

Development and Application of the Low-Cost 3D Printable Servo Module with the Worm Gear Reduction Mechanism Capable of Switching between Open and Driven States

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Abstract—In robotics research that uses actuators to replace actual work in system integration, there is a growing demand for servo modules that we can use in various robots. We require the module to have the following three functions. 1) Supporting its weight without using energy, 2) the function to move the output link by external manipulation, and 3) being inexpensive and easy to duplicate and combine. In this study, we developed servo modules with openable worm gear reduction mechanisms ready for mass production to support a large load in the driven state and to move passively in the open state. As example configurations, we show 1: a winch for suspending a robot, 2: a non-backdrivable hand, 3: a teaching device, and 4: a carrying cart that can support its weight and carry heavy objects, demonstrating that the module can be easily used in a variety of configurations while fulfilling its intended functions.

I. INTRODUCTION

In recent years, we have conducted system integration research to automate tasks in factories and homes. Among them, especially in robotics research to replace physical tasks, a wide variety of robot forms have been proposed for various environments and applications, such as on land, in water, in the air, indoors, and outdoors, and in particular, by reconfiguring conventional servo motors, robot arms with various structures can be configured. The high-performance servo motors widely used tend to be capable of infinite rotation, measurement of current joint angles, temperature, and current values, and covering a variety of assembly methods.

For adapting to more diverse robots, the following three additional functions are required to increase the number of degrees of freedom and to improve the load capacity.

- 1) Continuously support loads caused by its own weight or external forces without using energy.
- 2) The ability to operate the drive output link by external manipulation for storage or teaching.
- 3) Ease of duplication of the modules with low cost.

First, when increasing the DOFs of robots, the joints are moved by their own weight and external forces, making it impossible for the robot to stand without a power source. Second, adding a brake mechanism to the joints has the disadvantage of increasing weight and size, so it is necessary to integrate the mechanism with a reduction gear to reduce weight and size. Third, it is essential to be able to mass-produce modules with additional functions inexpensively and simply when constructing a robot with multiple degrees of freedom that is easily damaged because

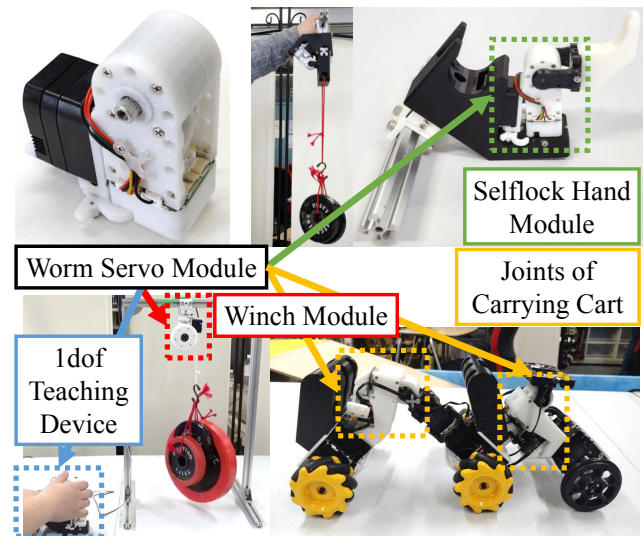


Fig. 1: The Compact Multi-Robot Configuration Kit Servo Module with the Worm Gear Reduction Mechanism.

it operates in a high-load environment, so it is desirable to be able to configure it inexpensively and quickly using a 3D printer or PCB manufacturing and mounting service.

In this study, we develop servo modules with worm gear reduction mechanisms that can switch between open and drive states using inexpensive and easy methods for replicating and reconfiguring examples of its application in multiple applications. The proposed worm gear reduction mechanism satisfies the following three requirements. 1) the worm gear can mechanically support a load due to its self-locking property, 2) we can switch the worm gear from the outside by disengaging the worm gear, and 3) we can fabricate the worm gears by 3D printing, which is inexpensive and can make various shape parts.

