This effectively integrates the control circuit and the main structure of the chassis, facilitating rapid assembly and reducing the number of required components.

In the wheel drive section shown in Figure 12, each deformable wheel is controlled by two motors simultaneously. Through a gearbox, these motors independently drive the coaxial main wheel shaft and the transformation control plate. One motor is directly connected to the control plate for power transmission, while the other motor rotates the main shaft through the transition of pinions. By controlling the phase difference between these two shafts, the wheel's configuration is controlled. The chassis design also incorporates a module docking mechanism. At the rear, a module coupling component powered by a servo motor is designed, enabling the robot to complete required tasks through the interaction between modules.

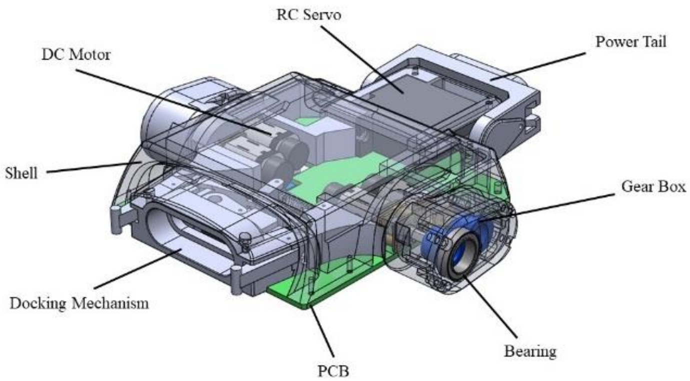

Fig. 11. Orimo chassis design.

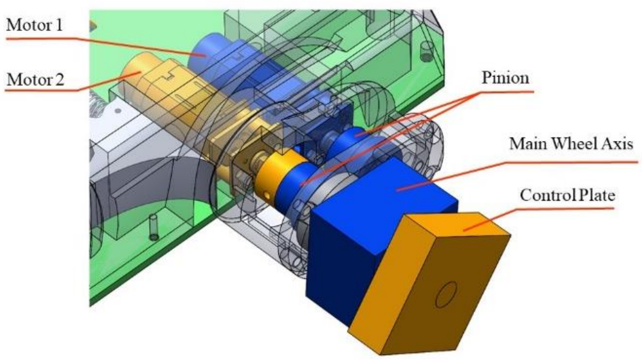

Fig. 12. Driving mechanism of Orimo.

The conceptual design of the modular robot requires modules to be interconnected and assembled, utilizing power-driven interactions between modules to provide the robot with greater flexibility, as depicted in Figure 11. The motion between modules is driven by a servo motor, and the connection between modules is realized through the docking mechanism. The docking mechanism is designed to provide sufficient clamping force to support the pulling force between modules during the robot's task execution. It is also intended to enable autonomous control of the connection action. Therefore, the docking mechanism is controlled by a small servo motor, and a linkage design achieves self-locking of the clamping mechanism. Additionally, a bistable spring is employed to reduce the power requirements during clamping. Furthermore, the mechanism ensures clamping retention even without power, effectively preventing failure due to the lack of power.

Figure 15 illustrates the docking mechanism, designed to offer sufficient clamping force and save clamping energy consumption with bistable characteristics. To prevent machining errors of the small parts, utilize the linkage design for converting rotational motion into linear motion. To meet these design requirements, the docking mechanism is mainly divided into three parts. The toggle mechanism in Figure 13 enhances the clamping force during locking and benefits from the self-locking feature of the toggle mechanism. The power source for controlling the locking and unlocking of the toggle mechanism is derived from Watt's straight-line motion mechanism [18] composed of the input crank, linkage one, and linkage two. This mechanism forms linear motion within a small range of motion, converting rotational power into linear motion to evenly open the toggle mechanism on both sides. Finally, through the coordination of a bistable spring and linkage two, a bistable state of opening and closing is created, effectively reducing the motor's power consumption. The docking mechanism is a crucial design for modular interconnection, realizing self-locking and low-energy consumption, allowing the robot to consume minimal energy for module coupling while ensuring the stability of module connections.

