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Development Force Control of a Series Elastic Actuator to Excavator for Mechanization of Manual Work*

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Abstract— **Automation can address labor shortage and enhance worker safety in construction. However, workers continue to perform majority of the work at construction sites that can be automated. Construction machinery require force control for automation, which can absorb external shocks and provide appropriate forces along with environmental forces. This study proposes a force-controlled excavator that fulfills these requirements by replacing the hydraulic system with a series elastic actuator (SEA). Few studies have applied SEA to large high-output construction machinery. We designed the structure of the SEA to deliver high output power in a compact form that can be mounted on an excavator. A 2.5-T class excavator equipped with this SEA is designed, which achieved a force resolution of 15–35 N at the tip. The effectiveness of this excavator in automating a major portion of the manual work is demonstrated.**

I. Introduction

According to several labor surveys and investigations [1], labor shortages in the construction industry of Japan are becoming severe owing to the declining birthrate and aging population of the country. The population of Japan is predicted to decrease by approximately 30% by 2045 compared with 2015. Experts have raised concerns that this might lead to a significant decrease in the workforce at construction sites [1]. Furthermore, construction sites are among the most dangerous working environments in the industry, with the risk of accidents increasing as the population of senior workers with declining attention spans increases [2]. Notably, exposure of workers to strong heat stress due to climate change will reduce the outdoor working hours [3].

Several pieces of automation technology for the construction industry have been developed to counter labor shortages and improve worker safety. A recent survey [4] proposed levels of automation for excavators and dozers, as well as a roadmap for developing the necessary technology. However, the study was limited to dozers and other equipment that were already mechanized. Examples of onsite applications of robots include welding and material handling robots [5]; however, their application range is limited because their specialist nature.

In the last few decades, the nature of work has been gradually evolving from manual to mechanized, automated, or autonomous; however, several construction works that could otherwise be mechanized continue to heavily involve manual labor [6]. Especially, tasks such as fine alignment and fitting of materials can only be performed by hand because only humans can accurately sense the forces generated between their hands and the environment and perform the work. Therefore, if force sensing and control can be handled by machines, the overall work can be automated to a certain extend and the burden on workers can be reduced.

Actuators are used to automate machine-aided processes. Figure 1 illustrates the drive systems and features of some major actuators. Hydraulic actuators, such as hydraulic motors conventionally installed in construction machinery, have the advantages of being compact, powerful, and unbreakable even under heavy impact owing to their high-power density. However, achievement of precise operation in response to the forces has been difficult due to variables such as valve responsiveness. While studies have reported the installation of pressure sensors in hydraulic actuators to estimate external forces [7,8], they focused on providing feedback to the operator of the construction machinery and not at properly handling forces.

An electro-hydrostatic actuator (EHA) consists of a pair of pumps and a hydraulic motor, and the pumps are driven by servomotors [9]. Although it has high back-drivability and can sense force from pressure measurements, it does not achieve stable and precise operation due to changes in the characteristics caused by the ambient temperature of the hydraulic fluid.

Meanwhile, electric motors can achieve precise motion. In [10], a method for brick piling using an electric industrial robot was proposed, which performed the task with high precision. However, during operation on construction sites, the reduction gear of the motor can be damaged by unpredictable external forces. Similarly, sensors such as load cells mounted for force sensing may be damaged by external impact. To solve this problem, [11] proposed series elastic actuator (SEA) system in which an elastic body such as a spring is mounted on the output

	Actuator Type	Force Control	Position Control	Shock Absorption	Response Time
Hydraulic	Conventional system: Pump → Valve → Hydraulic Motor → LOAD			✓✓	
Hydraulic	EHA (Electro-Hydraulic Actuator): e-Motor → Pump → Hydraulic Motor → LOAD		✓✓	✓✓	✓
Electric	Electric motor+Reduction Gear: e-Motor → Gear → LOAD	✓	✓✓		✓✓
Electric	SEA (Series Elastic Actuator): e-Motor → Gear → Spring → LOAD	✓✓	✓✓	✓✓	✓

Fig. 1 Comparison between actuators

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side of the reduction gear to absorb shock and protect it. The SEA is a piece of technology that has garnered research interest as producing precise motion and shock absorption, as reported in a recent study on its application in the legs of a quadruped robot [12]. However, few examples of large actuators with high outputs are available, such as those used in construction machinery.