II. RELATED WORK.

As servo modules and drive systems that are costly to build but provide high functionality, researchers have proposed modules with large outer rotor motors and low reduction ratio planetary gears [1], [2], or with torque sensors and elastic elements in addition to reduction mechanisms and motor drivers [3], which we can use for force-controlled, environmentally friendly operation. In addition, they also proposed a method that can withstand instantaneous high current and achieve high torque and

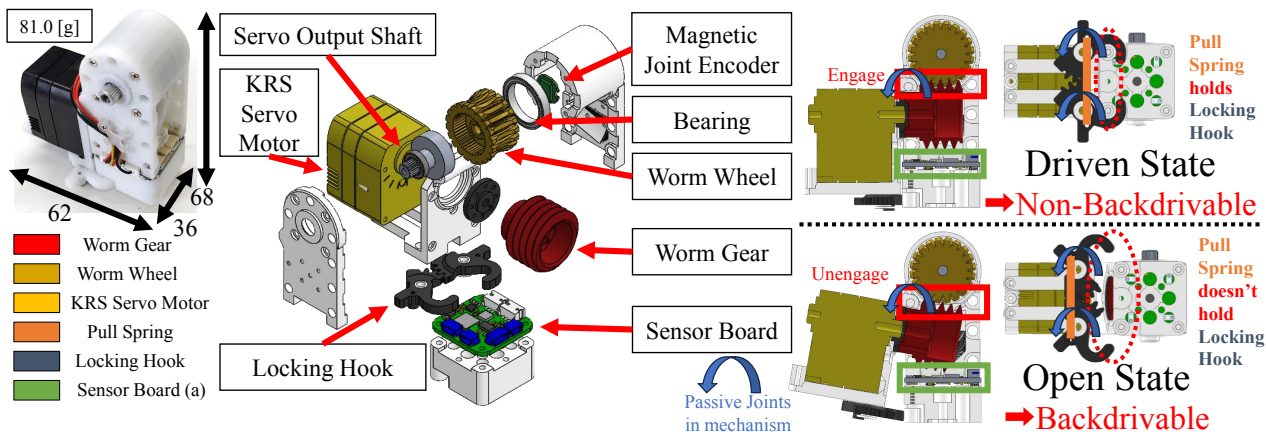


Fig. 2: Design of Compact Worm Servo Module(KRSR-20) Capable of Switching between Driven and Open States. Module has three passive joints and we can change state by manipulating the locking hook and an engagement of gears.

joint speed by cooling the motor [4], [5], achieving high motion capability.

In recent years, researchers have been investigating methodologies to construct diverse structures rather than achieving maximum specifications. They have proposed a variety of soft robots that can be 3D printed [6], [7], cycloid reduction mechanisms [8], and variable reduction mechanisms [9] using 3D printable materials, to reduce assembly time and mass production at low cost and lightweight by constructing them as a single unit. As for methods to construct robots by combining modules, they have been working on the method for constructing detachable mechanisms [10], [11], [12] and the body structure and controller exploring method [13], [14].

In our research on how to construct these modules, we use many manufacturing methods that focus on mass production, manufacturing speed, and low cost, such as inexpensive FDM 3D printers [15] used to manufacture plastic parts and printed circuit board manufacturing services that are available across countries. As described above, as robotics research progresses and the range of applications increases, we assume that there will be a transition from research that uses high-cost servo modules to configure a small number of robots to research that uses low-cost modules to configure many types of robots. Among these studies, we show how to construct servo modules that we can easily mass-produce by proposing the structure to be fabricated by a home-use 3D printer or PCB manufacturing and mounting service.

III. DESIGN OF LOW-COST SERVO MODULE WITH WORM GEAR WITH SELFLOCKING MECHANISM

A. Concepts of the Mechanism Design.

We present three concepts of the mechanism design.

- 1) The ability to support a load with a simple mechanism that does not use energy.
- 2) The function to move the joint with an external force or torque with the simple mechanism.

- 3) Able to manufacture dedicated parts at low cost and high speed in multiple size and shapes.

