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High-Step Climbing by a Crawler Robot DIR-2
- Realization of Automatic Climbing Motion -

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***Abstract*— We introduce a unique shaped crawler robot aimed for high-step climbing that is considered the most necessary ability in urban search and rescue operations. The crawler robot is composed of two triangular-shaped crawler devices connected by a center shaft, a straight crawler device and a two-link mechanism connecting the shaft and the straight crawler. The robot is very compact and light weight compared to other rescue robots. It has eight D.O.F. in total, four of which are for crawlers and the others are for shifting the shape of the robot. We confirmed that the proposed robot can get over 36 cm high-step one-and-a-half times as high as its original height. We also implemented a height-independent climbing motion algorithm based on statics and geometrical analysis in climbing process. Various hardware experiments showed a capability of the developed robot and feasibility of the proposed climbing motion algorithm.**

***Index terms*— Crawler robot, Triangular-shaped crawler, Urban search and rescue, Inspection, High-step climbing, Automatic climbing motion algorithm.**

I. Introduction

IN recent years, various types of mobile robots have been proposed so far for urban search and rescue operations or inspection services [1]–[14]. Mobile robots for the above operations are broadly classified into three types by its moving method; a crawler type, a wheel type and a legged type. A crawler type in general has superior ability in traveling on a bad road surface, a slope or slight steps, but has difficulty in raising moving speed on a flat ground or turning on a high friction ground compared to a wheel type. A wheel type can move faster than crawler types, but is inferior to the crawler type in climbing capability, and easily slips on a low friction ground, e.g. a beach and a snow field. The legged robots seem to be inferior to above two types in moving speed and climbing capability. However, the special kind of six legged robot represented by Whegs [13] or RHex [14] has made it possible for climbing high-steps and moving on rubbles. We adopted the crawler type moving method to our robot to realize high-step climbing considering various merits described in the following sections.

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Rescue robots or inspection robots require an ability of getting over obstacles, high steps or rubbles besides traveling on a bad surface ground. Therefore, mobile robots developed so far have been focusing on those abilities. There are several elaborate mobile robots superior in those abilities; robots that making the front crawler inclined to upper side to climb over obstacles [1]-[3] ; having a heavy mass inside and transfer it from back to front while climbing [4]; having flipper arms, represented by iRobot's PackBot [5], and pushing them against a step and lifting the whole body to climb steps [6]-[8]; a snake type robot which can raise its head upon a step and then get over it [9], [10]; and having mechanical links designed for lifting a camera or other devices which are also used for lifting the front body to surmount a step [11], [12]. The DAGSI Whegs in ref. [13] can climb a 40 cm obstacle utilizing a passively compliant body joint besides rotating 6 legs like a wheel with fixed phase differences between them. The important point for climbing steps that is common to all the above mobile robots is how to transfer its center of gravity (C.O.G. hereafter) to top of the step from the ground. The main theme in this paper is to propose a novel crawler robot design which has an ability of transferring C.O.G. of the robot, and to confirm its feasibility by hardware experiments.

Besides the C.O.G. transferring ability, a mechanism for avoiding a deadlock state such as being upside down or fitting in a hole is also necessary for rescue or inspection robots. For most of mobile robots having cameras or other sensing devices on top of the body, turning over may become a fatal matter for continuing operations. In the following section, we refer the problem again and propose one of solutions by our robot. Though we still have many issues to be discussed on rescue robots such that a variety of sensors to be embedded for internal and external sensing, controlling interfaces and robustness to various environments, in this paper we address a mechanical design enabling high-step climbing and an automatic climbing motion algorithm.

In section II, we introduce a unique shaped crawler robot and its design concepts; in section III, we present the robot hardware and its control system in detail. In section IV, an automatic climbing motion algorithm based on statics and geometrical analysis is proposed. In section V, various hardware experiments are shown to prove capability of the prototype robot and feasibility of the proposed motion algorithm. In section VI, we describe concluding remarks and future works.

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II. Proposal of Robot Structure Enabling High-Step Climbing

A. Concepts of Robot Design

We summarize concepts of our robot design first that seem to be useful and effective for rescue or inspection operations.

