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Connected Tracked Robot with Offset Joint Mechanism for Multiple Configurations

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Abstract - **This paper describes various configurations of two connected unit crawlers. By changing the relative position of the two connected vehicle units, the overall robot comprising such a mechanism can automatically adapt to surface obstacles on the field, including complicated structures such as disaster-generated debris.**
In addition, we analyzed the effect of axis arrangements in order to simplify the realization of the switching function so as to achieve the four basic configurations.

Keywords: Search and Rescue robot, Connected Crawler, Double joint mechanism, Multiple configurations

I. INTRODUCTION

Recent years have witnessed a number of both natural and manmade disasters around the world, with a large number of deaths caused either directly or through post-disaster fatigue. To help cope with the aftermath of these tragic events, there has been significant effort in the research community to build search-and-rescue robots [1]-[4], amongst which the "crawler" design is of particular interest, named for its elongated contact with the ground. Examples include the "Soryu" [4], with a serially connected structure, and the "Talon", in a parallel configuration [5]. The mobile crawler robot from INUKTUN [6] has an inclining parallel structure, and the crawler units can change into a serial, or a normal parallel configuration. However, this must be done manually, with the deployed

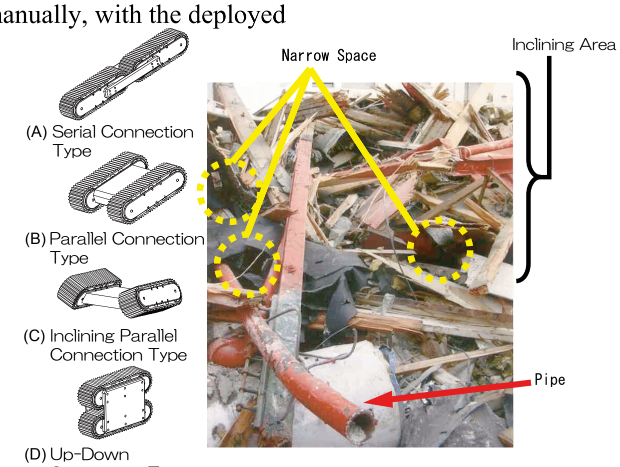


Fig. 1: Example of debris (including pipes)

crawler vehicle returned to its human operators in order to change its configuration.

Such specific configurations of crawlers have distinct advantages and drawbacks inherent to their different structures. In addition, a disaster area contains a number of chaotic environmental structures including narrow spaces, pipes, inclining steps and slopes and debris, as shown in Fig. 1. It is notoriously difficult to navigate above, around, and inside such complex obstacles, which is why in search-and-rescue missions it is necessary for crawler robots to be able to automatically change their configurations.

This paper presents a novel kind of joint mechanism designed to change the modes of a connected vehicle so as to obtain various kinds of configurations.

II. DOUBLE GEAR JOINT MECHANISM

2.1 Basic configuration

The basic configuration of the "Double Gear Joint Mechanism" (DOG-Joint) is shown in Fig. 2[7]. There are four rotary joints. Two of them rotate along the roll axis, while the other two rotate in the pitch axis. The pitching joints are in the middle of the mechanism, and the two rolling joints are on the outer side. Each of the end sides is connected to the crawler, or any other kind of driving unit.

Here, if the rotational angle of the two rolling joints is the same, the inner part of the entire joint mechanism rotates relatively along the rolling axis. As a result, the two inner joints change the rotational axis from pitch to yaw. This autonomous mode changing is the most important feature of this mechanism.

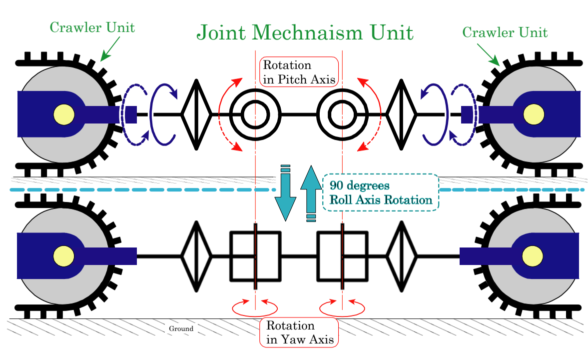


Fig. 2: Mode changing of the Double Joint Mechanism

In the pitching mode, the connected crawler can lift the front crawler unit up so as to facilitate climbing over relatively high obstacles. On the other hand, in the yawing mode, it can bend itself in the horizontal plane and execute small-radius turns or head into narrow passages.
Using this joint mechanism, the relative position and posture of the two crawler units can be changed as illustrated in Fig. 3.

