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Paper:

Development of "Souryu I & II" -Connected Crawler Vehicle for Inspection of Narrow and Winding Space-

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In large-scale disasters such as earthquakes, people who have been trapped inside collapsed houses or buildings must be located and rescued as soon as possible, because it becomes difficult to survive, as the time passes. The prototype of "Connected Crawler Vehicle for Inspection of Narrow and Winding Space", named "Souryu" has been developed for the purpose of searching for such victims. In order to stand practical use, the necessity of easy control and toughness are the basic concepts of this vehicle, and based on these principles, we determined the actual vehicle mechanical characteristics. In this paper, the mechanical design and performance of "Souryu I", and the way of improvement for "Souryu II" will be discussed and the effectiveness will be confirmed by some basic experiments and field tests.

Keywords: connected crawler vehicle, inspection, rescue

1. Back Ground

In large-scale disasters such as earthquakes, people who have been trapped inside collapsed houses or buildings must be located and rescued as soon as possible. However, the rescue-team workers usually cannot hear the voices of trapped people because of external noise. So, there is a real need for a moving device that can move inside collapsed houses and structures to look for survivors[1,2].

2. Purpose

A moving device to search for survivors inside collapsed structures should have the following functions[3-5]:

1) High mobility over debris
2) Space to carry equipment used to search for victims
3) Independent driving
4) Remote, wireless control
5) Resistance against water, dust, high and low temperatures, gas and other hostile environments
6) Light weight, easy to carry
7) Low-cost to mass-produce
8) High reliability and easy to use

For this purpose, moving devices can be classified into wheel type, connected-body type or leg type moving devices. Wheel type moving devices have very low mobility over rough terrain, while leg type moving devices can perform well on that kind of terrain. However, it is very difficult to build a small, leg type moving device for practical applications. Thus, a connected type moving device should be considered. Since the segments of the device are coupled in longitudinal direction, the front area can be very small. Besides, it can have high mobility over rough terrain, ability to move into collapsed structures, and space in its body segments to carry equipment to search for victims, which make the connected body type the most suitable moving device for the proposed tasks.

Connected body type moving devices can be classified into active propulsion and active joint, and it is much easier to move on irregular terrain if both propulsion and joints are active. So, in this paper we will describe an active connected crawler vehicle.

In other studies of active, connected vehicles, every body segment has left and right independently driven wheels, and every segment has 3 degrees of freedom - roll, pitch and yaw - in order to improve mobility. So, a 2-segment moving device has 7 degrees of freedom, with 5 additional degrees of freedom for every segment that is added to the vehicle. With this increase in degrees of freedom, its weight also increases, and maintenance and reliability can become serious problems[6]. Moreover, the additional actuators increase the cost, and this is not desired in rescue devices. Thus, we should consider reducing the total degrees of freedom of the mobile device.

Firstly, if the right and left crawlers are driven independently, the vehicle can accomplish skid steering, but as the number of segments increase, skid steering seems to become unsuitable. So, when turning, the vehicle can adopt the shape of an arc, as shown in **Fig.1**, by just modifying the yaw angle of each segment. In this action, there is only one degree of freedom, because all the joints adopt the same attitude. Secondly, it is possible to overcome vertical steps by just changing the pitch angle, as can be seen in **Fig.2**. Again, all the joints have the same

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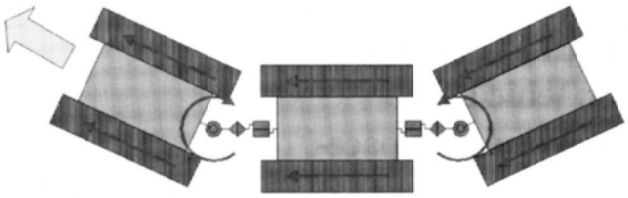

Fig. 1. Steering by yawing.

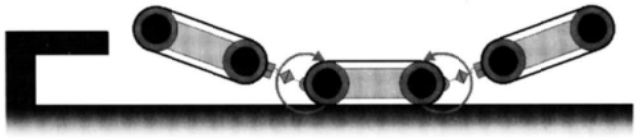

Fig. 2. Overcoming by pitting.

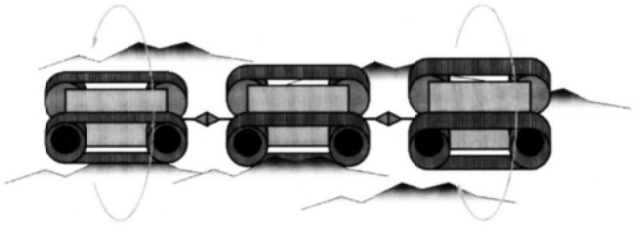

Fig. 3. Fitting with terrain by rolling.

attitude, so there is needless degree of freedom. The distortion operation can be accomplished by combining yawing and pitching, and such a movement is used to recover the vehicle after tipping over. Besides, to fit the ground surface, the vehicle must change its posture over the roll axis, like in **Fig.3**, and this action becomes possible by passively changing the elasticity of the joints[7]. That means it is possible to obtain high mobility over irregular terrain with only 3 degrees of freedom. Obviously, the vehicle will move with higher stability if it has more degrees of freedom, but to conform a rescue device we adopted this configuration of minimized degrees of freedom. Furthermore, the introduction of elasticity may provide additional passive degrees of freedom, which can complement the limited postures of the vehicle.

