

# Enhanced Omni-Ball: Spherical Omnidirectional Wheel Achieving Passive Rollers with High Load Capacity and Smoothness through an Offset Rotational Axis

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**Abstract**— This paper introduces an innovation of the Spherical Omnidirectional Wheel, designed to achieve omnidirectional driving motion. In previous models, the supporting shaft was placed at the center of the mechanism. However, achieving both smoothness and high load-capacity in such designs proved challenging. The mechanism proposed in this study features an offset design, enabling outer support for the wheel. A prototype was developed and its basic motion was experimentally validated.

**Key Words:** Mechanism Design, Wheeled Robots

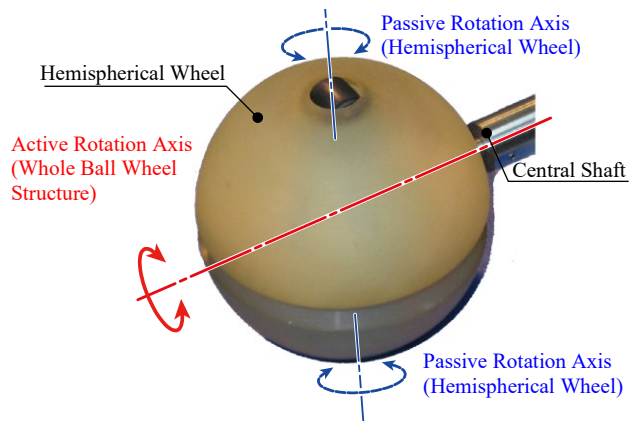
## I. INTRODUCTION

Omnidirectional vehicles with steering axes have the disadvantage that it takes time to change the direction of the wheels and instantaneous changes of direction are impossible. Conventional compound wheel mechanisms (e.g., [1]-[5]) enable instantaneous changes of direction, but have extremely low ability to traverse bumps because the diameter of the small wheels that passively rotate is small relative to the entire mechanism (e.g., [12]-[14], [17]). Friction power transmission also has the problem of limiting the driving force generated to the running surface. The spherical omni-directional wheel, also known as “Omni-Ball”, previously developed by the authors, consists of two independent, facing hemispherical passive wheels that share a rotating axis and an active axis that rotates the entire hemispherical wheel. The most significant feature of this spherical omni-directional wheel is that the diameter of the hemispherical passive rotating wheel is equivalent to the size of the entire mechanism, thus providing significantly higher step traversing performance than conventional wheels with passive rotating rollers[4]. Moreover, the direct rotation of the drive shaft eliminates the problem of insufficient driving force of the above-mentioned friction type. The “Omni-Ball” has significantly higher step traversing ability than conventional omni-directional wheels[6][16]. From the view point of larger wheel, we have proposed and made embodiment[17]. However, the sphere must be divided in order to pass the active axis of rotation through the center, resulting in a loss of smoothness because the cross section is not perfectly circular.

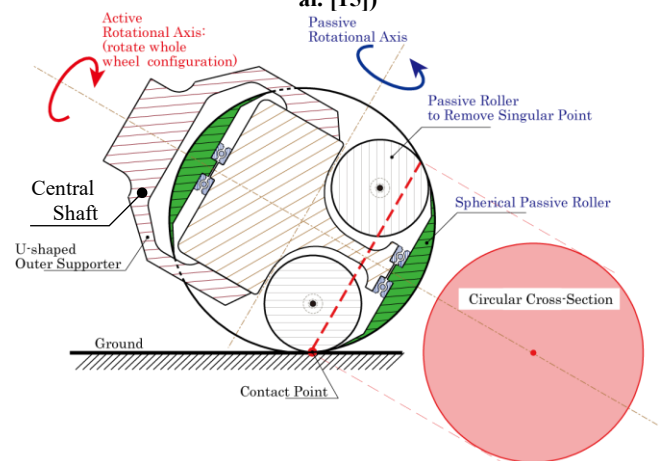
In addition, if the diameter of the active axis of rotation is increased to improve load carrying capacity, it is necessary to increase the width of the division. As described above, there is

a trade-off between smoothness during running (i.e., the degree of perfect circularity of the cross section) and load carrying capacity, and it has been impossible to achieve both.

In view of the above problem, we proposed a new omni-directional spherical wheel mechanism that can achieve both smoothness during running and load carrying capacity. In this report, we report on the design and prototyping of the proposed mechanism, and experimentally confirm the effectiveness of the proposed mechanism.



**Fig. 1: Omni-Ball: Spherical Wheel(Kenjiro TADAKUMA et al. [15])**



**Fig. 2: Proposed Concept of Outer Supported Omni-Ball**

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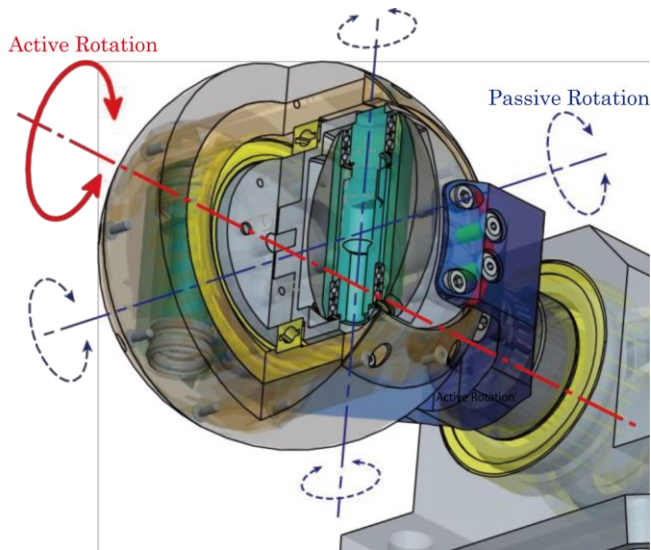