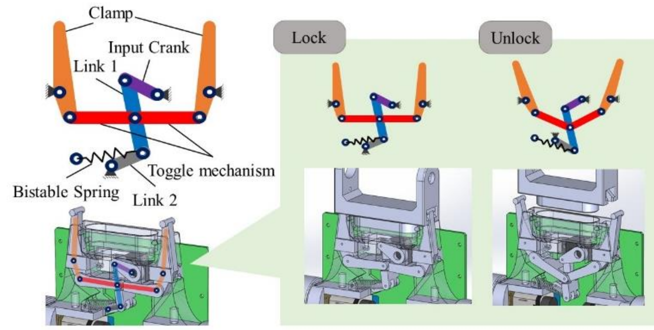

Fig. 13. Docking mechanism.

C. Circuit design

The control of the robot is achieved through the main control microcontroller and its peripherals, which work together to coordinate various robot functions. The robot's functionality extends beyond motor drive, encompassing the integration of numerous sensors and functional modules into the circuit design. With the complexity arising from the integration of numerous electronic components and modules, the circuit of the robot, as designed in this paper, is manufactured using printed circuit boards (PCB) to ensure a compact and reliable circuit design.

Figure 14 illustrates the fundamental architecture of the robot's circuit design. Power is supplied by two 7.4V lithium polymer (Li-Po) batteries, divided into two sets. One for the signal end, providing power to the microcontroller and sensors, and the other supplying power to the motors. This separation of high-current motor drive and low-current signal components effectively reduces signal interference. The main control of the robot is facilitated by a microcontroller (ESP-32), capable of transmitting and receiving all control signals. Equipped with a built-in Wi-Fi module, users can wirelessly control multiple robots through a web server, managing the collaboration of robot modules.

Incorporating sensors into the circuit, an inertial measurement unit (MPU6050) measures posture, while a power sensor (INA219) monitors energy consumption, including motor current measurement. The circuit design incorporates an encoder zeroing procedure, utilizing the increase in current during mechanical limits to detect the initial position and achieve torque zeroing during initialization.

The actuation system includes motor drivers (TB6612), encoder counter chips (LS7366R), motors, encoders, and other electronic components for driving the robot. Through motor drive and encoder position feedback, precise control of motor speed and angle is achieved, ensuring accurate control of the robot's leg movements. The circuit design seamlessly connects power, control, sensing, and actuation, integrated into a single printed circuit board for a comprehensive and compact system. This compact design allows for miniaturization of the robot, providing advantages in manufacturing speed and cost-effectiveness.

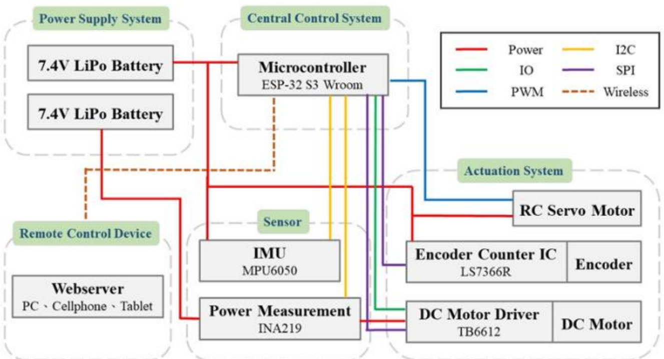

Fig. 14. Circuit design of Orimo.

III. EXPERIMENTAL RESULT

A. Robot mobility test

The robot's motion control is facilitated through the wireless communication module of the microcontroller, allowing for Wi-Fi-based remote control. The control interface is presented in the form of a web page. Any device within the same network domain can establish a connection for control. The control interface enables the manipulation of various robot functions, including movement, transformation, and speed settings. This setup empowers users to have complete command over the robot's actions.

Each single-module robot is equipped with two wheels, utilizing differential drive for turning without the need for a steering mechanism. This design choice effectively simplifies the complexity and manufacturing challenges associated with the robot. Figure 15 illustrates the fundamental mobility capabilities of the robot, showcasing its agility in both turning and forward motion. The absence of a steering mechanism does not hinder the robot's ability to navigate with flexibility, easily completing routes that test the robot's agility.

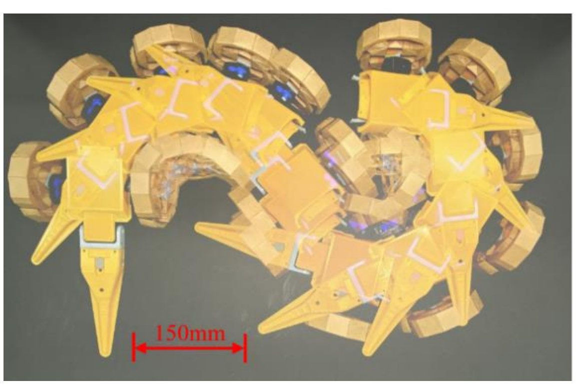

Fig. 15. Mobility test.