1) Compact and light weight structure: The compact and light weight robot structure must be effective in narrow space operations, for easy handling and carrying, and for extending battery life.

2) A robot structure with no upside or downside: A robot structure having no upside or downside such as rotation symmetry structure around horizontal axis is preferable to recover various deadlock situations.

3) C.O.G. transferring function: We realize the C.O.G. transferring function using a plural-link mechanism described in the following. This mechanism is also used when the robot got into the deadlock situation.

4) Installation of a variety of sensors: For practicability of small mobile robots, a variety of internal and external sensors such as temperature and humidity sensor, gas detection sensor, cameras, acceleration sensor and gyro, should be installed according to tasks.

5) Remote control, real-time monitoring and information transfer / gathering function using wireless communication: Remote control and real-time monitoring functions are necessary for search and rescue tasks. For future networking applications with multiple mobile robots, an information transfer function using P2P adhoc network should be supported.

6) Intuitive GUI system for easy operation: An intuitive GUI system that anybody can use at sight is preferable. We adopted a laptop PC with touch screen for operating the robot and displaying sensor information of the robot.

B. Proposal of Robot Structure

We have developed the robot system based on the above design concepts. Figure 1 shows appearance of the developed crawler robot. This is a second prototype developed in cooperation with Advanced U-Corporation Inc. [15] in Gunma, Japan. We named the robot as DIR-2 (a Dexterous Inspection Robot) targeting an inspection robot market in Japan, e.g. inspection under the floor of Japanese wooden houses. Figure 2 shows an assembly diagram of 5 robot components and 8 driving parts in the robot.

The robot is composed of two triangular-shaped crawler devices ("triangular crawler" hereafter) placed in parallel, two-link mechanism ("Link A" and "Link B" hereafter), and a straight crawler device ("straight crawler" hereafter). There are dome-shaped sensor cases on both sides of the triangular crawlers. As shown in Fig. 2, each shaft ("center shaft" hereafter) protruded from left and right side of Link A is inserted into the center hole of each triangular crawler through a bearing. Each triangular crawler can be rotated about each center shaft with 360 degrees by a servomotor embedded in the triangular crawler. Both Link A and Link B, Link B and the straight crawler are connected by joints and can be driven within 240 degrees range by servomotors embedded in Link A and the straight crawler. There are two batteries inside Link B. All the rotation axes toward the same direction as the center shaft.

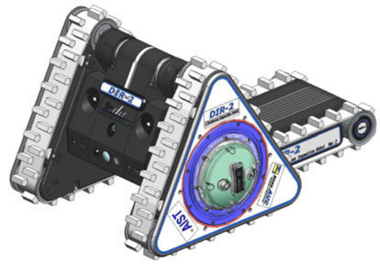

Fig. 1 Appearance of Dexterous Inspection Robot, DIR-2.

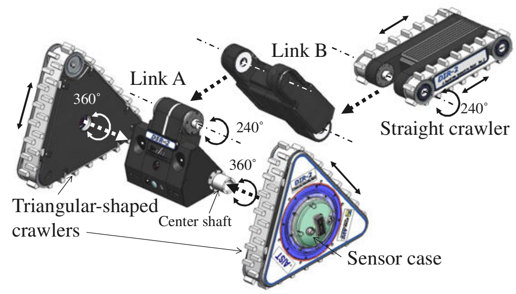

Fig. 2 Assembly diagram showing 5 components and 8 driving parts.

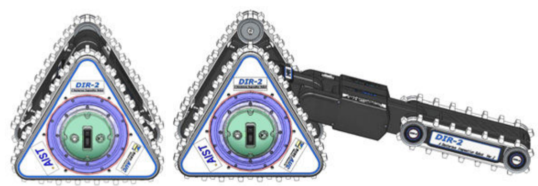

Fig. 3 Folding state (left) and Extended state (right). Link B and the straight crawler can be completely folded inside the triangular crawler unit in the side view.

