Snake Robot Gripper Module for Search and Rescue in Narrow Spaces

Sangchul Han, Sanguk Chon, JungYeong Kim, *Associate Member, IEEE*, Jeahong Seo, Dong Gwan Shin, Sangshin Park, Jin Tak Kim, Jinhyeon Kim, Maolin Jin, and Jungsan Cho

***Abstract*—This letter presents a gripper module for a snake-like robot to perform search and rescue tasks in a narrow space. The proposed gripper module has three features: (1) It can accommodate the fingers inside its body. (2) It has three fingers that can grip objects with irregular surfaces stably. (3) One of the fingers is equipped with a camera on the fingertip to search in a narrow space. To implement the above features in a small, light, and compact gripper module, we propose a novel design of a gripper module with three fingers and eight degrees of freedom. The joint configuration of the proposed gripper is unique compared with a general-type gripper. A prototype of the proposed gripper module has been integrated into a snake-like robot to demonstrate its capability of performing rescue tasks in a collapsed environment. The three features of the proposed gripper module are experimentally verified: it is light (0.4 kg), small (less than 68 mm in diameter), and powerful (grasping force = 2.48kgf).**

***Index Terms*—Search and rescue robots, grippers and other end-effectors, mechanism design, snake-like robot.**

Fig. 1. Illustration of using snake robot for search and rescue tasks.

I. Introduction

SINCE it was first introduced by Hirose [1], snake-like robots have been extensively investigated because they can be used in various terrains and situations. One of the representative applications of snake-like robots is urban search and rescue (USAR) at collapsed sites, as shown Fig. 1. For example, Carnegie Mellon University (CMU) researchers deployed a snake-like robot composed of 16 modules to search for trapped survivors in a collapsed apartment building [2]–[4]. The CMU snake robot can access narrow spaces because it has a really small diameter. It can traverse a wide range of terrains, including open flat regions, piles of rubble, and stairs [5]. The CMU snake robot, however, has only one camera on its head, and there were no other sensors or grippers to detect or help survivors.

The T^2 Snake-3 robot with a soft gripper was introduced by Tanaka [6], [7]. It has an omnidirectional soft gripper to grip an object or to rotate a valve. The T^2 Snake robot shows excellent object handling performance; however, sensors cannot be attached to the gripper, and the size of the robot is big to move in a narrow space.

To effectively perform search and rescue tasks, two additional functions are required simultaneously for a snake-like robot (Fig. 2). First, a snake robot should be able to move its eyes and look in all directions without moving its body, and second, the snake robot should be able to remove small objects, such as collapsed debris, in narrow spaces. A smart and powerful gripper module for snake robots is required to performs search and rescue tasks in a narrow space.

Robotic grippers have been extensively studied in recent years. 2-finger grippers [8]–[11] and 3-finger grippers [12]–[16] have been developed to grasp objects. An adaptive mechanism is applied to the finger link in these grippers, and most grippers have an under-actuated mechanism that drives a large number of joints using a small number of actuators. They are used in various industrial fields because they are structurally simple. However, the fingers are exposed to external environments. Additionally, it is impossible to perform a search task using a fingertip camera

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Sangchul Han, Sangshin Park, Jin Tak Kim, Jinhyeon Kim, and Jungsan Cho are with the Hydraulic Robot Laboratory, Robot R&D Group, Korea Institute of Industrial Technology, Ansan 15588, South Korea (e-mail: bomber21@kitech.re.kr; pss@kitech.re.kr; jintagi@kitech.re.kr; qkrb0117@kitech.re.kr; chojs@kitech.re.kr).

Sanguk Chon, JungYeong Kim, and Jeahong Seo are with the Robotics and Virtual Engineering, University of Science and Technology (UST), Daejon 34113, South Korea (e-mail: jsoman@kitech.re.kr; kjy880527@kitech.re.kr; jh_seo88@kitech.re.kr).

Dong Gwan Shin and Maolin Jin are with the Human-centered Robotics Center, Korea Institute of Robotics & Technology Convergence (KIRO), Pohang 37666, South Korea (e-mail: shingun@kiro.re.kr; mulimkim@kiro.re.kr).

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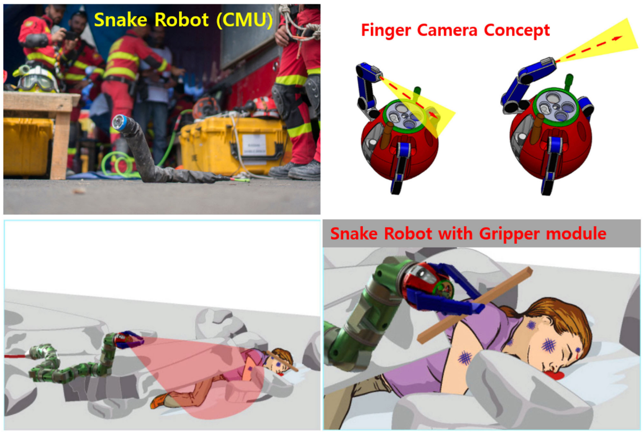


Fig. 2. Functions of a snake robot integrated with a gripper with a finger camera.

in a narrow space because of the under-actuated mechanism. There is a limit to reducing the size of these grippers because they have a complex link structure. Anthropomorphic robotic hands have been developed to mimic human hands as closely as possible in terms of kinematics, beyond the ability of simple grippers.