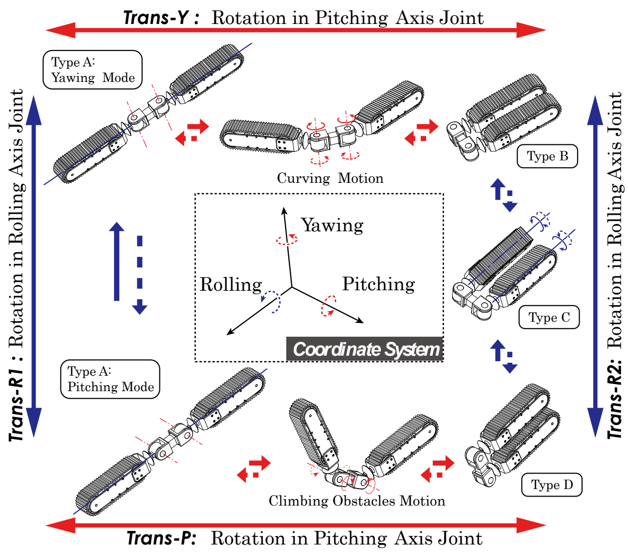


Fig. 3: Changing mode of various configurations

2.2 Offset addition

It is possible to prevent interference between the drive units by adding an offset to the double joint mechanism. Two kinds of offset positions can be considered. Figure 4(b) shows the pitch and roll axes being on the same line, as well as the connection in between crawler units offset by the roll axis. However, while preventing inter-unit interference by adding the said offset is effective in the Up-Down configuration, it fails in the parallel case. Figure 4(c) shows the axis placement so as to arrange an earlier roll axis offset by the pitch axis. This last layout induces an offset to both the Parallel as well as the Up-Down configurations, thereby allowing for easier changes in between all four configurations.

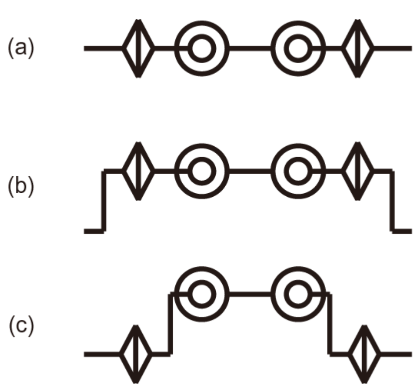


Fig. 4: Offset addition

III. Simulations

3.1 Turn radius

The geometric parameters necessary to introduce the aforementioned offset are illustrated in Fig. 5. As in the Serial configuration curving mode shown in Fig. 6, the pitch axis is shifted from the center of the crawler because of the induced offset. As a result, when rotation occurs, there is a difference in the turning radius depending on the pitch axis position. Here, θ is assumed to be the pitch turning angle, with the small turn radius R_S defined as:

$$R_S = \frac{1}{2\sin\theta}\left\{d_1 + 2\left(d_2 + \frac{l}{2} - os\cdot\tan\theta\right)\cos\theta\right\} \quad (1)$$

Similarly, the big turn radius R_L is defined as:

$$R_L = \frac{1}{2\sin\theta}\left\{d_1 + 2\left(d_2 + \frac{l}{2} + os\cdot\tan\theta\right)\cos\theta\right\} \quad (2)$$

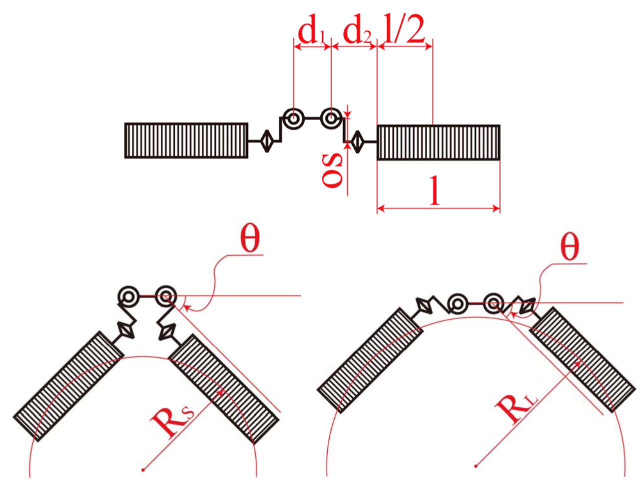


Fig. 5: Turn radius in the Serial Type Yawing Mode

The relation in between the turn radius, offset length, and pitch axis turn radius is simulated and shown in Fig. 6. Here, we assume d_1 = 30 [mm], d_2 = 33 [mm], and l = 305 [mm], corresponding to a real machine.