The robot has eight degrees of freedom in total. Four of which are used for driving crawler belts of triangular crawlers and straight crawlers. Two of which are used for rotating triangular crawlers about each center shaft. Other two-D.O.F. is used for driving joints between Link A and Link B, Link B and the straight crawler. The robot shown in Fig. 1 is in the ordinary locomotion style. In this style, the robot can move forward, back, and turn to left and right by controlling velocities of crawlers.

As the robot structure is rotation symmetry around the center shaft, there's no need to determine upside or downside, but for easy understanding we call the left part in Fig.1 front and call the posture in Fig. 1 as upright state. The robot can get back to the upright state using the link mechanism even if it falls into upside down. The dome-shaped sensor cases also help the robot to recover its posture when tumbled over to the side.

Figure 3 shows a folding state and an extended state of the robot. The robot can fold Link B and the straight crawler completely inside the triangular crawler unit in the side view.

The robot can also move and turn in a narrow space, ideally 35 cm in width and 25 cm in height, by that state. The folding state is so compact that it's easy to deliver and store. In the extended state, Link B and the straight crawler part can be extended to about 40 cm backward. It is considered the limit of height that the robot can climb in an ideal case.

In the robot structure, weight of the front part including two triangular crawlers and Link A is about 5.6 kg in total. It is designed heavier than the rear part, Link B (1.3 kg) and the straight crawler (1.7 kg). Climbing process is achieved by putting the heavier front part on a step first and then pulling up the rear part.

C. Climbing Process and Evaluation of Triangular-shaped Crawler

Figure 4 shows basic climbing motion sequences by the robot and calculated C.O.G. position in each step. The climbing process can be divided into three steps as follows.

(1) The robot is facing to a step and touching with the tip of triangular crawler. Rotate the triangular crawler until one of sides of that touches the side surface of the step ((a) to (b) shown in Fig. 4). During this process, crawlers are slightly driven toward the step to force the triangular crawler against the step.

(2) Lift the triangular crawler along the step to top of the step by extending Link B and the straight crawler accordingly ((c) to (d)).

(3) After the C.O.G. position completely moves on the top of the step, pull up Link B and the straight crawler ((e) to (f)).

The robot can surmount a high-step about one-and-a-half times as high as its original height by a series of motions in Fig. 4. On the other hand, in the case of stairs length in depth of surmountable step by the robot is calculated to be more than 18 cm by the condition shown in (f) where C.O.G. of the robot is required to be on the step.

Figure 5 shows comparison of rotation symmetry crawler shapes in the same height; triangular-shaped, square-shaped and circular-shaped. As shown in the figure, position of C.O.G. of the triangular-shaped crawler is lowest among three shapes. This means that it is possible to shorten length of links compared to others in the case of climbing a same height step. It also has merits in climbing a steep slope because the lower the position of C.O.G., the lesser the chances that the robot rolls down backward. Furthermore, as a side of triangular-shaped crawler is longer than that of square-shaped shown in the figure, the former can hang its edge on higher steps than the latter. We adopted the triangular-shaped crawler by those reasons.

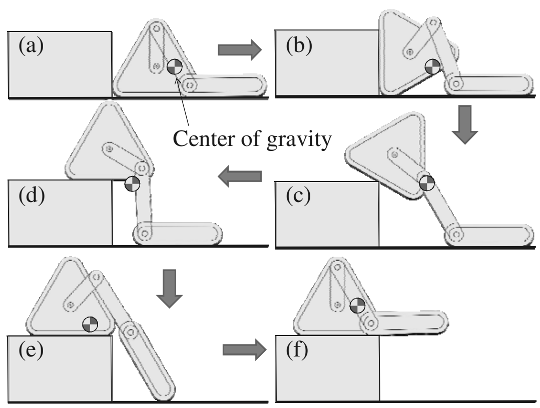

Fig. 4 Basic climbing motion sequences. Marks in the figure show positions of center of gravity in each step.

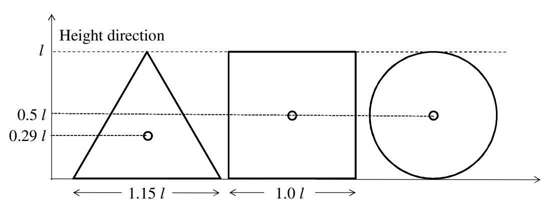

Fig. 5 Comparison of rotation symmetry crawler shapes in the same height;; triangular-shaped, square-shaped and circular-shaped.

