

Flexible Omnidirectional Driving Gear Mechanism with Adaptation over Arbitrary Curvatures

Moses Gladson Selvamuthu¹, Kazuki Abe², Kenjiro Tadakuma² and Riichiro Tadakuma¹

Abstract—A support structure for flexible displays such as OLED or flexible LEDs was developed using the flexible omnidirectional driving gear mechanism. It is a gear mechanism having two degrees of freedom on one surface. This flexible display mechanism is expected to be placed inside a car dashboard as a human interface and for workspace optimization. In this study, we propose a novel flexible omnidirectional driving gear for supporting flexible displays discussing its design, motion range, repeatability, positional accuracy, and adaptability to any guide surface through magnetic coupling. The experiments showed satisfactory results for positional accuracy and repeatability with adaptability over a wide range of curvatures.

I. INTRODUCTION

The emergence of flexible display technology [1], [2], [3] represents a paradigm shift in the world of electronic devices. Unlike their rigid counterparts, flexible displays have the remarkable ability to bend, curve, and adapt to different surfaces. The design of support structures for flexible displays is highly intricate especially achieving the right balance between structural integrity and flexibility can be challenging. Several existing technologies include curved and foldable hinges for foldable smartphones [4], [5] and watches [6] where hinges are designed to allow folding and unfolding of flexible displays. However, continuous folding of a particular section over time leads to durability concerns. Rollable mechanisms [7], [8], [9] enable displays to be rolled up for compact storage or transportation, but the display becomes stiffer during operation, particularly when unrolled or extended. Sliding supports [10], [11], [12] were used to allow the display to adapt to specific tasks and body movements. Support structures are also fabricated from 3D printing [13], [14] and additive manufacturing with complex and customized support structures tailored to the shape and requirements of the flexible display. While these support structures are essential for maintaining the integrity of flexible displays, they still limit the degree of flexibility that the device can achieve. The current technologies do not effectively utilize the flexibility of the display devices during its dynamic operation. Mostly the flexibility of the mechanism relies on the display and the support mechanism itself is rigid. In this study, we propose a flexible omnidirectional driving gear mechanism as a support structure for flexible

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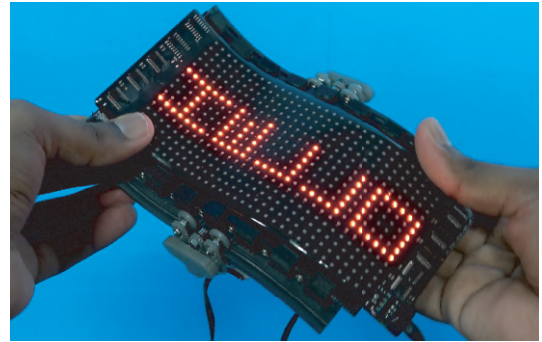


Fig. 1. Omnidirectional gear based support structure for flexible displays

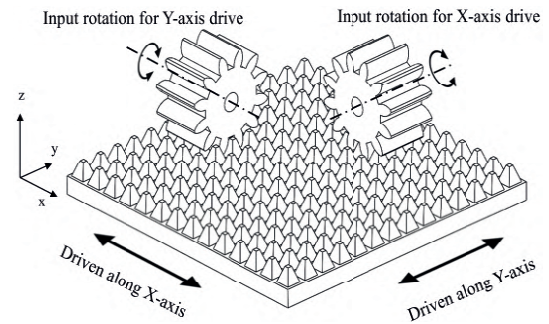


Fig. 2. Concept of omnidirectional driving gear

display, providing structural rigidity while maintaining its flexibility throughout the operation as shown in Fig. 1. The idea of bending gears is not new [15], [16], [17]. However, using a flexible omnidirectional driving gear mechanism imparts two degrees of freedom motion possible on a single surface making the overall system small and compact.

The omnidirectional driving gear mechanism [18], [19], [20], [21] is composed of two spur gears and a planar gear engraved with two perpendicular racks as shown in Fig. 2. Input from the X-axis drive gear passively moves the omnidirectional driving gear in the X-axis direction, during which the Y-axis drive gear slides between the teeth. The same applies to input from the Y-axis gear. The output obtained by simultaneous input from the X and Y-axis drive gears can be derived by combining vectors. The basic idea of flexible omnidirectional driving gear mechanism was introduced previously [22]. In this study, we focus on developing a prototype of omnidirectional gear mechanism for flexible display discussing its mechanical design, adaptability across different curvatures, positional accuracy experiments, and material selection. The drive unit was fixed and the flexible

