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Review of the Latest Research on Snake Robots Focusing on the Structure, Motion and Control Method

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Abstract: Unlike other types of robots, the snake robot performs unique motions and can move on various terrains such as gravel, stairs, and pipes. Therefore, snake robots are used as exploration robots, rescue robots, and disaster robots. However, the snake robot requires to choose actuators, sensors, and controllers appropriately for overcoming the real environment by using various types of gait. In this paper, we summarized research trends of snake robots for understanding the state of the art technologies of snake robots. We focused on the various development of the snake robots based on previous snake robots' literature. To look more closely at these research trends, we introduced trends of motion, actuators, sensors, kinematic structure design, control method and application that are related with the snake robots. Snake robots can conduct several motions such as sine wave, side winding, rolling, and so on. These motions are generated by servo motors, DC motors, pneumatic actuators, and smart materials like SMA, IPMC, etc. Also, snake robots require certain data from sensors and proper kinematic structure design to achieve their purposes of operation. Sensors such as camera, force sensor, distance sensor, and kinematic structure design such as passive wheel and motorized wheel can be applied in snake robot for implementing the function or increasing the driving performance. Based on these physical components, the control method is important for operating the snake robot. Navigating algorithms and overcoming terrains with restrictions on movement have been studied with a various control methods.

Keywords: Actuators, biomimetic robot, physical development, sensors, snake robot.

1. INTRODUCTION

Recently, many robots are being developed to perform exploration of disaster areas. In disaster areas, there are two kinds of representative methods for driving the exploration robot. The first one is the wheeled method. This robot has good maneuverability but it is not suitable for overcoming various types of obstacles [1–3]. The other method is the walking method. This method can be possible to overcome some obstacles such as stairs by using robot legs; however, these robots have slow moving speed and the cannot move through narrow space [1,4,5]. To solve these problems, researchers are considering various kinds of mobile robots. Aerial robots which have advantages of excellent maneuverability and low interference with obstacles [6,7]; they can also monitor disaster situations in the air [8,9]. However, their operation time is short and it is difficult for them to work in narrow spaces or isolated environments [10]. As a result, many researchers have studied snake robots which have a high degree of freedom and ability to drive in narrow space or isolated environments. However, snake robots require multiple control nodes, so the driving pattern is complicated as shown in Table 1. Also, selecting the components of the snake robots is important for using the snake robots in disaster areas. Therefore, the development of the snake robots has been studied in various ways.

The purpose of this paper is providing the summary, insight, pros and cons about overall field of the snake robots. In this paper, we discuss snake robots in terms of trends of motion, actuators, sensors, kinematic structure design, control method, and application. In motion section, the sine wave that snakes perform in nature basically is the general motion. Recently, many types of researches have been conducted for inspection inside a narrow pipe or driving the snake by winding outside of the pipe. These various motions are generated by servo motors, DC motors, pneumatic actuators, and smart materi-

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Table 1. Comparison of wheeled robot and snake robot.

	Wheeled robot	Snake robot
Advantages	- Maneuverability - Easy control - Simple design and maintenance	- Special gait for specific terrain (Tree, underwater, stairs) - Inspection of narrow space
Disadvantages	- Restrictions of environment - Hard to recover from a fall	- Maneuverability - Complicated control with high DOF