B. Obstacle climbing test

The design philosophy of the deformable wheel robot aims to enhance terrain negotiability by utilizing the deformation of wheels. Try to retain the advantages of conventional wheels, achieving more efficient movement. This experiment primarily focuses on testing the improvement in terrain negotiability with the assistance of the deformable wheels. The experimental environment includes a single-step staircase with a height of eight centimeters. When climbing, the robot utilizes leg deformation to hook onto the obstacle, enabling it to climb obstacles with a height 1.6 times its wheel radius. Figure 16 shows the climbing process of a single module. The experiment validates the enhanced mobility brought about by the deformation of the transformable wheels, as shown in Table I. In wheel mode, the robot can only traverse obstacles with a height of two centimeters, while in leg mode, the climbing height increases to eight centimeters. The obstacle-crossing ability of a single module is comparable to other robots. Furthermore, by employing modular interconnection, the robot's obstacle-crossing capability can be significantly increased, providing greater flexibility in overcoming obstacles with various strategies.

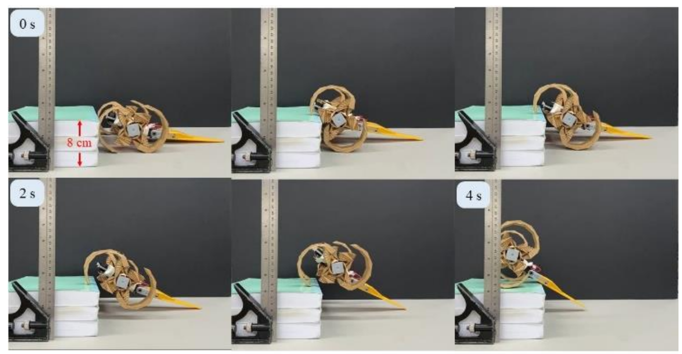

Fig. 16. Step climbing test.

TABLE I. Step climbing test results in different modes

Operation Mode	Max Step Climbing Height
Wheel	25 mm
Leg	80 mm

IV. CONCLUSION

This paper presents the design of a modular robot based on the concept of origami mechanisms. The use of origami mechanisms allows the robot to transform between wheel and leg modes, enhancing its terrain negotiability. Additionally, the modular robot concept enables interactions between modules, allowing them to collectively perform tasks that a single robot cannot accomplish.

The current progress has successfully verified the basic functionality of a single-module robot, including the transformation wheel mechanism, basic robot control, and module connecting mechanism verification. The single-module robot can climb up to 80 mm, which is 1.6 times the radius of the wheel. The specifications of the single-module robot are listed in Table Ⅱ, with a body length of 135 mm and a total weight of 288 grams. It is equipped with an inertial measurement unit and power measurement capabilities for future development. In addition, Orimo integrates an energy-absorption structure to increase durability and is designed with module interconnection functionality for flexible utilization in various tasks. This robot breaks the conventional impression of single-function transformation wheel robots. It not only enhances its own mobility but also demonstrates collaborative capabilities, making it superior to other designs.

Future work will involve conducting performance tests on the single-module robot, such as energy-absorption testing and energy consumption testing. Multiple-module interconnection tests will also be carried out to evaluate different gaits in different configurations and multi-module cooperation, demonstrating the experimental effectiveness of modular robots. Ongoing efforts in robot design will focus on optimizing both the mechanism and circuit design to achieve superior motion performance.

TABLE Ⅱ. Specification of an Orimo module

Length		135 mm
Body Width		122 mm
Leg-to-Leg Width		168 mm
Height		100 mm
Wheel-leg Diameter		100 mm
Max Wheel-leg Diameter (Leg Mode)		160 mm
Weight	Body	190 g
	Wheel (each)	21 g
	Battery	56 g
	Total	288 g
Actuator	Driving	DC Motor (×2)
	Tilting	RC Servo (×1)
	Docking	RC Servo (×1)
Sensor	IMU	(×1)
	Power Measurement	(×2)

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