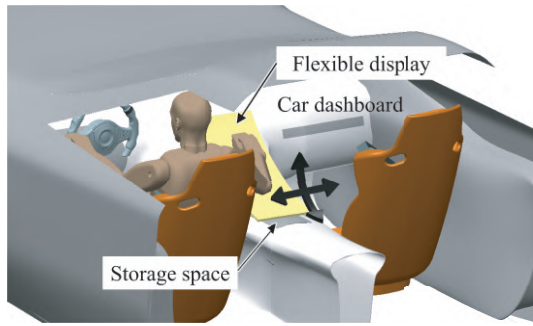


Fig. 3. Concept of flexible display in car dashboard

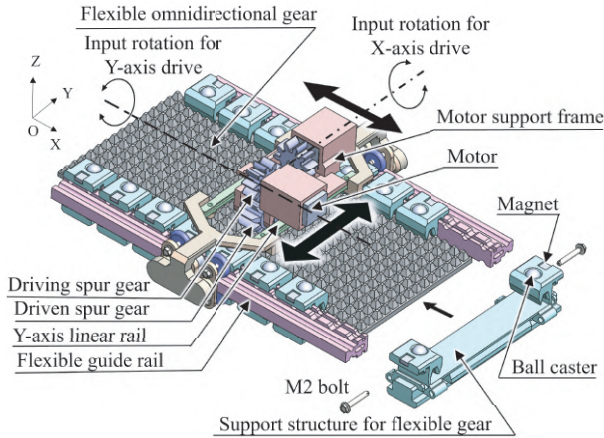


Fig. 4. Basic design of the flexible omnidirectional driving gear mechanism

gear was driven over arbitrary curvatures. The developed mechanism can be incorporated in a car dashboard, enhancing human interaction and optimizing workspace with storage beneath the display as shown in Fig. 3. Alternatively, it can serve as a movable, flexible display for interactive art and entertainment, providing a tactile engagement with digital art and functioning as a haptic device for VR.

This article introduces a novel flexible omnidirectional gear based support structure for display devices. Section II describes the design and control theory. Section III experimentally verifies the characteristics of the mechanism and discusses its potential applications. Section IV concludes the article. Section V is acknowledgement.

II. FLEXIBLE OMNIDIRECTIONAL DRIVING GEAR MECHANISM

A. Design of flexible omnidirectional driving mechanism

The motivation for the development of flexible omnidirectional driving gear mechanism was to increase the adaptability of the omnidirectional driving gear mechanism for different surfaces. The design challenges were the development of a flexible guide rail and roller mechanism, and a support for the flexible gear. Fig. 4 shows the basic design of the mechanism. The flexible components include omnidirectional driving gear and guide rails. The flexible omnidirectional gear of the mechanism was 3D printed from flexible TPU 95A (Thermoplastic polyurethane). The

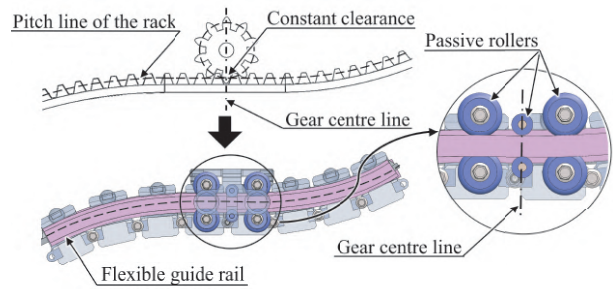


Fig. 5. Mechanism for constant clearance between the gears

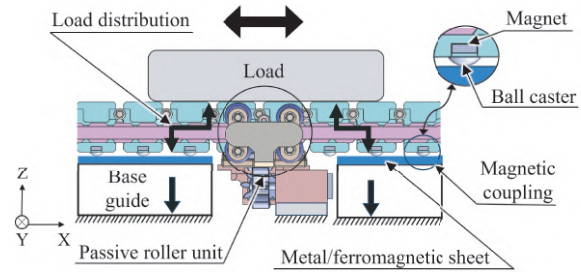


Fig. 6. Load distribution and magnetic coupling of the flexible omnidirectional gear mechanism to the base guide

guide rail was fabricated from Flexible 50A resin using the FormLabs Form 3 printer. The flexible omnidirectional driving gear is secured within a 3D-printed (PLA) support frame with passive hinges fastened by M2 bolts. This frame incorporates two neodymium magnets and ball casters on each end as shown in Fig. 4.

The flexible omnidirectional driving gear and guide rail is fixed to one end of the support frame and the other end is free to slide, to account for change in curvature during bending. The flexible gear can be deformed passively to form any arbitrary curvatures supported by the 3D printed backbone. Flexible gears suffers from variations in geometric pitch when bending. Hence, appropriate passive roller unit as shown in Fig. 5 that can travel freely along the flexible rails was designed and incorporated. The design favors a constant clearance and geometric pitch between the mating gears.

A thin metal or ferromagnetic sheet is fixed on the base guide frame. The support frame supporting the flexible gear adheres to the guide surface through magnetic coupling as shown in Fig. 6. When the curvature of guide surface changes, the gear remains magnetically coupled, enabling adaptation to various curvatures. The strength of magnetic coupling affects the bending capability which depends on strength of magnets, type of metal/ferromagnetic sheet, and the space between them. When a load is placed on the mechanism, majority of the load is distributed to the base guide via the ball casters. A fraction of the load taken by the passive guide rollers is transmitted to the base via motor support frame with load distribution depicted in Fig. 6.

