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Mechanical Design of the Wheel-Leg Hybrid Mobile Robot to Realize a Large Wheel Diameter

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***Abstract*—In this paper, a new category of the wheel-leg hybrid robot is presented. The proposed mechanism can compose large wheel diameter compared with the previous hybrid robot to realize a greater ability to climb obstacles. A prototype model of one Wheel-Leg module of the proposed robot mechanism has been developed to illustrate the concept. Actual design and mode changing experiment with a test mechanical module is also presented. Basic movement tests and a test of the basic properties of the rotational fingertip are also shown. The Basic configurations of wheel-leg retractable is considered well. The integrated mode is also described.**

I. INTRODUCTION

There is much research and development of wheel-leg hybrid mechanisms to realize both speedy motion on flat areas and efficient movement on rough terrain (e.g.[1]-[6], [9]-[26]). Basically, there are three categories of this sort of hybrid robot as shown in Fig. 1[7]. Previous wheel-leg hybrid robots have been categorized as (a): leg mechanisms with the wheels at the end of the legs (e.g. [1]-[5]) (b): the wheel modules on the body of the mobile robot (e.g.[6],[23],[24]) (c): wheeled legs [25]-[27]. Most of them have the wheel smaller than the leg mechanism as a whole. Therefore, the ability to move on rough terrain in wheeled mode tends to be low.

In this paper, a mechanism to realize a large diameter of wheel is presented with an actual prototype model and the effectiveness of this mechanism is shown through basic experiments.

In the next section, the concept of the retractable wheel-leg module is shown, and in section 3, the actual prototype model of the proposed robot is shown. Following that, basic movement experiments of this robot are shown in section IV.

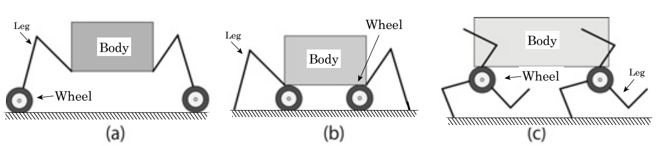

Fig. 1: Categories of the Wheel-Leg Hybrid Robot

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II. RETRACTABLE WHEEL-LEG MODULE

A. Concept

The concept of the retractable wheel-leg module is shown in Fig. 2. The wheel consists of the all of the leg segments, therefore, it can realize a large diameter of wheel. Also, the bending direction of the joint can be reversed in order to realize a leg with a footpad for stable contact with the ground as shown in Fig.4.

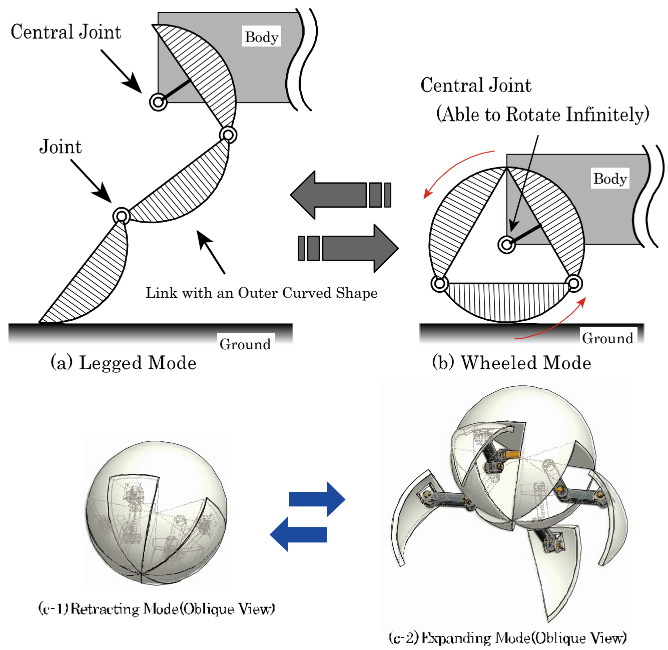


Fig. 2: Retractable Wheel-Leg Module

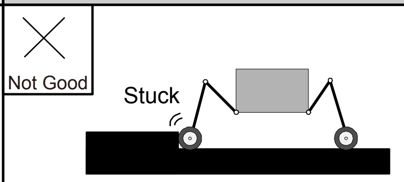
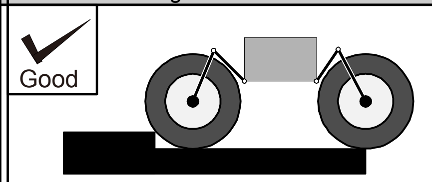
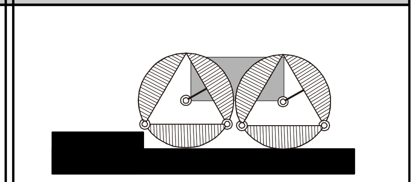
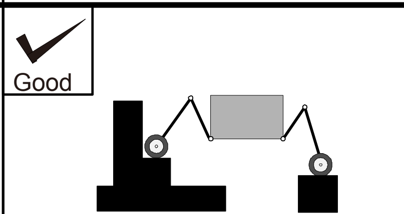
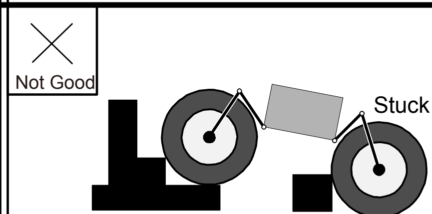
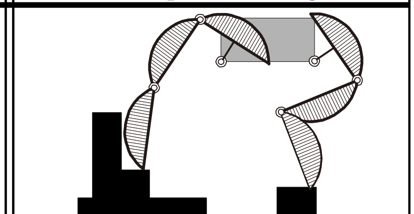
B. Comparison with the Previous Wheel-leg Module

