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A Modular Crawler-driven Robot: Mechanical Design and Preliminary Experiments

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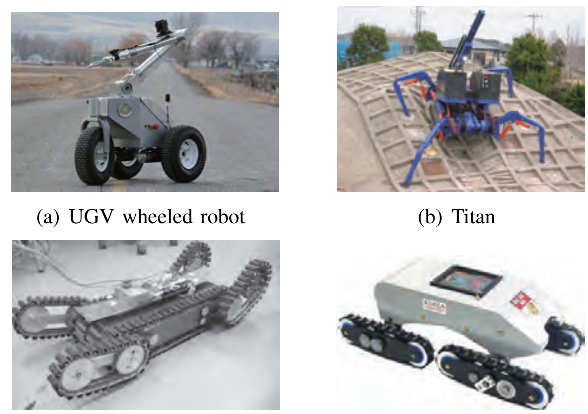
***Abstract*— This paper presents a tracked robot composed of the proposed crawler mechanism, in which a planetary gear reducer is employed as the transmission device and provides two outputs in different forms with only one actuator. When the crawler moves in a rough environment, collision between mechanism and environment inevitably occurs. This under-actuated crawler can absorb the impact energy that should be transmitted to the actuator. A modular concept for the crawler is proposed for enlarging its use in robot systems and mechanical design of a modular crawler is conducted. Using this crawler module, a four-crawler-driven robot is realized by easily assembling. Experiments are conducted to verify the proposed concept and mechanical design. A single crawler module can well perform the proposed three locomotion modes. The four-crawler-driven robot has good adaptability to the environment which can get over obstacles both passively and actively.**



(a) UGV wheeled robot (b) Titan (c) Aladdin (d) Macbot

Fig. 1. Different kinds of robot systems used in irregular environments

I. Introduction

Rescue robots are usually considered to search for victims in natural and man-made disaster areas. Development of an efficient mobile system is an urgent task for the researcher dedicated to robotics. Traditional wheeled robots can be programmed to travel over relatively smooth terrain easily; however, mobility over rugged terrain is limited by the diameter of the wheels of a robot [1], [2], such as the UGV wheeled robot. Legged robots can move well in rough terrain, but they encounter several challenges, including difficulty of control, lack of stability [3], [4] such as Titan. Due to the fact that tracked robots have advantages, like excellent stability, low pressure to terrain and simplicity of control, they have been widely deployed in irregular environment. Tracked mobile mechanisms, however, are still somewhat limited due to some mechanism parameters, such as the diameter of the front sprocket [5], [6]. The most general way to improve the mobility and adaptability of tracked mobile mechanisms is to build a multi-track robot by linking several active or passive units in serial or parallel way [7], [8], [9], [10]; for example, Aladdin and Macbot. However, to provide assisting actions and control system correctly, it is necessary to add some extra actuators, mechanisms and control elements. The additional mechanisms and actuators will increase the weight of the robot and cause increased energy loss. In other words, the assisting actions cannot be performed autonomously.

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To resolve the difficulties outlined above, we have proposed a crawler mechanism with polymorphic locomotion [11], [12]. This mechanism, which is equipped with a planetary gear reducer, makes use of only one actuator to provide two outputs. By determining the reduction ratio of two outputs in a suitable proportion, the crawler is capable of switching autonomously between locomotion modes according to the terrain. The main characteristic of the mechanism is that the polymorphic locomotion is provided by one actuator, and the switch between locomotion modes occurs autonomously. When a robot moves in rough terrain, it inevitably collides with various obstacles, creating an impact effect on the driving actuator. In our proposed crawler robot, the interior kinematic redundancy makes the mechanism possibly absorb the impact energy. This impact absorption makes the actuator subject to less impact energy, and thus more safe [13]. Since the crawler mechanism has the above advantages, it is preferable to design this crawler as a modular mobile unit for robot system. The modular crawler should be easily connected to the anticipated robot body to promote the locomotion of the robot. Based on this modular concept we develop a new modular crawler robot.