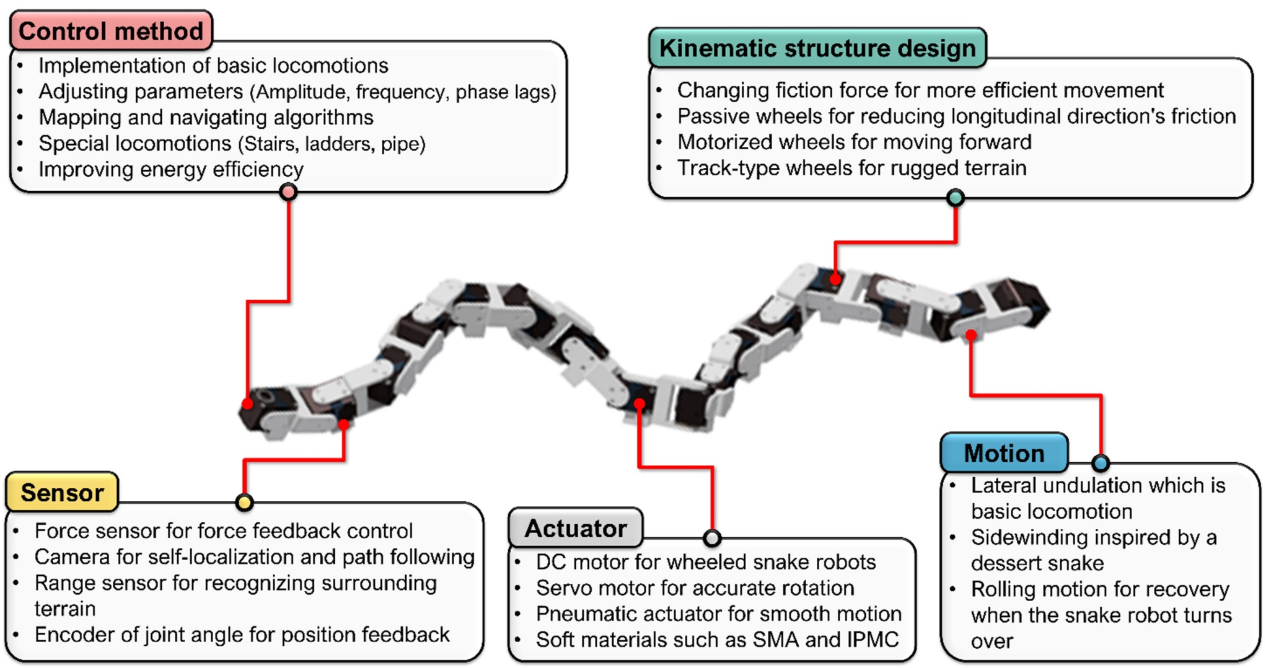

Fig. 1. Conceptual diagram of the components of the snake robot.

als like SMA, IPMC, etc. Many researchers have developed snake robots by intersecting servo motors at 90 degrees in order to mimic the multi-joint of snake robots. Also, snake robots require environment data from sensors to achieve their purposes of operation. The force or torque sensor is one of the sensors that is often utilized in snake robots. The reason is that these sensors can provide information about the interaction with the surrounding terrain and this can improve the driving performance by measuring the torque of the snake robot itself to control multi-joint nodes. In terms of control, researchers have combined reinforcement learning with the existing control method for optimizing the complex driving method of the snake robot recently. This paper will provide researchers with information and insight for developing snake robots as shown in Fig. 1. These recent trends and information will be helpful for achieving further robot development.

2. MOTION

Conventional snake robots generally use three types of motion to overcome narrow space or certain obstacles.

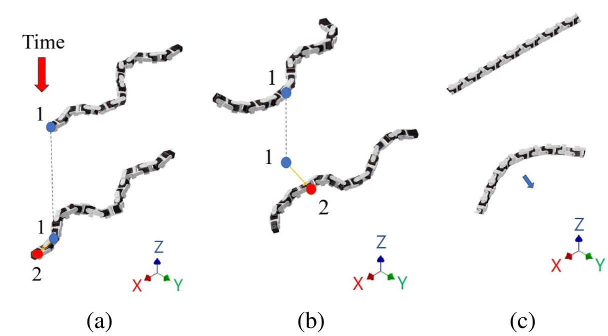

Fig. 2. Three typical motions of snake robot; (a) Lateral undulation motion. (b) Side winding motion. (c) Rolling motion.

The typical three motions of a snake robot in an orthogonal coordinates system are shown in Fig. 2. Blue and red markers indicate the movement trajectory for each motion.

The first motion is a sine wave that moves forward by shaping the body to an S-shaped form is shown in Fig. 2(a). Sine wave movement also called lateral undulation