With the relevant and consolidated techniques proposed in the literature, this study proposed a large SEA system that could be implemented in construction machinery to mechanize manual work. The main contributions of this study are as follows: i) compact design of a new elastic element of the SEA that enables high output power and can be mounted on an excavator; ii) electrification of the bucket, arm, and boom joints; iii) implementation of the system in a prototype based on a 2.5-T class commercial excavator; and iv) demonstration of the mechanization of manual tasks such as alignment of materials.

The remainder of this paper is organized as follows. Section II describes the structure of the proposed SEA structural design problems with the conventional SEA, and solutions for its application to an excavator. Section III offers an overview of the prototype installed in the SEA. Section IV presents the results of several experiments performed manually, such as maneuvers required to align materials. Finally, in Section V, we draw conclusions and discuss possible future developments of the proposed system.

II. LARGE SERIES ELASTIC ACTUATOR (SEA) DEVELOPMENT

A. Structural Design Issues of SEA

In this study, we applied an SEA to the arm and boom joints of an excavator used as a construction machine. Prior to this, we solve three structural design problems: i) the structure of the elastic body of the SEA, ii) the structure of the entire SEA system, and iii) the electrification of joints. These issues and their solutions are discussed in the following section.

B. Structure of Elastic Part of SEA

Various materials and shapes have been proposed for the elastic part of the SEA (hereinafter referred to as the elastic element (EE)). Although the use of a torsion bar is the most common method for joint applications [13], the desired spring constant could only be achieved with a long torsion bar, making mounting the system on an excavator difficult. While a special alloy called "rubber metal" has been used for the torsion bar [14], it must be fabricated from an ingot, which makes it an expensive material. There are several reports on miniaturizing the spring by manipulating its shape [15,16]. However, this is difficult to achieve for excavators that receive large torques owing to design and manufacturing restrictions on the shape of the spring. Research has also been conducted on the use of nonferrous materials, such as silicon [17]; however, they cannot be used in excavators because of the payload and environmental conditions. Based on these considerations, we adopted a configuration of coil springs for EE, which have a low temperature dependence and are highly resistant to the environmental variations. Details of the developed EE are shown in Fig. 2. To protect the reduction gear from external shocks, multiple coil springs were connected to achieve the desired spring constant, forming a unit structure. In this study, we designed an EE based on the assumption that an unexpected external force would cause the bucket tip to collide with the ground while the arm is extended. The design was based on actual measurement data during excavation. The output of the reduction gear drove housing B, which connected housing A to the output shaft via a coil spring. The effects of friction and other factors in the mechanism produced hysteresis, leading to control issues. This was addressed using a model of the characteristics to design the estimator, which is described in the following section. By fabricating a spring unit as a unit construction, we can replace the EEs and modify the spring constant or form a rigid connection, depending on the target of operation.

C. Structure of SEA

The basic structure of the SEA consists of EEs attached to the reduction gear output. As a common practice, the different readings of the encoders installed in the input and output sections of the EEs are used to measure the spring displacement. However, when this configuration is adopted directly, the SEA unit becomes excessively large for installation in excavator joints. In particular, mounting an encoder on the input of an EE is difficult, and few types of hollow-type encoders are compatible with large models. If a solid-type encoder uses a timing belt, accurate measurement of the spring displacement is challenging owing to belt elongation and backlash. The cross section of the SEA is illustrated in Fig. 3(b), which shows a nested shaft construction to make the unit compact and allow the installation of an excavator. Furthermore, this design allows the spring displacement to be read from the relative displacements between the input shaft and the output using a single encoder. With this configuration, the spring displacement can be measured directly and accurately without using a hollow-shaft encoder or an intervening belt. The absolute angle of the joint was acquired from the encoder attached to the servomotor.

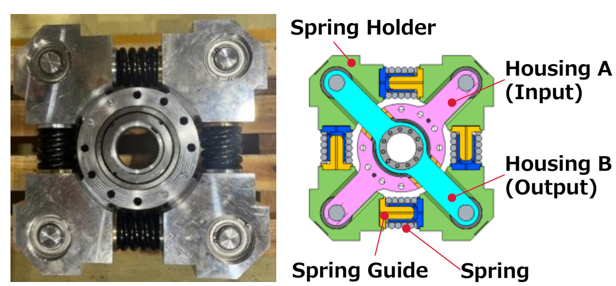

Fig. 2 Structure of the elastic element (EE)