This paper is organized as follows. The proposed concept of crawler mechanism with polymorphic motion is introduced in Section II. Section III gives the design of a modular crawler mechanism. Section IV conducts the experiments of a single crawler performing the three locomotion modes, and a four-crawler robot overcoming obstacles using passive and active methods. Section V concludes the paper.

II. Basic Concept of a Crawler Mechanism

The proposed crawler mechanism is capable of providing two kinds of output with just one actuator. The first output is transmitted to the crawler-belt and drives the crawler to move forwards; the second one is employed to drive the connecting frame that links two sprockets of the crawler to negotiate an obstacle, as shown in Fig. 2.

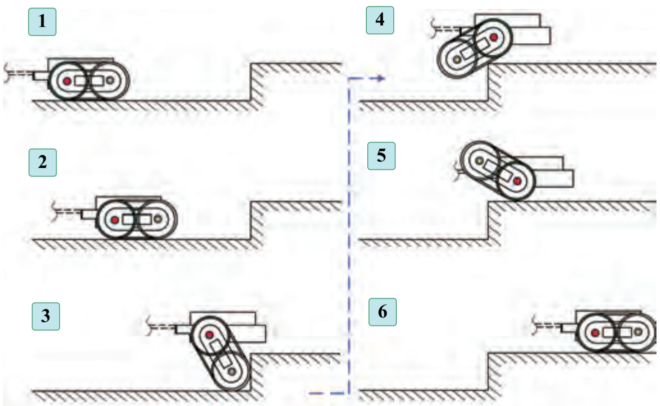


Fig. 2. The basic concept of the crawler including motion mode, rotation mode, and recovering mode

To describe the whole locomotion process while the crawler moves in irregular environment, we present three locomotion modes, referred to as "motion mode", "rotation mode" and "recovering mode".

Motion mode (1, 2, 6 in Fig. 2): The crawler mechanism moves on an even terrain or slope like a normal tracked vehicle since the power of the actuator is transmitted to crawler-belt.

Rotation mode (3, 4 in Fig. 2): When the crawler mechanism contacts an obstacle, since the rotation of the crawler belt is stopped by the friction from the ground and the power has to be transmitted to the connecting frame, the rotation of connecting frame drives the crawler mechanism to climb over the obstacle.

Recovering mode (5 in Fig. 2): Once the crawler mechanism has climbed over the obstacle, the power is transmitted to the connecting frame and drives the crawler mechanism to return back continuously until it recovers to the initial position.

To achieve the proposed locomotion autonomously in irregular environments, the power transmission of the crawler must be designed to meet the following three conditions:

1) One motor input gives two outputs in the transmission.
2) The two outputs must rotate in the same direction.
3) The two reducer ratios are selected in a certain range.

Condition 1) and 2) can be easily satisfied through adopting a suitable reducer mechanism. Concerning the most important condition 3), we can determine the proportion of reduction ratios of two outputs within a certain range. The details can be found in [11].

In motion mode, to drive the crawler mechanism to move on even ground or slope like a normal tracked vehicle, propulsion on the crawler belt should be larger than motion resistance. At the same time, rotation torque on the connecting frame should be smaller than the rotation resistance generated by gravity of crawler and payload.

In the same way, when the crawler mechanism contacts an obstacle, in order for it to climb over the obstacle in the proposed locomotion mode instead of track-slipping, the propulsion on the crawler belt should be smaller than the friction resistance so that the crawler belt can be fixed. Concurrently, the rotation torque must be larger than the rotation resistance to lift vehicle body to climb over the obstacle.

After the crawler mechanism has climbed up the obstacle, it can recover to the initial position autonomously.

III. Mechanical Design of a Modular Crawler

According to the design rules stated in Section II, a possible mechanical transmission scheme for modular crawler is proposed first. Subsequently, the mechanical design of a modular crawler is conducted, based on the proposed transmission scheme. Waterproof and dustproof qualities are also considered in this design process.