3.2 Moving range

If the offset is too large, a part of the joint near the crawler can interfere during turns in the Serial configuration curving mode or while climbing obstacles in the Serial configuration climbing mode. However, when the pitch axis spur gear is made big enough to prevent this issue, the joint mechanism itself becomes relatively big as compared with the crawler module. For a large joint mechanism, the weight will increase causing the machine to fall. Moreover, there is a possibility that the joint mechanism causes issues when running on an unlevelled surface in the Serial configuration Climbing Obstacle mode. It is therefore necessary to design the joint so as to obtain a wide range of movement by minimizing its size. Simulation results assuming the relevant parameters to be (a) $B = 30$ [mm], (b) $A = 30$ [mm] and (c) $d_1 = 45$ [mm] are depicted in Fig. 8.

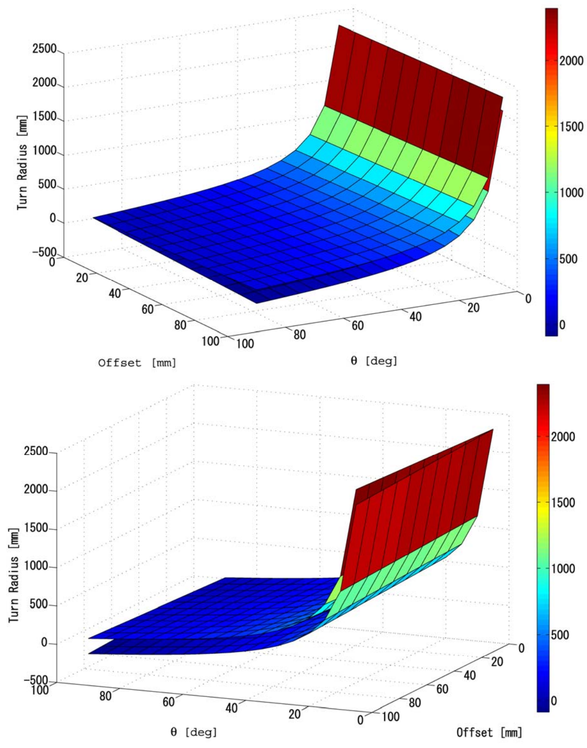


Fig. 6: Turn radius from the Serial Type Yawing Mode simulation results

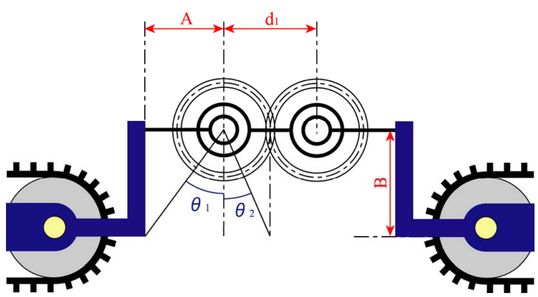


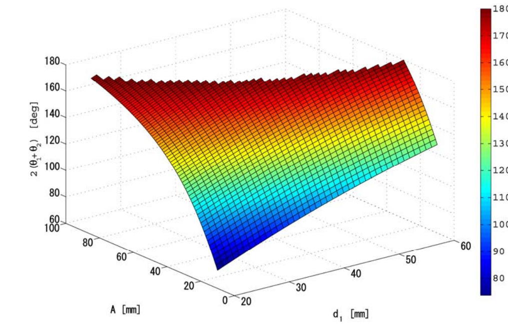
Fig. 7: Interference between Two Crawler Units in the Offset Joint Model

$$MR = 2(\theta_1 + \theta_2) = 2\left[\sin^{-1}\left\{\frac{A}{\sqrt{A^2+B^2}}\right\} + \sin^{-1}\left\{\frac{d_1/2}{\sqrt{A^2+B^2}}\right\}\right] \quad (3)$$