As shown in Table1,

(a) Previous wheel-leg module with small wheels(e.g. [1]-[5]):

When it is in wheeled mode, it is difficult for this type of mobile configuration to climb a small single-step or traverse a single-gap as shown in table.1(a)upper part. On the other hand, when it is in walking mode, thanks to the small footprint, the mobile robot can select the position of the end of the foot on rough terrain as shown in table1(a); lower part.

Table1: Basic Comparison with 3-Types of Wheel-Leg Module

	(a) Previous Wheel-Leg Module with Small Wheels	(b) Previous Wheel-Leg Module with Large Wheels	(c) Retractable Wheel-Leg Module
Small Single-Step or Gap	 Low Step-Climbing (Gap Traversing)	 High Step-Climbing (Gap Traversing)	 High Step-Climbing (Gap Traversing)
Some Steps or Gaps (Rough Terrain)	 • Selectable • Large Motion Range	 • Unselectable • Small Motion Range	 • Selectable • Large Motion Range

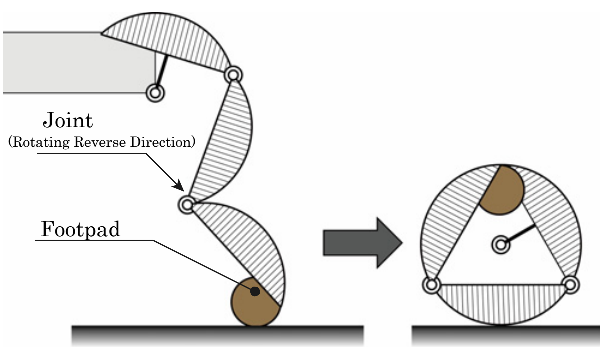


Fig. 3: Retractable Wheel-Leg Module with Reversed Joint

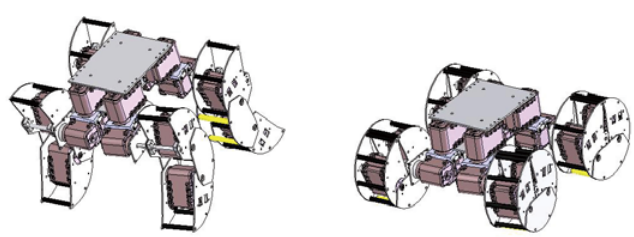


Fig. 4: Concept of the Mobile Robot with the Retractable Wheel-Leg Module

(b) Previous wheel-leg module with large wheels

When it is in wheeled mode, it is easy for this type of mobile configuration to climb a small single-step or traverse a single-gap as shown in table1. On the other hand, when it is in walking mode, because of the large footprint, it is difficult for the mobile robot to select the position of the end of the foot on rough terrain as shown in table1. In addition, the motion range of the leg is limited.

(a) and (b) can take the wheeled mode and legged mode at the same time but the motion control of the robot becomes quite complicated especially on rough terrain with a complicated surface structure. Therefore, we considered the mode separation to realize the large diameter of wheel as follows.

(c) Proposed Retractable Wheel-Leg Mechanism

When it is in wheeled mode, thanks to the large diameter of the wheel, it is easy for this type of mobile configuration to climb the small single-step or traverse the single-gap as shown in table1. On the other hand, when it is in walking mode, thanks to the small footprint, the mobile robot can select the position of the end of the foot on rough terrain as shown in table1.

III. Actual Prototype Model

A. Basic Module Configuration

Regarding, the structure of the module mechanism, the center of gravity should be at the same position of the central joint of this module mechanism in order to reduce the energy loss during movement in wheeled mode. Therefore, every actuator that is heavier than the structural frame should be located at the proper position. The design of the wheel-leg module has been realized based on these considerations.

B. Central Rotational Joint

The joint which connects the wheel-leg module to the steering joint on the body has to work as a central axis of a wheel when the robot is in wheeled mode. Therefore, this joint should be able to rotate indefinitely. To realize the unlimited rotation of this joint, there are some ways of composing the wheel-leg mechanism.

1) Mechanical Transmitting way

In order to rotate the each joint in the leg module, the mechanical transmission: gear train can be used. It can realize the configuration without any motor in the leg module, therefore, there is no need to care about the wire twisting problem. However, this configuration could be complicated so that the following way has been adopted as a first prototype model.