A. Transmission Scheme of a Modular Crawler

A transmission scheme of a modular crawler is shown in Fig. 3. Only one motor is deployed to give two outputs in this modular crawler.

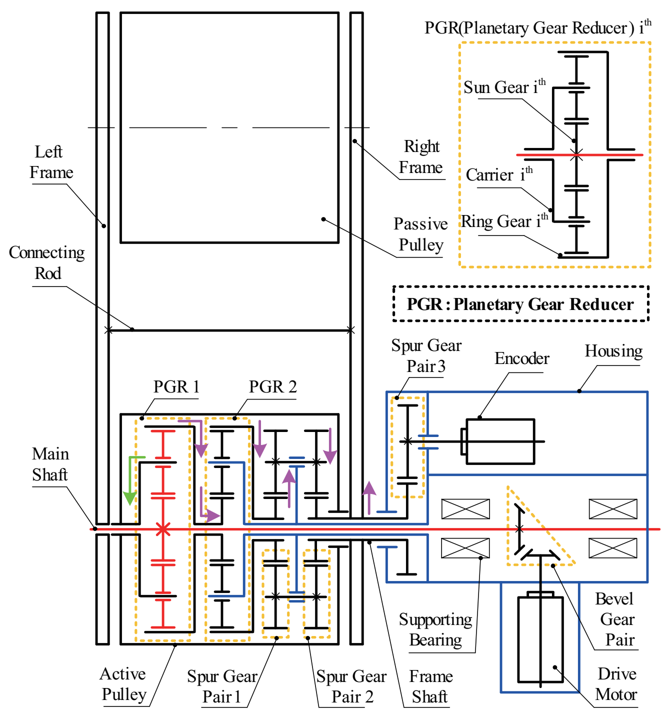


Fig. 3. Transmission scheme of a modular crawler

As shown in Fig. 3, power is transmitted to the "main shaft" from "drive motor" via a pair of bevel gear. Since the "main shaft" is fixed with "sun gear 1" of the "planetary gear reducer (PGR) 1", the power is transmitted to the first planetary gear reducer and then separately to the "carrier 1" and “ring gear 1”, respectively. Due to the truth that “carrier 1” is fixed to the “active pulley”, the output of “carrier 1” is transmitted to the active pulley to drive the crawler to move forwards as the first output. As another output of the “planetary gear reducer 1”, the power of “ring gear 1” is transmitted to the “sun gear 2” of the “planetary gear reducer 2”. Since the “carrier 2” is fixed with “Housing”, without any movement, the output power from “ring gear 2” is transmitted to the “spur gear pair 1”, and then to the “spur gear pair 2”, finally to the “right frame” as the second output.

The transmission components are arranged inside the active pulley. The “left frame” and “right frame” are fixed via a part named “connecting rod”. A timing belt adopted as the crawler track, connects the “active pulley” and “passive pulley” to propel the crawler. The “right frame” is connected to an encoder through “spur gear 3”. The rotation angle of the frame is measured by the encoder.

B. Mechanism Design of a Modular Crawler

Based on the scheme proposed above, the detailed design of a modular crawler robot is developed while considering waterproof and dustproof characteristics. The mechanical model of a new modular crawler is shown in Fig. 4.