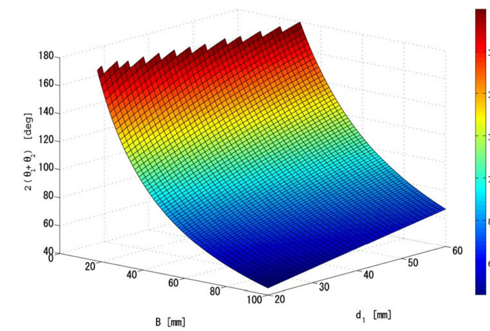
IV. Development of the DOG joint mechanism

During the design of the DOG joint, the distance between the pitch axis d_1 and the amount of offset *os* should implement the following assumptions in order to prevent the crawler units from interfering (geometric parameters are illustrated in Fig. 9):

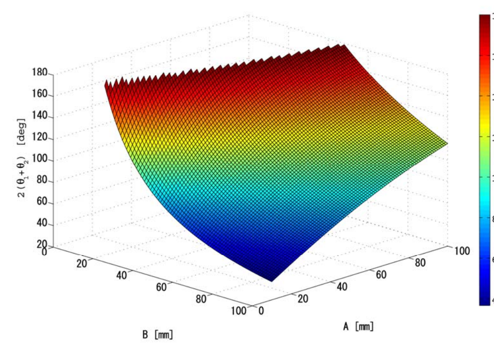
(a)Assumption for a Parallel configuration
In the Parallel configuration, the crawler units will not interfere when the sum of the offset amount and the half-distance between pitch axes is lager than half of the crawler



(a) Relationship between *A* and d_1 [B=30mm]



(b) Relationship between d_1 and *B*[*A*=30mm]



(c) Relationship between *A* and *B*[d_1=45mm]

Fig. 8: Interference between Two Crawler Units in the Offset Joint Model

unit width. That is to say that the assumption for Parallel configuration is

$$os + \frac{d_1}{2} > \frac{b}{2} \quad (4)$$

(b) Assumption for Up-Down configuration
In the Up-Down configuration, the crawler units will not interfere when the sum of the offset amount and the half-distance between pitch axes is larger than half of the crawler unit height. That is to say that the assumption for Up-Down configuration is

$$os + \frac{d_1}{2} > \frac{a}{2} \quad (5)$$

(c) Assumption for Inclining Parallel configuration
In the Inclining Parallel configuration, the crawler units will not interfere when the sum of the offset amount and the half-distance between pitch axes is larger than half of the crawler unit opposing corner length in section. That is to say that the assumption for Inclining Parallel configuration is

$$os + \frac{d_1}{2} > \frac{\sqrt{a^2 + b^2}}{2} \qquad (6)$$

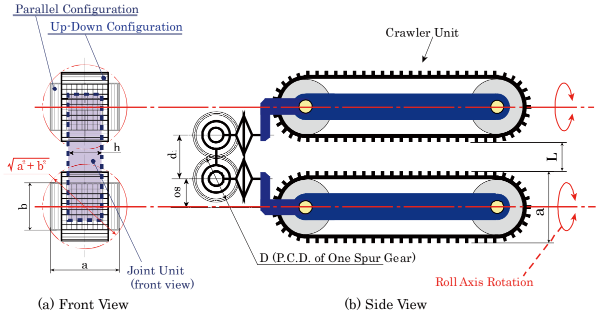


Fig. 9: Assumption that crawler unit does not interfere

V. TYPE TWO TEST MODEL

Figure 10 shows a specific structure designed to achieve the model with added offset as illustrated in Fig. 4(c) (It is called the type at following C). Inside pitch axis rotation can be achieved with spur gears having the same number of teeth number and the same module as shown in Fig. 10. Outside roll axis rotation can be achieved with a spur and bevel gears shown in Fig. 10 Gear-Set-Root2. A general view of the test model in a serial configuration of the second machine is shown in Fig. 11.

As shown in Fig. 9, the joint mechanism was designed assuming A = 115[mm] and B = 154 [mm], anticipating a real machine is to be developed in the future. The offset length distance between pitch axes were, respectively, os = 72 [mm] and, d_1= 0.50 [mm]. Figure 12 shows the transformation of the test model type two into the parallel configuration.

It was then confirmed that the two crawler units did not interfere due to the offset in the roll axis, allowing it to form a Parallel configuration. Moreover, it was able to adopt the inclining parallel configuration by rotating the roll axis of the joint in a Parallel configuration (Fig. 13). The change into an Up-Down configuration is then shown in Fig. 14. Further pattern compositions were possible without any interference thanks to the presence of the offset.