An anthropomorphic robotic hand [17]–[23] consists of 4–5 fingers, and it can grip and precisely manipulate various objects, including not only simple spherical and cylindrical objects but also irregular objects, using numerous degrees of freedom (DOFs). It has high dexterity and versatility; however, it has a difficulty in accumulating actuators in a small hand. Soft grippers that use soft materials have been developed in recent years [24]–[29]. These grippers are operated using a gripper-shaped chamber fabricated from a soft material and injecting a fluid into the chamber to apply pneumatic or hydraulic pressure. As soft grippers are inherently compliant, it is possible to grip objects with complex shapes relatively easily and grip objects with a soft surface without force control. However, soft grippers have limitations in terms of durability, and they require a complex system to control each joint. In summary, the aforementioned grippers [10]–[31] cannot be directly used for a snake robot because they are considerably large and heavy and do not have dexterous searching cameras.

The gripper module of a snake robot must be small and versatile to work in narrow spaces. The outer diameter and length (including fingers) of the gripper module hinder the movement of a snake robot through narrow spaces and obstacles such as curvature tubes. To prevent this, the maximum diameter and length of the gripper module should be similar to the diameter and length of the snake robot body. Furthermore, the gripper module should have a dedicated joint configuration to perform search and rescue tasks using fingertips and grab objects with irregular shapes such as collapsed debris.

In this paper, we propose a gripper module for snake robots that perform USAR tasks in narrow spaces. A snake robot can manipulate small objects through the proposed gripper module and effectively search using a fingertip camera without moving the snake body. The proposed gripper module is composed of three fingers (eight DOFs) for grasping and manipulation of irregular objects. The fingers can be accommodated inside the module by adopting grooves and a wide range of motion actuators. Such an accommodation mechanism improves the mobility of the snake robot in a narrow space. Finger 1 of the proposed module consists of the distal interphalangeal (DIP) joint and proximal interphalangeal (PIP) joint. Fingers 2 and 3 consist of the DIP, PIP, and metacarpophalangeal (MCP) joints. The MCP joint is not used in finger 1 because the proposed gripper module does not require high in-hand manipulation performance. In addition, sufficient power grasping and pinch grasping can be achieved using two MCP joints. One of the fingers is equipped with a camera on the fingertip for convenient searching to perform search and rescue tasks. The finger joint of the gripper module has a pan-tilt structure; thus, it can point to a three-dimensional space and search a narrow space using the fingertip camera. The diameter and height of the manufactured gripper module are 68 mm and 106 mm, respectively, and it is designed to perform USAR tasks in a narrow space with a diameter of 100 mm and a radius of curvature of 250 mm. The proposed module is integrated into a snake robot to show its capability of performing rescue tasks in a collapsed environment. The accommodation mechanism, stable grasping, and improved searching of the gripper module are confirmed through experiments.

The rest of this paper is organized as follows: Section II describes the design conditions and kinematics of the proposed gripper module. Section III describes the mechanical and electronic design of the module. Section IV presents the experimental validation and evaluation results. Finally, Section V presents the conclusions.

II. Kinematics of Proposed Gripper Module

The following design conditions are considered for the proposed gripper module: the gripper module should stably grasp and manipulate a small object; the finger of the module should not hinder the movements of a snake robot when it is attached to the snake robot; finally, the size of the gripper module should be similar to the size of the driving module of the snake robot. Fig. 3 shows the schematic of the proposed gripper module based on these conditions.

The gripper module is composed of three fingers to stably grasp and manipulate irregularly shaped small objects. Finger 1 is composed of PIP and DIP joints with pitch–pitch DOFs, and fingers 2 and 3 contain MCP, DIP, and PIP joints with roll–pitch–pitch DOFs. The MCP joint of finger 1 is removed because power grasping and pinch grasping can be performed using the MCP joints of fingers 2 and 3 and high-level in-hand manipulation is not required. The removal of the MCP joint of finger 1 provides a space for accommodating the fingers and arranging the control board. The MCP and PIP joints of fingers 2 and 3 are of the pan-tilt type with a roll–pitch configuration. This configuration can effectively secure a search area in a narrow space.

To reduce the size of the gripper module, it is important to consider not only the number of sensors, such as actuators,

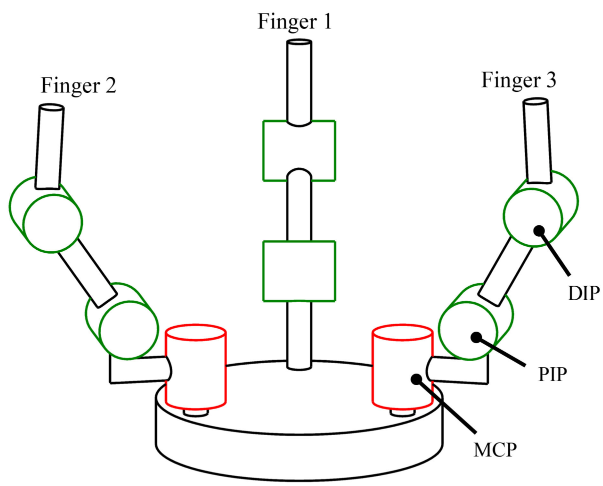


Fig. 3. Schematic of the proposed gripper module.