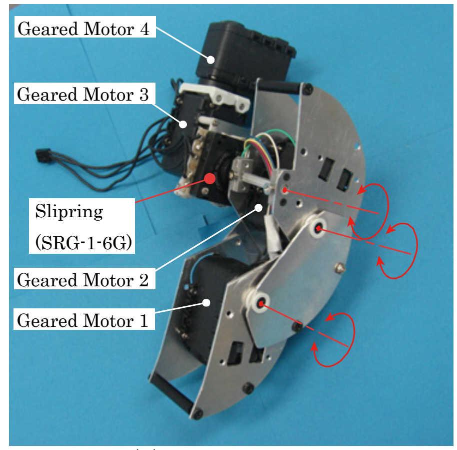
2) Electronic Solution

For another way to realize the infinite rotation of the wheel, the electronic way can be taken. A slipring can be used to prevent the wire twisting and it can also relay the control signals. We use the SRG-1-6G as shown in Fig.6.

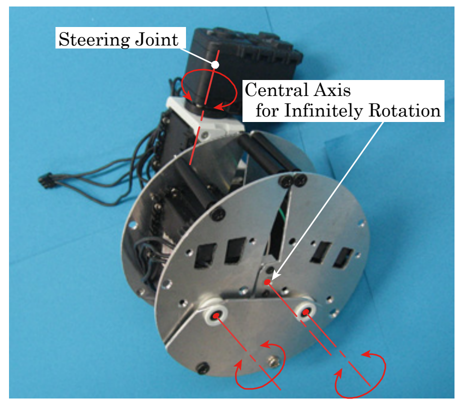
Fig. 5: Slipring for the Infinitely Rotating Joint

Table 2: Specification of the Prototype Robot on Wheeled Mode

Length	252[mm]
Width	225[mm]
Height	142[mm]
Diameter of the Wheel	100 [mm]
Width of the Wheel(Leg)	45.5 [mm]
Geared Motor	BTX030 Dynamixel AX-12+
Weight	1577.2 [g]



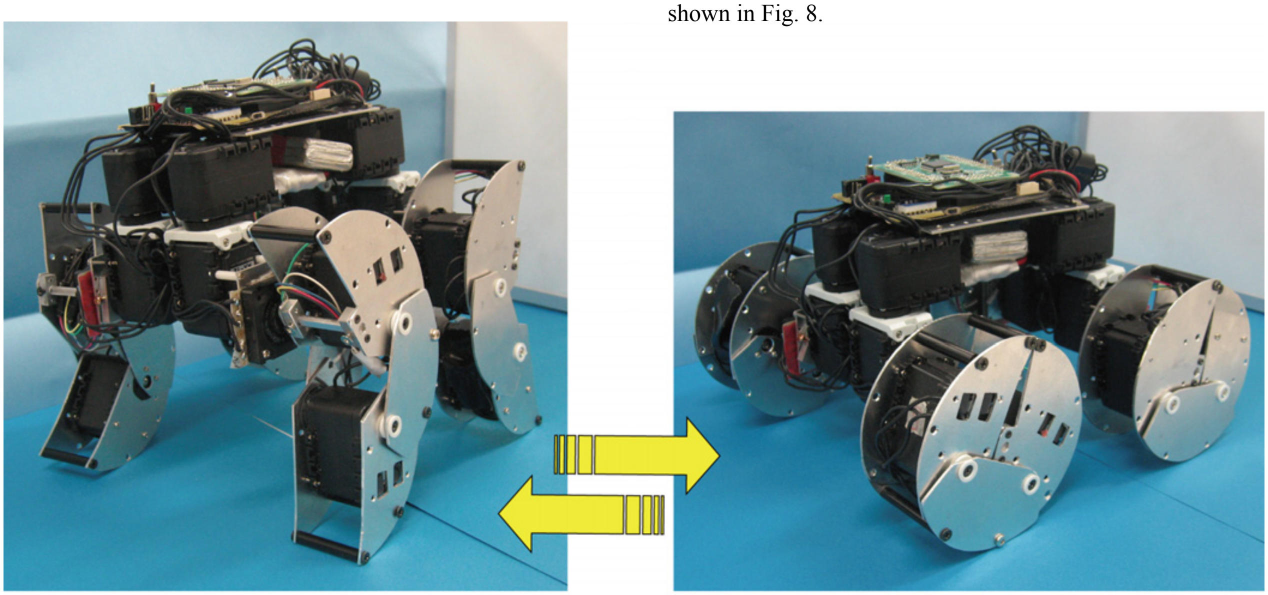
(a) Legged Mode



(b) Wheeled Mode

Fig. 6: The first prototype model of the wheel-leg module

Based on the above condition, the first prototype model has been built as shown in Fig.7. The middle link of this module sandwiches the first and third links so that the module can cover a large angle range easily. And overview of the mobile robot with this module is shown in Fig. 8.



Legged Mode　　Wheeled Mode

Fig. 7: Overview of the Wheel-Leg Hybrid Robot

As described in the previous section, this module can realize a large diameter of wheel using all links of the leg mechanism.

Currently it uses servo motors for the actuators of the joints of the legs, and therefore the girth of the leg is quite large. In subsequent revisions, an actuator will be chosen to reduce this bulky aspect.

C. *Body of the Mobile Robot*

At present, the body of the prototype robot is a rigid one, but considering the movement in wheeled mode, there is a need to add some kind of suspension mechanism between the body and the wheel-legged modules. In addition, the equalizer mechanism at the center of the body is effective for movement on rough terrain.

On the other hand, considering the movement in legged mode on rough terrain, the body should be completely rigid and there a desire to have no suspension mechanism.