Nevertheless, there was a weight increase as the articulating mechanism of the type two test model was not optimized for lightness. This led to poor weight balance between the crawler units and the joint mechanism, causing falls. The main reason for the weight increase of the joint mechanism was the use of many gears. Subsequently, a test model type three was produced with a lightened articulating mechanism.

Tab.2: Specification of the Type 2 Test Model

	Serial Connection	Parallel Connection	Up-Down Connection
Length	801[mm]	410[mm]	410[mm]
Width	148[mm]	338[mm]	148[mm]
Height	162[mm]	115[mm]	345[mm]
Weight	6138[g]		

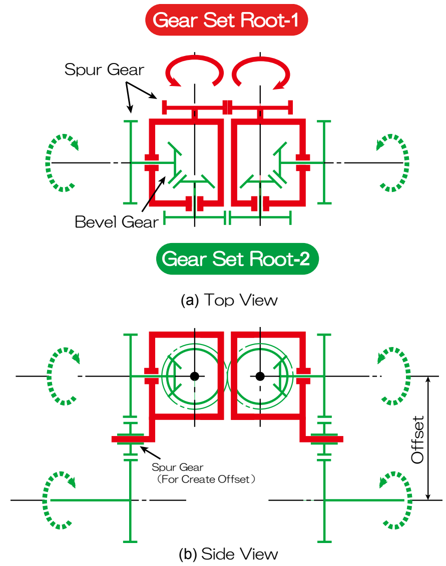


Fig. 10: Joint Mechanism composed with offset

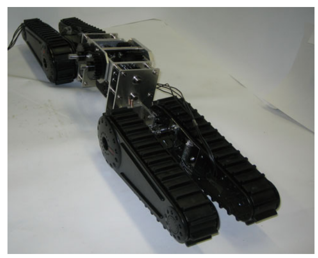


Fig. 11: Type 2 Test Model (Serial)

Fig. 12: Type 2 Test Model (Parallel)

Fig. 13: Type 2 Test Model (Inclining Parallel)

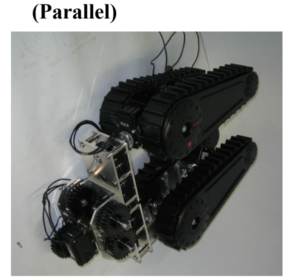


Fig. 14: Type 2 Test Model (Up-Down)

VI. TYPE THREE TEST MODEL

Weight reduction in the test model type three was achieved by allowing a separate driving mechanism through the removal of mechanical synchronization of the roll axes rotation. As the synchronization involved many gears, removing them led to substantial weight savings. The features when synchronizing the rotation of the roll axis by mechanical restraint and by synchronization control of two servo motors is described as follows.

Mechanical restraint

- High power motor needed due to the loss of power.
- Many gears are needed making a lightweight built difficult.

Synchronization control

- Need to control the synchronization of two motors.
- Easy to achieve a lightweight built.
- In a parallel type, the lateral motion is possible by the rotation of the roll axis to the same direction like "omni-crawler"[8].

If two motors are used to drive the roll axis, they can operate independently, allowing the crawler unit to adjust to its contact area. In the future, the two connected crawlers will use a sensor to adjust to the contact area, which is why out test model type three uses two motors to drive the roll axis.

The offset length and distance between pitch axes in the test model type two joint mechanism were, respectively, os = 80[mm] and d_1 = 50[mm]. These parameters were carried onto the type three test model, whose dimensions A and B shown in Fig. 9 are, respectively, 115 [mm] and 167[mm].

A general view of the test model is shown in Fig. 15 (Serial configuration). Figure 16 shows the test model type three undergoing a transformation into the parallel configuration. It was confirmed that the two crawler units did not interfere due to the presence of a roll axis offset. Moreover, the model was able to achieve an angled inclining parallel configuration by rotating the roll axis of the joint while in a Parallel configuration (Figure 17).The change into the Up-Down configuration is shown in Fig. 18. It was confirmed to form a composed pattern devoted of any interference, thanks to the presence of the aforementioned offset.