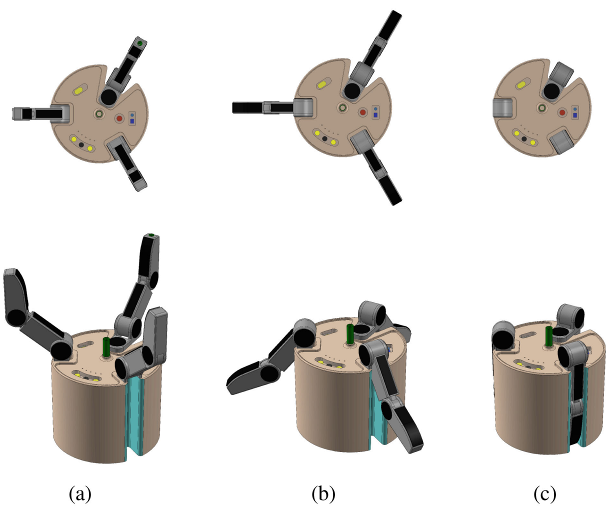


Fig. 4. Finger folding method.

control boards, and cameras, but also the configuration of the fingers. A finger that protrudes from the gripper module increases the outer diameter of the gripper module and makes it difficult to contact various obstacles. This problem can be solved by accommodating the fingers inside the gripper module, as shown in Fig. 4. In addition, the accommodation mechanism can reduce the outer diameter of the gripper module and remove the shaded area of the sensor placed in the gripper palm. Fig. 4(a) shows the preparation step for a task such as object manipulation and searching. Fig. 4(b) shows the process of accommodating the fingers in the module. Finally, Fig. 4(c) shows that the fingers are completely accommodated inside the module. The change in the outer diameter of the gripper module is shown by the top views depicted in Fig. 4. Large DOFs of the finger joint and groove are required to implement this accommodation mechanism.

Incidentally, we have considered the other accommodation mechanism: gathering the fingers together in front of the gripper palm and using a slide link. However, these methods have the disadvantage of being complicated and generating a shaded area of the sensor.

TABLE I
KINEMATIC PARAMETERS OF GRIPPER MODULE FINGERS

	Joint	Range of motion [deg]	Phalange length [mm]
Finger 1	PIP	0 – 180	36 (PIP to DIP)
	DIP	0 – 100	37 (DIP to fingertip)
Finger 2 and 3	MCP	0 – 164	19 (MCP to PIP)
	PIP	-10 – 180	36 (PIP to DIP)
	DIP	0 – 100	37 (DIP to fingertip)

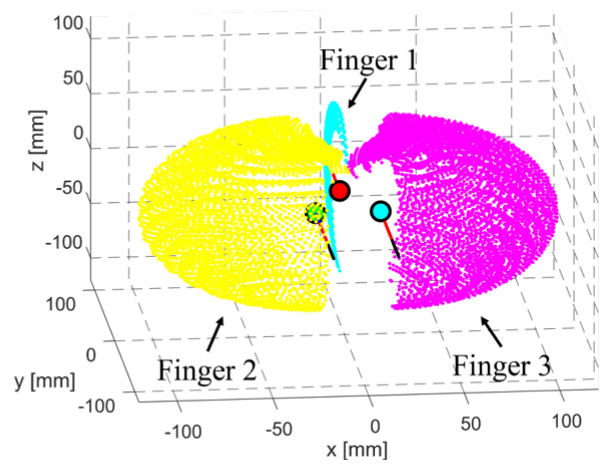


Fig. 5. Workspace of gripper module finger.

Table I shows the range of motion and phalange lengths of the fingers of the gripper module. The kinematic parameters are determined by considering the outer diameter of the gripper module and accommodation mechanism. The length of the PIP joint is the minimum length between the axes of the actuator. The length of the DIP joint is determined using the ratio between the size of the fingertip camera and the length of the PIP joint. The length of the MCP joint is based on the thickness of the actuator and the interference between a finger and gripper module body when accommodating the finger. For the fingers to be accommodated in the gripper module body, the range of motion of the PIP joint must be more than 180° so that the fingers can be fully folded back. The range of motion of the DIP joint is determined by considering pinch grasping using the fingertips and power grasping using the palm. Considering the thickness of the actuator, the range of motion of the MCP joint must be 164° to accommodate the fingers in the gripper module.

Fig. 5 shows the point cloud of the finger workspaces calculated using the kinematic parameters to check the manipulability of the gripper module. The workspaces of fingers 1, 2, and 3 are indicated in cyan, yellow, and purple, respectively. On the basis of the range of motion, the workspace of finger 1 is semicircular and those of fingers 2 and 3 are hemispherical. The human hand shows high dexterity, and the overlap area of the workspaces of the fingers is large. In contrast, in the proposed gripper module, the overlap area of the workspaces of the fingers is small. However, considering the volume of the objects to be manipulated, the workspaces are sufficient for power grasping and pinch grasping.