3. Souryu-I

In order to accomplish the previously mentioned actions, we developed the prototype of "Connected Crawler Vehicle for Inspection of Narrow and Winding Space", named "Souryu I", shown in **Fig.4**. This vehicle is 1160mm long, 175mm wide, 140mm high and weights 10.2kg. The vehicle is composed of 3 segments - front, center and rear bodies - and crawlers on both right and left sides of every segment. Besides, the front tip and the

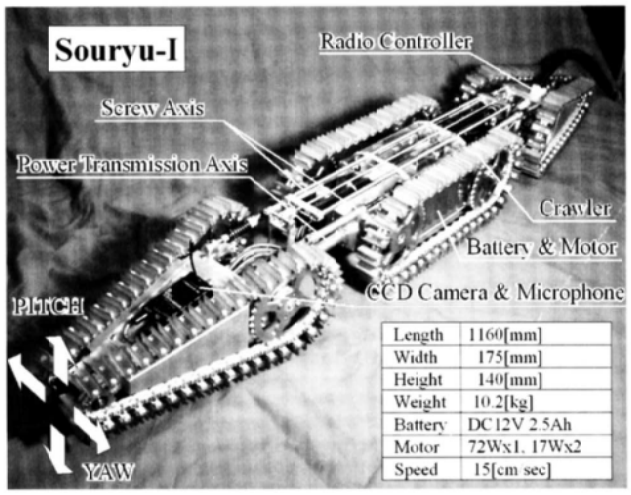

Fig. 4. "Souryu-I".

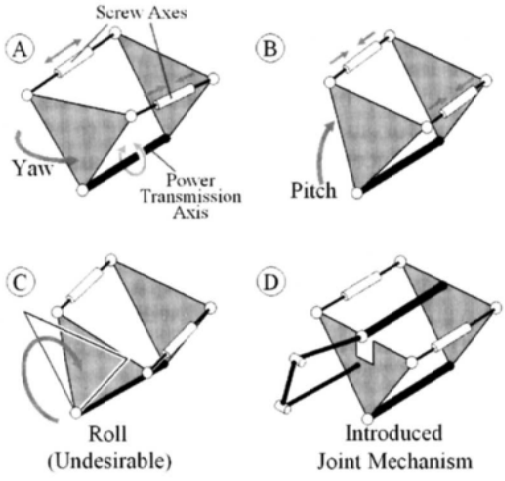

Fig. 5. Principle of 2D active articulation.

rear end have sharpened shapes in order to make it easier to move into debris. All crawlers are driven simultaneously by the motor, located in the center body segment, via torque tubes connected by universal joints, and can drive the vehicle forward and backward. The front and rear segments are connected to the center body segment by special 2 dimensional joint mechanisms, and posture is changed symmetrically around the yaw and pitch axes by two screws, driven by 2 motors located in the center body segment. The front body includes a CCD camera and a microphone to find victims, the center body includes the driving actuators of the whole system and batteries, and the rear body includes the radio receiver. So, this vehicle is a self-contained system that can be teleoperated by a remote operator.

4. Active Connection Mechanism

Consider the following mechanism as a basic module of the body segments: 2 boards connected by 1 supporting shaft, which has 1 universal joint on one side, and 2

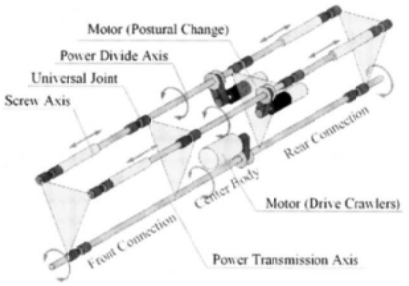

Fig .6. Power dividing system.

screw axes, which have 2 universal joints on both sides. By these 2 screw axes, it is possible to change posture around yaw and pitch axes shown in **Fig.5(a)** and **Fig.5(b)**. These screw axes are driven by motors fixed on the back board, via the universal joints, and if the support shaft can freely rotate, it is possible to transmit the power between 2 boards. However, with only these 3 axes connection, the rolling is freely produced, as shown in **Fig.5(c)**. Then, to restrict this rolling, the joint mechanism shown in **Fig.5(d)** is introduced.

By equipping the structure of the vehicle with this mechanism, like in **Fig.6**, the posture of front and rear segments can be changed symmetrically when the motors in the center body segment drive the 2 screw axes simultaneously. For that task, the power divide axis is used. Besides, a motor in the center body can drive all crawlers simultaneously via a power transmission axis.

5. Required Elasticity

This machine requires 2 types of elasticity, as shown in **Fig.7**. The first type is elasticity around the roll axis, which improves the "fitting" of the vehicle on different ground surfaces. The second type is elasticity around the roll, pitch, and yaw axes in order to absorb impacts. These two types of elasticity are implemented with a certain degree of elasticity in the axis that prevent the roll motion, and elasticity in the screw shafts used to change the vehicle posture around pitch and yaw axes, as shown in the **Fig.8**.