Fig. 3 : Basic Configuration of the First Prototype Model



Fig. 6 : Overview of the First Prototype Model

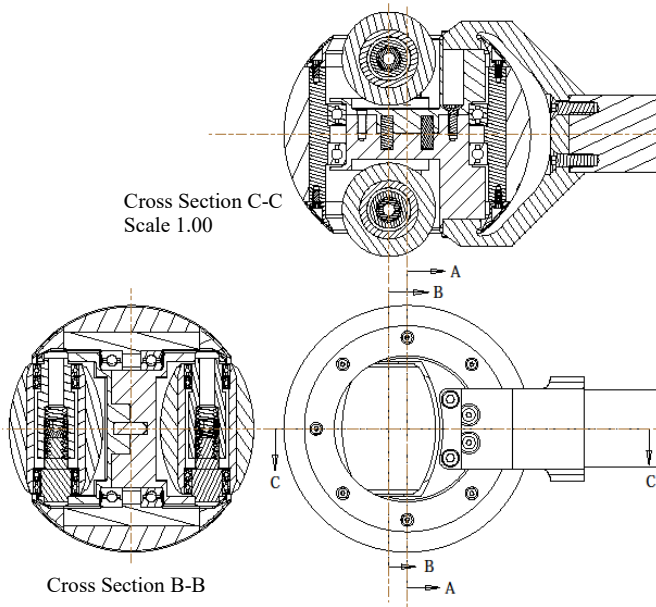


Fig. 4 : Detail Design of the First Prototype Model



Fig. 5 : Each Mechanical Parts of the First Prototype Model

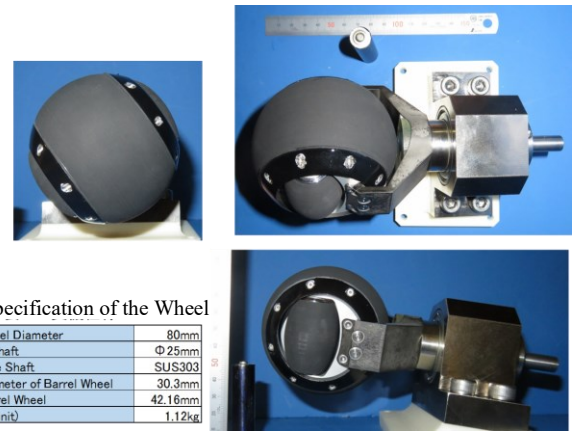


Table 1: Specification of the Wheel

Spherical Wheel Diameter	80mm
Diameter of Shaft	Φ25mm
Material of the Shaft	SUS303
maximum Diameter of Barrel Wheel	30.3mm
Length of Barrel Wheel	42.16mm
Weight (One Unit)	1.12kg

Fig. 7 : Three Sides View of the First Prototype Model

## II. OFFSET SPHERICAL OMNI-DIRECTIONAL WHEEL MECHANISM WITH EXTERNAL SUPPORT SHAFT

### A. Basic Configuration

Figure 2.1 shows the basic configuration of the spherical omni-directional wheel proposed in this study, which can achieve both smooth running and high load carrying capacity. The main feature of this mechanism is that the spherical omni-directional wheel is externally supported by a U-shaped support. The principle of this wheel mechanism is as follows:

(1) Offset placement of the singularity avoidance passive wheel: The singularity avoidance roller attached to the "Omni-Ball" is offset from the center of rotation of the spherical rotating passive wheel to a U-shaped external support;

(2) By placing the singularity avoidance roller, which is attached to the "Omni-Ball" at a position offset from the center of rotation of the spherical rotating passive ring, an access space can be provided to the spherical inner support;

(3) The U-shaped support of the spherical passive wheel from the outside can support the spherical rotating passive wheel without dividing it in the center.

#### (4) Diagonal arrangement of axles

Furthermore, the axles are tilted from the horizontal line. Placing them at an angle increases the distance between the active rotating axle and the running surface (ground or floor). This has the advantage of making it easier to avoid getting stuck when traveling over bumps and ditches.

Hence, the active rotating axis at the base can be larger in diameter than the diameter of the spherical passive rotating wheel, depending on the design, to achieve extremely high load carrying capacity.

#### B. Specific Design

In the cross-section of the singularity-avoiding roller, if the curve and curvature are the same as the diameter of the entire sphere, as is conventionally the case, misalignment will occur at the edge, necessitating a unique curve and curvature (Figure 5).

Figure 7 shows the specific design and Figure 8 shows the appearance of the actual prototype. Experiments using a dolly equipped with a wheel mechanism confirmed that the smooth circular cross section allows the machine to run. Depending on the design, the external support can be made as large as possible to provide high load capacity. The external support itself can also be made into a passive roller. This allows excessive external forces to be released even if the support contacts an obstacle when the wheel moves in the right direction as shown in Figure 7.