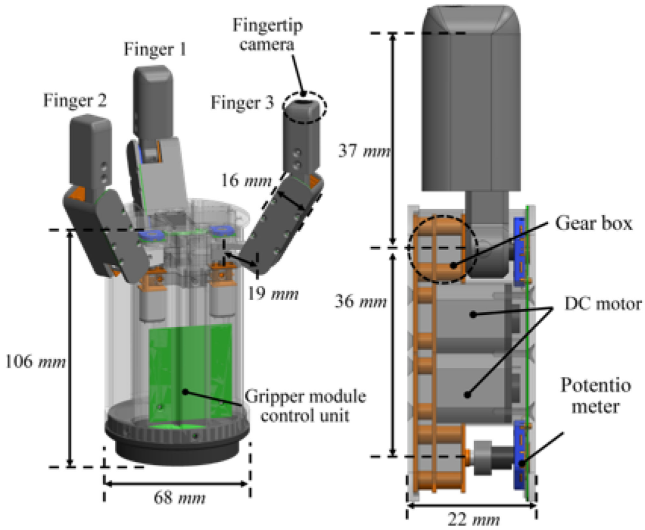


Fig. 6. 3D model of gripper module.

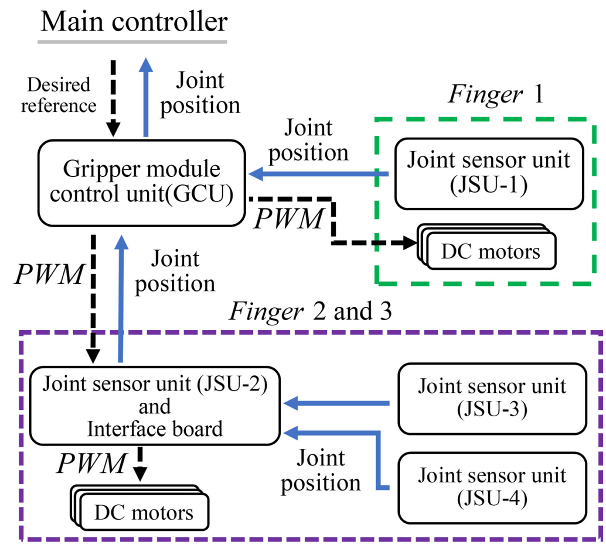


Fig. 7. System block diagram of gripper module.

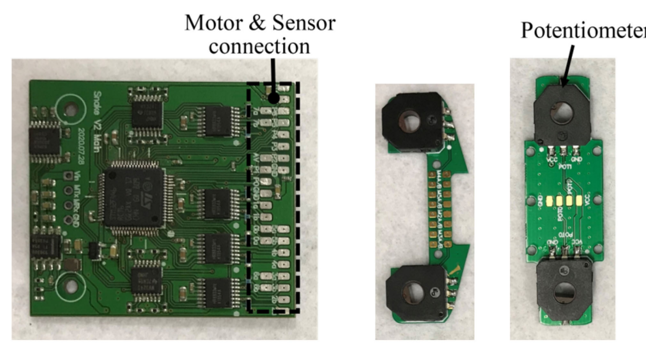
III. Design of Proposed Gripper Module

It should be possible to mount the proposed gripper module on a snake robot that moves in a narrow space with a diameter of 100 mm and a radius of curvature of 250 mm to perform USAR tasks. To satisfy these conditions, the diameter of a snake robot module should be less than 70 mm, and the length of a module should be less than 150 mm. In addition, the head module of a snake-like robot should also satisfy the limiting conditions. The gripper module should be small, light, and powerful; besides, the exposure of components, such as the actuator's gear, sensors, and control boards, should be minimized because we will deploy the snake-like robot in a harsh environment. The sensor or finger structure should not protrude outside the module.

Fig. 6 shows the 3D model of the proposed gripper module. The outer diameter of the gripper module is 68 mm, and its height is 106 mm including the length of the fingers. The width, thickness, and height of the fingers are 22 mm, 16 mm, and 85 mm, respectively. There are three grooves on the gripper module to accommodate the fingers.

The two MCP joint actuators are arranged vertically considering the space required to accommodate the fingers. In this arrangement, a separate gear is not required to change the power transmission direction. This structure enables the actuator to be placed outside to utilize the internal space. The PIP and DIP joints of all fingers have the same structure, and the actuators of the PIP and DIP joints are placed on the PIP link to provide space for installing sensors, such as a camera, on the fingertip.

The gripper module uses a small and light commercial geared DC motor. The GM12F motor is used for the MCP joint. It has a small size, with a width, thickness, height of 12 mm, 10 mm, and 35 mm, respectively. The GM12 L motor is used for the PIP and DIP joints. Its width, thickness, and height are 24 mm, 10 mm, and 19 mm, respectively. The weight of the DC motor is approximately 10 g, the rated torque is 147mNm, and the stall torque is 343mNm. The control board is arranged in the internal space of the gripper module.



(a) (b) (c)

Fig. 8. Embedded boards for gripper module.

