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Abstract—
In this paper, a tetrahedral mobile robot with central axis for transformation to the flat vehicle is presented. The throwable robot with the function of going into narrow spaces when its in the flat-vehicle mode is explained in detail. A prototype has been developed to illustrate the concept. Motion experiments confirm the novel properties of this mechanism: mode changing function and omnidirectional motion. Basic Motion experiments, with a test vehicle are also presented. Keywords: Search and Rescue, Throwable, Tetrahedral Shaped, Omni-Ball, Transformation, Mechanical Design

I. INTRODUCTION
A. Throwable Robot for Access to the Field
Concerning ways to access a disaster area, there are several methods used all around the World. Some of them are as follows.
1) Throwing [1]
2) Air deployment [2]
3) Ladder [3]
4) Base unit [4][5]
There exit as well ways which are combinations of the above methods to access a disaster area.
In this paper, we focus on the first one: Throwing, and the second one: Air deployment, to access such kind of dangerous place for search and rescue robot (e.g. [6]-[10]) as shown in Fig. 1. As a throwable robot with protected body, we propose-, the tetrahedral shape because of the benefit of its symmetric property.

B. Tetrahedral Mobile Robot
The tetrahedral mobile robot has its body in the center of the whole structure. The driving parts that produce the propelling force are located at each corner. As a driving wheel mechanism, we have developed the “Omni-Ball[11]” with one active and two passive rotational axes as shown in the expanding view in Fig.2. The normal omni-wheel(e.g. [12])
On the other hand, there are requirements for search and rescue robots which move in collapsed buildings as shown in Fig.4[18]. After the robot would pass the narrow spaces, there still exists the possibility of the robot becoming trapped by debris or fallen down the suddenly and unexpectedly on rough terrain. Therefore, in such event, it is desirable that the robot has a retractable mechanism in order to protect the core body of it.

In next chapter, the retractable configurations are discussed and developed.

II. Expanding Mechanism for Tetrahedral Mobile Robot

A. Basic Two Expandable Mechanisms

Two different kinds of expanding mechanism are considered as shown in Fig.5. One is the linear expanding type at each of the four arms of the tetrahedral mobile robot, the other is a rotational type at the center of the core-body.

1) Linear Expanding Type

In the linear expanding type, the tetrahedral mobile robot needs one linear expanding mechanism on each leg. Thereof, 4 numbers of actuators are needed for this configuration. Considering the requirements of light weight for the throwing, a small number of actuators is desirable.

2) Rotational Expanding Type

As shown in Fig.6, and the attached video to this paper, the tetrahedral mobile robot can change its whole shape into the flat vehicle mode with just only one rotational axis at the center of that body.

The equations of the geometrical conditions are show in equ.(1), and (2). Because of its symmetric condition, AO=BO=CO=DO in Fig. 7(a) and (b).

![Geometrical Condition](image)

D < W= L / tanθ…………………..(1)
θ=sin⁻¹ [(2/3)½]…………………..(2)

The proportion of the actual prototype model shown afterwards meets these conditions.

A. Comparison between Two Expandable Mechanism

The height on the retracting mode, height of the camera as the device for searching disaster victims and the volume of the
core-body are compared between these two expanding mechanism.
When the tetrahedral robot take the maximum filling factor,
the proportion of the position of each wheel take the as shown
in Fig 13 (left one). The equations and geometrical conditions
are shown in Fig.13 (right one).

1) Size on the retracting mode (smaller is better)
The height of the robot when it is in the retracting mode, the
The result of the comparisons is shown in Fig.11. The height
of the vehicle on retracting mode in linear expanding type is
1.82 compared with the 1.0 of the rotational type as shown in
Fig12. This means that, on the retracting mode, rotational
expanding type can go into much narrow spaces in up-down
direction in disaster areas.
As a result, rotational expanding type is better than the linear
expanding type (Smaller is better).

2) Height of the Camera (higher is better)
It is defined that the position of the camera is put on the center
of the one of the Omni-Ball. To compare the two type, the
expandable ratio is depends on the stroke of the linear
actuator in linear expanding type, so we estimated the height
of the camera on each stroke of the linear actuator as shown in
Fig. 12. The value “1.0” in the vertical axis in Fig. 12 shows
the height of the camera in rotational expanding mode as a
criteria. The dots in this figure show the value of the ratio of
the height of the camera between linear one and rotational one.
In short, the height of the camera of the linear one is lower
than rotational one when its ration of the stroke is smaller
than 0.4. Basically it is difficult build the linear expanding
mechanism larger than 0.4 in practical, so that the height of
the camera could be lower than the rotational type in
practical.

Fig. 11: Comparison of the Height on Retracting Mode

Fig. 12: Comparison of the Height of Camera in the Each
Tetrahedral Mode

Fig. 13: Highest Filling Factor in Tetrahedral Mode
III. Basic Configurations of Prototype Model

In this section, the basic configuration of the proposed tetrahedral mobile robot with transformation capability is described.

The first mechanical prototype model has been developed based on the geometrical condition shown in Fig.7. The overview of the tetrahedral mobile robot with transformation capability on tetrahedral mode and 4-wheeled flat vehicle mode is shown in Fig.16 and Fig.17 respectively. In addition, the specification of the prototype on each mode is shown in table1.