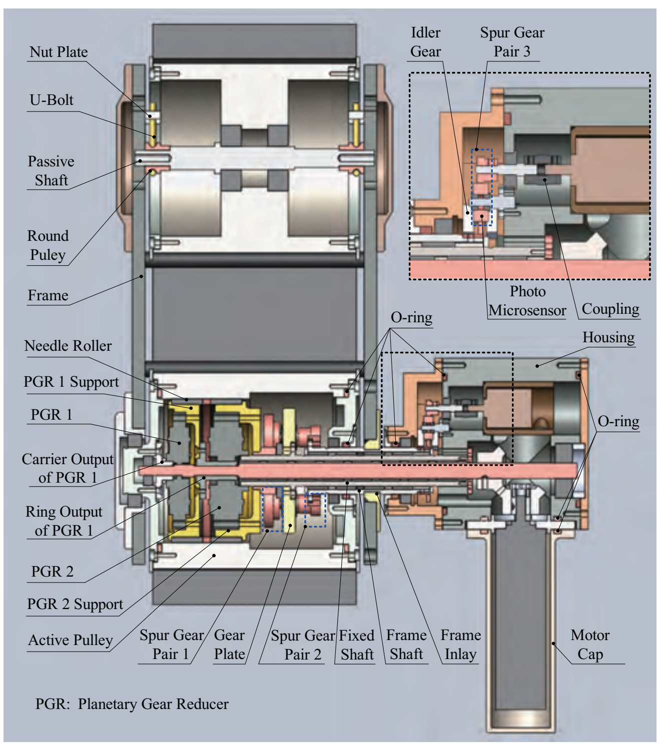


Fig. 4. Mechanical model of a modular crawler

1) Distribution of Reducer Ratios: The design of two reducer ratios for the two outputs from one input is pretty crucial in that it must meet the second and third terms stated in Section II. From the static analysis in three locomotion modes, the first reducer ratio i_1 from “main shaft” to the “active pulley” and the second reducer ratio i_2 from “main shaft” to the “frame” are selected to be 4 and 27, respectively.

The reducer ratio from “sun gear 1” to “carrier 1” in the “PGR 1” is adopted as the reducer ratio of the first output i_1, the value of which is 4. Thus, according to the basics of planetary gear reducer, the reducer ratio from “sun gear 1” to “ring gear 1”, named i_{21}, is -3. Due to the fact that the “ring gear 1” is connected with the “sun gear 2” using serration and the “carrier 2” is fixed with the housing statically, the reducer ratio of the second planetary gear reducer from “sun gear 2” to “ring gear 2” named i_{22} is selected to be -3. The “ring gear 2” transmits power to the frame through the “spur gear pair 1”(reducer ratio $i_{23} = -1$) and “spur gear pair 2”(reducer ratio $i_{24} = -3$). Thus the reducer ratio from the “main shaft” to the “frame” i_2 can be calculated by

$$i_2 = i_{21} \times i_{22} \times i_{23} \times i_{24} = (-3) \times (-3) \times (-1) \times (-3) = 27 \quad (1)$$

Since both the reducer ratios i_1 and i_2 are positive, the two outputs certainly run in the same direction.

The “carrier 1” is connected with “carrier output of PGR 1” which is fixed to the “active pulley”. Thus, output of “carrier 1” is deployed as the first output to the active pulley. The “ring gear 1” of the “planetary gear reducer 1” is fixed with “PGR 1 support” which is supported by a “needle roller” in the active pulley. The “PGR 1 support” is also fixed to “ring output of PGR 1” which is connected to “sun gear 2” by serration. The “PGR 2 support” also supported by a needle roller in the active pulley is fixed to the “ring gear 2” and the first gear of “spur gear pair 1”, respectively. Since the “carrier 2” is fastened with “fixed shaft” which is fixed with the “housing”, the single output of “PGR 2” from the “ring gear 2” is transmitted to “spur gear pair 1”. The output gear of “spur gear pair 1” and input gear of “spur gear pair 2” are fixed on a shaft which is supported by rolling bearing inside the hole of “gear plate”. The “gear plate” is fastened with “fixed shaft” with screws as a static part. The output gear of “spur gear 2” is fixed to “frame shaft” on the left side which is supported on “fixed shaft” with needle rollers. The middle of “frame shaft” is fixed to the “frame inlay” which is also fixed to the “frame” through screws. The right side of “frame shaft” is connected to the input gear of “spur gear pair 3” for encoding the rotation angle of the frame. Lastly, the power is transmitted from the “spur gear pair 2” to the “frame” as the second output.