Embedded boards are developed to reduce the size of the gripper module. These include a control board for driving and controlling the module and a sensing board for measuring the position of joints. Fig. 7 shows the block diagram of communication flow between the electronic components of the gripper module and main controller. The gripper module control unit (GCU) communicates with the main controller computer via RS232. It collects the position data measured at each joint through a joint sensor unit (JSU) and transmits it to the main controller. In addition, it performs position control for each joint through PID control. The JSU is built into finger 1, and it directly transmits the position data of the PIP and DIP joints to the GCU. In the case of fingers 2 and 3, the position data of the DIP and PIP joints are transmitted to the GCU through JSU-2, which acts as an interface board and acquires the position data of the MCP joint. Fig. 8 shows the GCU, JSU & I/F, and JSU board of the gripper module. The main control unit (MCU) of the GCU (Fig. 8(a)) is STM32F446, and the size of the GCU is 40 mm×45 mm. The GCU is mounted on the module body, and it controls the gripper with a control cycle of 1 ms. JSU-2 (Fig. 8(b)) is mounted on the palm of the module. Similar to

TABLE II
SPECIFICATION OF GRIPPER MODULE

Quantity	Value
Number of fingers	3
Degrees of freedom	8
Dimensions	O.D 68mm, H 106mm
Total weight	0.4kg
Max. payload	2.48kgf at envelop grasping
Communication	RS232

JSU-2, JSU-1, JSU-3, and JSU-4 (Fig. 8(c)) consist of two potentiometers and measure the position of the PIP and DIP joints. The JSU board thickness is set as 0.4 mm to reduce the finger size.

IV. EXPERIMENTS

We had verified the performances of the proposed gripper module through several experiments. In the first experiment, the accommodation, power grasping, pinch grasping, and searching functions were checked. In the second experiment, the maximum gripping force (or gripper payload) in the grasping mode is measured. In the third experiment, the grasping ability of the proposed gripper module was examined. Finally, the gripper module was integrated into a snake robot system to perform some USAR missions.

Table II shows the specification of the gripper module prototype. The weight of gripper module is 0.4 kg including the electric parts. When the fingers are accommodated, the outer diameter and height of the module are 68 mm and 106 mm, respectively.

A. Mode Changing

The proposed gripper module has four modes. The first is the movement mode, where the fingers of the gripper module are accommodated inside it so that it can move in a narrow space. The second is the power grasping mode, which uses a finger and the palm to grasp a target object. In this mode, the object is in contact with the palm and finger, and the gripper can hold the object strongly and stably. The third is the pinch grasping mode, where only the fingertip contacts an object. Pinch grasping is mainly used when the thickness or diameter of an object is small. The fourth is the searching mode by using a fingertip camera mounted on the tip of finger 3.

The modes are applied in the following order: moving mode, power grasping mode, moving mode, pinch grasping mode, moving mode, searching mode. Fig. 9(a) shows the result of the experiment in which the gripper module changes modes. In Fig. 9(a), parts 1 and 2 show the moving and power grasping modes, respectively. Parts 4 and 6 show the pinch grasping and indexing modes, respectively. Parts 3 and 5 show the power grip and pinch grip, respectively. Fig. 9(b) shows the variation in the joint angle of finger 3 with time. The numbers correspond to the parts of Fig. 9(a). The red dotted line denotes the position control input of finger 3, and the blue solid line denotes the measured position.

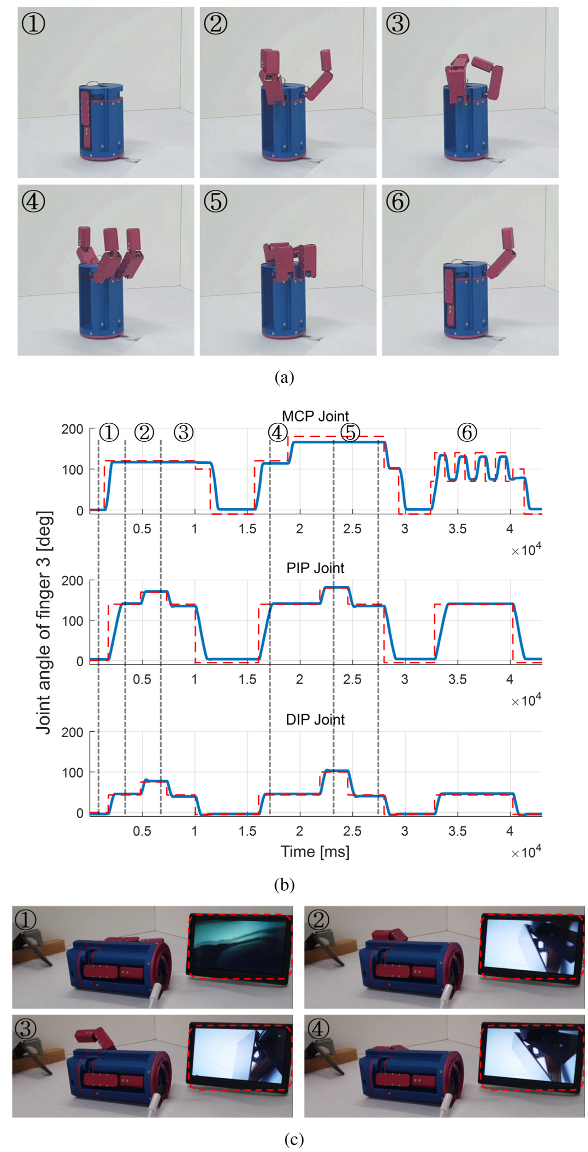
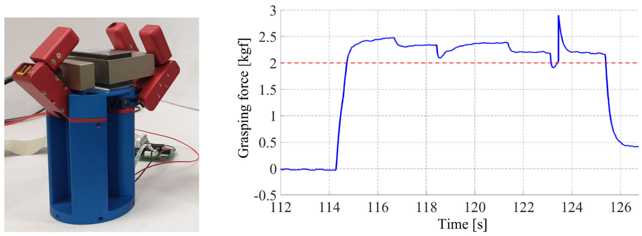