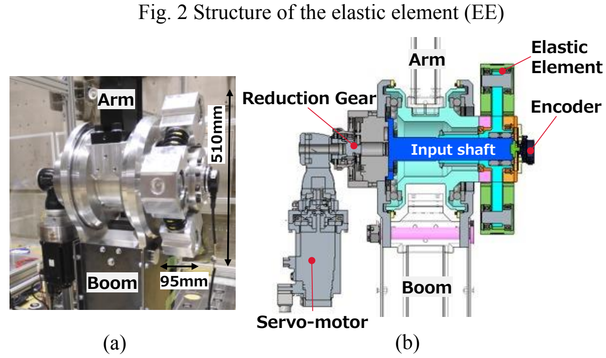

Fig. 3 Series elastic actuator (SEA) for arm joint

D. Electrification of Boom, Arm, and Bucket joint

The boom, arm, and bucket joints of conventional excavators are driven by hydraulic cylinders. Considering the use of an electric actuator to replace a hydraulic cylinder, a typical method involves employing a link mechanism with an electric cylinder that preserves the same configuration [18]. However, the use of an electric cylinder leads to two issues: poor mountability owing to the increased size and weight caused by the ball screw, and reduced movement speed. In this study, a combination of a high-revolution servomotor and high-reduction-ratio gear, which has a proven track record in industrial robot applications, is used to realize a large output in a compact form, thereby solving difficult of installation. This method also enables higher movement speeds than those of conventional models. As shown in Fig. 3(b), the arm joints are directly attached to the joints. A precision reduction gear with low backlash and two-stage reduction through an orthogonal hypoid gear was used to achieve compactness and a high reduction ratio. The servomotor capacity was selected based on the workload data of a conventional excavator.

III. Prototype Development

A. Prototype Overview

For this study, a YANMAR ViO25 2.5-T class mini excavator [19] was modified as a prototype for implementing the SEA and testing its performance. An overview of the prototype is illustrated in Fig. 4. The engine and cabin were replaced with a lithium-ion battery. The traveling motor, turning motor, and blade cylinder were driven by hydraulic pressure, and the hydraulic pump was driven by an electric motor. Three joints (boom, arm, and bucket) were electrically driven using a servomotor and reduction gear. The specifications are presented in Table 1. For safety function, an emergency stop switch was provided to remotely shut off the power supply.

B. Electrified Joints with SEA

We applied the proposed SEA to the boom and arm joints, but electrified only the bucket joint (Fig. 5). The spring constants of the EE are set to 2,060 and 909 Nm/° for the boom and arm shafts respectively, to accommodate the external force when the bucket tip impacts the ground with the arms extended.

Fig. 4 Prototype overview

Table 1 Specifications of the prototype

Parameter [SI unit]		Prototype	Excavator (2.5-T class)
Operating weight [kg]	-	3,500	2,500
Maximum digging force [kN]	Bucket	11.2	23.1
Lifting capacity [kg]	Load weight	209	200
Range [°]	Boom	135	133
	Arm	210	106
	Bucket	186	182

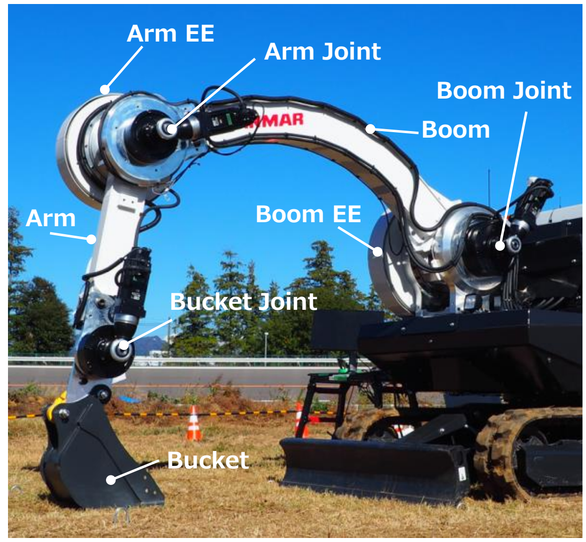

Fig. 5 Prototype installed with SEA-powered boom and arm.

The allowable torque of the boom shaft was approximately 7,200 Nm, which is equivalent to approximately twice the load torque based on the actual measurement data during excavation.