In the case of the V-shaped groove with a diagonal tilt, when the environmental model moves from the larger V-shaped groove to the smaller V-shaped groove, a brake similar to a bogen in skiing is thought to apply, in addition to reduction of foreign objects such as dust[7]. The same phenomenon has been reported for the radial configuration type of the early version of “Omni-Disc” developed by Hirose et al.

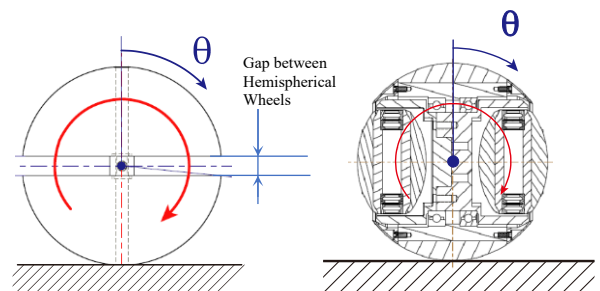
In the present study, when supporting the spherical omnidirectional wheel from the outside, which our research team has been working on for some time, the singularity avoidance roller is offset to provide space for its outer support. the U-shaped wheel support method can also be found in conventional casters and [11], but it has not been used in the conventional. The most significant feature of this structure is that the space for mounting the support can be secured while maintaining the circular cross section by offsetting the singularity-avoiding roller, which has existed in the center [6], and by changing the curvature of the singularity-avoiding roller from that of the sphere's cross section.

Even though it is more of a design problem, the offset addition method devised in this research is very important for the concrete formulation of the principle in an actual machine. The relative diameter of the circular cross section is reduced by the inclination of the active axis of rotation, and the ability to traverse steps and ditches, to which the diameter size contributes, is reduced. This structure can satisfy these two contradictory elements at the same time.

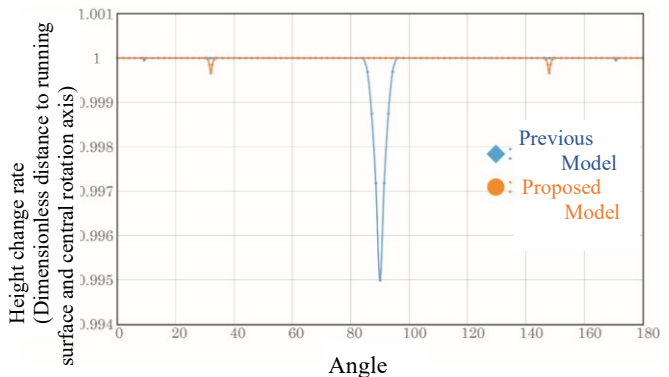
### III. PROTOTYPING

#### A. Comparison of Running Smoothness

A comparison was made between the smoothness of running of the conventional type and the externally supported type. The comparison was made by calculating the change in height of the center of the sphere from the ground point when the active rotation axis of the spherical wheel rotates  $180^\circ$ . The rotation angle of the spherical wheel was set as shown in the upper part of Figure 6. By setting  $\theta = 0$  to  $180^\circ$  and  $\theta = 180$  to  $360^\circ$  as shown in the figure, the radius of the circular cross section perpendicular to the active rotation axis becomes smaller than that of the conventional machine because the active rotation axis of the externally supported type is placed at an angle. Therefore, the height is non-dimensional by dividing the height by the radius of the spherical wheel. The relationship between the rotation angle of the active rotating axis and the degree of height change is shown in the lower part of Figure 6. In the conventional type, the height change occurs at the singularity-avoiding roller attachment point (around  $\theta = 9.2$  and  $\theta = 170.8$ ) and at the groove between the two hemispherical wheels (around  $\theta = 90$ ). In contrast, the externally supported type does not divide the sphere, so the height change occurs only at the singularity-avoiding roller attachment point (around  $\theta = 32.1$  and  $\theta = 147.9$ ). The groove that caused a large height change in the conventional machine was eliminated, and the maximum height change was calculated to be 0.034[%] of the wheel radius.



(a) Previous Omni-Ball (b) Proposed Wheel Mechanism



(c) Relationship between Angle and Height Change Rate

**Fig.8: Comparison of the Smoothness of Locomotion**

The maximum height change of the externally-supported type is approximately 93.2% less than that of the conventional type. In the case of the prototype spherical wheel with a radius of 80 mm, the maximum vertical movement of the externally supported type when traveling on a flat surface was less than 0.013 mm. From this result, it can be said that the smoothness of the externally supported type is improved compared to the conventional type.

## B. Comparison of load bearing capacity

### B-1 [Simulation]

The load capacity of the conventional type and the externally supported type was calculated based on the minimum safety factor of each type. The minimum safety factor of the conventional type was 0.238307 when the ball wheel was grounded and 0.211751 when the barrel roller was grounded. The smaller of these values was used to calculate the load capacity. In contrast, the minimum safety factor of the externally supported type was 2.39347 when the ball wheels were grounded and 2.48096 when the barrel rollers were grounded. Using the smaller of these values to calculate the load capacity, it was confirmed that the externally supported type has a load capacity approximately 11.3 times that of the conventional type.