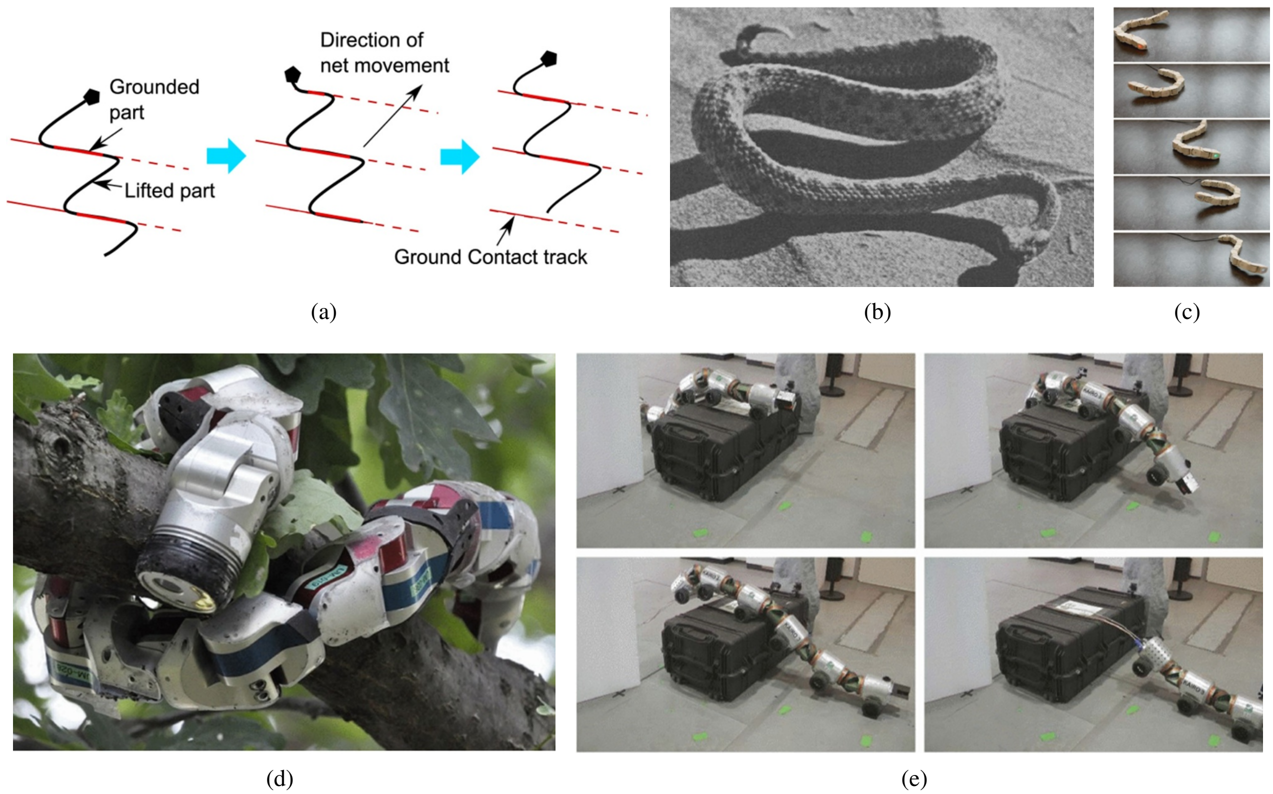

Fig. 3. Locomotion of the snake robot. (a) Concept diagram of the side winding motion of real snake. (b) Side winding motion of a real snake. Courtesy of Nagoya University [46]. (c) Side winding of snake-like robot without passive-wheel. Courtesy of SINTEF ICT [18]. (d) Rolling motion of unified snake robot. Courtesy of Carnegie Mellon University [28]. (e) Overcoming a huge box using a caterpillar locomotion. Courtesy of FZI Research Center for Information Technology [41].

and helps the snake robot can move forward by using the frictional forces. In addition, motion using a sine wave makes it possible to move in an oblique line direction using the repulsive force and driving force induced by the contact between the snake robot and the ground. Besides, this motion is the combination of sideways motion and body undulation [11], and research on creating the basic driving motion of a snake robot by mimicking the sine wave motion of a real snake has been actively conducted [12–14]. Also, the characteristic of sine wave movement is that it can be used for rescue operations by overcoming various terrain such as water, gravel, and so on. 'Aiko [15]', 'Kulko [16,17]', and 'Mamba [18]' robots are typical examples of robots using sine waves. The sine wave movement boasts excellent energy efficiency among the motions in which the head direction and the moving direction match, and as a result of finding a straight motion with good energy efficiency using reinforcement learning, it has a motion similar to that of the sine wave movement [19].