First, regarding the load support, we present the self-locking mechanism of the reduction mechanism using a worm gear and worm wheel, which we can easily duplicate by 3D printing and the structure has the advantage that the gear can be configured with a reduction ratio that suits the application. Next, for the function that can be moved by an external force, researchers have proposed methods that provide back drivability by controlling the worm gear with vibration [16]. In this research, we realize autonomous changes in body functions even in robots using commercially available servomotors, which have limited functions, by constructing a simple function that can physically release the engagement of the worm gear. Finally, we designed the parts to be manufactured by a method that does not depend on a specific vendor, i.e., a home-use 3D printer and printed circuit board manufacturing service, so that they can be designed and manufactured to various shapes and specifications and easily used for various manipulator robots.

B. Mechanical Design of Servo Module

We show the design of the servo module in Fig.2. The conventional worm gear reduction mechanism has a self-locking feature and can support the load without a power supply, but at the same time, it cannot be driven when we want to drive externally for teaching or storage. In this research, a pair of locking hook mechanisms constrain the relative positions of the worm gear and worm wheel for the switching mechanism. The worm reduction mechanism becomes the open state when we separate the relative positions of the worm gear and worm wheel by opening the locking hook and becomes the driven state when they are engaged by closing the hook. This locking mechanism decreases the losses due to friction in the engagement of the worm wheel and worm gear in previous research [13] by avoiding using the spring for engagement directly.

TABLE I: Specifications of Worm Gears

Specification	Parameter
Module of Worm Gear(m_x)	1
Rows of Worm Gear(Z_1)	1
Reference circle diameter of Worm Gear(d_1)	21 [mm]
Standard cylinder torsion angle of Worm Gear(γ)	2.73 [deg]
Number of tooth of Worm Wheel(Z_2)	20
Reference circle diameter of Worm Wheel(d_2)	21 [mm]

$$\gamma = \arctan(m_x Z_1 / d_1) \quad (1)$$

The worm gear mechanism used in this module can be freely made according to the target specifications of joints by fabricating the 3D modeled structure by 3D printing. The parts of servo modules are configured by adjusting the module and reference circle as the main parameters, and the various dimensions are shown in Table.I. The parameters set by the user are m_x, d_1, d_2, Z_1, Z_2 , which are defined to achieve the desired reduction ratio and module size. By using parameters to define multiple sizes of parts, the overall shape can be changed simply by changing a few parameters.

We print parts of this worm gear with UP300(FDM type Printer)¹ using UP Fila (ABS+) as the material, and we set the density of printing to 99%. In addition, we have connected to the output shaft of the module the same servo horn as the servo motor used for the module, so that ready-made servo arms and frame parts sold at [17] can be used without modification. We have adjusted the parameters at the time of printing so that the support material does not stick to the tooth surface. We can use the printed gears without lubrication for the gear tooth surface. Furthermore, we fixed the permanent magnet magnetized in the radial direction to the bottom of the output link to measure the rotation angle with the magnetic encoder.

C. Circuit Hardware System of Servo Module

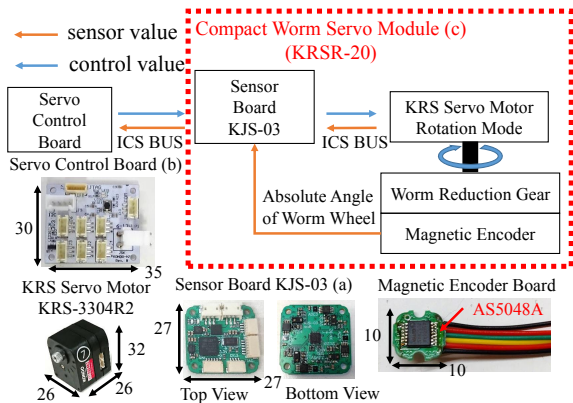


Fig. 3: Detail of Hardware System of KRSR-20.

We show the circuit hardware system of this module KRSR-20 in Fig.3. The circuit hardware of this module

consists of a composite sensor board module[18] with multiple external interfaces and a magnetic encoder AS5048A² with the SPI interface. The servo and the sensor board have a scalable configuration that can be daisy-chained using the same UART communication system and cable. The magnetic encoder has a 14-bit resolution with no dead zone and can be used for position and velocity control. Also, the magnetic encoder has no electrical contacts to the magnet on its surface, so it can operate robustly even under conditions where other materials cover the encoder sensor. The footprint of the encoder itself is only 7 mm square we can mount the sensor on various module shapes, making it possible to construct similar servo modules with other specifications of size or torque.