Fig. 9. Results of mode change experiment.

The performance of the fingertip camera in the searching mode is depicted in Fig. 9(c). The numbers correspond to the parts of Fig. 9(a). The diameter of camera is approximately 8 mm. The area enclosed by the dashed red rectangle (Fig. 9(c)) shows the camera screen. The display on the screen changes according to the movement of finger 3. It can be concluded that the snake robot can move the fingertip camera and look in all directions without moving its body in narrow spaces.

B. Grasping Force Test

The whole-body control of the gripper and snake robot is required to manipulate an obstacle in a narrow space. In particular, the gripper module must be able to firmly grip an object. For this reason, the proposed gripper module uses a small geared motor with a high reduction ratio. The maximum grasping force of the gripper module is measured through an experiment.



(a) (b)

Fig. 10. Results of grasping force experiment.

Fig. 10 shows the load cell used to measure the grasping force of the gripper module in the 3-finger grip. The SBA-500 L load cell is used. It can measure a maximum force of 500kgf and has an error of 0.15kgf. The experimental results are shown in Fig. 10(b). The red line denotes the expected grasping force of 2kgf, and the blue line denotes the measured grasping force. The grasping force is approximately 2.48kgf at 116 s, and it decreases owing to the movement of the load cell. At 123 s, a peak grasping force of approximately 3kgf is measured with a new control input.

The experimental results confirm that the maximum grasping force of the proposed gripper module and the expected grasping force are exceeded. Although the maximum grasping force is approximately 3kgf, it may cause the breakage of the gripper module. Therefore, the maximum payload of the proposed gripper module that can be stably maintained is 2.48kgf.

C. Grasping Pose Test

To perform USAR missions, a snake-like robot should be able to remove various small debris from the trapped survivors. The shape of actual rubble is quite irregular. We conducted experiments to verify that the gripper can grasp objects with irregular shapes. As all shapes cannot be tested, we consider circular, rectangular, and pillar shaped objects. The circular objects include a spherical baseball and a disk. The rectangular objects have different thicknesses, and the pillar shaped objects have different diameters.

Unlike an anthropomorphic robotic hand, the gripper module does not require sophisticated force control because it is not necessary to consider the damage to the object. The gripper module must securely hold and move collapsed debris, except in the case of special objects such as glass. The gripper module uses a conventional current-based position controller. This controller has an inner loop with the current controller. A reference value of the current controller is created from an outer loop controller, which is the position controller.

The experimental results are shown in Fig. 11. The circular objects are stably held in the power grasping and pinch grasping modes. Similarly, the rectangular and pillar shaped objects are stably gripped by selecting the power grasping or pinch grasping modes according to the thickness and diameter.

A large overlapping area of the fingers is advantageous for stably grasping an object. Even though the overlapping area of the workspaces of the fingers of the presented gripper module is

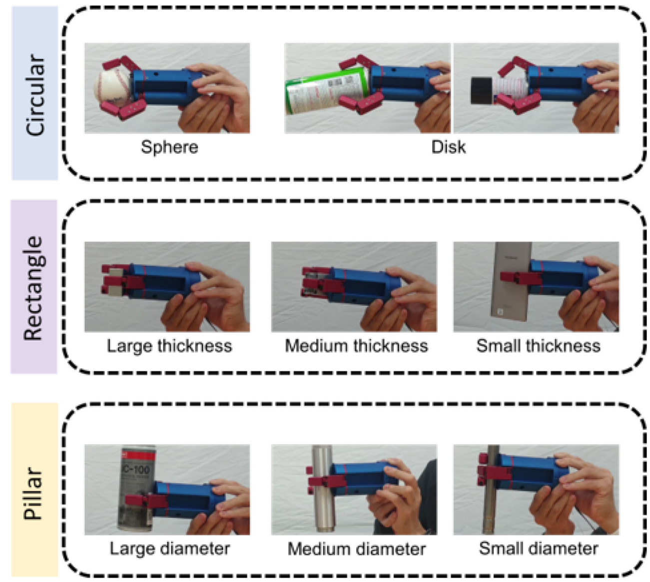


Fig. 11. Test of object grasping pose.