In order to realize these two conflicting functions, we are developing a 3-state actuator which can change its own state as the 'driving mode', 'locked mode' or 'free-to-rotate mode' using a single linear actuator, as shown in Fig.8. When the mobile robot is in wheeled mode, this actuator assumes the locked mode for rigid supporting function. On the other hand, when the mobile robot is in wheeled mode, this actuator assumes the free-to-rotate mode for the equalizing function of the center of the body. Driving mode can be taken for movement on rough terrain with a slope, large step or gap and so on.

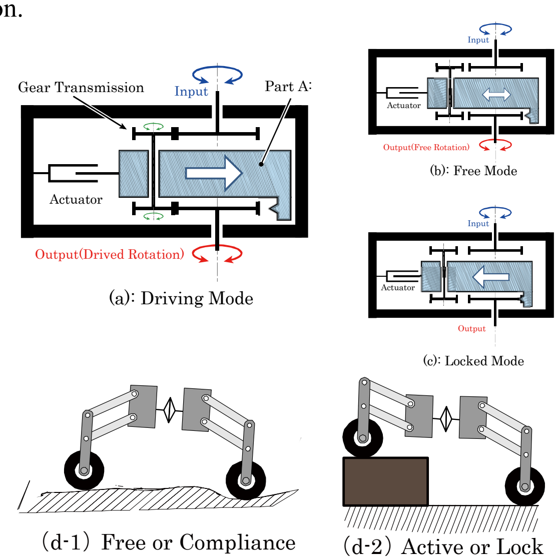


Fig. 8: 3-States Actuator for the Joint of the Body

D. *Control System*

The control system of the one wheel-leg module of the prototype robot is shown in Fig. 10. We selected the dynamixel AX-12 geared motor in order to reduce the number or the wires by making use of the protocol communications between an actuator unit and a host computer.

The lithium-polymer battery: LP-2S1P240S was selected as the battery of the prototype mobile robot with the light weight characteristic being a major influence on the decision.

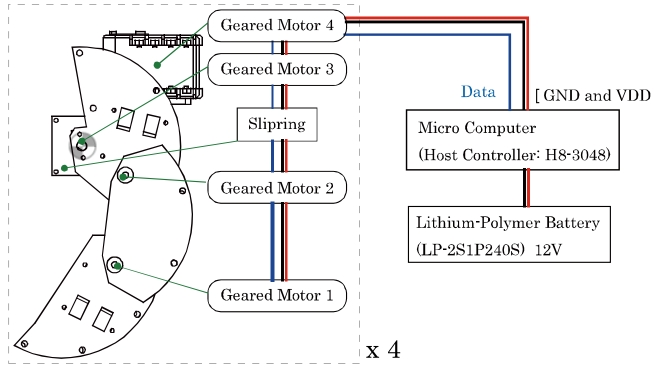


Fig. 9: Control System of the Prototype Robot

IV. Basic Movement Experiments

A. *Mode Changing*

The mode changing motion of this robot should be confirmed. One example of such a motion is shown in Fig.9. It was observed that this prototype model has the ability to smoothly change its mode from wheeled mode to legged mode and vice versa. Please see the movie attached to this paper. At present, each posture of the leg is changed at the same time by making the curved part of the module make contact with the ground. When the mobile robot with this module moves on rough terrain, considering the stability of the robot, it is effective to change those modules' mode one at a time. Development of the most effective sequence is still ongoing.

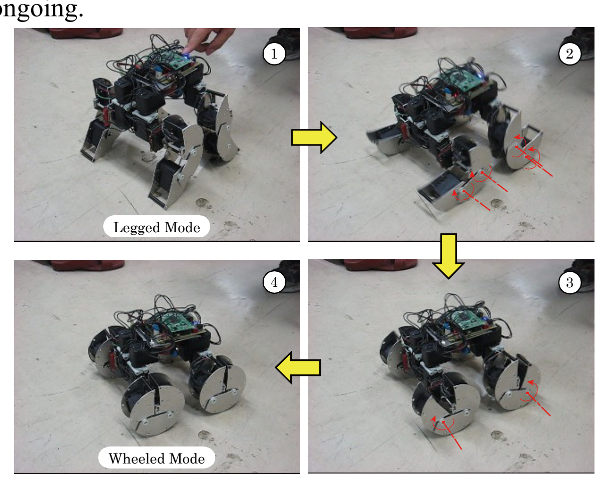


Fig. 10: Motion of Mode Changing

B. *Movement on Wheeled Mode*

(B-1) Straight Motion

As one of the basic mobility criteria of this robot, the ability to move in wheeled mode should be confirmed. One example of such motion is shown in Fig.11. It was observed that this prototype model can move about 155[mm/s] smoothly as shown in Fig. 11. Please see the movie attached to this paper.

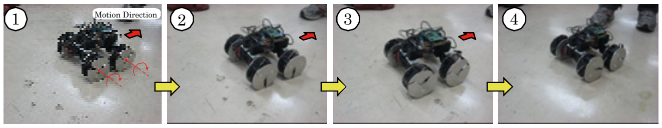


Fig. 11: Moving on the Wheeled Mode

(B-2) Steering, Rotational Motion

On the wheeled mode, this prototype one can change its steering angle as shown in Fig. 12. The curving motion and the rotation on the spot should be confirmed. One example of such a whole shape of the robot is shown in Fig.12(a), and that of the rotation on the spot mode is shown in Fig.12(b) respectively. One example of such a motion is shown in Fig.13, and that of the rotation on the spot mode is shown in Fig.14 respectively.