2) Setup of the Encoder and Zero Positioning of the Frame: To obtain a high resolution of the rotation angle of the frame, the mechanism of “spur gear pair 3” should be designed with a larger reducer ratio. If two gears are adopted here, the size of input gear should be designed much bigger to get a high reducer ratio. This will inevitably cause the outer housing to become much larger. Thus, to prevent this undesirable effect on the outer dimension of the housing, an idler gear is deployed in the transmission of “spur gear pair 3” shown in Fig. 5. Consequently, this reducer ratio from the frame to the encoder is selected to be 4 considering other related dimensions.

Since an incremental encoder is adopted to obtain the rotation angle of the frame, it is extremely crucial to decide

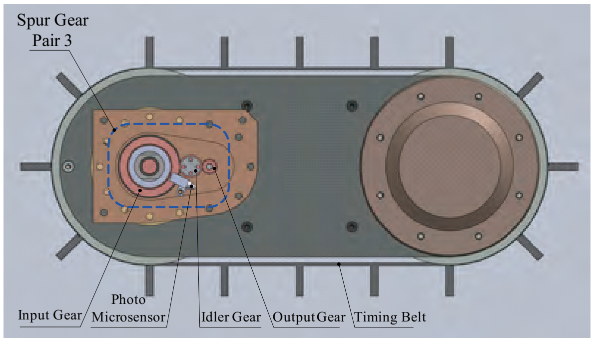


Fig. 5. Zero positioning for the frame

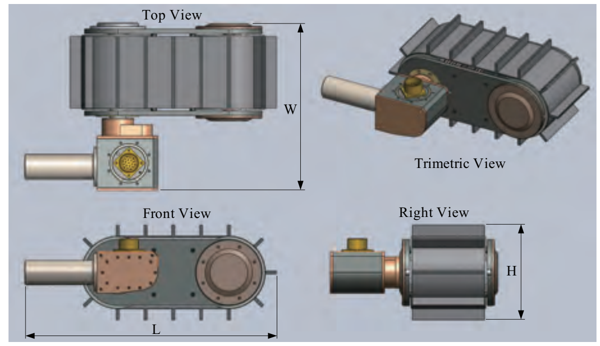


Fig. 6. CAD views of the modular crawler

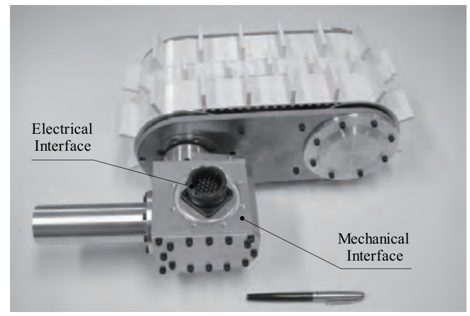


Fig. 7. Prototype of a modular crawler

the zero position for the incremental encoder. As shown in Fig. 5, a photo micro sensor is fixed on the housing statically with the input gear of "spur gear pair 3" penetrating its U slot. A small hole drilled near the edge of the input gear turns the photo sensor light on while the other area prevents the light penetrating so as to turn the photo sensor light off. This on/off signal is used to judge whether the zero position of the frame is reached. The current position in Fig. 5 is considered as the zero position of the frame.

3) Tension Mechanism for the Belt: As shown in Fig. 5, the timing belt is deployed as the track which connects the active pulley and passive pulley. There are several cogs exposed on the exterior side of the timing belt. The cogs can increase the friction effectively to improve the locomotion of crawler in rough terrain. Tension mechanism is a necessary part to keep the belt always tight. As shown in Fig. 4, "passive shaft" is located in the U-shaped hole of the frame which enables the passive shaft to move freely in the tension direction of timing belt. "Nut plate" fixed with the frame cooperates with the "U-bolt" to change the distance between passive pulley and active pulley so as to keep the timing belt always tight.