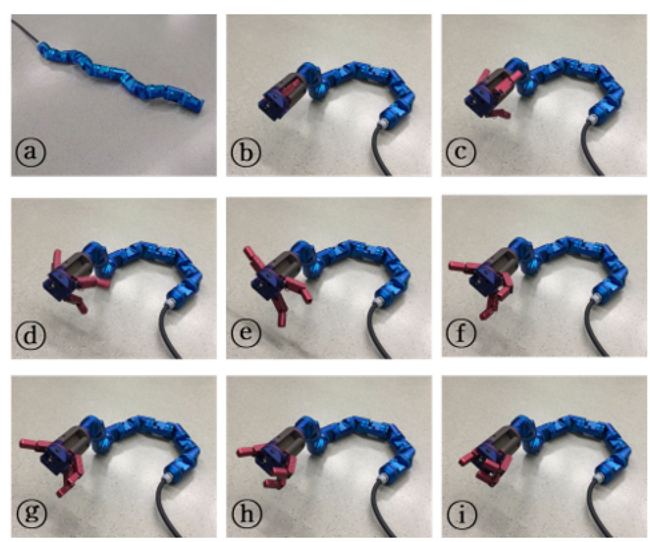


Fig. 12. The gripper module with snake robot: test of mode change.

small, the experimental results confirm that this is not a critical factor because the proposed gripper module does not manipulate objects with small volumes or thicknesses.

D. Snake Robot With the Proposed Gripper Module

The gripper module is integrated into a snake robot system as a snake-head module. Fig. 12(a) shows the snake robot, and Figs. 12(b)–(i) show the operation of the snake robot with the gripper module. The modes are changed in the same order as that used in the mode change test.

Fig. 13 shows the advantages of a snake robot equipped with a gripper module to perform USAR tasks. As shown in Fig. 13, the snake robot discovers and approaches survivors. And, the snake robot uses the gripper module to remove dirt and obstacles

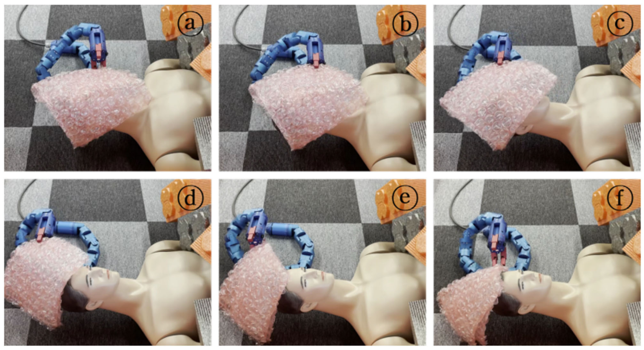


Fig. 13. Snake robot rescue operation experiments with gripper module.

around the trapped survivors. The mechanical and functional performances of the proposed gripper module were verified.

V. Conclusion

This study proposes a unique design of a gripper module to improve the USAR performance of a snake-like robot in a narrow space. The proposed gripper module consists of three fingers to stably grip and manipulate objects with irregular shapes. And, it has a mechanism for accommodating the fingers into its body to improve the mobility of the snake robot in a narrow space. Moreover, it has a fingertip camera to see various directions. As a result, the proposed gripper module is small, light, and compact; it satisfies the requirements for performing USAR tasks in a narrow space.