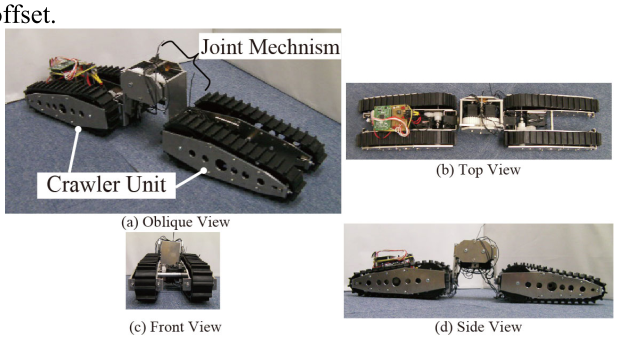


Fig. 15: Type 3 Test Model (Serial)

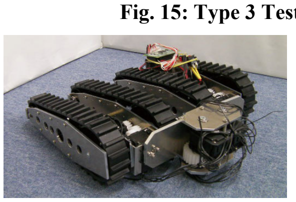


Fig.16: Type 3 Test Model (Parallel)

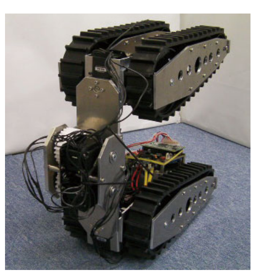


Fig. 18: Test Model Type 3 (Up-Down)

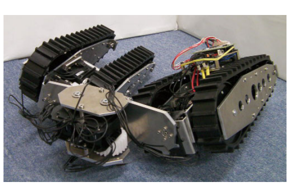


Fig. 17: Type 3 Test Model (Inclining Parallel)

Finally, the test type three models did not experience any lack of balance or falls, in contrast with the type two model.

Tab.2: Specification of the Type 3 Test Model

	Serial Connection	Parallel Connection	Up-Down Connection
Length	740[mm]	390[mm]	390[mm]
Width	167[mm]	380[mm]	167[mm]
Height	177[mm]	115[mm]	340[mm]
Weight	4900[g]		
Battery	18.4[V] (HP-LG325-2500-4S)		
Motor	Dynamixel RX-64 (Robotis)		

VII. EXPERIMENTS WITH TYPE THREE TEST MODEL

7.1 Transformation from the Serial climbing obstacle mode into the Parallel configuration

Figure 19 shows the transformation process from the Serial configuration climbing obstacle mode into the Parallel configuration. The entire process took about 0.5 seconds. The rotation angle of each servo motor for both the roll and pitch axes is 90 degrees. The joint mechanism pitch axis is rotated by 180 degrees, which was achieved by rotating the motor by 90 degrees.

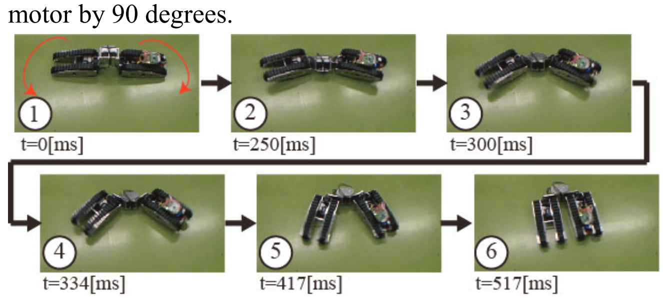


Fig. 19: Transformation from the Serial configuration climbing obstacle mode into the Parallel configuration

7.2 Transformation from the Parallel configuration into the Inclining Parallel configuration

Figure 20 shows the transformation from the Parallel configuration into the Inclining parallel configuration, achieved by rotating the roll axis. All of the servo motors rotate by the same angle at the same time, with the roll and pitch axes rotating simultaneously by 90 degrees. The process is manually controlled by an operator.

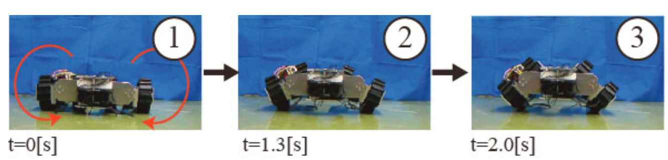


Fig. 20: Transformation from the Parallel configuration into the Inclining Parallel configuration

7.3 Transformation from the Serial configuration climbing obstacle mode into the Up-Down configuration

Figure 21 shows the transformation process from the Serial configuration climbing obstacle mode into the Up-Down configuration. The pitch servo motors rotate by 90 degrees, and the entire process lasts about 1.5 seconds. This transformation cannot be completed on a horizontal surface, but it can occur on a 20 degree incline.