It was observed that this prototype model has the ability to change smoothly its direction of curving and rotation on the spot. When the robot rotates its own wheels with driving in the same direction, this robot can move sideways. At present, the space for the motion range of the steering is not enough, therefore wheels cannot have the steering 90 degrees, the basic performance of this motion is confirmed . Please see the movie attached to this paper.

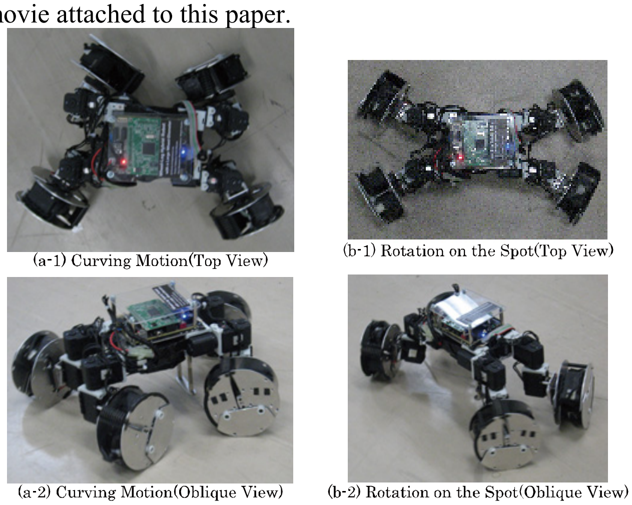


Fig. 12: Curving and Rotation on the Spot Mode

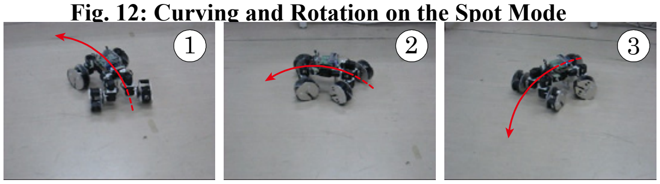


Fig. 13: Curving Motion

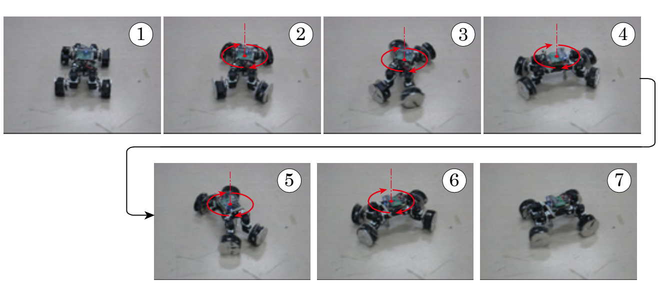


Fig. 14: Rotational Motion on the Spot

C. Walking Motion

The robot's walking motion was also confirmed. It was observed that the prototype with retractable wheel-leg modules can walk with rotation on the spot π/6[rad/s] on a flat surface as shown in Fig. 13.

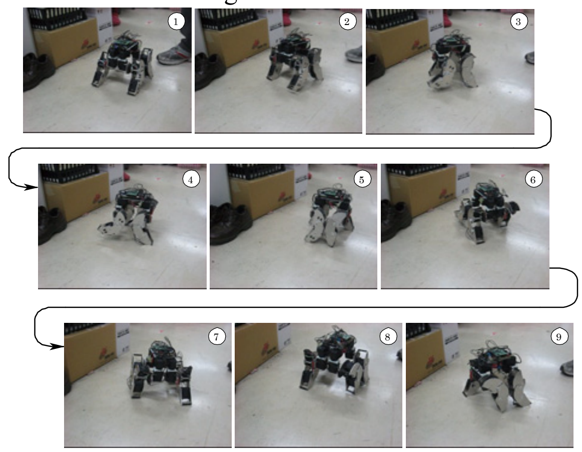


Fig. 15: Turning on the Legged Mode

The walking motion on the rough terrain is going to be conducted. The combined motion of wheel and leg can also be considered.

V. Motion Experiments of Grasping

A. Another Application of the Module

(A-1) Basic Concept

As an example of another function of this robot, there is the rolling grasping motion. When in legged mode, this mechanism can work as a gripper with some joints able to realize the grasping as shown in Fig.14 (a). On the other hand, when the mechanism is in the retracting configuration, this mechanism can work as a gripper with large roller as shown in Fig. 14(b) like Nagata showed[9]. As described, this mechanism can realize a large diameter of the wheel, even if the grasped object has some concave or convex surfaces, the roller can pull the object with rotation using only the compliance of the joint at the root of the gripper as shown in Fig.14(b).