D. Cost of Production of Servo Module

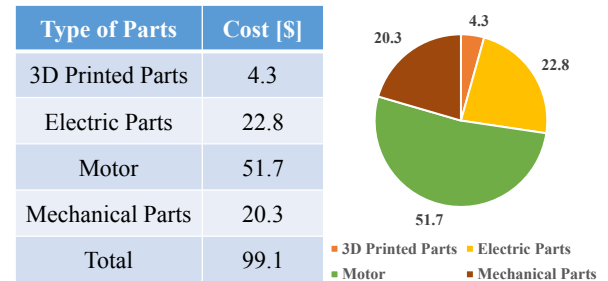


Fig. 4: Costs of Parts for making one Servo Module.

We show the cost required to configure one servo module in Fig.4. The cost of 3D printed parts is calculated by the weight of the filament, and the cost of electronic circuit parts includes ICs and cables. The cost of Mechanical Parts such as bearings and screws excludes the cost of 3D printed parts. As shown in Fig.4, we need 99.1[\$] to make one module. The 3D Printed Parts and Motor determine the output torque, especially when changing only the reduction ratio, which is inexpensive. It is possible to produce different specifications inexpensively, especially when only the reduction ratio is changed.

IV. APPLICATIONS OF SERVO MODULE(KRSR-20) FOR ROBOTS

We show examples of robot applications of the servo module (KRSR-20) for single-axis and multi-axis robots. As single-axis applications, we show 1: a winch for suspending a robot using its non-backdrivability, 2: a non-backdrivable hand, and 3: a teaching device using its openable feature. As an example of application to a multi-axis robot, we show 4: a humanoid equipped with a carrying cart using the servo module to support its own weight and heavy objects.

A. Single-axis Applications

By replacing parts connected to the end of the output link and the main body, we show examples of single-axis applications in Fig.5. For each application, the fixing

¹<https://www.tiertime.com/up300/>

²<https://ams.com/ja/as5048a>

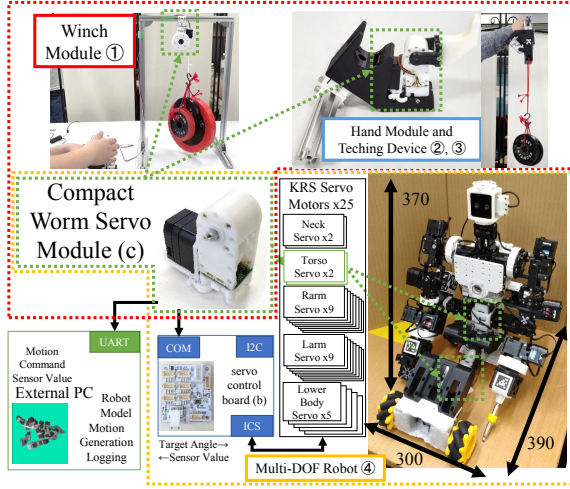


Fig. 5: Applications of Compact Worm Servo Module.

claws can be manually operated to switch between a driven state which is un-back dribble and can be used to support loads without a power supply, and an open state which is free and can be moved freely by external force. First, for use in a winch for suspending a robot(①), we attach a pulley with a radius of 25[mm] to the output link, and Dyneema (maximum tension: 173[kg]) with a diameter of 1.5[mm] is fixed to the pulley. Next, regarding using it for non-back drivable hands(②), it is possible to maintain the grasping state without using energy or to fix the hand in the environment to continue supporting its weight, since this hand can bear loads even without a power source. Finally, as for the use of the open state in teaching devices(③), we present an example in which a module integrated into the winch module is taught by a similar module outside the device while it is still in the drive state.

B. Multi-axis Application

For an example of application in a multi-degree-of-freedom, we show a humanoid(④) whose lower body is a carrying cart that utilizes a servo module at its waist axis for supporting its weight and a load of heavy objects. Since the upper body can change the function of the servo module according to the purpose, the robot can realize self-weight support and carrying function in the driven state and rough terrain movement in the open state.