C. Control System

An overview of the control architecture is presented in Fig. 6. In the experiments, a human operator controlled the prototype using a remote controller. The velocity commands for each joint or the target reaction force commands for the bucket tip were input to the controller. The target motor velocity v_d and torque feedforward command T_d were input to the servo amplifier (Servo Amp.). Angle θ_m of each motor was measured by an encoder embedded in the motor and was input to the Servo Amp. and controller. For the boom and arm joint, the angle difference $\delta\theta$ of the input and output axes of the mounted EE was measured by the encoder and was input to the controller.

The control system (Fig. 7) consisted of two control loops, namely force and position control loops, and was equipped with an estimator of the reaction force required for force control. The estimator first calculated the torque applied to the joint using the measured spring displacement, subtracted the

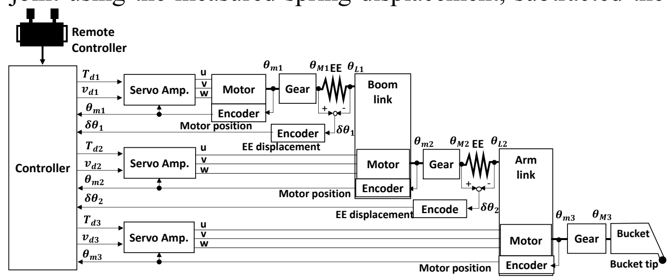

Fig. 6 Overview of control architecture

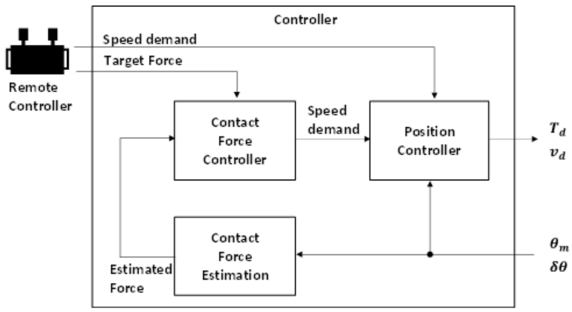

Fig. 7 Layout of control system

dynamics and gravity terms from the estimated boom and arm-joint torques, and then estimated the bucket-tip reaction force using inverse kinematics.

The joint torque can be estimated from the spring constant and displacement. However, the SEA exhibited hysteresis characteristics between the spring displacement measured by the EE and torque. Therefore, a model was developed around these characteristics, and torque was estimated based on this model. Figure 8 depicts a block diagram of the torque estimation. The block in the dashed line represents the model estimations. The modeling was conducted based on time-series data of the hysteresis characteristics. The torque was estimated from the calculation of spring force T_k [Nm], which is the spring displacement δ [°] acquired by the encoder multiplied by the spring constant and adding the torque hysteresis T_h [Nm], which is the displacement hysteresis amount δ_h [°] multiplied by the transition characteristic k_h [Nm/deg] between hysteresis. The estimated torque value T_o [Nm] was calculated by multiplying the amount of torque hysteresis T_h [Nm] by the characteristic K_h[Nm/°]. Here, K_h was estimated from the width of the hysteresis curve.

The force controller transmitted a command to the bucket-tip speed in order to follow the reaction force estimate to the target force. To prevent the vibration of the bucket tip around the target force value of 0 N, a dead band was provided to control the deviation of the reaction force.

The position controller calculated the bucket-tip position according to the velocity command transmitted by the force and remote controllers and output the angular velocity command v_d and torque feedforward command T_d for each joint such that the bucket-tip position followed. The magnitudes of gravity and dynamic compensation were calculated as torque feedforward commands. In addition, vibration-suppression compensation was applied to the target joint angles to suppress the vibration of the springs mounted on the boom and arm joints. Vibration-damping compensation was achieved by controlling the motor like damper to dissipate the energy of spring. In detail, the compensation dampened the vibration by correcting the target joint angles such that the

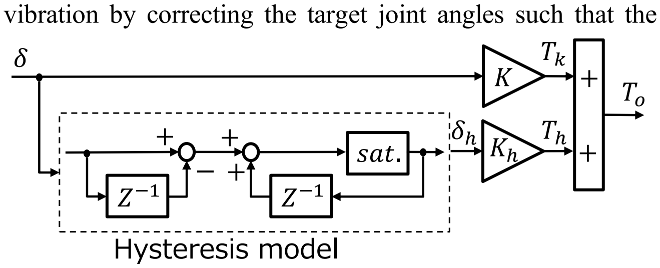

Fig. 8 Block diagram of torque estimation

target position of the spring origin was back-driven according to the magnitude of spring extension and contraction. This magnitude was calculated as the difference between the reference spring displacement and the measured spring displacement using the bucket-tip reaction force command and gravity-compensation torque at each joint.