III. Robot Hardware

A. Development of Prototype

Figure 6 shows photos of the second prototype, DIR-2, and functions of each part. We have been developing the prototypes for inspection usage in a narrow space where access by human is difficult. In the case of inspection under floor of Japanese old wooden houses, the robot has to get over laying pipes, wirings and about 15 cm height steps between rooms under the floor. The following functions are also necessary for under floor inspection robot; remote control by users watching real-time camera image and remote sensing

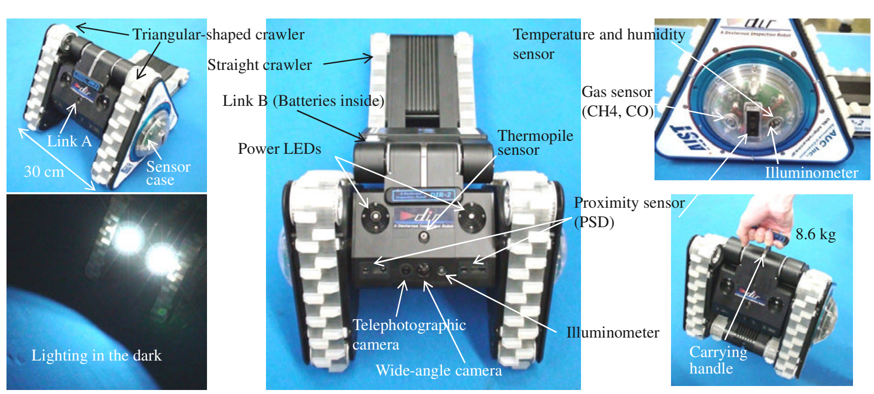

Fig. 6 Photos of DIR-2

TABLE I
SPECIFICATIONS OF DIR-2

Item	Value
Size	Folding state: 35cm(W)×24cm(H)×27cm(L) Extended state: 35cm(W)×24cm(H)×64cm(L) One side of triangular crawler is 27cm in length.
Weight	8.6 kg
Moving method / Max. speed	Triangular shaped crawler and straight crawler / Max. 2 km/h
Gradeability	Max. 30 degrees (depends on friction of slope)
Turning circle radius	0 cm
D.O.F.	8 (crawler (4), link mechanism (2), axial rotation of triangular-shaped crawler device (2))
Actuators	Two types of A10 developed servo motors (2.4 Nm (18.5VDC) for crawlers and 8.0 Nm (18.5VDC) for others)
CPUs	Renesus SH7145 on main-controller board and Atmel ATmega168 on each servomotor, sensor board and interface board
Internal communication	RS485 multi-drop connection (115.2k bps)
RF communications	Futaba 2.4 GHz RF modem and 1.2 GHz wireless video transmitter (Covered 200 m wide area in visible site)
Battery	Two Li-Po batteries (18.5V 8.4 Ah in total)
Operation time	2 to 3 hours (depending on situation)
Sensors / devices	Wide-angle camera, Telephotographic camera, Illuminometer, Infrared proximity sensor, Thermopile sensor, 3-axis acceleration sensor, Gyro sensor, Digital compass, Power LEDs, Digital temperature and humidity sensor, GAS sensor (CH4, CO)

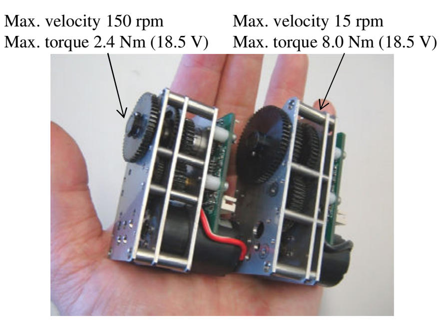

Fig. 7 Developed A10 servo motors. The left is for driving crawler belt and the right is for other parts requiring high torque.

such as danger gas detection, measurement of temperature and humidity, and so on. Specifications of DIR-2 are summarized in Table 1.