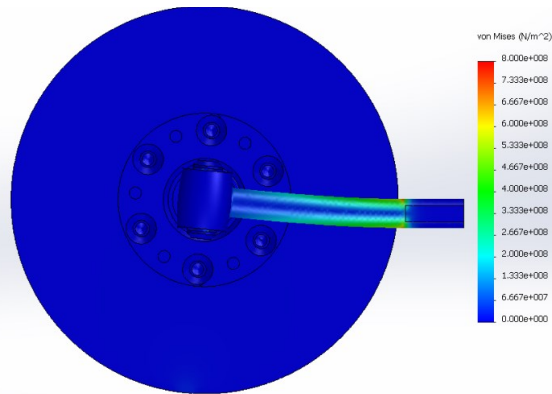


Fig. 9 : Load Bearing Simulation for Ring Part

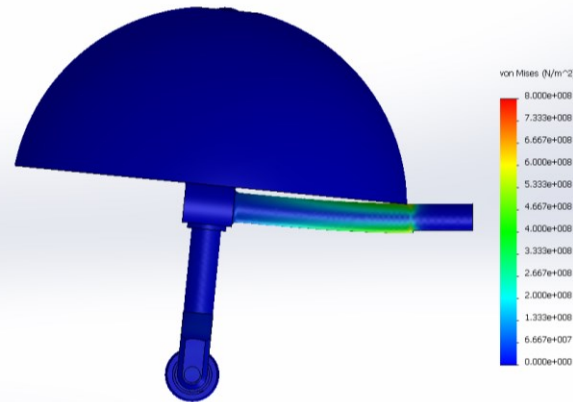


Fig. 10 : Load Bearing Simulation for Barrel Wheel Part

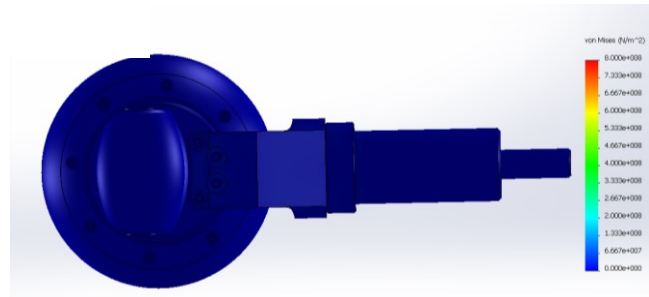


Fig. 11 : Load Bearing Simulation for Ring Part

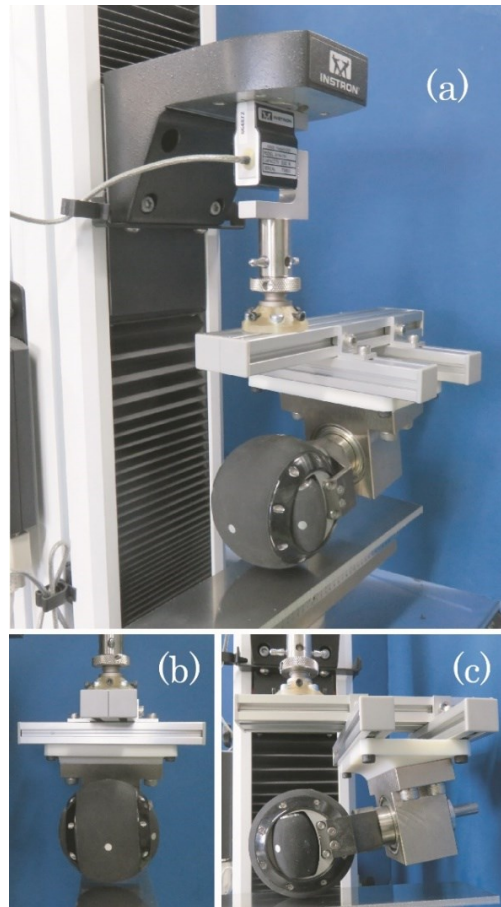


Fig. 12 : Load Bearing Experiment for Ring Part

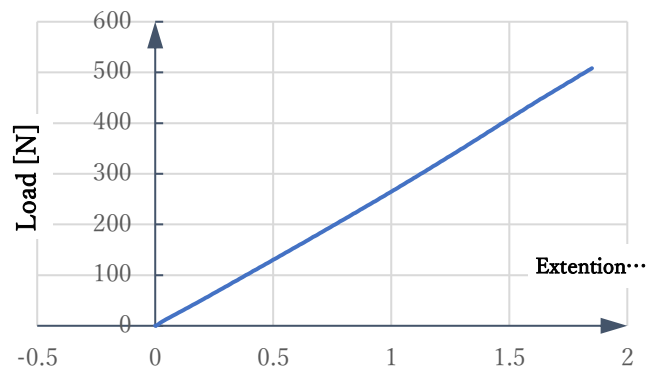


Fig. 13 : Result of the Load Bearing Simulation for Ring Wheel Part

## B-2 [Test apparatus on actual equipment]

Load capacity tests were conducted on spherical wheels made of metal and rubber by applying a vertical load using a universal testing machine. Vertical loads were applied to the spherical wheels using an INSTRON 3342 single-column universal testing machine. Loads of 100, 200, 300, 400, and 500 N were applied in steps in the direction that the spherical wheel of the spherical wheel was grounded, and loads of 300, 400, and 500 N were applied in steps in the direction that the barrel roller was grounded. Finally, a load of 500 N was applied only once, changing the ground plane of the barrel roller. All of these tests were performed on one ball wheel only. The test was set to terminate when the vertical displacement reached 2.5 mm or when the load reached the set value. The testing machine was set to apply a vertical load at 5 mm/min. Load and displacement data were recorded every 10 ms. Figure 4.5 shows the experimental situation. The spherical wheel was pressed against the stage and deformed by applying a load from directly above.