IV. Experimental Results

A. Experimental Validation

The performance of the SEA installed on the prototype was assessed by evaluating its force-control accuracy. We set up the test environment with load cells, as depicted in Fig. 9. Figure 10 illustrates the results of the control in which a load cell is placed on the floor and the bucket tip is pressed against it with a target force input prior to the experiment. The results confirmed that the proposed system could perform to a control accuracy of approximately 15 N.

To evaluate the manual work maneuver, the results of tests conducted with three different maneuvers are described in the next section: lifting assistance, aligning the U-shaped drain, and placing panels on the wall.

B. Lifting Assist

A heavy object handling-assistance function was implemented as a task using force control. This function compensated for the weight of heavy objects and moves them in the direction of the force applied by the operator. This function enables possible a single worker to perform tasks that were previously performed by several workers, including the worker positioning the material manually and the operator

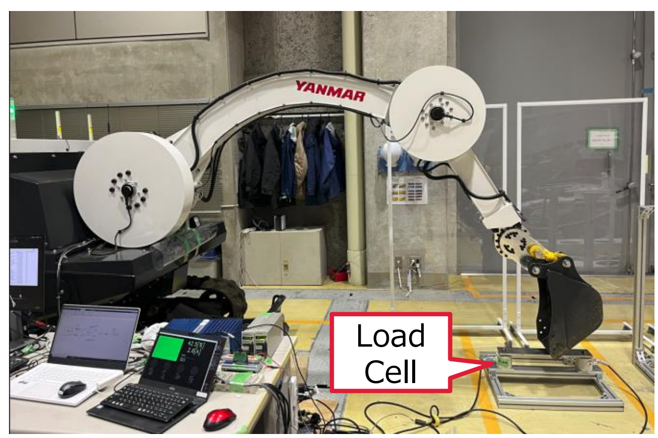

Fig. 9 Test environment for validation test

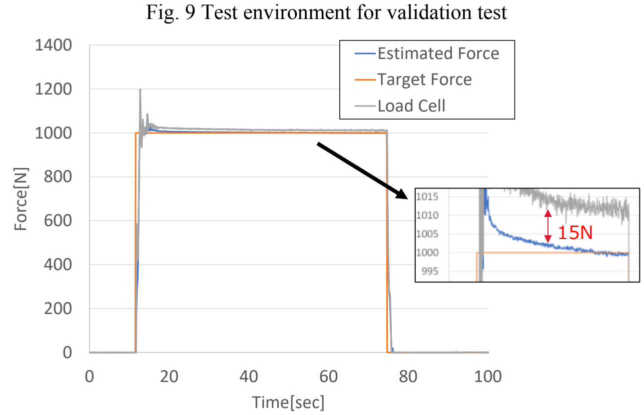

Fig. 10 Validation test results

controlling the machine. In this test, the weight of the heavy materials was input in advance assuming that the weight of the materials was known. The test maneuver is illustrated in Fig. 11, and the results are shown in Fig. 12. Because the force control dead-band width was set to 30N, the machine follows the worker when the operator applies a force of 35 N or more. The accuracy of the force estimation depends on the dead-band width, which in turn depends on the hysteresis characteristics of the SEA. Improvement of the mechanism to reduce the hysteresis for an operational feel is a future direction of this research.

C. Aligning U-shaped Drain

The test in the previous section was extended by replacing the bucket with an attachment that could grip the U-shaped drain rigidly, allowing the machine to lay the drain directly (Fig. 13). In this test (Fig. 14), a U-shaped drain was placed on the ground and the machine over another adjacent U-shaped drain while applying a constant target force on the ground surface. In this test, the dead-band value was set to 10 N. The test results are shown in Fig. 15. As the surface was moved in alignment with the ground, control was achieved with an accuracy of approximately 15 N, confirming that the system could be deployed in actual work.

D. Attachment of Panels on Walls

The implementation of force control should enable the application of architecture equipment. To demonstrate the working of this design, we conducted a test with the task for the machine was to a panel on the wall. Accordingly, a tool for gripping the panel was fabricated following the same procedure as installing the U-shaped drain (Fig. 16). Figure 17 illustrates the test maneuver for attaching the panel. This function also enable a single worker to perform tasks that were previously performed by several workers, similar to previous tests. The test results are shown in Fig. 18 and 19. The Y-axis represents the vertical direction, the X-axis the front-back direction. Force control could be performed in each both directions, enabling the panel-attachment operation. The panel was first pressed against the wall. Then, while maintaining a certain reaction force, the wall surface was flattened, and the panel was inserted into the panel holder at the bottom. The results confirmed that panel fitting could be performed to an accuracy of approximately 35 N.