We have newly developed two types of servomotors for DIR-2 named A10 shown in Fig. 7. The left motor is for driving crawler belt and the right motor is for rotating the triangular crawler and driving links where high torque is required. The circuit board of A10 includes a magnetic rotary encoder (absolute-value type), a motor driver, a power circuit, an AVR microprocessor and RS-485 two-wire serial communication chip. We preprogrammed the following functions in the microprocessor; 360˚ position control with speed control, rotation speed control, software limit function which limits range of movement, origin setting at any points within 360˚, pulse count function for dead reckoning. The

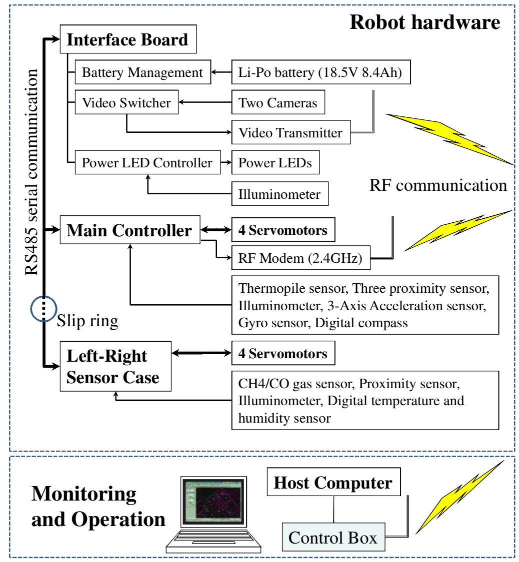

Fig. 8 Schematic of DIR-2 system configuration.

A10 servomotors can be electrically connected in multi-drop connection with four wires, two power lines and two RS-485 serial communication lines. They are easily controlled by sending a command packet with ID through RS-485 bus. Development of A10 servomotors made it possible to control robot motions more precisely while climbing.

We designed outer cases of DIR-2 to be dust and drip proof structure. It can operate under dusty or drizzly situations with no problem. We also attached a carrying handle on the top of Link A for easy handling.

B. *System Configuration of DIR-2*

Figure 8 shows system configuration of DIR-2. There are a main controller, an interface board, 8 servomotors and left and right sensor cases in the robot hardware. They are connected by RS-485 serial communication bus indicated by bold line in the figure. In DIR-2, usual electric wirings between Link A and triangular crawlers are impossible, because the triangular crawlers rotate with 360˚ freely. We solved the problem using slip-rings which can electrically connect the lines between rotational objects and fixed parts.

The main controller embedded in Link A controls other onboard microprocessors by writing / reading data on / from each control table in a centralized manner. The host computer outside sends / receives control commands or data packets to / from the robot hardware using RF communication via control box. Camera image is transmitted by a video transmitter in the robot to the control box and input to the interface software on PC. Sensor information is stored periodically in the control table of each microprocessor and can be taken into the host PC at any time by RF communication.

C. *Monitoring and Operation Software on PC*

Figure 9 shows a screen image of monitoring and operation software on PC. We adopted a PC with touch screen for controlling the robot intuitively by users. Robot control

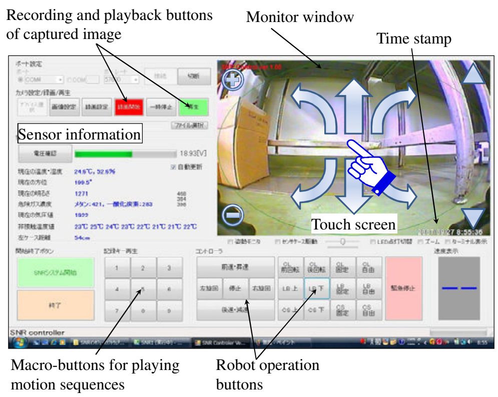

Fig. 9 Screen image of monitoring and operation software on host PC.

commands are made accordingly with the touched button or position on the screen shown in Fig.9. They are sent to the robot in real-time using RF communication. At the same time, sensor information of the robot is taken into the PC and displayed in the sensor information window.