All graphs show a nearly linear relationship between displacement and load. Some of the graphs show a step-like shape before the linear relationship is formed. This is thought to be the result of the gap-filling movement during the assembly of the parts or the thrust misalignment of the bearings. After this movement ceases to occur, the parts begin to deform, and the relationship is considered to be a linear one. In the graphs where this shape is not observed, it is assumed that the sphere contacts the stage before the start of the test and the motion between the parts has already ceased to occur.

The results are compared for the case where the load was applied to the barrel roller in stages, with a maximum load of 500 N applied at the end, and with a maximum load of 500 N applied only once. The displacements in the linear portions of the graphs are both approximately 2 cm. This indicates that the deformation of the part was the same when the load was applied in stages and when the load was applied only once. In other words, the deformation caused by the applied load was within the elastic deformation of the spherical wheel components.

In addition, we observed the change in the spherical wheel when the load was removed by lifting the spherical wheel after the load was applied. Figure 4.15 shows the change that occurred. In this case, the shape change was observed to recover in the external support in the video image. This is because the external support was particularly deformed in the simulation results of the strength analysis described in section 4.2, and the simulation results were confirmed in the actual machine. However, the changes were hardly visible to the naked eye, and no defects appeared on the wheel after the experiment, suggesting that the deformation was only slight.