A DC geared motor (Pololu 1000:1, brushed DC motor) with hall sensor-based encoder drives the flexible gear in both X and Y axes. Motor supports and drive gears are fabricated

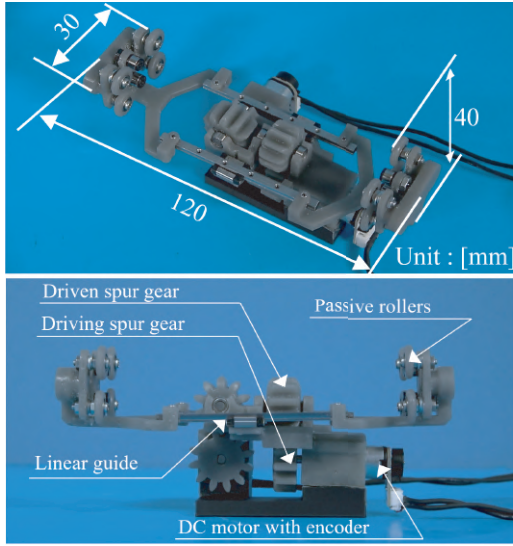
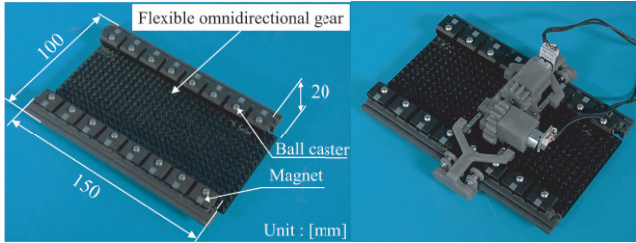


Fig. 7. Fabricated drive unit



(a) Flexible omnidirectional driving gear (b) Assembled mechanism
Fig. 8. Fabricated omnidirectional driving gear mechanism

from Draft resin using the Formlabs Form 3 printer. When X-axis spur gear is rotated, the flexible gear moves under the influence of passive rotation from the roller unit to achieve X displacement. When Y-axis spur gear is rotated, the flexible gear slides along the Y-axis linear guide for Y displacement. Combining X and Y-axis motions by activating both spur gears enables 2-DOF motion on a single surface. This single surface omnidirectional mechanism makes the overall system small and compact. The module of the gears was 1.5mm and the dimensions of the flexible gear are $150 \times 70 \times 4$ mm, where 4mm is the pitch height of the gear. Design parameters like module and number of rack teeth were constrained by the size of flexible display to be fixed on the mechanism but can be scaled up or down for different applications. Fig. 7 shows the fabricated drive unit and Fig. 8 shows the actual fabricated prototype of flexible omnidirectional driving gear mechanism. The prototype weighed approximately 200g. To achieve high positional accuracy and minimize backlash, the mechanism was driven with theoretical pitch circle distance.

Teensy 3.5 microcontroller and two TA7291P Toshiba motor drivers control the X and Y-axis drive motors. The omnidirectional gear is actuated via a 2-axis joystick or through serial communication between PC and Teensy 3.5. Limit conditions are defined based on the X and Y-axis motion range, with motion controlled by feedback from the

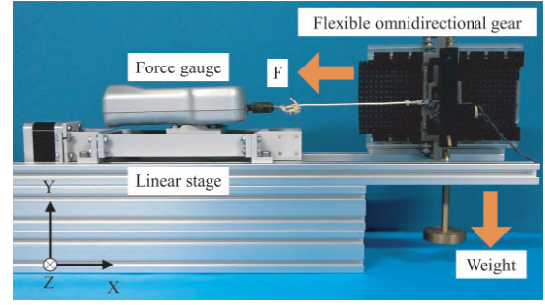


Fig. 9. Experimental setup for measuring sliding friction between the gears

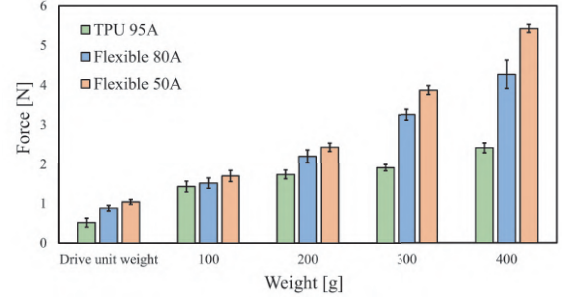


Fig. 10. Sliding frictional force between gears for different materials

motor's encoder. To drive the flexible omnidirectional gear along different trajectories, the instantaneous position $P(x,y)$ is derived and the equation converting this position to motor angle θ is given by

$$\theta_i = \begin{cases} \frac{P(x) \cdot 2\pi}{\pi m z_i} & (\text{X-axis motor}) \\ \frac{P(y) \cdot 2\pi}{\pi m z_i} & (\text{Y-axis motor}) \end{cases} \quad (1)$$

where m is the module, z is the number of teeth on the spur gear and $i = x, y$.