Moving operation of the robot by user is achieved by tracing the lines, not shown actually, in the monitor window with a finger tip. It is also possible to shift the robot shape only by tapping buttons below the monitor window. By pushing a macro-button at the lower left of the window, a series of button operations can be recorded and stored in the robot as a key sequence data. This recording function is used for playing back a group of motions such as climbing known height steps, getting back to a locomotion mode, and so on.

Real-time camera images at monitor window can be recorded with time stamp into the PC and replayed any time. Zooming of camera image is also possible that is achieved seamlessly by combining a software digital zooming and switching cameras from wide-angle to telephotographic, by tapping the areas indicated + and – in Fig. 9.

IV. Automatic Climbing Motion Algorithm

So far, in previous prototype DIR-1 climbing motions have been realized by playing back stored key sequences. However, there were problems that it cannot be applied to unknown height steps and the robot cannot climb steps properly if timing of motion was shifted by slips or any other reasons while climbing. In this section, we propose a height-independent automatic climbing motion algorithm based on statics and geometrical analysis of center of gravity. In section V, we confirm feasibility of the algorithm using real hardware.

A. Statics and Geometrical Analysis While Climbing

Figure 10 shows forces and torques while climbing. R_1 and R_2 are drag forces from contact surfaces. T_1, T_2 and T_3 are torques of motors. F_2 and F_1 are tangential force components by torque T_1 and R_1 at the contact point between the triangular crawler and edge of the step. The left schema in Fig. 10 shows a state that the robot is climbing without slipping because both perpendicular components of R_1 and R_2 on each contact surface toward moving directions shown in the figure. This

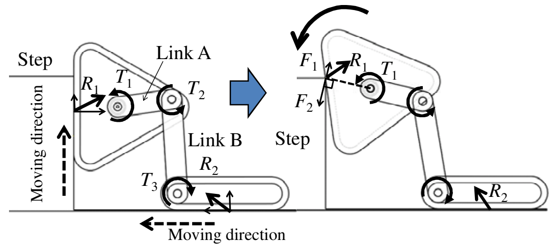

Fig. 10 Forces and Torques in climbing process.

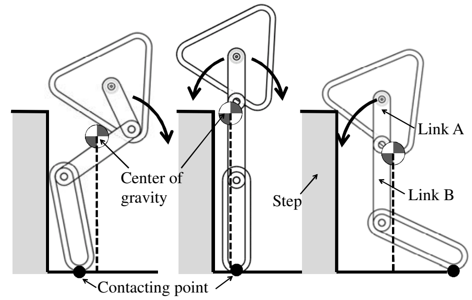

Fig. 11 Analysis of COG positions in different shapes and postures.

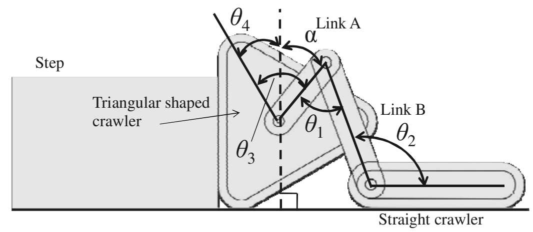

Fig. 12 Parameters for climbing motion algorithm.

state must be kept in climbing process.

As shown in Fig. 10, a constant torque T_1 is always put on each triangular crawler for rotating forward. Triangular crawlers will always start to rotate forward when the force $F_2 > F_1$. By checking the rotation angle of triangular crawlers against the vertical line, it is possible to know whether the robot has completely reached the top of the step or still on the way. Starting rotation point of triangular crawler is determined by force balance between F_2 and F_1. When the F_2 is much larger than F_1, triangular crawlers start to rotate below the edge of step and fall down. On the other hand, when F_2 is much smaller than F_1, triangular crawlers will not rotate forward after reaching the edge. The value of T_1 can be chosen arbitrarily within the range that the side of triangular crawler keeps touching to side surface of step without rotation as shown in Fig. 10 left.