V. EXPERIMENTS

A. Experiments of Single-axis Application

TABLE II: Comparison of Specifications of developed Servo Module and conventional servo motor. (Power Supply:12V).

Name	Weight	Output	Velocity
KRS-3304R2	32.7 [g]	980 [Nmm]	545 [deg/s]
KRSR-20(CW)	81.0 [g]	367.5 [Nmm]	27.27 [deg/s]
KRSR-20(CCW)	81.0 [g]	2205 [Nmm]	27.27 [deg/s]

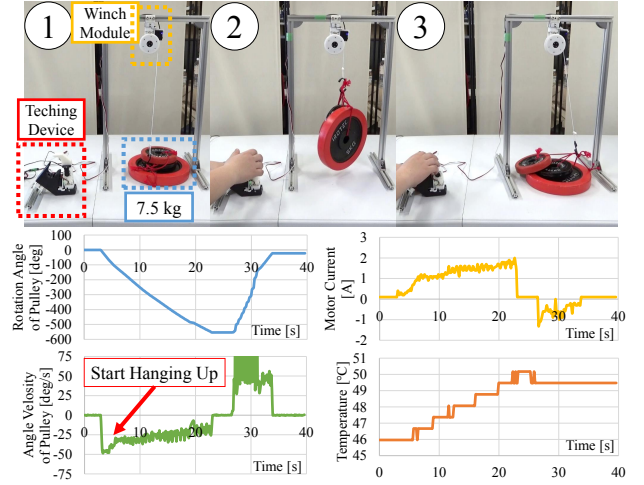


Fig. 6: Setting and Result of Evaluation of Single KRSR-20 Module.

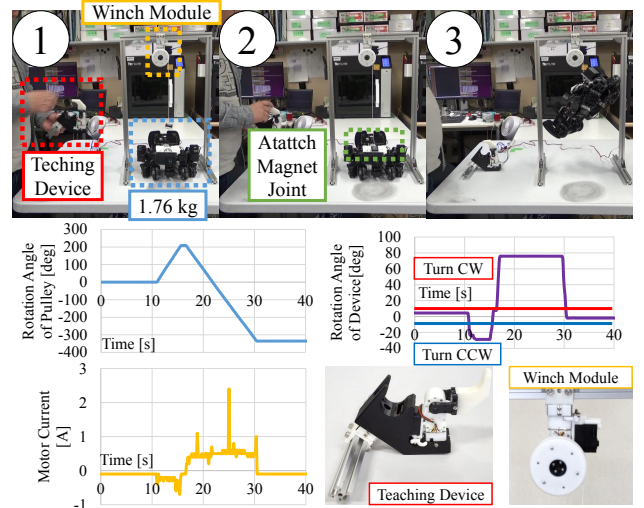


Fig. 7: Setting and Result of Experiment with Winch Module and Teaching Device using KRSR-20.

We show the experimental appearance of the evaluation of the single axis KRSR-20 in Fig.6 and the results in Table.II. We fixed a pulley, also used in the winch module, to the output link of the KRSR-20 configured in this paper and the KRS-3304R2, an off-the-shelf product also used in this module, and evaluated whether it is possible to lift a known weight with a Dyneema string. The KRSR-20 was able to produce about 2.25 times the torque of the KRS-3304R2 in counter clock wise direction(CCW), but the transmission efficiency was about 11.25[%] because of the reduction ratio of 20 in the worm gear. This is lower than that of conventional worm gears made of metalworking. On the other hand, the clock wise direction(CW) worm gear could only suspend a smaller load due to ratcheting caused by the separation force in the direction of the worm gear peeling off.