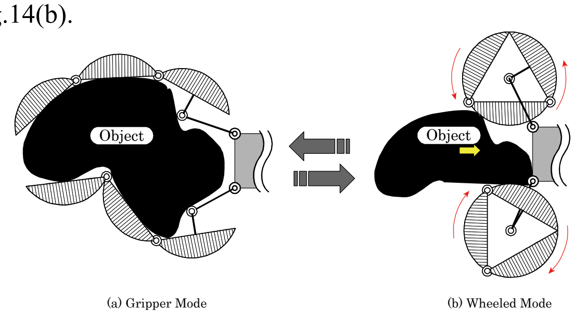


Fig. 16: Grasping with Some Contact Points and Rolling

(A-2) Example of the Configuration

The configuration of additional axis of the wheel-leg module to realize the grasping motion is shown in Fig. 17 right part. There is the rolling axis at the root of the one wheel –leg

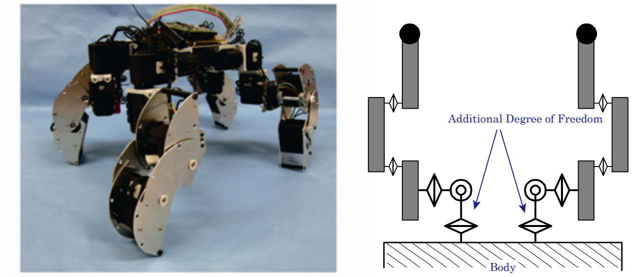


Fig. 17: Prototype Model with 1-additional D.O.F.

retractable module, therefore, when it turns, the pitching axis of the wheel-leg module can be changed into the yawing axis, and grasping motion can be realized as shown in Fig. 18.

B. Grasping Motion

Fig. 16 shows the grasping posture in gripper mode. There is the supporting rod under the body of this robot to take this grasping posture. As shown in this figure, the prototype one can grasp the object with many links.

Fig. 17 shows the mode changing motion from wheeled mode to grasping mode. It was observed that this prototype model has the ability to grasp an object and roll it smoothly. Please see the movie attached to this paper.

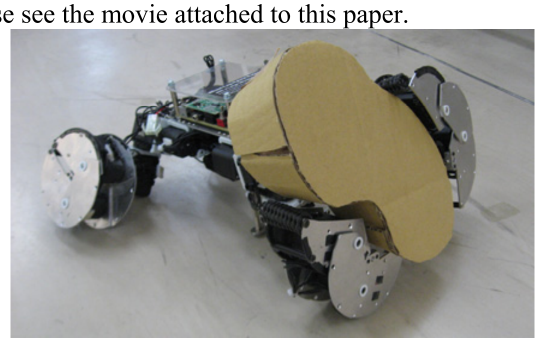


Fig. 18: Grasping with the Wheeled-Leg Retractable Module

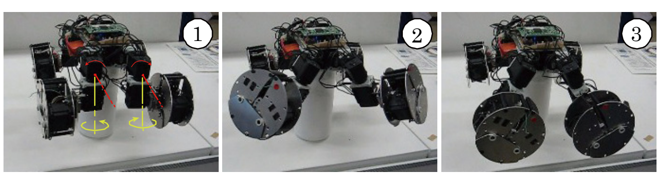


Fig. 19: Mode Changing from Wheeled Mode to Grasping with Roller Mode

C. Rolling Grasping Motion

As one of the basic mobility criteria of this robot, the ability to grasp the object and operate by using the rolling motion of the retracted wheel-leg module of the end of the finger should be confirmed. One example of such a motion is shown in Fig.18. The red markers on the surface of the first link are added to aid viewing of the motion. The over view of the rolling grasping mode is shown in Fig.

It was observed that this prototype model has the ability to grasp an object and rotate the end of the finger to manipulate the object smoothly, as shown from number 3 to number 5 in this figure. Please see the movie attached to this paper.

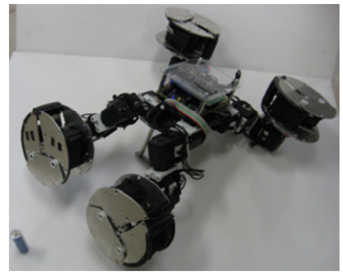


Fig. 20: Oblique View of the Prototype on the Mode of the Roller Gripper

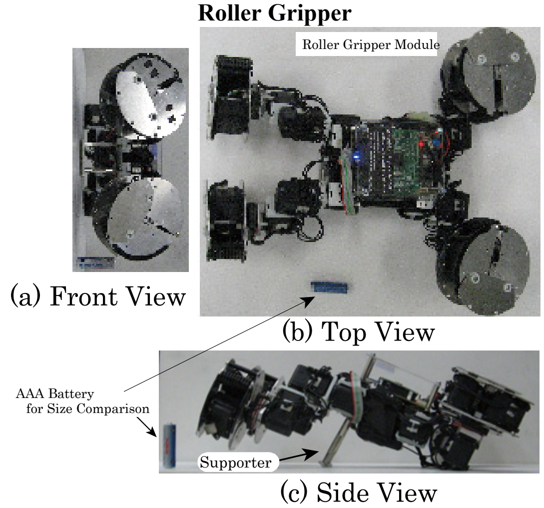


Fig. 21: Three Sides View of the Prototype on the Mode of the Roller Gripper

D. Fractal Gripper

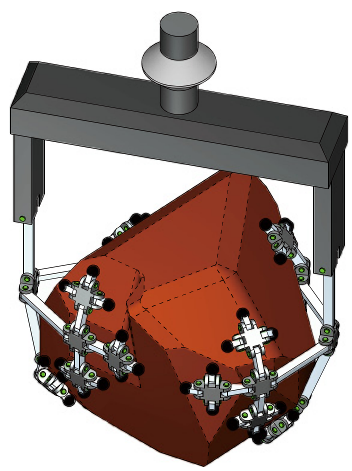


Fig. 22: Overview of the Concept Figure of the Fractal Gripper

The concept of the fractal gripper is shown in Fig. 22. As one of the expanding the concept of the retractable leg module used for the gripper as shown before in this paper, this kind of gripper can be suggested for the usage of the molding to the contour of the shape of the objects.