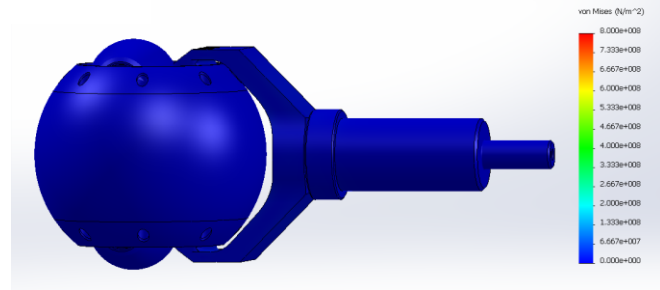


Fig. 14 : Load Bearing Simulation for Barrel Wheel Part

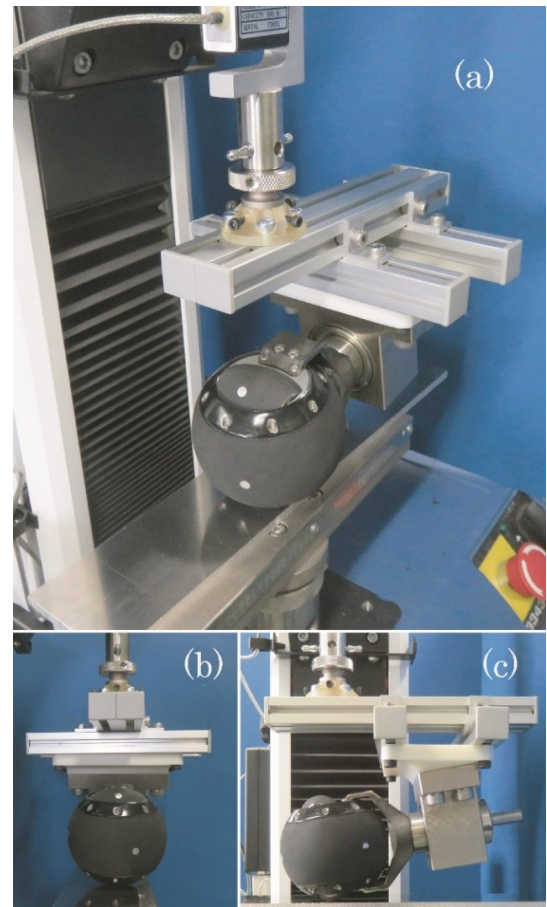


Fig. 15 : Load Bearing Experiment for Barrel Wheel Part

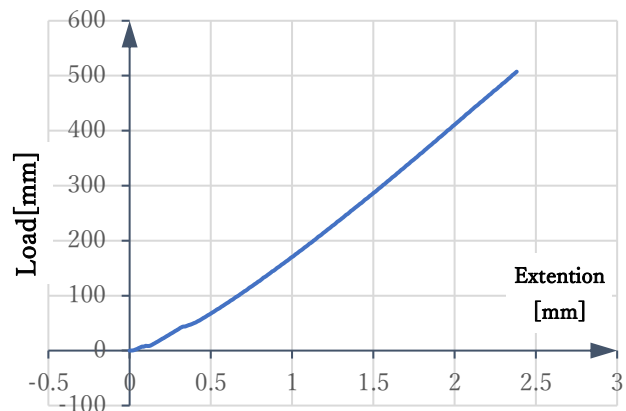


Fig. 16 : Load Bearing Experiment for Barrel Wheel Part

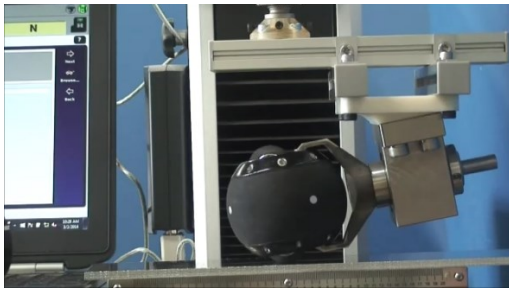


Fig. 17 : Overview of the Load Bearing Experiment for Barrel Wheel Part

#### IV. BASIC EXPERIMENTS

It can be seen that the externally supported spherical wheel has lower stress and smaller deformation than the conventional type on the active rotating axis. This indicates that the external support structure allows the diameter of the active rotating shaft to be enlarged, increasing its load-bearing capability.

Figure 12 shows a four-wheel model composed of an offset spherical omni-directional wheel with a prototype externally supported shaft. Figures 13 and 14 show various running tests.

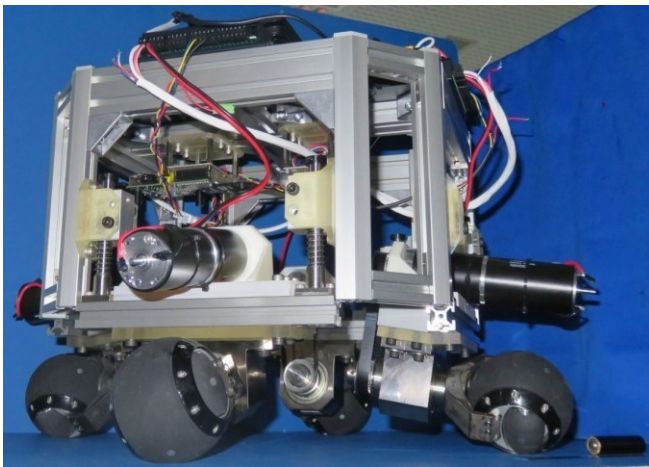


Fig. 18 : Overview of the Prototype Omnidirectional Vehicle with proposed mechanism

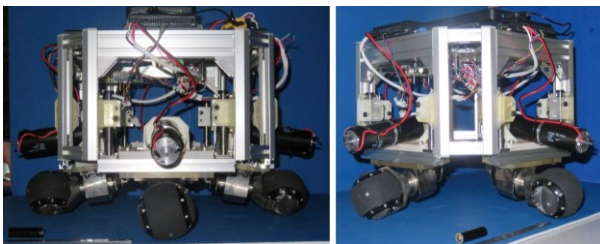


Fig. 19: Overview of the Load Bearing Experiment for Barrel Wheel Part

Table1: Specification of the First Prototype Model

Whole Height	356mm
Distance of Ground Points of Each Wheel	415mm
Whole Weight	22.15kgf
Battery	21.6V
Motor Power	150W
Stroke of the Suspension	26mm