The rolling deformations must be generated by the vehicle's own dead weight, and should not interfere with the proper operation of other connecting mechanisms. Besides, elasticity is also necessary for absorbing impacts. Therefore, as the bending increases, the elasticity should decrease, and the shaft should behave as a hard spring, different from the application of only accommodating the vehicle on the ground surface. Therefore, the spring shown in **Fig.9** is proposed for this machine. This spring works as a soft spring within the range of deformation to allow accommodation of the vehicle's segments on the ground surface, without preventing the operation of the connecting mechanisms. When the load exceeds this range, the soft spring touches the frame supported by the hard spring, and it starts to behave as a hard spring.

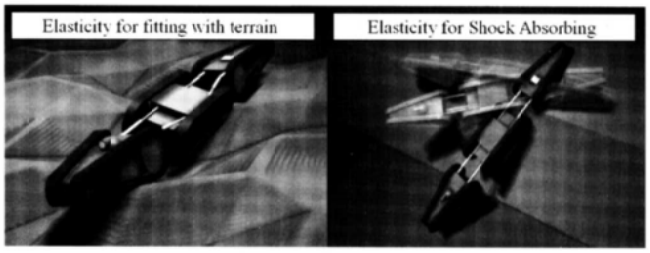

Fig. 7. Required 2 types of elasticity.

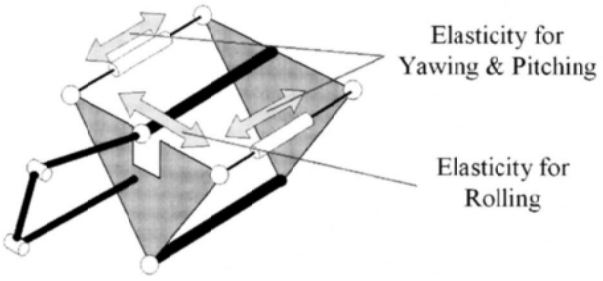

Fig. 8. Introducing elasticity.

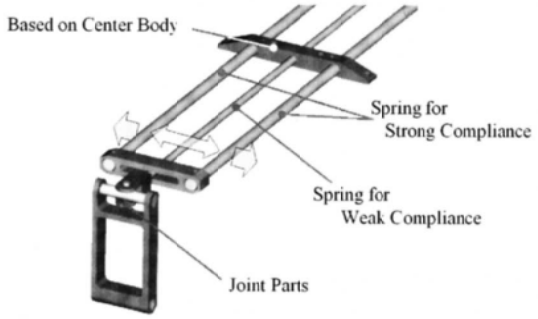

Fig. 9. Introduced elasticity for rolling.

The pitching and the yawing deformations must not be generated by the vehicle's dead weight, because these deformations decrease the ability to cross gaps and to climb vertical obstacles. Therefore, a spring mechanism that cannot act while the load is smaller than the vehicle's own wait is proposed for this machine. The spring mechanism is attached to the universal joints, which support the screw axes, as shown in **Fig.10**. This mechanism consists of a slide shaft, which is equipped with 2 stopper pins, and a slide base, which has 2 flanges and the spring. The interval between stopper pins and the interval between the flanges are the same, and the spring is installed between this interval in a compressed state, as shown in **Fig.11**. When the screw axis is pulled, the spring is pressured between the right side stopper pin, which is based on the slide shaft, and the left side flange, which is based on the slide cover. When the screw axis is pushed, the spring is pressured between the right side flange, which is based on the slide cover and the left side stopper pin, which is based on the slide shaft, as shown in **Fig.12**. Therefore, if the load is smaller than the pressure used to compress the spring the slide base and the slide shaft can not move mutually, if the load is larger, such as when absorbing

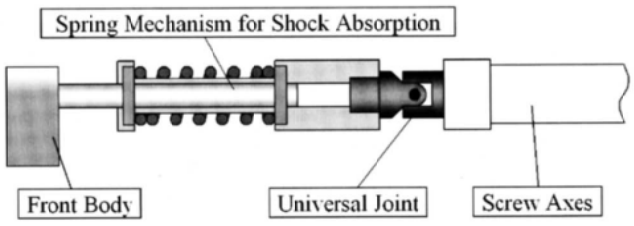

Fig. 10. Introduced mechanism for pitching and yawing.

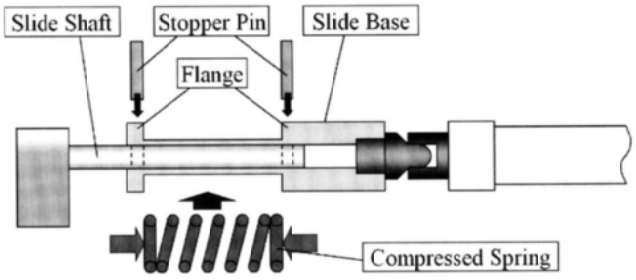

Fig. 11. Composition of the spring mechanism.