Figure 11 shows calculated C.O.G. positions using real CAD model in three situations. The robot needs to extend the links in accordance with step height. This will cause unstable states and the robot might turn over. In the Fig.11 left case, the robot will fall down rightward since the horizontal position of C.O.G. locates at the right side of the contact point of straight crawler. In the middle case, there's a possibility to fall down to either sides. In the right case, the robot surely falls down to the left side. It is found from the analysis in Fig. 11 that the robot will never turn over backward as long as Link B is kept vertically and maximum angles of links, θ_1 and θ_2 in Fig. 12, are limited to 180˚. In that case, horizontal position of C.O.G. always locates at left side of contact point of straight crawler on ground.

B. Proposal of Automatic Climbing Motion Algorithm

We propose a height-independent automatic climbing motion algorithm based on discussions in IV-A. In the algorithm, whole shape and posture of the robot are calculated only by using the posture angle of Link A, denoted by α shown in Fig. 12, and motor angles. The value of α is calculated by acceleration sensor values. The motor angles between Link A and Link B, Link B and the straight crawler are denoted by θ_1 and θ_2 respectively in the figure. The rotation angles of triangular crawler against Link A and the vertical line are denoted by θ_3 and θ_4 respectively (here, $\theta_4 = \theta_3 - \alpha$).

Proposed algorithm is as follows.

1: The robot is facing to a step and touching with the tip of triangular crawler as shown in Fig. 4 (a). (here, θ_1 = 30˚, θ_2 = 120˚)

2: Rotate the triangular crawlers about the center shaft with the constant torque T_1 (= 2.5 Nm) until one of sides of triangular crawler touches the side surface of the step. (Fig. 4 (b))

3: Driving four crawlers toward front with the same driving force (= 20 N each).

4: If detect the situation that the triangular crawler rotated to wall surface (θ_4 = 30˚, Fig. 4 (b)), start to increase θ_1 from current angle to 180˚ by a constant rotation speed (= 0.25π rad/s). (The process of increasing θ_1 is executed by the servomotor in the background.)

5: If inclination angle of Link B against vertical line expressed by $\theta_1 - \alpha$ goes negative, control the angle θ_1 to α as the Link B is kept to be vertical.

6: If θ_1 is over 100˚, start to increase θ_2 from current to 180˚ by a constant speed (= 0.25π rad/s). (This process is also executed by the servomotor in the background.)

7: If detect the situation that the triangular crawler completely surmounted on the step (θ_4 = 120˚), move on to the process 8, or else back to the process 5.

8: Stop increasing θ_1 and start to increase θ_2 from current to 180˚ by a constant speed (= 0.25π rad/s) if not initiated yet. Remove the torque T_1 and let the rotation about the center shaft free. Initiate the sequence of pulling up LinkB and the straight crawler to top of the step.

In the algorithm, actual parameters such as T_1, driving forces of crawlers, rotation speeds of Link B and the straight crawler are determined experimentally repeating trials. The parameters, if only once determined properly, can be applied to steps in various height and conditions as will be shown in the following sections.

V. Hardware Experiments

A. Verifications of Automatic Climbing Motion Algorithm

We verified the automatic climbing motion algorithm proposed in IV-B using real hardware. Figure 13 shows hardware experiments on climbing steps in the cases that step height is 10 cm (1 concrete brick), 20 cm (2 bricks) and 30 cm (3 bricks). In any cases, the robot can climb steps smoothly as shown in the figure according to the steps' height by the proposed algorithm. The results prove that the proposed algorithm can be applicable to any height steps if they are right-angled steps like a concrete brick. Movies of hardware experiments are available at DIR-2 performance movies site [16].

B. Climbing Experiments in Various Situations

We carried out challenging hardware experiments in various situations. As shown in Fig. 14, DIR-2 could successfully climb stairs, a cylindrical object, an irregular-shaped stump in the field and a 36cm high-step using the automatic climbing motion algorithm. In the climbing experiment on stairs, the robot could climb over all the steps corresponding to one floor by initiating the algorithm at each step manually. It was also confirmed that the proposed algorithm can be applied to climb a cylindrical object which has no edges to hang on, or irregular-shaped objects in the field. The climbable step height by DIR-2 is 36 cm currently which is one-and-a-half times as high as its original height. This means there is a possibility of making much smaller robot using the proposed robot design, which can climb ordinary stairs in urban search and rescue operations.