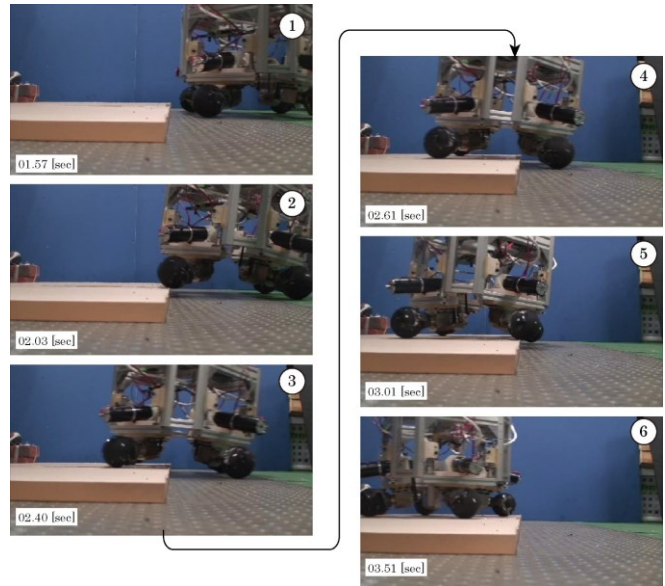


Fig. 20 : Basic Step Climbing of the First Prototype Model

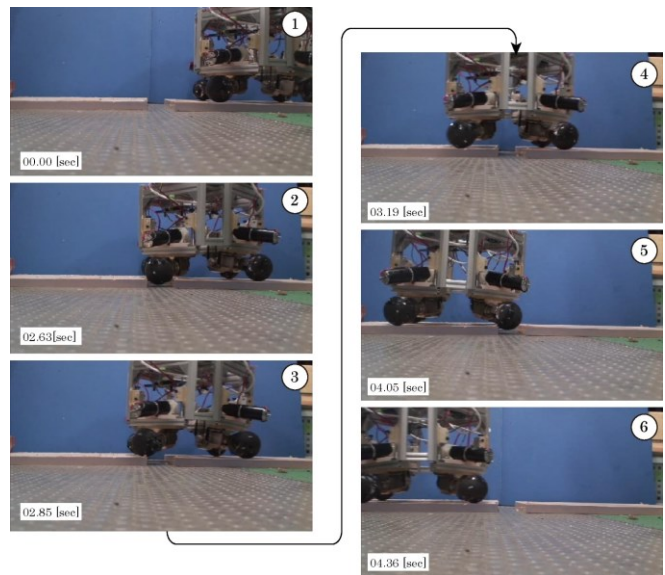
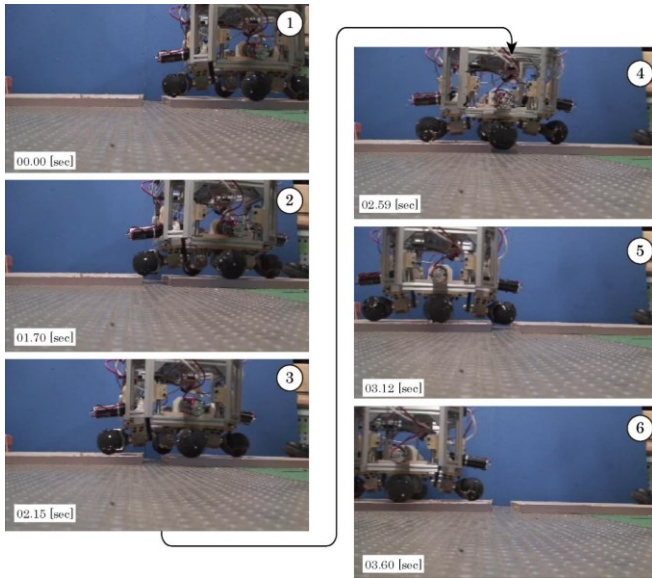


Fig. 21 : Basic Gap Traversing of the First Prototype Model

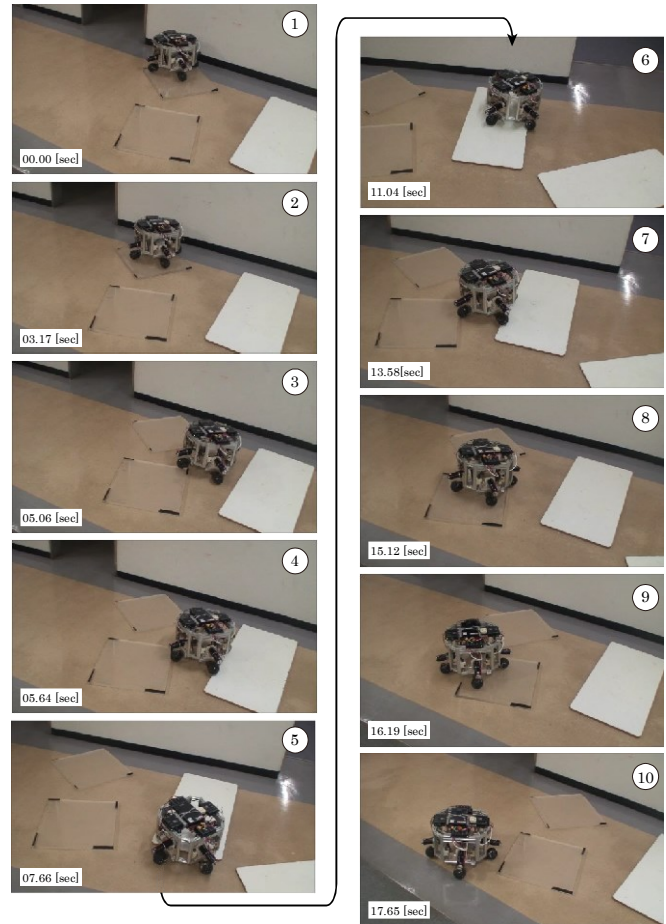


**Fig. 22 : Basic Gap Traversing of the First Prototype Model**  
(from one wheel)

Four boards were placed on the path and tested on randomly uneven ground. The maximum thickness of the boards used was 20 mm. Figure 4.29 shows a scene from this running experiment. It was confirmed that the prototype omnidirectional mobile vehicle could move without getting stuck even on this road surface.

In this experiment, it was confirmed that it was possible to trample steps up to 20 mm high and ditches up to 70 mm wide. In the experiment, it was confirmed that the robot was able to traverse steps and ditches with relative ease. However, when only one wheel contacted a step first, the time required to overcome the step was similar to the time required for two wheels to enter the step, and the time required to overcome the step was also irregular. The reason for the difficulty of stepping over a step with only one wheel is that the active axis of rotation is tilted from horizontal to flat, so that when one wheel collides with a step, a force is exerted in the direction that pushes the wheel to the ground. In addition, the round bar that constitutes the suspension is also considered to tilt slightly from the vertical to the step side to push the wheels against the ground.

Finally, four boards were placed on the path and tested on randomly uneven ground. The maximum thickness of the boards used was 20 mm. The figure below shows a scene from this running experiment. It was confirmed that the prototype omnidirectional mobile vehicle was able to move without getting stuck even on this road surface.