The second motion is sidewinding, a method of moving to the side by fixing the head and tail. Side winding in Fig. 2(b) is a type of movement used mainly by snakes living in the desert. It is a method that fixes the head, tail, or part of the body on the ground and moves the body to the side with repulsive force while pushing the ground as shown in Figs. 3(a)-3(c). This motion can also be used to overcome obstacles by using high maneuverability and incline ascent. 'FUM-snake 5 [20]' and 'KAEROT-snake IV [21]' are representative robots that implemented side winding motion. In addition, many studies on sidewinding motion have been actively conducted [15,18,20–26]. As a result, the sidewinding motion can be universally operated in various terrains as well as in deserts [27], but it may have difficulties in overcoming obstacles.

The last motion is rolling which is a motion that consecutively rolls body of snake robot sideways as shown in Fig. 2(c). This motion is similar to the sidewinding motion in that direction of movement is lateral. Rolling motion can be used for recovery when the snake robot turns over. This motion has a disadvantage in that if the camera is installed at the head of the robot, the camera view continuously rotates 360 degrees. However, by wrapping the structure and rolling the body, this motion can be applied to climb trees as shown in Fig. 3(d). Typical robots using rolling motion are the 'Unified Snake [28]' and 'CMU modular snake robot [29]'. With this motion, these robots can easily climb or pass through vertical structures, and so they have advantages in reconnaissance and surveillance. Due to these advantages, lots of research is underway to achieve various goals by applying rolling motion [16,21,25,28–32].

Besides the three previous types of motion, other kinds of motion are being studied to overcome various types of obstacles as shown in Fig. 3(e). Except for three types of typical motion, some researchers studied the caterpillar locomotion to overcome the stairs using snake robot, and the certain snake robot used the wheels and skin that can produce another snake locomotion for fast-moving or overcoming the various terrain [33–44]. Most of these motions are made using feedback control [45], and there is a characteristic that the control technique is diverse for each obstacle.

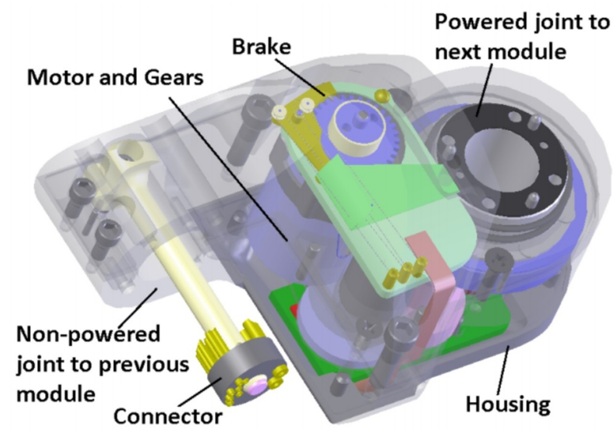

Fig. 4. A single actuator module for snake robot with DC motor and gear system. Courtesy of Carnegie Mellon University [28].

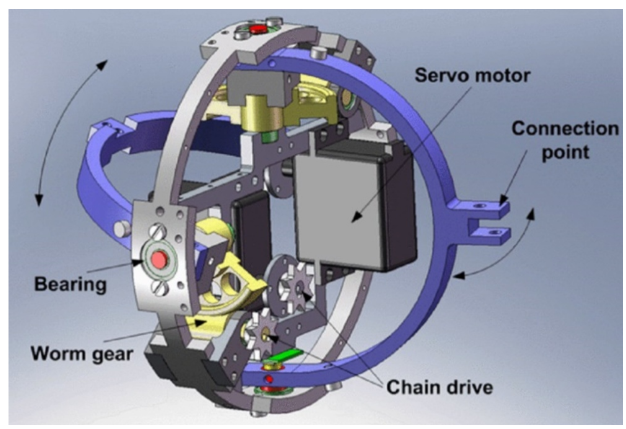

Fig. 5. Single actuator module for snake robot with servo motor and gear system. Courtesy of SINTEF [16].

3. ACTUATOR

Regarding the motion of a hyper-redundant robot, snake robots can make the motion by using the three methods such as rotational motor, pneumatic actuation, and a smart material like SMA. Snake robots consist of many modules and can crawl with the help of actuator motion from individual joints between modules. In most papers, to achieve a crawling motion, researchers used rotational electric motors as shown in Fig. 4. Some research teams made the actuation module that includes rotational DC motors, gears, potentiometers, and batteries, and these modules combined to make a snake robot that can overcome the various terrains [15,21,38,43]. Other researchers developed snake robots that include servo motors and microcontrollers [32,47,48]. Snake robots that use DC motors mostly move by wheels. The biggest reason to choose a DC motor is that it is the most suitable type of motor for fast and continuous rotation.