V. Conclusion and Outlook

This paper proposes a novel large-scale SEA system for excavators to perform manual work using force control. To evaluate the operation, the developed SEA was mounted on a

Fig. 11 Test maneuver for lifting assist

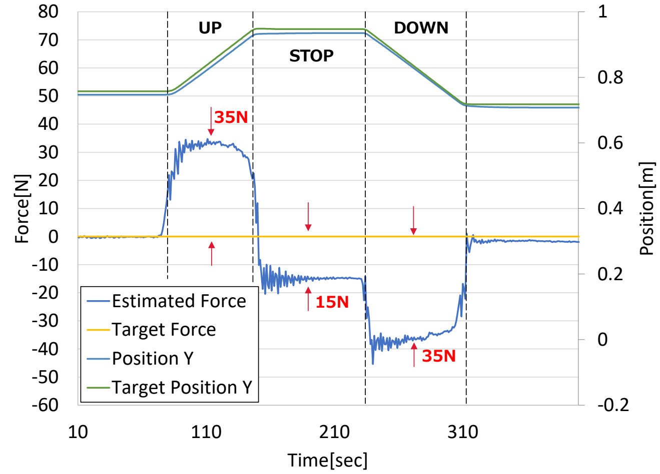

Fig. 12 Lifting assist test result

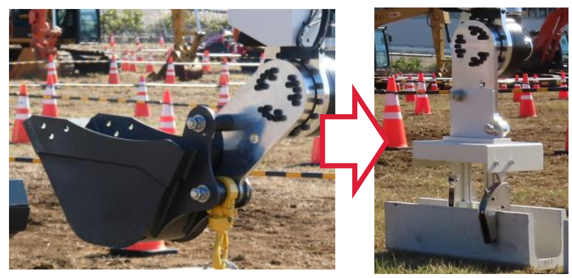

Fig. 13 Replacement of bucket with a grip

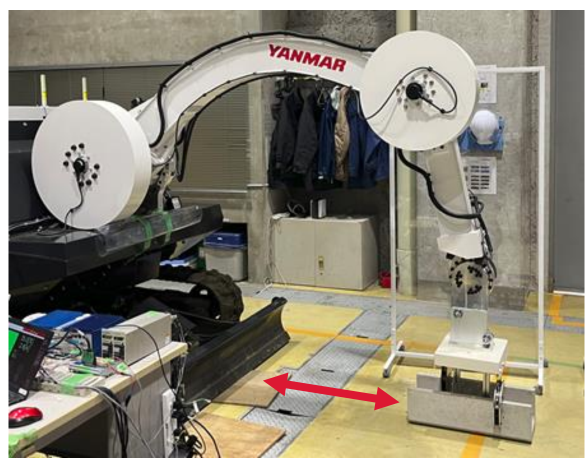

Fig. 14 Test maneuver for U-shaped drain alignment

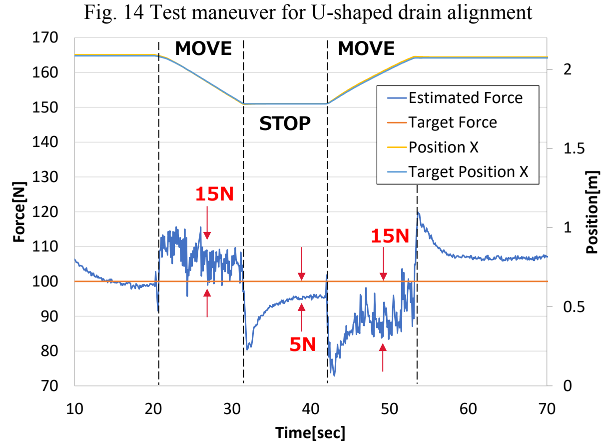

Fig. 15 Test result for U-shaped drain alignment

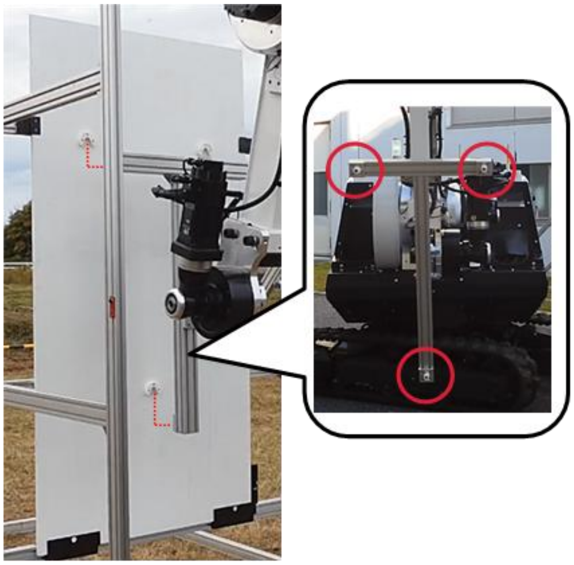

Fig. 16 Panel attachment

prototype modified based on a 2.5-T class excavator. Three manual work maneuvers were performed using the force-control function, and the test results demonstrated a control accuracy of approximately 15-35 N. A large-scale SEA with a large output that can be applied to excavators is unprecedented worldwide. It has also demonstrated acceptable performance to compensate for labor shortages. We demonstrated its use in an excavator that as a force control method to perform most of the work in a task with the guidance of a single worker, which would otherwise require multiple workers. conventionally performed by multiple workers, but now performed by a single worker. We shall further automate construction work by using sensors and force controllers to partially automate manual work.