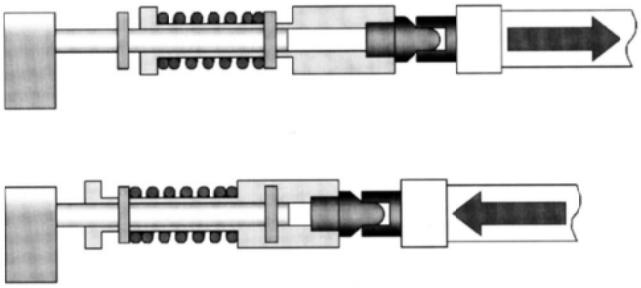

Fig. 12. The motion of the spring mechanism.

shocks, this spring mechanism can provide elasticity for yawing and the pitching.

6. Mobility

6.1. The Steering

This vehicle can turn by changing the posture of the connections around the yaw axis. Let all crawlers be driven at a speed V, the gradient of the front and rear crawler is to be α, and the gradient of the yawing be φ. In the center body, the propulsion power of the crawlers is received at the center of the body, because the crawlers are touching the ground with their whole surfaces. The front and rear crawlers are tilted and contact the ground only with the large wheels, so the propulsion power of the crawlers is received at the middle point of the large wheels of the front and rear bodies. The speed of every segment is as follows:

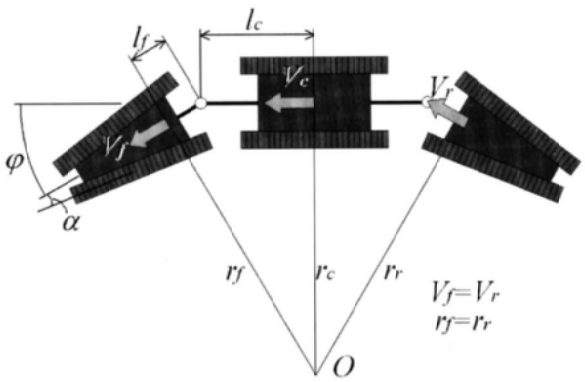

Fig. 13. The radius of turning.

center body $V_c = V$

front and rear bodies $V_f = V \times \cos\alpha$

If the steering is carried out only by the front and rear crawlers, the turning center is located in the intersection point of normal lines of velocity vectors of head and rear bodies, shown in **Fig.13**.

In this case, the turning radius r_c of the center body and the turning radius r_f of the front and rear bodies are

$$r_c = \frac{l_c + l_f \dfrac{1}{\cos\varphi}}{\tan\varphi}$$

$$r_f = \frac{l_c + l_f \dfrac{1}{\cos\varphi}}{\sin\varphi} - l_f \tan\varphi$$

and the angular velocity of the front and rear bodies are

$$\omega_f = \frac{V_f}{r_f}$$

$$= \frac{V \cdot \cos\alpha}{\dfrac{l_c + l_f \dfrac{1}{\cos\varphi}}{\sin\varphi} - l_f \tan\varphi}.$$

If the speed of the center body by this angular velocity is equal to the speed of the crawler of the center body, there is no contradiction to do the steering. But when it is different, the crawlers of the center body will slip. The speed of center body V'_c by angular velocity ω_f must be

$V_c' = \omega_f \cdot r_c$.

Therefore, if only the crawlers of the center body slipped, the slip ratio ξ becomes

$$\xi = \frac{V_c' - V_c}{V_c}.$$

In this machine, the universal joint of the connection defined the largest angle-of-yaw as 30 degrees. By adopting the following dimensions:

α = 8 [deg]

l_f = 50 [mm]

l_c = 255 [mm]

the calculated slip ratio ξ is seen in the graph shown

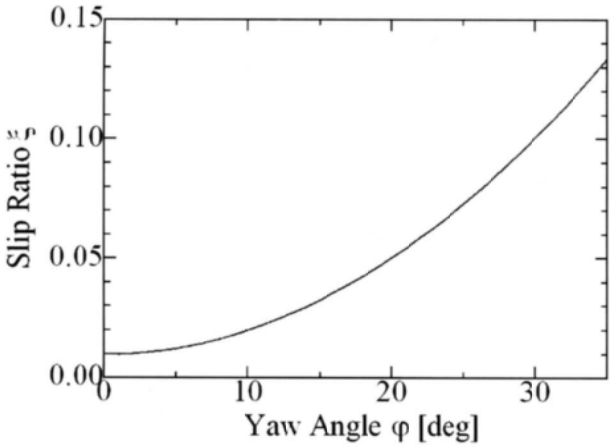

Fig. 14. Slip ratio of the center vehicle.

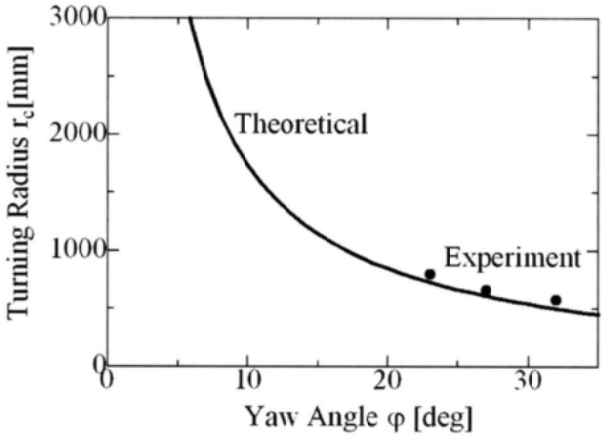

Fig. 15. Graph of yaw angle-turn radius.

in **Fig.14**. By this graph, it is proven that when the angle increases the slip ratio of center body is also increased. Therefore, the turning radius would be larger than the theoretical value, when the angle of the yaw is large, because the center and the rear body also slip actually similar to the center body.