We attached a magnet detachable mechanism to the tip of a winch module, and the results of an experi-

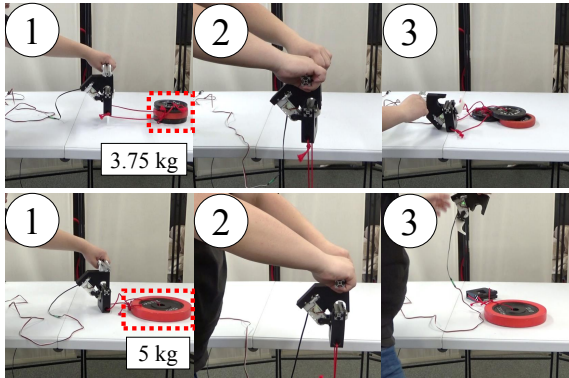


Fig. 8: Setting and Result of Experiment with Hand Module and Teaching Device using KRSR-20.

ment of suspending the humanoid by manipulating the direction of the winch rotation with a separately prepared teaching device using KRSR-20 are shown in Fig.7. In this experiment, the winch pulley is switched between forward, reverse, and stop according to the positive and negative of the current angle including the dead zone of the device to suspend a humanoid on the ground. As shown in Fig.7, we can confirm that the humanoid with a weight of 1.76[kg] continues to be lifted even after the drive power is turned off while the humanoid is suspended. Since the external force does not directly appear as a load on the servomotor because this module has un-back-drive characteristics, we confirmed that the angle of the output link, which is directly measured by the magnetic encoder, did not fully follow the target angle since the load increases discontinuously at the moment of lifting.

B. Experiments of Multi-axis Application

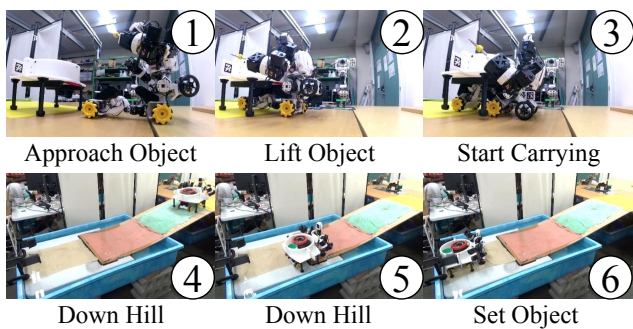


Fig. 9: Overview of the Experiment of modifying the driving state of Carrying Cart for carrying the heavy object.

Regarding the experiment using a transport cart with a servo module, we show the results of the experiment using servos in the driven state in Fig.9 and Fig.10 and the experiment using servos in the open state in Fig.11 and Fig.12. First, in the case of Fig.9, we can use the servo module of the carrying cart in the driven state for self-weight bearing and lifting heavy objects. As shown in Fig.10, we can confirm that the servo motor consumes current during the lifting operation, but the servo motor

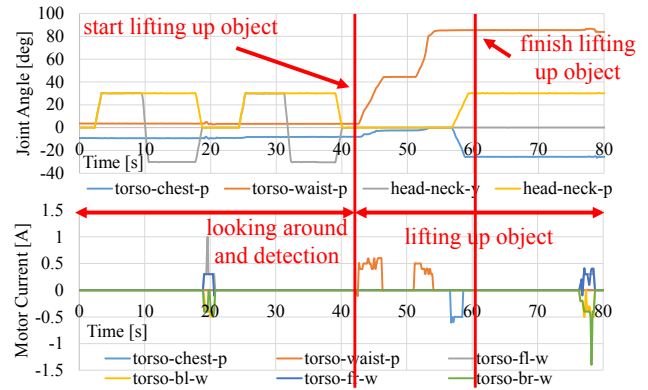


Fig. 10: Result of the Experiment of modifying the driving state of Carrying Cart for carrying the heavy object.

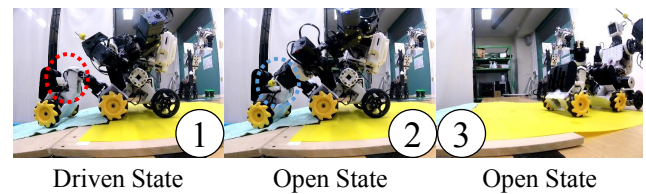


Fig. 11: Overview of the Experiment of modifying the driving state of Carrying Cart for moving over rough terrain.

can support its weight and load without current flow before and after the lifting operation. Next, the small robot pauses at the floor and switches the servomotor to the open state from the driven state using the left arm bit in ① and ② of Fig.11. By using the open state of the servo module to allow the all six wheels of the transport cart to touch the environment passively in ③ of Fig.11. The carrying cart can move on rough terrain with six wheels passively touching the environment. As shown in Fig.12, the humanoid determines that it can perform a rough terrain movement with the cart and executes the movement by detecting that the humanoid is in the state that waist actuator is in the open state. As described above, the humanoid achieved multiple movements by switching the operation state of the servo module according to the target movement.