When this transformation is attempted on a flat, horizontal plane, one crawler unit lifts up and the center of mass is no longer in contact with the surface. As a result, the two connected crawlers stand on the joint mechanism which leads to a fall. However, when the process occurs on an inclined plane, the center of mass is moved towards the lower crawler. As a result, no fall occurs and the transformation can be completed. This experiment shows that the two connected crawlers need an assistance mechanism to allow the transformation to occur on a horizontal surface.

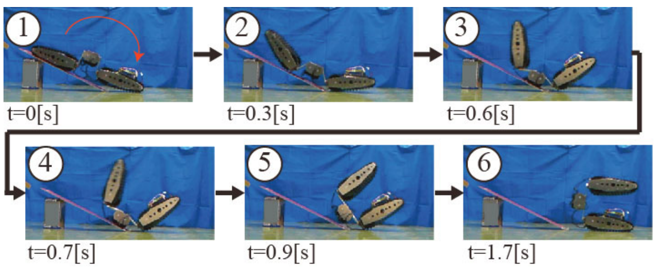


Fig. 21: Transforming from Serial configuration climbing obstacle mode to Up-Down configuration

7.4 Crawler motion in the Serial configuration climbing obstacle mode

Figure 22 shows the motion of the crawler in the Serial configuration climbing obstacle mode. The height of the obstacle is 100[mm], which is almost equal to the crawler's height.

First, the crawler belt touches the obstacle, following which the front crawler unit lifts up. At the same time, the rotation of the pitch axis assists the movement in the direction of the joint mechanism. Then, the front crawler unit climbs over the obstacle and drags the rear crawler unit, with the assistance of pitch axis rotation. As both front and rear crawler units climb over and descend from the obstacle, the process is completed. It was done under visual operator control.

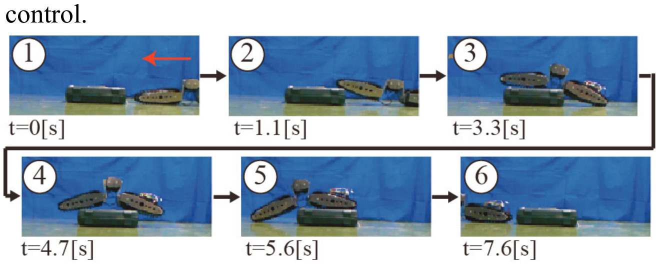


Fig..22: Crawler motion in the Serial configuration climbing obstacle mode

7.5 Crawler motion amongst debris in the Up-Down configuration

Figure 23 shows the motion of the crawler in the Up-Down configuration in presence of debris. Here, a piece of plywood was used as the obstacle. Both the upper and lower crawlers are rotated in opposite directions to each other. Therefore, upper crawler runs like crowd out the plywood.

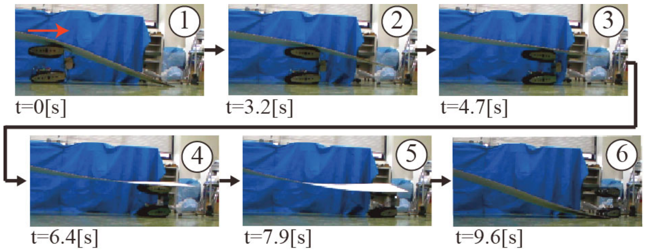


Fig. 23: Crawler motion amongst debris in the Up-Down configuration

VIII. CONCLUSION

This paper describes the connection between two unit crawlers in order to achieve various configurations. By changing the relative position and configuration of the two connected vehicle units, the resulting robot can automatically adapt to complex surface obstacles such as debris.

In addition, we analysed the effect of the each axis arrangement on the switching functionality so as to simplify the realization of four basic configurations. We also made a test model of the joint mechanism with an offset, as well as two connected crawlers of the test model type two. Two connected crawlers can transform themselves into to four configurations without any interference.

Nevertheless, we observed that the type two model presented an inherent lack of balance leading to falls due to the weight increase of the joint mechanism. As a result, we manufactured a type three model incorporating a lighter joint mechanism. This model can transform itself between the four configurations with no lack of balance or falls, and the transformations were observed experimentally. Nevertheless, one specific transformation—from the Serial configuration into Up-Down configuration—was assumed to work only on an inclined plane. Thus, the two connected crawlers need an assistance mechanism to allow for a complete transformation on a horizontal surface.

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