A swimming snake robot called 'AmphiBot' is actuated by DC motors mounted at every element that obtain feedback through an encoder [49]. However, servo motors are widely used instead of DC motors. Because, the joint configuration may become complicated when a rotating joint is implemented using a DC motor [28]. The snake robot by consisting of the servo motor module can perform many motions such as crawling, climbing, turning, and etc. Because the servo motor has a high capability of torque, fast and accurate rotation at a limited angle. So, the servo motor is a widely used actuation method for the snake robot as shown in Fig. 5. Also, servo motors have a set of gears and a potentiometer inside them, and this advantage can reduce the additional components for the actuation of the snake robots. Robots such as crawling snake robots for environments with obstacles [17,34]; snake robots with multiple abilities including crawling, sidewinding, rolling, in-place turning, and caterpillar locomotion [16,50]; and Mamba swimming snake robots [18] are composed of servo motors. In addition, servo actuators can design the precise configuration of each joint angle, and it can make the module design simpler. Also, if the robot uses only sine-wave motion, it could inactivate or remove the sensors for real-time control [30,51].

In the case of peneumatic actuation method, many researchers actively studied a soft snake robot by using pneumatic actuation recently [23,52,53] as shown in Figs. 6(a) and 6(b). These snake robots are composed of soft chambers and are commonly actuated by air pressure. When air pressure is applied to the chamber of each link, the air chamber is expanded. This expansion can adjust by changing the structure of each chamber, and it can help the snake robot do various motions. Compared to a hard robot, a pneumatic actuator makes the snake robot move engage in a more real snake-like motion. This flexibility makes the snake robot move better in obstacle-filled en-

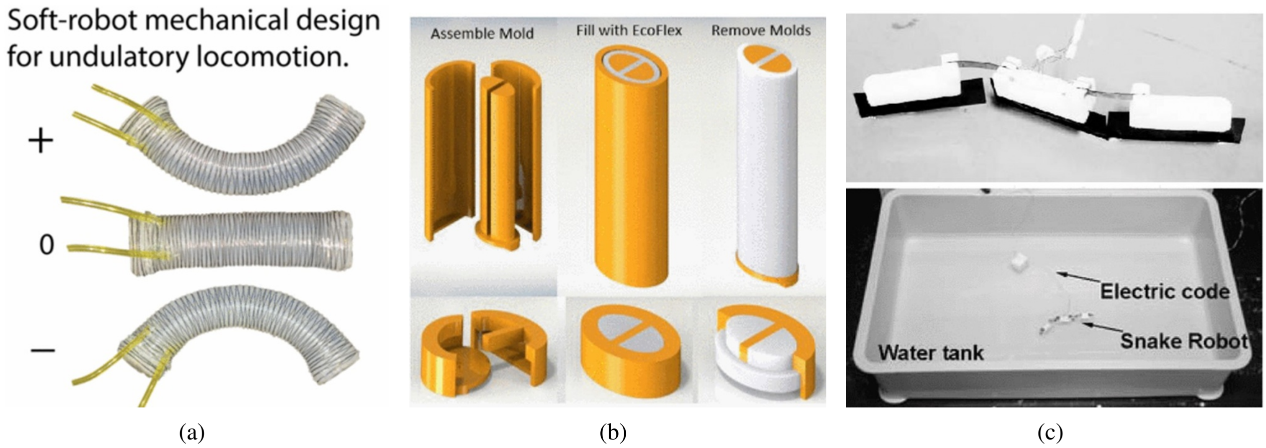

Fig. 6. Design of actuator module using smart materials. Courtesy of SINTEF [16]. (a) Mechanical design of soft chamber for soft snake robot. (b) Fabrication procedure of soft chamber. Courtesy of Oregon State University [52]. (c) Snake robot with IPMC module. Courtesy of Bio-mimetic Control Research Center [55].

vironments or narrow spaces. Also, pneumatic actuators have more strength than electric motors in terms of the magnitude of torque to weight ratio that can be produced. However, it is difficult to analyze the kinematics and dynamics of this type of robot. Besides, in the case of a snake robot using a pneumatic actuator, there is a disadvantage that a heavy pneumatic device must be attached, which causes limitations when making a mobile robot [54]. In addition, due to the time required for pneumatic expansion and contraction, the driving speed is slower than that of hard robots, and soft materials may be damaged when they come into contact with rough surfaces.