Measured turning radius are larger than theoretical value as shown in **Fig.15**.

When this vehicle takes slightly lower pitch angle, it is possible that it tilts the car body like in **Fig.16** and lifts the crawler of the inside. In this condition, it is possible to turn in smaller turning radii, which can be as small as 440mm.

6.2. The gap crossing

With passive connected vehicles, the front segments are not supported by the other segments, and they will eventually fall in gaps. On the other hand, with active connected vehicles, it is possible to cross wide gaps, since the segments in the rear can support the front segments.

To cross a groove, the crawler must have reached the other side of the gap before the center of gravity of the vehicle reaches the edge of the gap, as shown in **Fig.17**. The width of a groove the crawler can cross can be obtained by the following equation[8].

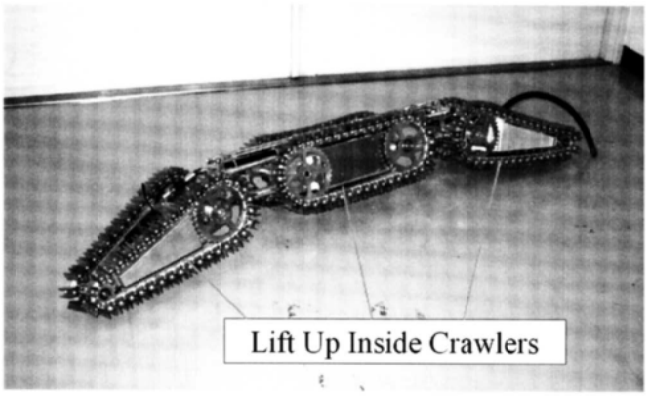

Fig. 16. Super turning.

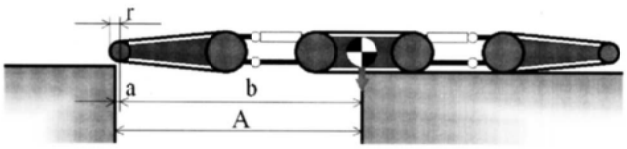

Fig.17. Trench width.

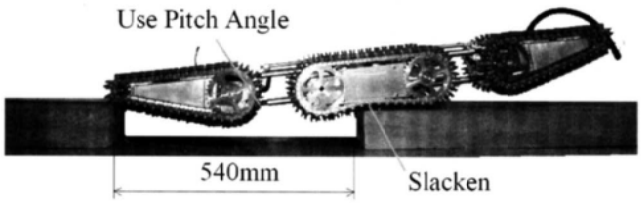

Fig. 18. Crossing a horizontal gap.

$$A = a + b$$

$$a = 0.8r$$

And this vehicle can cross 570mm width of the gap in theory, if the center of gravity is exactly at the center of the vehicle.

In the experiment the vehicle could not cross the 570mm gap, because the crawler of the center body was slacken and the front tip wheel dropped under the edge of the gap shown in **Fig.18**. So it had to change its posture around the pitch axis to cross the gap, and it crossed a 540mm wide gap in the forward actually. And since the center of gravity of this vehicle is not exactly in the center of the body, it can cross a 500mm wide gap in both ways (forward and backward)

6.3. Vertical Obstacle

The wheel center of the front tip must be higher than the space under the vertical obstacle in order to run on the obstacle[8]. This vehicle can lift up the front tip wheel by changing posture around the pitch axis and this vehicle can avoid the 210mm space under the obstacle shown in **Fig.19**. In this form, the front crawlers are pressed against the wall by the propulsion of the center crawlers, like in

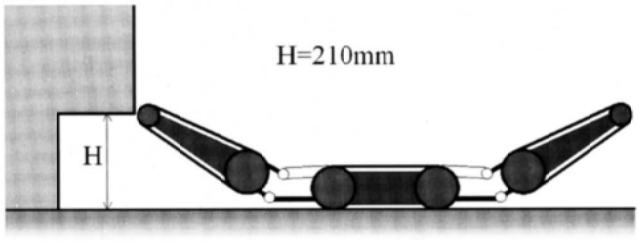

Fig. 19. Vertical obstacle with hollow.

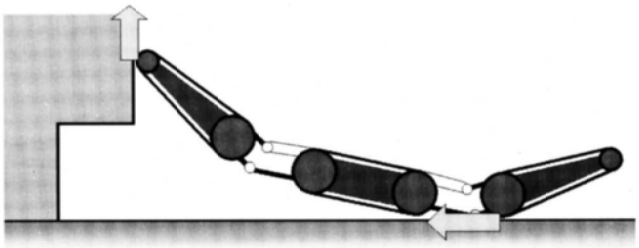

Fig. 20. Climb the vertical wall.