**Fig. 23 : Basic Omnidirectional motion of the First Prototype Model**

## V. CONCLUSION

The actual prototype was designed and fabricated based on the structure developed in this study. It was confirmed that the prototype externally supported spherical wheels can make smooth contact with the running surface. The smoothness of running and load carrying capacity were evaluated by calculating the change in wheel height, and the load carrying capacity was evaluated by static analysis simulation in comparison with the conventional type. The proposed externally supported type was confirmed to have superior performance in both smoothness and load carrying capacity compared to the conventional type. Furthermore, a vehicle equipped with the prototype wheel was constructed, and it was confirmed that the vehicle could move in all directions in an environment with steps and ditches of about 20 mm.

As a future prospect, the strength analysis confirmed that the externally supported type has parts that have a lower safety factor than the active rotary axis and are more prone to breakage. The design of these parts will be reexamined, and the optimum shape of the grocer on the surface of the spherical wheel will be studied to improve the performance of overcoming steps and grooves.

## REFERENCES

- [1] Shigeo Hirose and Shinichi Amano: "Development of a Large Load High Efficiency Omni-directional Vehicle," Proceedings of JSME Conference on Robotics and Mechatronics '93, pp. 350-355, 1993.
- [2] Inventor: Carl L. Hammonds, Humble, Assignee: Hammonds Technical Services, Inc. Revolvable hitch", US 8186461 B2.
- [3] Masayoshi Wada, Shunji Mori: "Development of a holonomic omni-directional mobile robot", Journal of the Robotics Society of Japan, vol.15, no.8, pp.1139-1146, 1997.
- [4] Z. Mori, E. Nakano, and T. Takahashi,: "On the basic principle of the omnidirectional mobile robot ODV9 and overcoming small steps," Journal of the Robotics Society of Japan, vol.18, no.1, pp.150-157, 2000.
- [5] Kenjiro Tadakuma, Explanatory paper, "The trick of omni-directional moving and driving," Journal of the Robotics Society of Japan, Vol.32, No.4, pp.354-357, 2014.
- [6] K. Tadakuma, "Tetrahedral Mobile Robot with Novel Ball Shape Wheel ", The First IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob 2006). Parallel Session 6: "Animal-Inspired Models and Mechanisms", February 20th, 2006, Page(s):946 - 952.
- [7] Spherical wheel, and vehicle implementing the wheel, WO 2013164327 A1, inventors Vincent CLERC, Bruno Maisonnier, patent applicant Aldebaran Robotics, Public Notice No. WO 2013164327 A1, Publication Type Application, Application No. PCT/EP2013/058949, Cited Patent, WO2005028243A1 \* 23 September 2003 March 31, 2005
- [8] Kenjiro Tadakuma, Riichiro Tadakuma, Shigeo Hirose, "Development of VmaxCarrier2: Omni-Directional Mobile Robot with Function of Step-Climbing", Proc. of the 2004 IEEE International Conference on Robotics and Automation (ICRA 2004), ISBN: 0-7803-8233-1, pp.3111- 3111-8233-1, pp. 3111- 3118, 2004.
- [9] Hikaru Yatagai, Yasuyuki Yamada, Shune Kikuchi, Genya Ishigami, "Evaluation of mobile robot's performance on uneven terrain," 2A1-A06, JSME Tronix Conference 2014.
- [10] Yuichi Tsumaki, Koki Watanabe, Feng Guo Kong, Riichiro Tadakuma, Kenjiro Tadakuma, "Small Spherical Omni-wheel for Sphere Drive," 3P2-K05, JSME Tronix Conference 2014.
- [11] J. Tanaka, S. Hirose, "Study of a mobile robot Raccoon with a sphere-wheel flipper arm [Report 4] Study on the characteristics of the vehicle body". SICE 2007 The 8th Conference of the Society of Instrument and Control Engineers, Systems Integration Division.
- [12] Shuichi ISHIDA, Noriyuki SHIMPUKU, Kazuo ISHII, Hiroyuki MIYAMOTO, "Holonomic Omnidirectional Vehicle with Ball Wheel Drive Mechanism and Application to RoboCup Soccer Middle Size League" , 2014 Volume 26 Issue 3, Pages 669-677.
- [13] Husam A. Neamah, Hussam Akkad, "A Comparative Review of Omnidirectional Wheel Types for Mobile Robotics" , August 2023, DOI, 10.2139/ssrn.4488112
- [14] "Omnidirectional wheel", Inventor: William Liddiard, WO2014165962A1, WIPO (PCT)
- [15] Kenjiro Tadakuma, Riichiro Tadakuma, and Jose Berengueres, "Development of Holonomic Omnidirectional Vehicle with "Omni-Ball": Spherical Wheels", IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp. 33-39, Oct. 2007.
- [16] Kenjiro Tadakuma, Riichiro Tadakuma, Akira Maruyama, Eric Rohmer, Kenji Nagatani, Kazuya Yoshida, Aiguo Ming, Makoto Shimojo, Mitsuru Higashimori, and Makoto Kaneko, "Mechanical Design of the Wheel-Leg Hybrid Mobile Robot to Realize a Large Wheel Diameter", IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp. 3358-3365, Oct. 2010.
- [17] Hamid Taheri, Chun Xia Zhao, "Omnidirectional mobile robots, mechanisms and navigation approaches", Mechanism and Machine Theory, Volume 153, November 2020, 103958