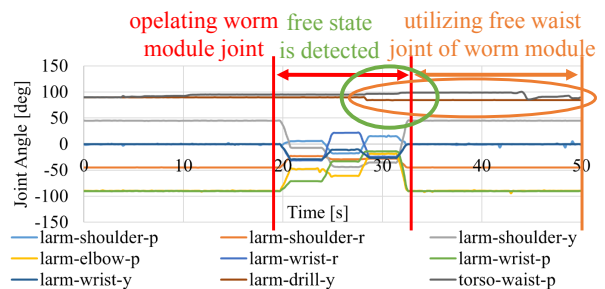


Fig. 12: Result of the Experiment of modifying the driving state of Carrying Cart for moving over rough terrain.

VI. DISCUSSION

First, about the evaluation of the single axis shown in the Subsection V-A, the module was able to lift a load of about 92.6 times its weight (7.5[kg]) when used for the winch module. Assuming that the maximum torque that can be exerted is constant, the maximum load that can be suspended depends greatly on parameters such as the radius of the moment arm=radius of pulley and worm gear specifications. By changing the various parameters for the object to be suspended and the speed at which it is suspended, it is possible to construct a winch that is both self-locking and openable without significantly changing the structure of the module.

The transmission efficiency of the worm gear fabricated in this study was as low as about 11.25[%], while that of commercially available worm gears fabricated by machining was at least about 30[%]. This is due to friction and mechanical loss caused by the worm gear's rough surfaces. We may decrease the loss by making worm gears using an optical 3D printer. As fabrication methods to reduce loss, even in the same 3D printing fabrication, there are methods to adjust the stacking direction and support material adhesion area in the case of the FDM method or to use optical fabrication or the SLS method, which enable smoother surface. By reducing losses in the gears, it is thought that the gripping force that can be exerted when using it for the hand can be increased.

Finally, regarding using a multi-axis robot for the waist axis, we configured the carrying cart shown in the experiment which can support its own weight and heavy objects without a power source. In the transportation experiment, the robot achieved to carry a maximum weight of (5[kg]), which was twice the robot's own weight (2.5[kg]), and achieved to continue supporting the load without using a dedicated mechanism such as a brake mechanism. Furthermore, by manipulating the servo module's function using the upper body arm after the carrying operation to a open state, the switching enabled the robot to move on rough terrain to continue placing its many wheels in the environment. This was achieved by configuring the switching function to be simple enough to be operated by a robot.

VII. CONCLUSION

In this paper, we proposed the KRSR-20, a small servo module with an openable worm gear reduction mechanism that can be easily replicated with the following three properties: (1) self-locking mechanism that can mechanically support a load, (2) external drive by disengaging the worm gear, and (3) 3D printed worm gear that can be applied to various shapes with a low cost. Through the configuration and experiments of four different applications (winch module, hand module, teaching device, and carrying cart), we have shown that the KRSR-20 can be used for various purposes. We show prospects. First, we need to develop the control method by estimating and utilizing the term that accounts for the external force in the joint torque

estimated by the joint encoder as described above for using the modules with un-back-drivable features for contact behavior in the environment. Regarding the proposal of other mechanisms, there are possibilities for us to develop the servo motors to have the mechanism with a linear degree of freedom and to utilize them in the tail and leg structure including those proposed in this study.