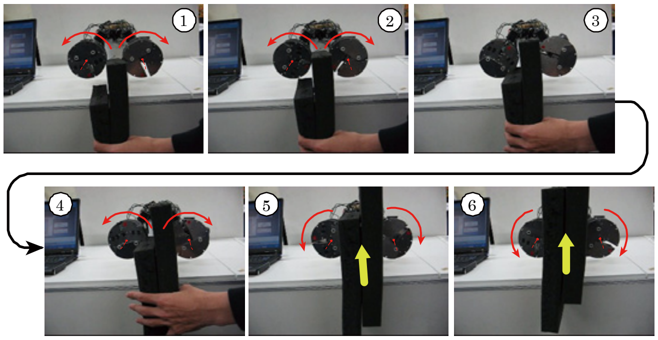
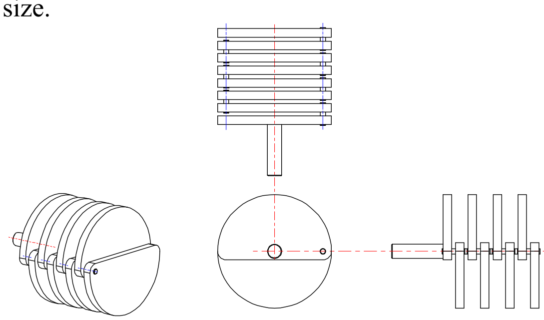


Fig. 23: Rolling Grasp with the Wheeled-Leg Retractable Module

E. Consideration of the Basic Wheel-Leg Module Configurations

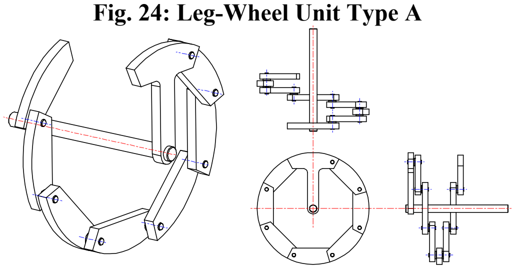
There are mainly two configurations to realize the wheel structure by using whole of the leg linkages as shown in Fig. 24, 25 respectively. The Type A as shown in Fig. 24 has the hemi-circular shaped linkage and that composes the wheel structure. The advantage of this structure is that the mechanism can stand to the large torque by using the central axis as a stopper.

On the other hand, the Type B-1 and B-2 compose the wheel structure with the all of the leg linkage as shown in Fig. 25 and Fig. 26 respectively. The most important advantage of these configurations is that it can realize the larger diameter size.



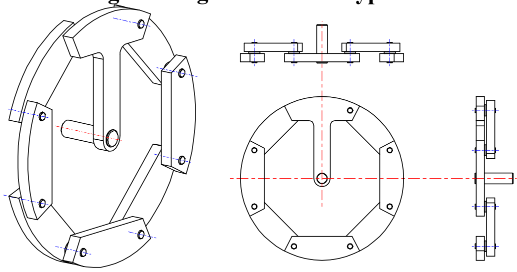
(a) Oblique View (b) Three Sides View

Fig. 24: Leg-Wheel Unit Type A



(a) Oblique View (b) Three Sides View

Fig. 25: Leg-Wheel Unit Type B-1



(a) Oblique View (b) Three Sides View

Fig. 26: Leg-Wheel Unit Type B-2

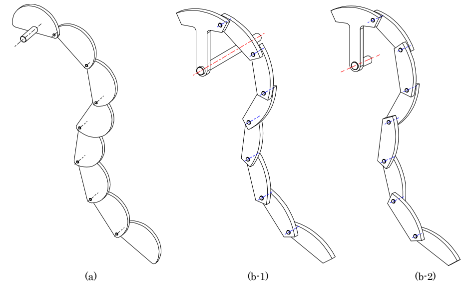


Fig. 27: Each Legged Mode

L: Length of the one linkage of the leg module
Da: Diameter of the type A unit in wheeled mode
Db: Diameter of the type B unit in wheeled mode
N: Numbers of the linkage

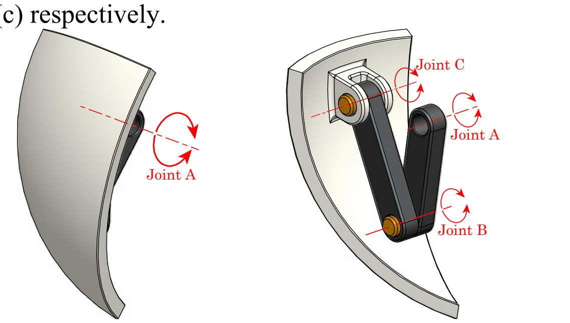
$$Da = L \quad \text{……………..} \quad (1)$$

$$Db = L/\sin(\pi/N) \quad \text{……………..} \quad (2)$$

If N is larger than three, the Db is larger than Da. The prototype model in this paper has the three linkages to adopt the above principle.