III. EXPERIMENTS

A. Experiment to measure the sliding frictional resistance

Three materials- TPU 95A, Flexible 80A, and Flexible 50A- were tested for suitability as flexible omnidirectional gears. During gear movement, at least one spur gear continually slides between the flexible gear teeth. Hence, choosing a material with minimal sliding frictional resistance is crucial for smooth operation and reduced motor power. Fig. 9 illustrates the experimental setup for quantitatively measuring sliding frictional resistance between the spur gear and flexible gear [23]. A constant pressing force is applied along the Y-axis using the attached dead weight.

The experimental setup consisted of a force gauge (FGPX-0.5, Nidec SHIMPO) fixed on the moving platform of a linear stage motion guide actuator driven by a NEMA 17 (14HS17-0504S) stepper motor. An inextensible string was connected between the drive unit and the force gauge. The force gauge, displaced at 1.5mm/s, passively moved the drive unit along the Y-axis under external weights. The force readings were recorded and indicate the sliding frictional force between

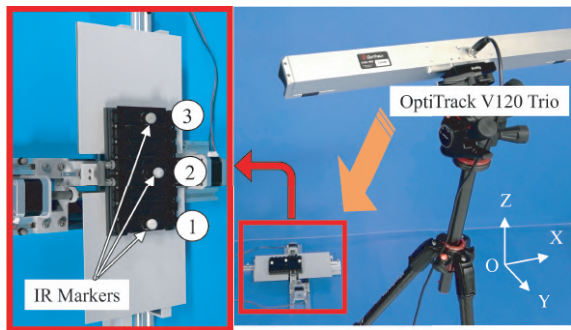


Fig. 11. Experimental setup for position tracking

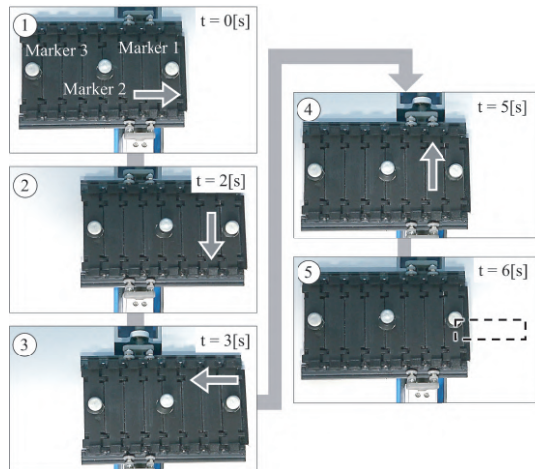


Fig. 12. Sequential motion of the omnidirectional gear mechanism with tracking markers along rectangular trajectory

the spur gear and flexible gear. Fig. 10 shows the sliding frictional force between the gears measured for different materials and pressing forces. The error bar indicates the standard deviation for five readings. TPU-based flexible gears exhibited lower frictional resistance than other materials, and hence was chosen for fabricating the flexible omnidirectional gear. In addition, alternative materials can be considered for fabricating the flexible gears. However, it is crucial that the chosen material minimizes sliding friction between the gears for smooth operational performance.

B. Positional accuracy, repeatability, workspace tracing and adaptability to different curvatures

Position tracking experiment was conducted to measure the prototype's positional accuracy and overall motion range. Fig. 11 shows the experimental setup used for measuring the displacement of omnidirectional driving gear. Two NEMA 17 (14HS17-0504S) stepper motors controlled the X and Y-axis gears. Infrared reflection (IR) tracking markers were fixed at three different points as shown in Fig. 11, with sequential motion of the mechanism depicted in Fig. 12. Positions of the markers were measured by the motion-capture system (OptiTrack V120 Trio; Natural Point Inc., Oregon, USA).

Fig.13(a) shows the motion of flexible omnidirectional gear on a flat surface driven along different trajectories using