REFERENCES

- [1] P. M. Wensing, A. Wang, S. Seok, D. Otten, J. Lang, and S. Kim, "Proprioceptive actuator design in the mit cheetah: Impact mitigation and high-bandwidth physical interaction for dynamic legged robots," *Ieee transactions on robotics*, vol. 33, no. 3, pp. 509–522, 2017.
- [2] B. G. Katz, "A low cost modular actuator for dynamic robots," Ph.D. dissertation, Massachusetts Institute of Technology, 2018.
- [3] F. Negrello, M. Garabini, M. G. Catalano, J. Malzahn, D. G. Caldwell, A. Bicchi, and N. G. Tsagarakis, "A modular compliant actuator for emerging high performance and fall-resilient humanoids," in *Humanoids2015*. IEEE, 2015, pp. 414–420.
- [4] J. Urata, T. Hirose, Y. Namiki, Y. Nakanishi, I. Mizuuchi, and M. Inaba, "Thermal control of electrical motors for high-power humanoid robots," in *IROS2008*. IEEE, 2008, pp. 2047–2052.
- [5] K. Kojima, T. Karasawa, T. Kozuki, E. Kuroiwa, S. Yukizaki, S. Iwaishi, T. Ishikawa, R. Koyama, S. Noda, F. Sugai, S. Nozawa, Y. Kakiuchi, K. Okada, and M. Inaba, "Development of life-sized high-power humanoid robot JAXON for real-world use," in *Humanoids2015*, 2015, pp. 838–843.
- [6] J. Z. Gul, M. Sajid, M. M. Rehman, G. U. Siddiqui, I. Shah, K. Kim, J. Lee, and K. H. Choi, "3d printing for soft robotics—a review," *Science and technology of advanced materials*, vol. 19, no. 1, pp. 243–262, 2018.
- [7] T. Wallin, J. Pikul, and R. F. Shepherd, "3d printing of soft robotic systems," *Nature Reviews Materials*, vol. 3, no. 6, pp. 84–100, 2018.
- [8] W. Roozing and G. Roozing, "3d-printable low-reduction cycloidal gearing for robotics," in *IROS2022*. IEEE, 2022, pp. 1929–1935.
- [9] T. Makabe, T. Shirai, Y. Nagamatsu, K. Kawaharazuka, F. Sugai, K. Okada, and M. Inaba, "Development of joint module with two-speed gear transmission and joint lock mechanism during driving for task adaptable robot," in *IROS2019*. IEEE, 2019, pp. 5123–5130.
- [10] T. Fukuda, T. Ueyama, Y. Kawauchi, and F. Arai, "Concept of cellular robotic system (cebot) and basic strategies for its realization," *Computers & electrical engineering*, vol. 18, no. 1, pp. 11–39, 1992.
- [11] J. Mrázek and J. Barnat, "Roficom—first open-hardware connector for metamorphic robots," in *IROS2019*. IEEE, 2019, pp. 2720–2725.
- [12] T. Makabe, K. Okada, and M. Inaba, "Development of the Assembling System for Structure Transformable Humanoid with Attach-Lock-Detachable Magnetic Coupling (in press)," in *Proceedings of The 2024 IEEE International Conference on Robotics and Automation*. IEEE, 2024.
- [13] K. Kawaharazuka, T. Makabe, K. Okada, and M. Inaba, "Daily assistive modular robot design based on multi-objective black-box optimization," in *Proceedings of the 2023 IEEE/RSJ International Conference on Intelligent Robots and Systems*, October 2023, pp. 9970–9977.
- [14] A. Zhao, J. Xu, M. Konaković-Luković, J. Hughes, A. Spielberg, D. Rus, and W. Matusik, "Robogrammar: graph grammar for terrain-optimized robot design," *ACM Transactions on Graphics (TOG)*, vol. 39, no. 6, pp. 1–16, 2020.
- [15] "Bambu Lab X1-Carbon 3D Printer(Bambu Lab)." <https://us.store.bambulab.com/products/x1-carbon>.
- [16] T. T. N. and Hisamatsu, "Worm gear mechanism with switchable backdrivability," *Robomech Journal*, vol. 6, pp. 1–10, 2019.
- [17] "KRS Servomotor Series (KONDO KAGAKU CO. LTD)." <https://kondo-robot.com/product-category/servomotor/krs>.
- [18] T. Makabe, N. Hiraoka, S. Noda, T. Anzai, K. Kimura, M. Hattori, H. Sato, F. Sugai, Y. Kakiuchi, K. Okada, and M. Inaba, "Design and Development for Humanoid-Vehicle Transformer Platform with Plastic Resin Structure and Distributed Redundant Sensors," in *ICRA2022*. IEEE, 2022.