F. Three Dimensional Wheel-Leg Module Configurations

The concept of the three dimensional wheel-leg retractable module is show in Fig.28. The end of the leg, there is the part of the sphere shield. The most different point of this mobile robot is that it composes the sphere wheel not only with legs but also the upper body as shown in Fig. 29. This robotic module can be used as the sole of legged walking machine, spherical wheel for mobile robot and grippers as shown in Fig. 30(a)-(c) respectively.



(a) Outer Side (with the Part of a Sphere) (b) Inner Side (with Retractable Lim)

Fig. 28: Oblique View of One Unit of the Three Dimensional Wheel-Leg Module

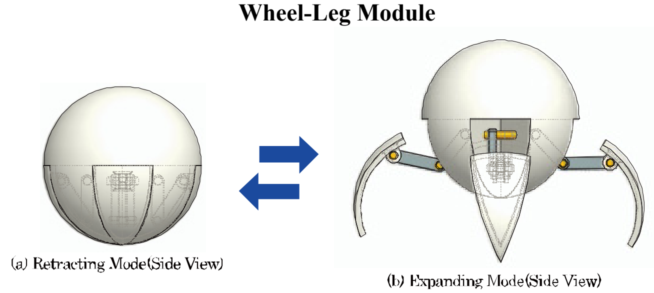


Fig. 29: Oblique View of the Three Dimensional Wheel-Leg Module

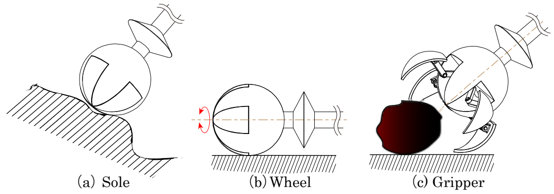


Fig. 30: Functions of the Three Dimensional Wheel-Leg Module

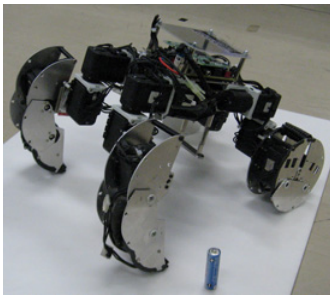


Fig. 31: Overview of the Prototype on the Leg-Wheel Integrated Mode

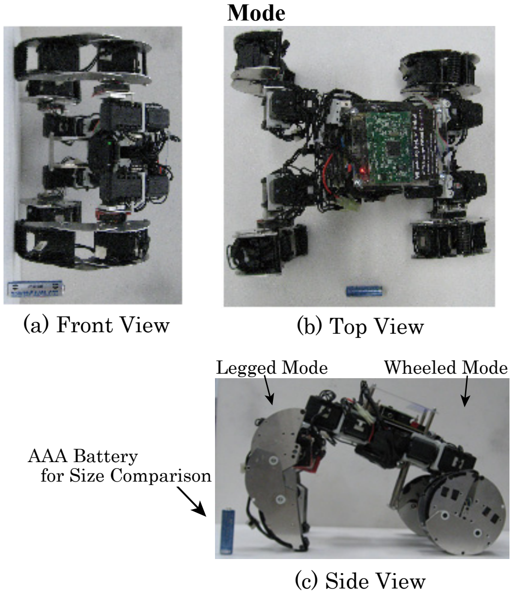


Fig. 31: Three Sides View of the Prototype on the Leg-Wheel Integrated Mode

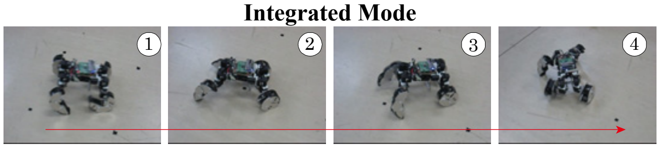


Fig. 32: Motion of the Leg-Wheel Integrated Mode

VI. Conclusion

In this paper, we presented a mechanical design of the wheel-leg hybrid module to realize a large diameter of wheel. We confirmed the basic characteristics of this wheel-leg hybrid module mechanism and the motions of the mobile robots with those modules through basic movement experiments.

Moreover the configuration to realize the rolling grasping with this wheel-leg retractable unit is shown and with the basic experiments of the prototype robot, the function of the roller grasping is confirmed. In addition, the general configurations of the wheel-leg retractable modules with plural numbers of linkages are discussed. The possibility of the usefulness of the three dimensional wheel-leg retractable module expanded concept of the two dimensional module shown in this paper, and the leg-wheel integrated mode of the prototype robot are described.

In future works, optimization of the proportion of the module mechanism will be conducted and an automatic mode changing motion will be developed. In addition, the practical model with some sensors will be developed for real mobile missions e.g. search and rescue mission and so on. The position and configuration of the degrees of freedom will be also studied deeper for the rolling grasping, molding to the contour of the shape of the objects. The functions of the integration of the robot will be studied deeper.

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