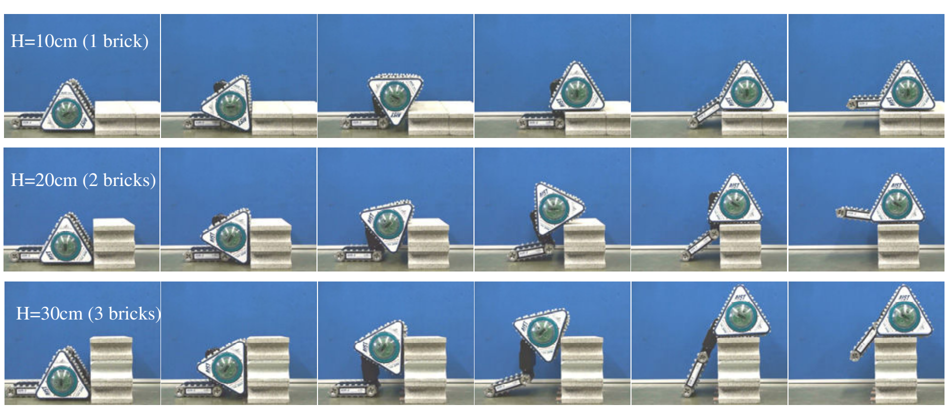

Fig. 13 Hardware experiments on different-height steps' climbing (10 cm, 20 cm and 30cm) using proposed climbing motion algorithm.

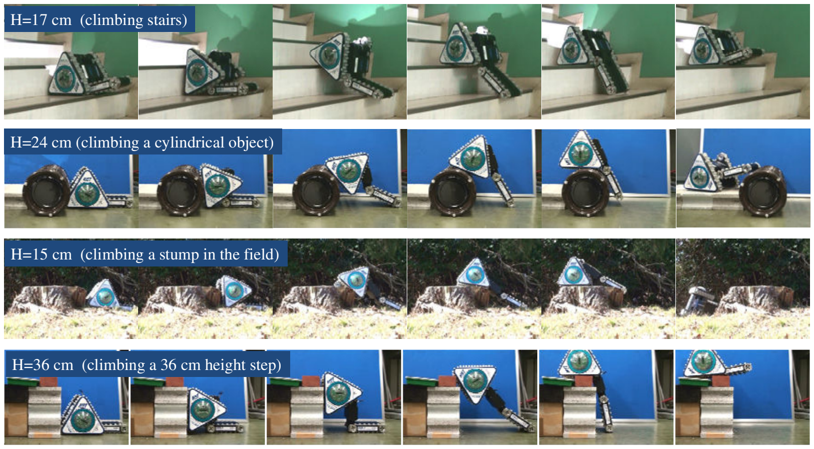

Fig. 14 Hardware experiments on climbing in various situations. These are challenging experiments. The robot can climb not only right-angled steps but also cylindrical obstacles or a stump in the field using the same climbing motion algorithm. Maximum height that the robot can climb is 36 cm currently. In the experiment on climbing a stump, the robot tumbled over once but soon recovered its posture and kept moving. All the movies are available in ref. [16].

VI. Concluding Remarks and Future Works

We proposed a unique shaped crawler robot named DIR-2 which is very compact and light weight but can climb high steps about one-and-a-half times as high as its original height. The robot is composed of two triangular-shaped crawlers connected by a center shaft, a straight crawler, and two-link mechanism connecting the center shaft and one of the ends of the straight crawler. It has eight D.O.F. in total.

We also proposed an automatic climbing motion algorithm and confirmed its feasibility and capability of the robot design by hardware experiments.

In this paper, we addressed the robot machanism and the motion algorithm enabling the robot to climb up high steps. However we have not dealt with a climbing down method from the higher place to the ground smoothly. It's alright jumping off from about 20 cm height step but the robot might break if it falls down from much higher places. We would like to develop an automatic climbing down algorithm as near future works.

Acknowledgment

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