4) Sealing of Transmission System: In this modular crawler, both waterproof and dust proof are considered in the design process. As shown in Fig. 4, "motor cap" is used to prevent water and dust to damage the motor. The interior transmission devices of active pulley and housing adopt closed mechanism. At the connecting interface, "O-rings" are deployed to keep the inside sealed.

5) Modular Interface: As a modular crawler, the crawler should provide a convenient connection interface to robot system. As shown in Fig. 7, the top surface of the housing with eight screw holes is used as the mechanical interface and an air plug is adopted as the electrical interface. The mechanical interface makes the modular crawler easily attachable to the anticipated robot body by screw fastening. The internal electrical signals including encoder of the drive motor, photo micro-sensor, encoder of the frame can be provided through the electrical interface.

CAD views of the modular crawler in front, top, right, and trimetric perspectives are shown in Fig. 6, and the real prototype is shown in Fig. 7. The outer dimensions of this modular crawler are listed in Table I.

As an example of the possible applications of the proposed modular crawler, a four-crawler-driven robot has been built, as shown in Fig. 8. Four crawler modules are connected to the robot body through their each interface.

IV. Experiments

Experiments were conducted to confirm the mobility of the proposed modular crawler mechanism. With regard to one crawler module, the experiment is used to verify the three locomotion modes in a real prototype. A four-crawler-driven robot which consists of four modular crawler mechanisms is also adopted as the object to do experiments in obstacle environment.

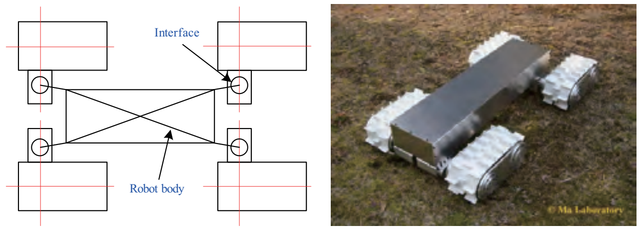
A. Experiment demonstrating a Single Modular Crawler

As stated in Section II, the underactuated system in which one motor input gives two different outputs makes it impossible to treat as an individual mobile system. Thus, in the following experiments the housing of the modular crawler is held horizontally by hand.

First, the air plug is connected and then the power is turned on. The experiment scenes of the housing of the modular

TABLE I
Major parameters of the modular crawler

Weight	11.5 [Kg]
Size(L× W× H)	453 [mm], 302 [mm], 169 [mm]
Reducer Ratio	4 (Output 1), 27 (Output 2)
Torque	5.1 [Nm], 34.4 [Nm]
Velocity	0.5 [m/s], 8.6 [rpm]