References

[1] S. Hirose, *Biologically Inspired Robots: Snake-Like Locomotors and Manipulators*. London, U.K: Oxford Univ. Press, 1993.
[2] M. Tesch, A. O'Neill, and H. Choset, "Using kinesthetic input to overcome obstacles with snake robots," in *Proc. IEEE Int. Symp*. Saf. Secur. Rescue Robot., Pittsburgh, PA, USA, 2012, pp. 1–6.
[3] D. Rollinson *et al.*, "Design and architecture of a series elastic snake robot," in *Proc. IEEE Int. Conf. Intell. Robot. Syst.*, Chicago, IL, USA, 2014, pp. 4630–4636.
[4] J. Whitman, N. Zevallos, M. Travers, and H. Choset, "Snake robot urban search after the 2017 Mexico city earthquake," in *Proc. IEEE Int. Symp. Saf. Secur. Rescue Robot.*, 2018, pp. 1–6.
[5] K. Lipkin *et al.*, "Differentiable and piecewise differentiable gaits for snake robots," in *Proc. IEEE/RSJ Int. Conf. Intell. Robot. Syst.*, San Diego, CA, USA, 2007, pp. 1864–1869.
[6] M. Tanaka, K. Tadakuma, M. Nakajima, and M. Fujita, "Task-space control of articulated mobile robots with a soft gripper for operations," *IEEE Trans. Robot.*, vol. 35, no. 1, pp. 135–146, Feb. 2019.
[7] M. Tanaka *et al.*, "Development and field test of the articulated mobile robot T2 Snake-4 for plant disaster prevention," *Adv. Robot.*, vol. 34, no. 2, pp. 70–88, 2020.
[8] ROBOTiQ, "ROBOTIQ 2F-85," Accessed: Feb. 20, 2021. [Online]. Available: https://robotiq.com/products/2f85-140-adaptive-robot-gripper
[9] Z. Hu, W. Wan, and K. Harada, "Designing a mechanical tool for robots with two-finger parallel grippers," *IEEE Robot. Autom. Lett.*, vol. 4, no. 3, pp. 2981–2988, Jul. 2019.
[10] N. Rojas, R. R. Ma, and A. M. Dollar, "The GR2 gripper: An underactuated hand for open-loop in-hand planar manipulation," *IEEE Trans. Robot.*, vol. 32, no. 3, pp. 763–770, Jun. 2016.
[11] Kinova, "Kinova grippers KG-2," Accessed: May 20, 2021. [Online]. Available: https://www.kinovarobotics.com/en/products/accessories/grippers
[12] K. Lee, Y. Wang, and C. Zheng, "Twister hand: Underactuated robotic gripper inspired by origami twisted tower," *IEEE Trans. Robot.*, vol. 36, no. 2, pp. 488–500, Apr. 2020.
[13] S. Donaire, J. Borras, G. Alenya, and C. Torras, "A versatile gripper for cloth manipulation," *IEEE Robot. Autom. Lett.*, vol. 5, no. 4, pp. 6520–6527, Oct. 2020.
[14] T. Nishimura, M. Tennomi, Y. Suzuki, T. Tsuji, and T. Watanabe, "Lightweight, high-force gripper inspired by chuck clamping devices," *IEEE Robot. Autom. Lett.*, vol. 3, no. 3, pp. 1354–1361, Jul. 2018.
[15] Y.-J. Kim, H. Song, and C.-Y. Maeng, "BLT gripper: An adaptive gripper with active transition capability between precise pinch and compliant grasp," *IEEE Robot. Autom. Lett.*, vol. 5, no. 4, pp. 5518–5525, Oct. 2020.
[16] L. U. Odhner *et al.*, "A compliant, underactuated hand for robust manipulation," *Int. J. Robot. Res.*, vol. 33, no. 5, pp. 736–752, 2014.
[17] S. Min and S. Yi, "Development of cable-driven anthropomorphic robot hand," *IEEE Robot. Autom. Lett.*, vol. 6, no. 2, pp. 1176–1183, Apr. 2021.
[18] M. Grebenstein *et al.*, "The hand of the DLR hand arm system: Designed for interaction," *Int. J. Robot. Res.*, vol. 31, no. 13, pp. 1531–1555, 2012.
[19] Z. Zhang, T. Han, J. Pan, and Z. Wang, "Design of anthropomorphic fingers with biomimetic actuation mechanism," *IEEE Robot. Autom. Lett.*, vol. 4, no. 4, pp. 3465–3472, Oct. 2019.
[20] D.-H. Lee, J.-H. Park, S.-W. Park, M.-H. Baeg, and J.-H. Bae, "KITECH-hand: A highly dexterous and modularized robotic hand," *IEEE/ASME Trans. Mechatronics*, vol. 22, no. 2, pp. 876–887, Apr. 2017.
[21] F. Ficuciello, G. Palli, C. Melchiorri, and B. Siciliano, "Postural synergies of the UB hand IV for human-like grasping," *Robot. Auton. Syst.*, vol. 62, no. 4, pp. 515–527, 2014.
[22] H. Yang *et al.*, "A low-cost linkage-spring-sendon-integrated compliant anthropomorphic robotic hand: MCR-Hand III," *Mech. Mach. Theory*, vol. 158, 2021, Art. 104210.
[23] C. Della Santina, C. Piazza, G. Grioli, M. G. Catalano, and A. Bicchi, "Toward dexterous manipulation with augmented adaptive synergies: The Pisa/IIT softhand 2," *IEEE Trans. Robot.*, vol. 34, no. 5, pp. 1141–1156, Oct. 2018.
[24] G. M. Achilli, M. C. Valigi, G. Salvietti, and M. Malvezzi, "Design of soft grippers with modular actuated embedded constraints," *Robotics*, vol. 9, no. 4, p. 105, 2020.
[25] J. Zhou, S. Chen, and Z. Wang, "A soft-robotic gripper with enhanced object adaptation and grasping reliability," *IEEE Robot. Autom. Lett.*, vol. 2, no. 4, pp. 2287–2293, Oct. 2017.
[26] S. Liu, F. Wang, Z. Liu, W. Zhang, Y. Tian, and D. Zhang, "A two-finger soft-robotic gripper with enveloping and pinching grasping modes," *IEEE/ASME Trans. Mechatronics*, vol. 26, no. 1, pp. 146–155, Feb. 2020.
[27] V. Alizadehyazdi, M. Bonthron, and M. Spenko, "An electrostatic/gecko-inspired adhesives soft robotic gripper," *IEEE Robot. Autom. Lett.*, vol. 5, no. 3, pp. 4679–4686, Jul. 2020.
[28] Y. Li *et al.*, "A dual-mode actuator for soft robotic hand," *IEEE Robot. Autom. Lett.*, vol. 6, no. 2, pp. 1144–1151, Apr. 2021.
[29] J. Zhou, J. Yi, X. Chen, Z. Liu, and Z. Wang, "BCL-13: A. 13-dof soft robotic hand for dexterous grasping and in-hand manipulation," *IEEE Robot. Autom. Lett.*, vol. 3, no. 4, pp. 3379–3386, Oct. 2018.