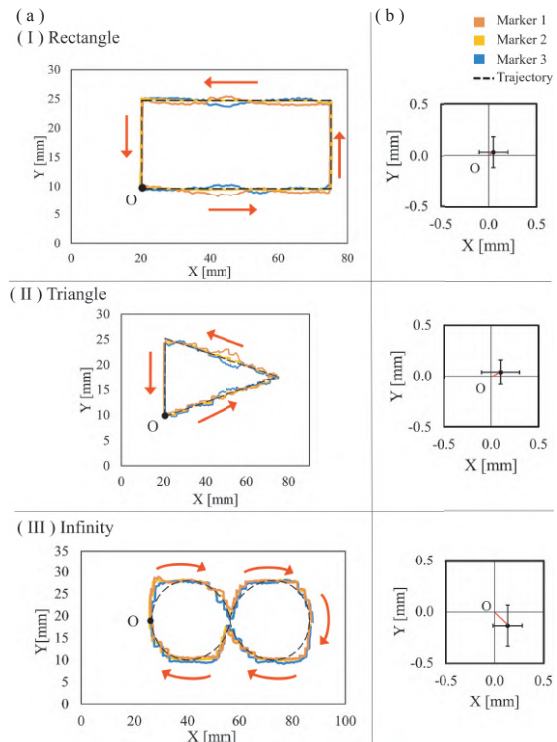


Fig. 13. Driving experiment of the flexible gear along different trajectories on a flat surface and results

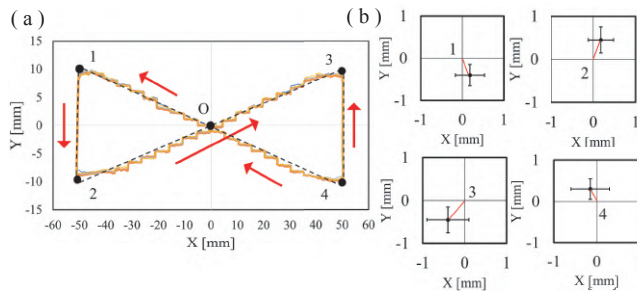


Fig. 14. Positional accuracy of the flexible omnidirectional gear mechanism

Equation (1). The markers correspond to the IR markers in Fig.12. Marker 2 exhibits a stable trajectory aligning closely with the actual path, while others show instability due to a single anchor point on the drive unit. To address this, adding an extra passive roller unit can constrain lateral displacement. Fig. 13(b) displays positional errors for tracking marker 2 about point O (start point of respective markers) after driving across various trajectories, with error bars indicating standard deviations from ten readings and tabulated in TABLE I. The flexible gear was also driven to four different setpoints along the trajectory shown in Fig. 14(a), to measure the positional accuracy of the mechanism. Fig. 14(b) shows the results of the experiment with error bar indicating the standard deviation for ten readings. The results show satisfactory positional accuracy with deviations less than 0.5mm from the target points.

Fig. 15 shows the adaptability of the mechanism along concave and convex guide surfaces fixed with SUS430

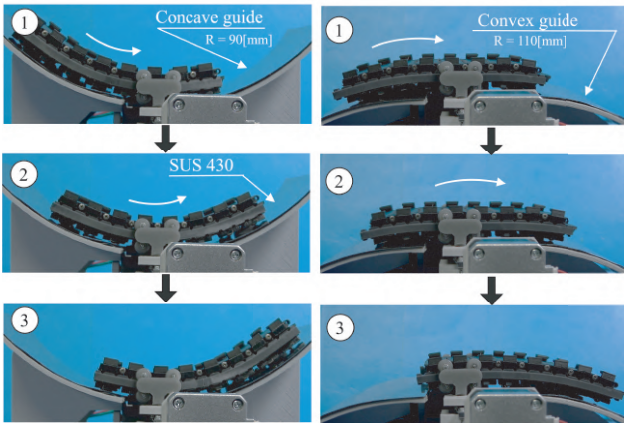


Fig. 15. Running experiment of flexible omnidirectional gear along concave and convex guide surface

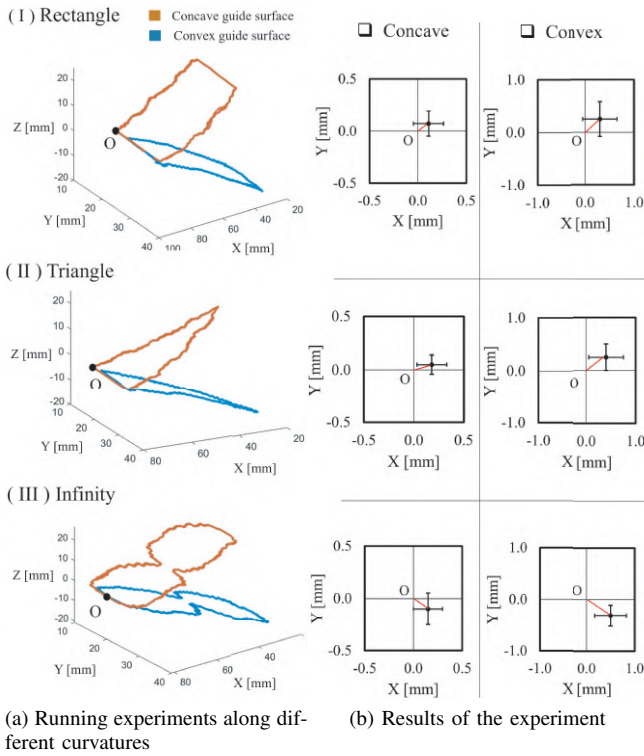


Fig. 16. Driving experiment of flexible gear along different curvatures

sheets. The mechanism achieves omnidirectional displacement along these curvatures through magnetic coupling. The mechanism successfully adapted to a concave guide of radius 80mm, limited by the end stops in the support structure which can be adjusted based on the bending capability of the flexible display. The mechanism also successfully adapted to a convex guide curve of radius 100mm, below which the magnetic coupling fails due to overall stiffness of the mechanism, which can be improved by using a stronger magnet. Fig. 16(a) shows the experimental results of driving the flexible omnidirectional gear along convex and concave guide surfaces. Fig. 16(b) shows the results of the positional error about point O with error bar indicating the standard