The third method is smart material for snake robot. The robot uses SMA, it is able to implement more flexible motion than snake robots using hard materials. For example, in the case of amphibious snake robots, this robot can change its dynamic through the use of an Ionic Polymer-Metal Composite (IPMC) combination material that responds to electrical activation as shown in Fig. 6(c) [55]. In addition, research is underway on snake robots made of soft materials such as silicon, which will allow them to move using smart materials such as SMA [56]. Using this flexible motion, it has the advantage of realizing a more dynamic and natural motion with a light object [57]. There is also a study extending the application of SMA to robots, using it to develop independent actuators for snake robots [58,59]. As a result, in the case of a snake robot made of smart material such as SMA or IPMC, the actuation of each module can be performed using a simple structure, which helps to reduce the weight of the snake robot. This advantage can increase the application field of the snake robot by helping to attach additional modules to the snake robot.

4. SENSOR

Snake robots are used mainly for exploration and disaster relief because they can move through narrow or dangerous places where people cannot go. So, snake robots require additional sensors in the body section to perform missions successfully. Encoders, cameras, wireless communication sensors, range sensors, force sensors, accelerometers, and gyroscopes are widely used in snake robots. In this section, the sensors that are mainly used in snake robots are described according to their roles and applications.

Among sensors mainly used in snake robots, encoders have been widely studied [11,16,21,32,60]. Encoders are used to control snake robot movement by receiving position feedback information, including joint angle. The snake robot ‘Kulko [16]’ measures the angle between two adjacent links using magnetic encoders attached to individual links; based on the collected joint angle information, an MCU attached to each joint is used to control the snake robot motion.

To recognize disaster environments at disaster rescue sites, cameras and wireless communication sensors are required and research has been carried out to apply these sensors to snake robots [16,17,24,31,39,40,51,55,61–63]. Cameras are attached to the head and tail of the snake robot and are used to observe the surrounding environment when the snake robot reaches a high place or narrow environment. The wireless communication sensor is used to remotely control the snake robot using data from the camera.

By examining obstacles or terrain around the snake robot, the range sensor can be used to move the robot through difficult areas. Among range sensors, infrared dis-