The proposed system has three degrees of freedom (boom, arm, and bucket), which are insufficient for practical

Fig. 17 Test maneuver for placing of panels on the wall

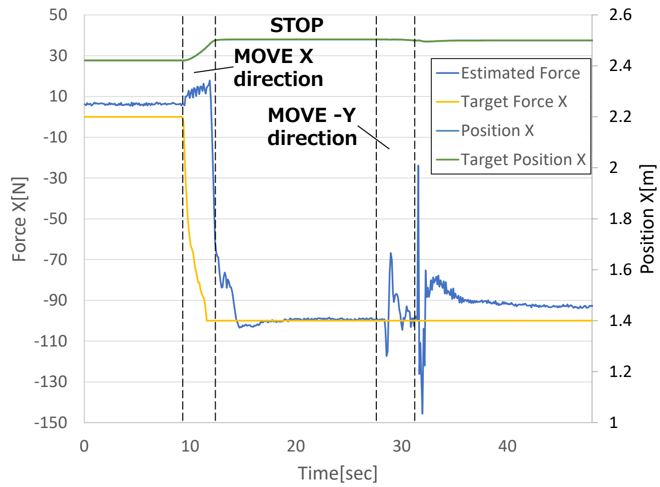

Fig. 18 Test results for placing of a panel in the X direction

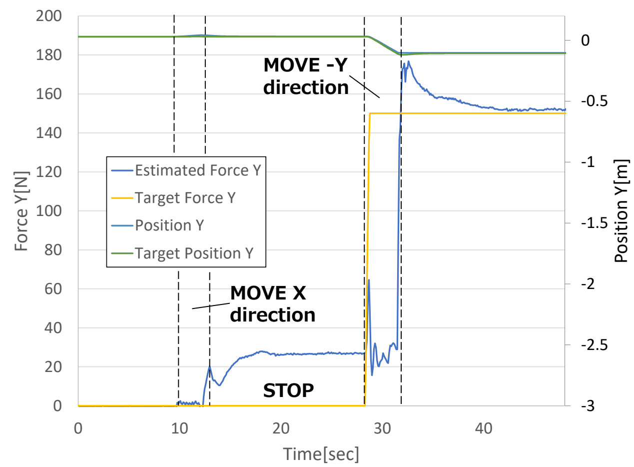

Fig. 19 Test results for placing of a panel in the Y direction

applications. Other necessary DOF and system extensions are the subjects of future research. In addition, the response to impact when subjected to an unexpected external force is a future research direction, as we have not yet quantitatively evaluated.

Regarding future developments, the proposed SEA is a general-purpose actuator that can be used for various applications. Further improvements in accuracy and simplification of the mechanism should be considered for a wider range of applications.

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References

[1] K. Tateyama, "Achievement and Future Prospects of ICT Construction in Japan," J.Robot.Mechatron., Vol.28 No.2, pp.123–128, 2016.