(a) Assembly (b) Prototype

Fig. 8. A four-crawler-driven robot

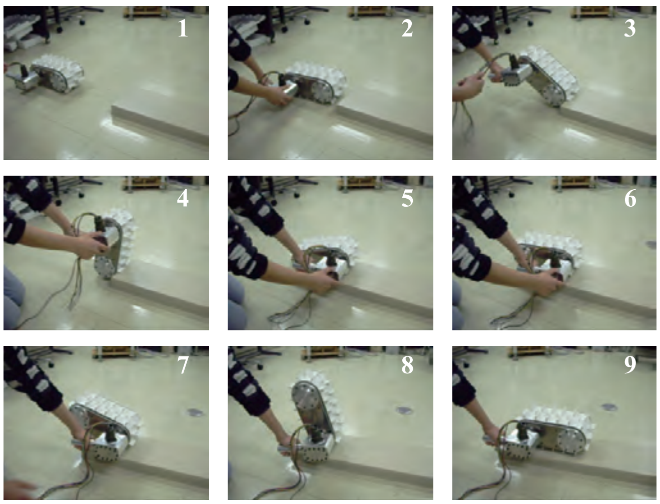


Fig. 9. Experiment scenes of single modular crawler

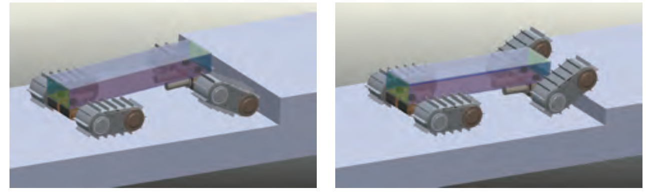
crawler held by hand are shown in Fig. 9. From scene 1 to 2, the crawler moves forwards as the normal tracked robot (motion mode). When the crawler encounters an obstacle, the first output for driving the track is limited and the second output for driving the frame plays a role in negotiating the obstacle, as shown in scenes 3, 4, 5, and 6. After overcoming the obstacle, the modular crawler begins to recover to the initial position, as shown in scenes 7, 8, and 9.

From the experiment shown in Fig. 9, we know that the proposed three locomotion modes of single modular crawler can be well realized in this modular design.

B. Experiment with a Four-crawler-driven Robot

A four-crawler-driven robot equipped with four modular crawlers can perform with good adaptability in rough terrain. This four-crawler-driven robot can overcome obstacles passively without any control as the single crawler module shown in Fig. 10(a). Additionally, the posture in which the front crawler modules are lifted up can be deployed to move over relative rough obstacles shown in Fig. 10(b). Thus this robot can negotiate obstacle actively with effective control.

1) The Crawler Robot Overcoming Obstacles Passively: When this crawler robot encounters an obstacle, the front modules overcome the obstacle passively and subsequently the rear modules overcome the obstacle passively. In this process of negotiating obstacles, it is not necessary to provide any control to the robot.



(a) Passively (b) Actively

Fig. 10. The different ways to overcome obstacles

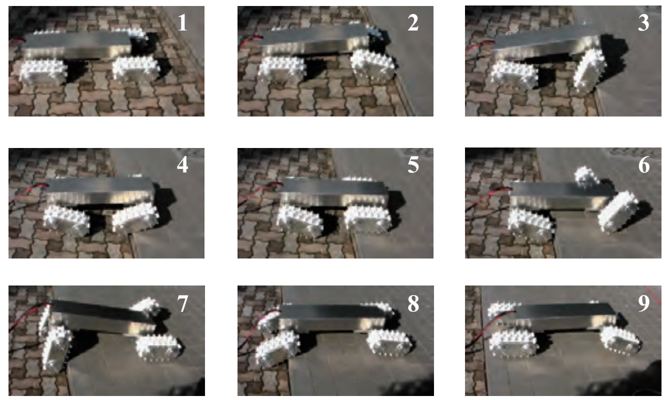


Fig. 11. Experiment scenes when four-crawler-driven robot overcomes an obstacle passively

As shown in Fig. 11, the robot moves forwards on a flat surface (motion mode) in scene 1. When there is an obstacle stopping the timing belts of the front crawler modules, the front crawler modules switch into rotation mode to overcome the obstacle from scenes 2 to 5. In this process the rear crawler modules continue to move forwards, pushing the front modules, since the front rotation velocity is much smaller than the rear moving speed. After climbing up the obstacle, the front modules begin to return to the initial motion mode in scenes 6, 7, and 8. When the rear modules touch the obstacle surface, they also begin to overcome the obstacle in the same manner as the front modules. After climbing over the obstacle, the rear modules also begin to return to the original position in scene 9.

2) The Crawler Robot Overcoming Obstacles Actively: The four-crawler-driven robot is an underactuated system, in which there is a kinematic redundancy. The internal interaction between the front module and the rear module can be used to realize the robot posture control [14].

The posture in which the front module is lifted up can be used to negotiate obstacles, as shown in Fig. 10(b). The fact that the posture can be kept has been proved through the numerical method.