TABLE I
POSITIONAL ERROR ABOUT POINT 'O' FOR TEN READINGS

Surface	Rectangle		Triangle	
	Ave (x, y) [mm]	Std (x, y) [mm]	Ave (x, y) [mm]	Std (x, y) [mm]
Flat	(0.05, 0.03)	(0.15, 0.13)	(0.12, 0.06)	(0.17, 0.09)
Convex	(0.18, 0.45)	(0.27, 0.32)	(0.42, 0.23)	(0.33, 0.24)
Concave	(0.10, 0.07)	(0.14, 0.12)	(0.18, 0.05)	(0.15, 0.09)
Infinity				
Flat	(0.15, -0.10)	(0.12, 0.18)		
Convex	(0.49, -0.31)	(0.32, 0.20)		
Concave	(-0.15, 0.11)	(0.11, 0.15)		

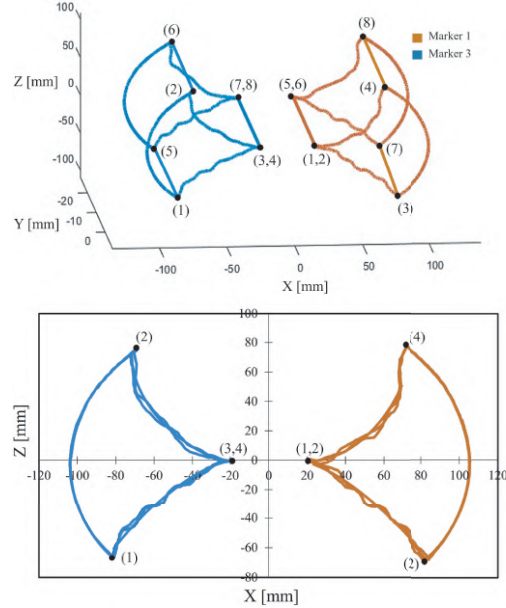


Fig. 17. Results of position tracking experiment for workspace tracing

deviation for ten readings. TABLE I lists the positional errors for different conditions with following observations.

- Positional accuracy of the mechanism is quite high with average error less than 0.5mm.
- Maximum deviation about point O is approximately 0.3mm, indicating high precision and repeatability.
- Positional error is slightly higher when the mechanism was driven along a convex surface due to a slight increase in mating distance, causing increased backlash.

The overall motion range of the flexible gear is plotted in Fig. 17. The points marked from 1 to 8 shows the corresponding positions of markers 1 and 3 at a given point in time. When marker 1 is at its extreme outer limit, marker 3 is at its extreme inner limit and vice versa. The flexible gear was passively bent to its limits using different guide surfaces and superimposed to trace the overall workspace. The center of the plot is empty because it houses the drive unit and the IR markers attached to the ends of the flexible gear cannot cross the drive unit. The estimated X-axis displacement is around ± 100 mm and the Y-axis displacement is around ± 12 mm. The motion range of the developed prototype is limited by the size of flexible display attached to the