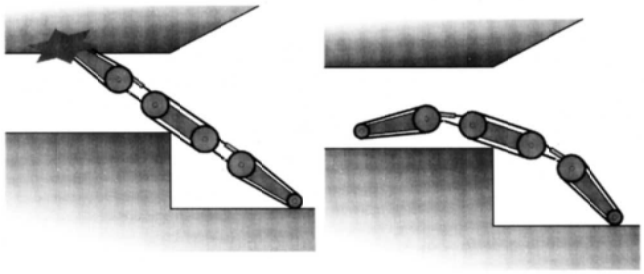

Fig. 21. Undesirable posture.

Fig. 22. Change posture.

Fig.20, and this vehicle can run on the obstacle.

If it intends to run on a vertical obstacle with the straight posture shown in **Fig.21**, the front tip rises and may collide with ceiling because there is very tight space inside collapsed structures. Then, it is possible to go into a low ceiling space by changing posture around pitch axis like **Fig.22**.

The height of the possible height to climb up in this condition is obtained by the following equation. In order to simplify this equation, the center of gravity is considered to be in the center of the center body segment and the crawlers sufficiently grip the terrain. The angle of the pitch is defined as ϕ and all elements of this vehicle are defined as shown in **Fig.23**. The horizontal distance from the grounding point to the center of gravity is defined as L_1, and the horizontal distance from the grounding point to the obstacle edge is defined as L_2. L_1 and L_2 must satisfy the following equations.

$L_1 > L_2$

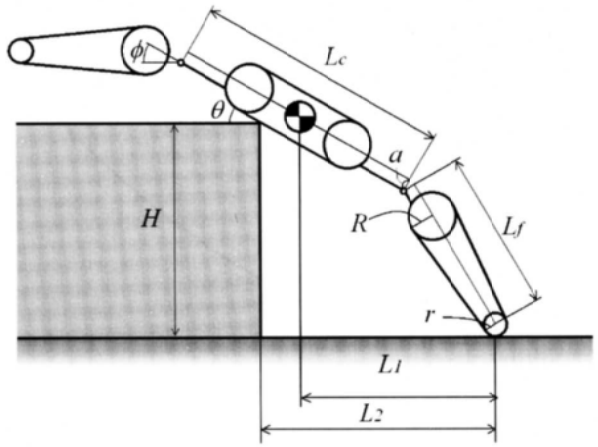

Fig. 23. Parameters for changing posture.

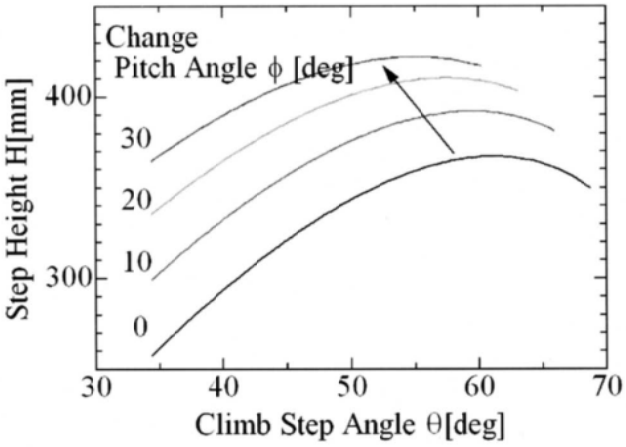

Fig. 24. Graph of obstacle height - step angle.

$$\begin{cases} L_1 = L_f\cos(\phi+\theta) + a\sin(\phi+\theta) - a\sin\theta + \dfrac{L_c}{2}\cos\theta \\ L_2 = L_f\cos(\phi+\theta) + a\sin(\phi+\theta) - a\sin\theta + \dfrac{R}{\sin\theta} \\ \quad + (H - r - L_f\sin(\phi+\theta) + a\cos(\phi+\theta) - a\cos\theta)\dfrac{1}{\tan\theta} \end{cases}$$

$$H < \frac{L_c}{2}\sin\theta - \frac{R}{\cos\theta} + r + L_f\sin(\phi+\theta) - a\cos(\phi+\theta) + a\cos\theta$$

Use the following dimentions,

L_c=508[mm]L_f=291[mm]R=70[mm]r=35[mm] a=23[mm]

the graph shown in **Fig.24** is obtained, and the top of this graph show the max height of the vertical step. And it shows also that the max height of the vertical step is increased when the vehicle changes its pitch angle, and by this action the climb step angle decreases. That is desirable because the front tip becomes lower.

In the experiment, it was possible to climb a 420mm high vertical obstacle avoiding a 200mm high hollow space like in **Fig.25**.

6.4. Recovery from Tipping Over

It is possible to do the recovery from tipping over by the distortion operation by combining postural change around pitch and yaw axes as shown in **Fig.26**.

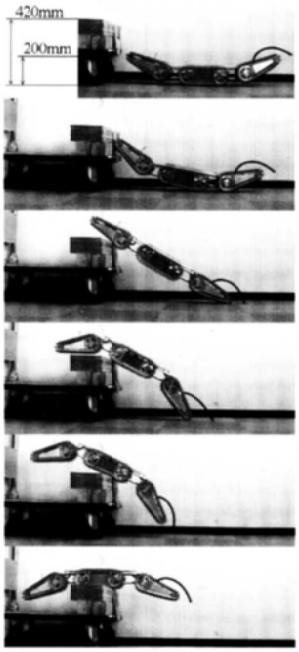

Fig. 25. Ascending a step.