$[\theta_f]$ is the desired front frame angle of the posture. As shown in Fig. 12, the current frame angle is larger than the desired frame angle $[\theta_f]$. The front frame should rotate in a clockwise direction so as to reach the desired goal angle. At this point, the front module is pulled by the rear module.

As shown in Fig. 13, the current frame angle is smaller than the desired frame angle $[\theta_f]$. The front frame should rotate in an anti-clockwise direction so as to reach the desired

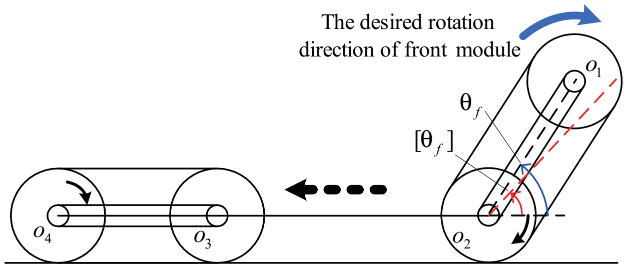


Fig. 12. Control concept when $\theta_f > [\theta_f]$

goal angle. At this point, the front module is pushed by the rear module.

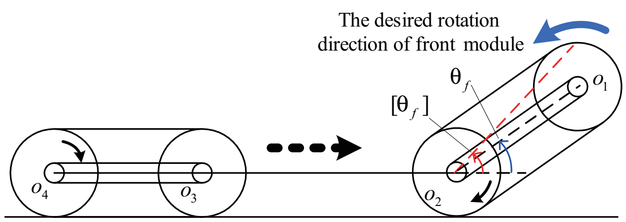


Fig. 13. Control concept when $\theta_f < [\theta_f]$

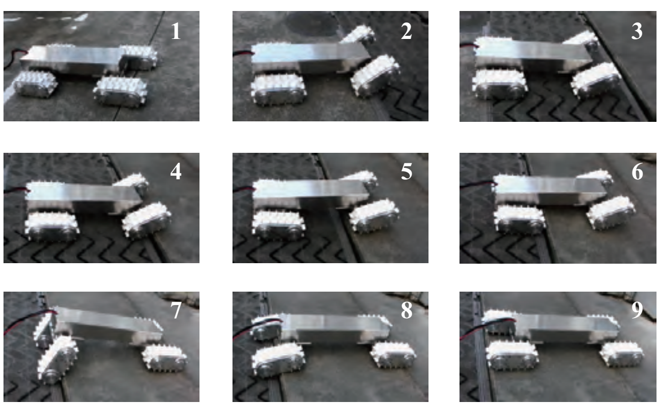


Fig. 14. Experiment scenes when four-crawler-driven robot overcomes an obstacle actively

Based on the principle discussed above, the front modules are controlled so as to be lifted up to overcome the obstacle. The experiment scenes are shown in Fig. 14. In scene 1, the crawler robot moves forwards in motion mode. In scene 2, the front modules of the crawler robot are controlled to be lifted up at the angle of 30°. The crawler robot overcomes the obstacle with the front modules lifted up in scenes 3, 4, and 5. After the front modules climb over the obstacle, the rear modules begin to overcome the obstacle as in the case of the passive experiment in scenes 6, 7, and 8. Consequently, the crawler robot successfully overcomes the obstacle in scene 9.

V. Conclusions

This paper introduced a tracked crawler robot in which a planetary gear reducer is adopted as the main transmission component and provides two outputs in different forms with only one actuator. A modular concept of this crawler robot has been proposed. The outline of this modular crawler has been decided, and its detailed mechanical design has been implemented while considering waterproof and dustproof qualities. Experiments with a single modular crawler showed that the crawler can achieve the proposed locomotion modes. Experiments with the four-crawler-driven robot composed of four modular crawler mechanisms demonstrated that the robot has good adaptability to rough terrain passively and can negotiate obstacles actively with effective control.

VI. Acknowledgments

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