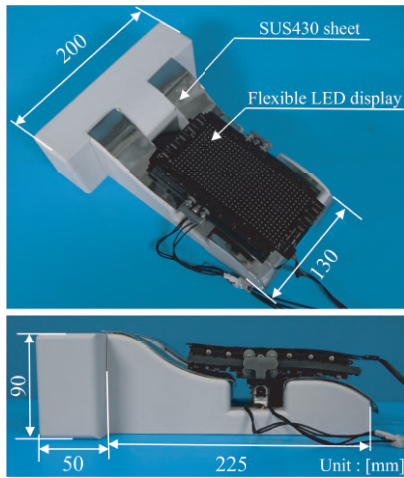


Fig. 18. Fabricated model of flexible display system

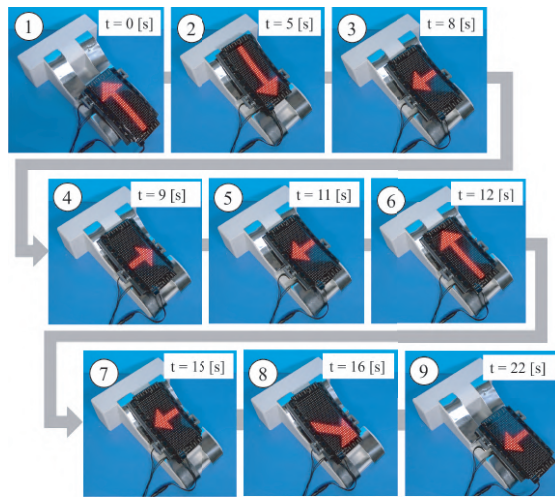
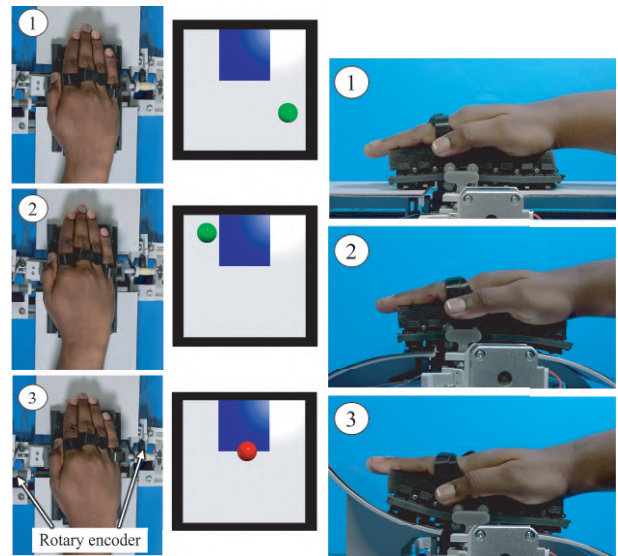


Fig. 19. Running experiment of the flexible display mechanism with graphical information represented physically

mechanism. However, the motion range of the mechanism can be increased by designing a larger flexible gear based on the application or extending the length of drive unit.

C. Potential applications of the mechanism

Experiments were conducted on the developed flexible omnidirectional driving gear prototype with flexible display to assess the feasibility and applicability of the mechanism in real-world application. Fig.18 shows the details of flexible display mechanism, utilizing a flexible LED display manufactured by SUBORAWOS. The display is attached to the flexible gear using a sliding sheet, allowing for curvature changes without damaging the display during operation. Fig.19 showcases the running experiment, highlighting the mechanism's adaptability to various guide surfaces and the physical interpretation of graphical information. The running experiments were successful, and the mechanism exhibited a reliable and smooth operation for different curvatures without damaging the display. A larger dashboard can be designed with larger display structure and storage spaces beneath the



(a) Interaction with objects in simulation environment (b) Slope of objects represented through different curvatures

Fig. 20. Flexible omnidirectional driving gear as a haptic device

display for effective utilization of workspace.

The mechanism can also be used as a haptic device where the X and Y spur gear rotations can be used as feedback using rotary encoders to move an avatar in a simulation environment and the interactions in the simulation environment can be translated to the hand by actuating the motors attached to the gears as shown in Fig. 20(a). It is also possible to drive the unit along different curvatures to indicate the slope or surface condition of the object in the simulation environment as shown in Fig. 20(b). The high positional accuracy of the flexible gear can be used to locate the position of hand in real world without using any positioning sensor.

IV. CONCLUSIONS

In this paper, we developed a compact 2-DOF support structure for flexible displays using the flexible omnidirectional driving mechanism. Our discussion covered the design and manufacture of a flexible omnidirectional driving gear mechanism capable of adapting to guide surface curvatures, with its motion range studied through position tracking. Running experiments with various guiding surfaces produced satisfactory results, demonstrating good positional accuracy and repeatability. Different materials were tested and the material with least sliding friction was chosen for fabrication of the flexible gear. The magnetic coupling between magnets in the support structure and the guide surface's metal sheet allowed the mechanism to adapt to any arbitrary curvature. In the future, we plan to create an actual prototype of the mechanism with OLED displays, intended for implementation as a graphical human interface inside automobiles.