[2] A. Argiolas, S. Casini, K. Fujio, T. Hiramatsu, S. Morita, M. Ragaglia, H. Sugiura and M. Niccolini, "Design, Development and Validation of a Dynamic Fall Prediction System for Excavators, " 2021 IEEE International Conference on Robotics and Automation (ICRA), 2021, pp.8523-8529.

[3] J. Takahashi, S. Fujimori, K. Takahashi, T. Hasegawa, Y. Honda, N. Hanasaki, Y. Hijioka and T. Masui, "Limited Role of Working Time

Shift in Offsetting the Increasing Occupational-Health Cost of Heat Exposure," Earth's Future, Vol.6, pp.1588-1602, 2018.
[4] H. Morikawa and T. Otsuki, "Study on the level concept of autonomous construction in mechanized construction," Proceedings of the 37th ISARC, pp.1114-1121, 2020.
[5] T. Bock, "Construction Robotics," J.Robot.Mechatron., Vol.28, No.2, pp.116-122, 2016.
[6] G. Carra, A. Argiolas, A. Bellisima, M. Niccolini and M. Ragaglia, "Robotics in the Construction Industry: State of the Art and Future Opportunities," Proceedings of the 35th ISARC, pp.866-873, 2018.
[7] M. Kamezaki, H. Iwata and S. Sugano, "Identification of Dominant Error Force Component in Hydraulic Pressure Reading for External Force Detection in Construction Manipulator," J.Robot.Mechatron., Vol.24 No.1, pp.95-104, 2012.
[8] H. Muramoto, K. Tomita and T. Morita, "Compliance Analysis of Construction Machinery Front by Direct Stiffness Method," J.Robot.Mechatron., Vol.20 No.3, pp.481-489, 2008.
[9] H. Kaminaga, J. Ono, Y. Nakashima and Y. Nakamura, "Development of Backdrivable Hydraulic Joint Mechanism for Knee Joint of Humanoid Robots," Proceedings of the IEEE International Conference on Robotics and Automation, pp.1577-1582, 2009.
[10] T. Sandy, M. Giftthaler, K. Dorfler, M. Kohler and J. Buchli, "Autonomous repositioning and localization of an in situ fabricator," 2016 IEEE/RSJ International Conference on Robotics and Automation (ICRA), 2016.
[11] G.A. Pratt and M.M. Williamson, "Series elastic actuators," Proceedings of the 1995 IEEE/RSJ International Conference on Intelligent Robots and Systems. Human Robot Interaction and Cooperative RobotsMill Valley, CA: University Science, 1995.
[12] Y. Kawashima, M. Kinoshita, N. Takasugi, K. Sugimoto, T. Kai, T. Kito, A. Sakamoto, K. Nagasaka and Y. Kawanami, "Tachyon: Design and control of high payload, robust, and dynamic quadruped robot with series-parallel elastic actuators," Proceedings of the 2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2021.
[13] R. Fukui, Y. Kusakabe, R. Ikeura and S. Hayakawa, "Impedance Control Considering Velocity Saturation of a Series Elasticity System with a Motor," J.Robot.Mechatron., Vol.33 No.4, pp.833-842, 2021.
[14] S. Sugano, H. Iwata and T. Sugaiwa, "Compliant Manipulation by Human-Symbolic-Robot TWENDY-ONE," Journal of the Robotics Society of Japan, Vol.31 No.4, pp.347-352, 2013. (in Japanese).
[15] N. Paine, J. S. Mehling, J. Holley, N. A. Radford, G. Johnson, C. L. Fok and L. Sentis, "Actuator Control for the NASA-JSC Valkyrie Humanoid Robot: A Decoupled Dynamics Approach for Torque Control of Series Elastic Robots," Journal of Field Robotics Vol.32, pp.378-396, 2014.
[16] S. Monteleone, F. Negrello, G. Grioli and M. G. Catalano, "dSEDA: a differential series elastic damped actuator," Proceedings of the 2022 IEEE/RSJ International Conference on Robotics and Automation (ICRA), 2022.
[17] M. Ikeda, R. Niiyama and Y. Kuniyoshi, "Proposal of Manufacturing Method for New Passive Elastic Joint and Prototype of Human Phantom," J.Robot.Mechatron., Vol.34 No.2, pp.402–412, 2022.
[18] K. Kurihara, H. Naka, Y. Shitara and H. Itani, "Study of full electric mini excavator," Komatsu technical report, Vol. 68, No.175, pp.2-7, 2022.
[19] YANMAR, "ViO25 excavator," https://www.yanmar.com/global/construction/products/excavator/vio25/