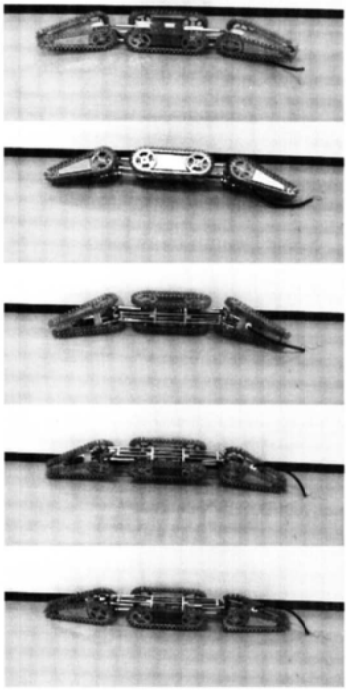

Fig. 26. Roll-over motion.

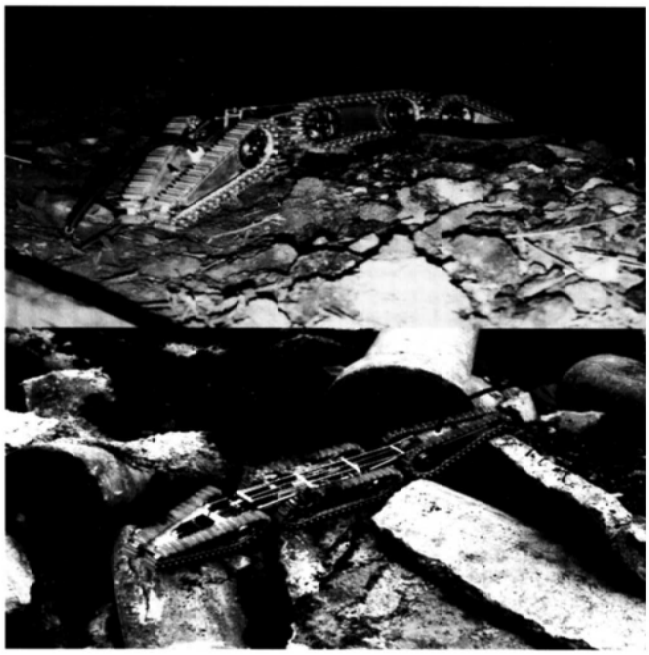

Fig. 27. Experiment on the real deblis.

6.5. Field Experiment

After performing experiments on real debris, it was confirmed that "Souryu-I" is able to move over collapsed structures, as shown in **Fig.27**. **Fig.28** shows the image registered by the on-board CCD camera when "Souryu-I" is moving inside a simulated collapsed structure. The operator can find the target object and, at the same time, confirm the normal operation of the crawlers by the same image.

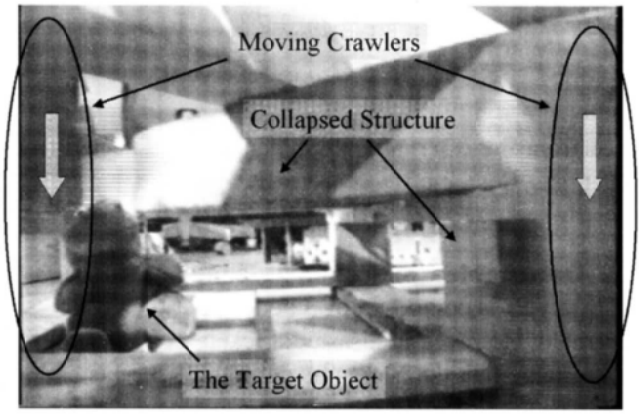

Fig. 28. View of the CCD camera.

7. Development of "Souryu II"

7.1. Total View of "Souryu II"

We developed "Souryu II"(**Fig.29**), an improved model based on "Souryu I". Souryu I was developed step by step and some parts, which were additionally equipped, became structural weak points. Moreover, some experiments showed that there were some point that needed to be improve. Therefore "Souryu II" was developed to improve those weak points. "Souryu II" is being exhibited at the National Museum of Emerging Science and Innovation.

7.2. Improved Point

The most important improved point is the length of the crawlers. In "Souryu I", the crawlers have the same length, and there were some problems to move over protuberances with constant pitch. For example, in the case of a stairway, when the pitch of the stairs and the pitch of the interval of the crawlers are the same, the crawlers cannot touch the ground surface and the vehicle becomes stuck, as shown in **Fig.30**. To solve this problem the crawlers of the front and rear bodies are longer than the crawlers in the center body in "SouryuII".

The shock absorbing mechanisms attached to the screw axes are assembled in the same axes. Besides, since the screw axes are near to the crawlers to provide the highest momentum for posture changes, large springs cannot be used in the mechanism, or there would be interference between the spring and the crawlers. With this restriction, the slide shaft becomes thin and, therefore, a mechanical weak point. Therefore, in Souryu II, the spring mechanism was assembled inside the vehicle body, under the universal joint (**Fig.31**), so that there would be enough space to use a larger spring, and with larger stroke to absorb shocks.