V. ACKNOWLEDGEMENT

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REFERENCES

- [1] Forrest SR. The path to ubiquitous and low-cost organic electronic appliances on plastic. *nature*. 2004 Apr 29;428(6986):911-8.
- [2] Lee SM, Kwon JH, Kwon S, Choi KC. A review of flexible OLEDs toward highly durable unusual displays. *IEEE Transactions on Electron Devices*. 2017 Jan 19;64(5):1922-31.
- [3] Koo JH, Kim DC, Shim HJ, Kim TH, Kim DH. Flexible and stretchable smart display: materials, fabrication, device design, and system integration. *Advanced Functional Materials*. 2018 Aug;28(35):1801834.
- [4] Han HJ, Cho WJ, Lee SJ, Park HM, Hwang I. P - 109: Stress - Free Folding Hinge for Foldable OLED Display Device. In *SID Symposium Digest of Technical Papers 2021 May* (Vol. 52, No. 1, pp. 1336-1339).
- [5] Fletcher R. Rothkopf, Andrew J. M. Janis, Teodor Dabov. Flexible display devices. U.S. patent US9504170B2. Nov, 2018.
- [6] Zhu K, Fjeld M, Ünlüer A. WristOrigami: Exploring foldable design for multi-display smartwatch. In *Proceedings of the 2018 Designing Interactive Systems Conference 2018 Jun 8* (pp. 1207-1218).
- [7] Han HJ, Park HM, Hwang I. P - 8.3: Novel Rolling Hinge for Rollable Mobile Device. In *SID Symposium Digest of Technical Papers 2021 Aug* (Vol. 52, pp. 903-906).
- [8] Gomes A, Priyadarshana LL, Visser A, Carrascal JP, Vertegaal R. Magicscroll: a rollable display device with flexible screen real estate and gestural input. In *Proceedings of the 20th International Conference on Human-Computer Interaction with Mobile Devices and Services 2018 Sep 3* (pp. 1-11).
- [9] Jung Hun Lee, Youn Joon Kim, Cheol Su Kim, Yoon Jee Shin, Sang Jo Lee, Jang Do Lee, Ju Suk Lee, Kyung Min Choi. Display device. U.S.Patent US20160034000A1. Feb, 2016.
- [10] Takanaka S, Yano H, Iwata H. Multitouch haptic interface with movable touch screen. In *SIGGRAPH Asia 2015 Haptic Media And Contents Design 2015 Nov 2* (pp. 1-3).
- [11] Michael B. Wittenberg, Owen D. Hale, Tatsuya Sano. Electronic devices having sliding expandable displays. U.S. Patent 2020/0329572 A1. Oct, 2020.
- [12] Weigel M, Lu T, Bailly G, Oulasvirta A, Majidi C, Steimle J. Iskin: flexible, stretchable and visually customizable on-body touch sensors for mobile computing. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems 2015 Apr 18* (pp. 2991-3000).
- [13] Zarek M, Layani M, Cooperstein I, Sachyani E, Cohn D, Magdassi S. 3D printing of shape memory polymers for flexible electronic devices. *Advanced Materials*. 2016 Jun;28(22):4449-54.
- [14] Oh H, Ta TD, Suzuki R, Gross MD, Kawahara Y, Yao L. PEP (3D Printed Electronic Papercrafts): An Integrated Approach for 3D Sculpting Paper-Based Electronic Devices. In *CHI 2018 Apr 21* (p. 441).
- [15] Matsuda R, Mavinkurve UK, Kanada A, Honda K, Nakashima Y, Yamamoto M. A Woodpecker's Tongue-Inspired, Bendable and Extendable Robot Manipulator With Structural Stiffness. *IEEE Robotics and Automation Letters*. 2022 Jan 31;7(2):3334-41.
- [16] Mateos LA. Bionic sea urchin robot with foldable telescopic actuator. In *2020 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM) 2020 Jul 6* (pp. 1063-1068). IEEE.
- [17] Nagase JY, Suzumori K, Saga N. Development of worm-rack driven cylindrical crawler unit. *Journal of Advanced Mechanical Design, Systems, and Manufacturing*. 2013;7(3):422-31.
- [18] Tadakuma, Kenjiro, Riichiro Tadakuma, Kyohei Ioka, Takeshi Kudo, Minoru Takagi, Yuichi Tsumaki and Mitsuru Higashimori, and Makoto Kaneko. Study on the omnidirectional driving gear mechanism. 2012 IEEE International Conference on Robotics and Automation, pp.3531-3532.
- [19] Tadakuma K, Tadakuma R, Ioka K, Kudo T, Takagi M, Tsumaki Y, Higashimori M and Kaneko M. Omnidirectional driving gears and their input mechanism with passive rollers. 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems 2012 Oct 7, pp.2881-2888.
- [20] Abe K, Matsui G, Tadakuma K, Yamano M and Tadakuma R. Development of the omnidirectional transporting table based on omnidirectional driving gear. *Advanced Robotics*. 2020 Mar 18;34(6):358-74.
- [21] Minoru Takagi, Mwai Moses Mukila, Kenjiro Tadakuma and Riichiro Tadakuma. Study of Omnidirectional Driving Gears Corresponding to Free-form Surfaces - Basic Operating Characteristics of a Drive Unit with Two Curvatures. *Journal of the Robotics Society of Japan*. 2018;36(7):497-507.
- [22] Selvamuthu M.G, Tadakuma R. Study on Free-form and Flexible Omnidirectional Driving Gear with Arbitrary Curvatures. In *2023 IEEE/SICE International Symposium on System Integration (SII) 2023 Jan 17* (pp.1-7).
- [23] Park and Chan I.L. Tooth friction force and transmission error of spur gears due to sliding friction. *Journal of Mechanical Science and Technology*, 33(3), pp.1311-1319.