As a application for the search and rescue robot, there is the camera mounted on one arm of the robot. As the first prototype model, for the ease to make in low cost, the size of the Omni-Ball is set smaller than that of the demanded one to protect the core-body as shown in Fig.16, so that there is not enough space to include the camera or other sensing devices into the inside of the Omni-Ball. Therefore, the camera is positioned below the Omni-Ball for the first prototype model, but the mechanical model with the camera inside of Omni-Ball will be considered.
V. Basic Experiments of the Prototype Model

In this section, we describe a set of experiments conducted to confirm the performance of a prototype of this tetrahedral mobile robot with transformation capability.

A. Omnidirectional Motion

Being a basic feature of this robot, the omnidirectional motion should be confirmed. One example of such motion is shown in Fig. 18. In this figure, the length of the square on the floor is 300mm. It was observed that this prototype robot has the ability to move in arbitrary direction. Considering that the mobile robot is to be used in somewhat rough terrain, and that precision is not be paramount in a disaster area, the ability of omnidirectional motion of this robot is considered sufficient through this experiments.

B. Mode Changing Function

The ability of change the mode of vehicle was also confirmed as shown in Fig.19. In the present prototype model, the center of the gravity of this robot is not at the precise center of this robot, so the posture of the robot is depends on the which way that C.O.G. exist at that moment. As a next model, by putting just only one simple arm, it will be able to change its center of gravity actively and able to choose the posture it takes.

C. Mode into the Narrow Space

The ability of getting into the narrow space by the flat vehicle mode has been confirmed as shown in Fig. 20. The height of the space under the desk is about 139.7mm. It is shorter than the height of the tetrahedral mode. The tetrahedral mode is useful for protecting the core body from a sudden tumbling and wide search by the camera at the top wheel of the tetrahedral robot. On the other hand, the 4-wheeled mode is useful for going into the narrow space as shown in this experiment. The tetrahedral robot with the central axis can change these two modes.

Tab. 1: Specification of the Tetrahedral Mobile Robot with Transformation Capability

| Specification                             | Value            |
|------------------------------------------|------------------|
| Length on Side in Tetrahedral Mode       | 294.4[mm]       |
| Height in Tetrahedral Mode               | 248.6[mm]       |
| Short Width in 4-Wheeled Mode            | 234.4[mm]       |
| Long Width in 4-Wheeled Mode             | 294.4[mm]       |
| Height in 4-Wheeled Mode                 | 45[mm]          |
| Weight                                   | 467[g]          |
| Diameter of the Wheel                    | 45[mm]          |
| Motor (Rotary Actuator)                  | 2.5W             |
| Batteryl Out of the Body                 | 12[V]5[Ah]      |
| Height of the Camera                     | 192[mm]         |

Fig. 18: Omnidirectional Motion on Floor

Fig. 19: Motion of Mode Changing

Fig. 20: Motion into the Narrow Space
D. Function of Central Axis

The function of central axis of this robot was also confirmed as shown in Fig.21. The height of the step is 52mm. It was observed that a prototype can make use of the function of central axis and make the C.O.G of the robot lower and then can keep the higher stability.

E. Walking Motion

As one of the advanced mobility criteria of this robot, the ability to produce walking motion has been confirmed. One example of such a motion is shown in Fig.22, and the height of the rock is about 15.5cm. It was observed that this prototype model has the ability to climb the higher rock compared with the wheeled mode.

VI. Stability Margin

In this section, in order to show the increasing of the stability in 4-wheeled mode of the tetrahedral mobile robot with the central axis, SNE : Normalized Energy Stability Margin[19] is calculated in two modes. The “SNE” is defined as follows,

SNE = hmax - h0

The angle OED is defined as “α” and angle ODE is defined as “β” in Fig.23. Based on the definition of SNE, and as shown in Fig.24(b-1), the minimum SNE in the tetrahedral mode is calculated as follows.

SNE = OE(1 - sin(α + γ))     …………………(3)

“γ” is defined as the angle of the slope which the robot stays.

As shown in Fig. 25 (b-1), he minimum SNE in the 4-wheeled mode is calculated as follows.

SNE = OE(1 - sinγ)     …………………(4)

As shown in Fig.24 (b-2), the maximum SNE in the tetrahedral mode is calculated as follows.

SNE = OC(1 - sin(β + γ))     …………………(5)

As shown in Fig. 25(a) and (b-2), the maximum SNE in the 4-wheeled mode is calculated as follows.

SNE = OC(1 - sinγ)     …………………(6)

Based on these equations, each SNE line is shown and compared in Fig. 26.
VII. Conclusion

In this paper, we showed the tetrahedral mobile robot with central rotational axis to realize the compact retracting mode in order to go into narrow spaces. The linear the tetrahedral mobile robot was also presented. We confirmed the basic characteristics of the tetrahedral mobile robot with central rotational axis and the motions of the robot through experiments.

In future works, we plan to optimize the mechanism of the driving mechanism: omni-ball, bumping mechanism of each arm as well as the sensors in the core body for search and rescue missions.

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