Since Souryu I is made of inner frames and the wheels are uncovered, sometimes debris is caught by the chain and causes the vehicle to stop. To solve this problem, an outer-frame composition was adopted for Souryu II, so that all the electric equipment and mechanisms are iso-

Fig. 29. Total view of "Souryu II".

lated from the external environment, and protected from water, gas, dust, etc.

7.3. Detachable Connection Mechanism

Souryu I is composed of 3 bodies, but they cannot be separated. However, in disaster-stricken areas, it seems to be desirable that the bodies be detachable. In this case, it would be easier for the rescue teams to prepare each body with special equipment to assist in the aid and relief tasks. For example, the front body could be equipped with jacks to assist the victims to crawl out from collapsed structures, with a first-aid kit to be handed to survivors who are still trapped inside the debris, or even with a discharger of several small microphones, which would be used to capture sounds of survivors. Moreover, the rear body could be equipped with a large battery, a wired control system or an "intelligent" computer for autonomous operation, as shown in **Fig.32**. These "upgrades" can be easily implemented because the functions of this vehicle are distributed efficiently along the three bodies. The power sources -motors and batteries- are inside the central body; the front body has only sensors; and the rear body is responsible for sending command signs to control the movement of the vehicle and its sensors. The connection mechanism of this vehicle is composed of four axes that connect the bodies together. In Souryu II, one side of each axis is fixed by screws and checkered nuts, so that it can be rotated by fingers, without special tools, and the bodies are detached easily, as shown in **Fig.33**.

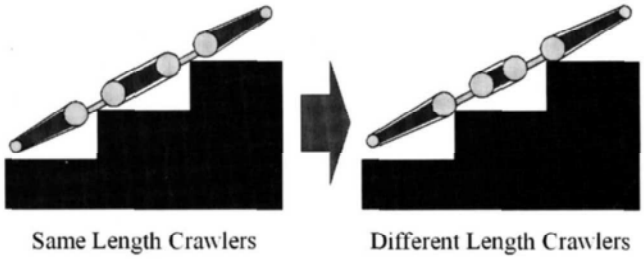

Fig. 30. The problem of the crawlers in "Souryu I".

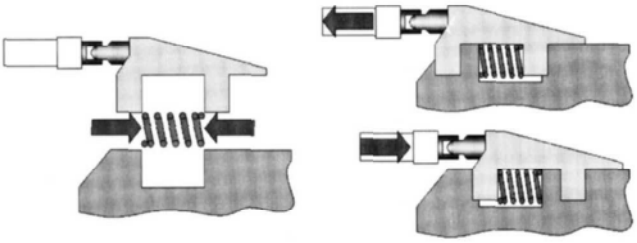

Fig. 31. Newly introduced spring mechanism.

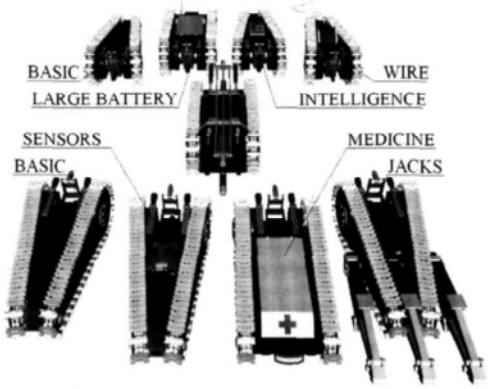

Fig. 32. Concept of "Upgrades".

7.4. The Folding Handle

It is hard to find where to grip when carrying this vehicle because it is covered all around with crawlers. Thus, Souryu II is equipped with carrying handles that can be folded not to project when the vehicle is in operation as shown in **Fig.34**.

8. Conclusions

We developed an active connected crawler vehicle that has only 3 degrees of freedom named "Souryu I", and "Souryu II" an improved model based on "Souryu I". We carried out some experiments and showed its effectiveness for motion on uneven terrain and in narrow and winding spaces. For future works, we plan to carry out more field experiments to develop a practical machine for rescue activity.

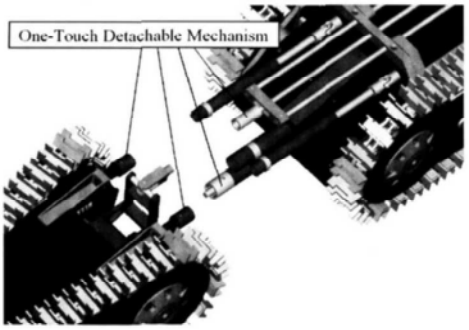

Fig. 33. Detached connection.

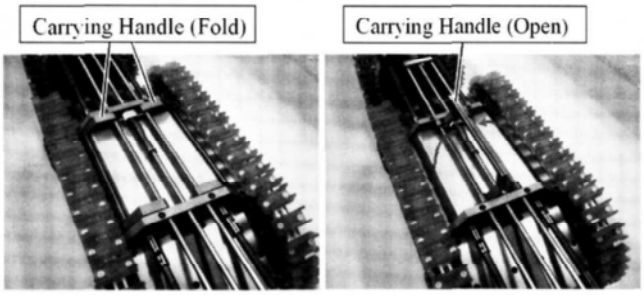

Fig. 34. 2 states of the carrying handle.

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