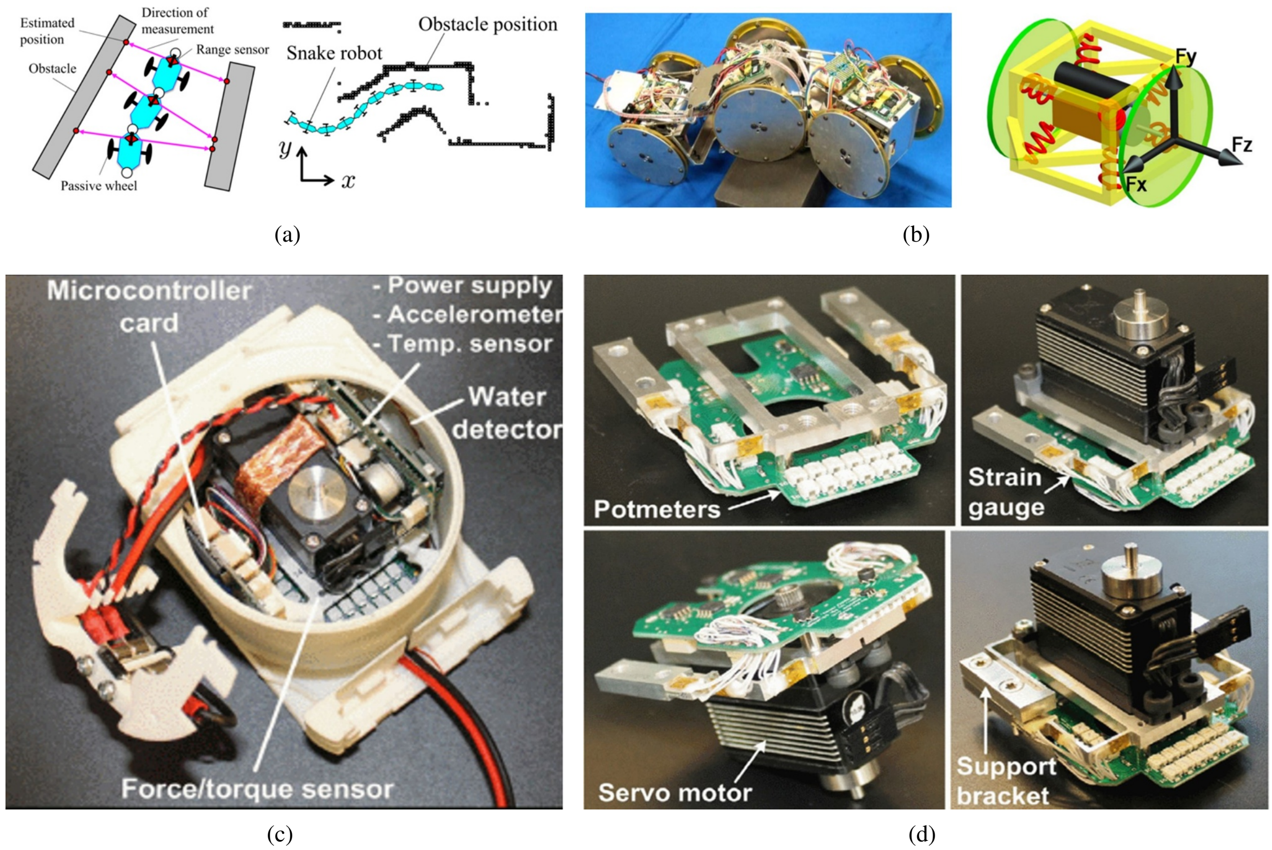

Fig. 7. Design of driving part for snake robot with a sensor fusion system and actuator. (a) Estimation method of obstacle position using the range sensor on each link. Courtesy of University of Electro-Communications [65]. (b) Semi-Autonomous snake robot. Courtesy of University of Tsukuba [35]. (c) Snake robot module with a force sensor. (d) A driving module of snake robot that is combined with actuator and sensor fusion. Courtesy of SINTEF ICT [18].

tance sensors are widely used; research has been conducted on applications of infrared distance sensors to snake robots [16,17,40,64,65]. The KOHGA robot developed by the University of Electro-Communications [65] can recognize obstacles and avoid them in every direction using range sensors attached to individual links, as shown in Fig. 7(a). The snake robot developed by the University of Electro-Communications [40] has five infrared distance sensors attached to the front, top, bottom, right, and left directions of the snake robot's head and tail modules and two infrared distance sensors attached to the body in the right and left directions, allowing semiautonomous navigation. Instead of using an infrared distance sensor, the 'Urban Search and Rescue (USAR) Robot' developed by Sathyabama University [64] uses an ultrasonic sensor to map the surrounding environment; it uses a PIR sensor (Passive Infrared sensor) to detect signals of survivors at rescue sites.

The main force sensor used in snake robots is the Force Sensitive Resistor (FSR) sensor; its usages are various. In the ACM-R8 developed by the Tokyo Institute of Technology [66], the force sensor measures the joint torque and the MCU controls the motion of the snake robot by receiving torque data. Part of the force sensor is composed of springs, which reduce the impact applied to the actuator and increase the similarity of the snake robot movement to actual snake movement. Another reason to use a force sensor on a snake robot is to implement semi-autonomous control for sophisticated motions. When a snake robot is in narrow or obstacle-filled environments, it is difficult to operate the robot with only images observed by a camera. The snake robot developed by the Tokyo University of Technology [35] uses a proprietary force sensor instead of an FSR sensor, as shown in Fig. 7(b). The group attached springs and LEDs to individual links and used a property in which the intensity of light changes according to the distance to produce a sensor that measures the force using measured distance and stiffness of spring to implement semi-autonomous control. In 'Mamba', developed by the Norwegian University of Science and Technology [18], the force sensor measures the contact force based using a strain gauge, so that the snake robot can sense and adapt to the environment and realize efficient locomotion in various environments as shown in Figs. 7(c) and 7(d).

In addition, studies using force sensors have been actively conducted [16,18,23,26,35,61,66].

In the Modular Snake Robot developed by Carnegie Mellon University [67], a current sensor and temperature sensor were used to prevent the overloading of motor and electronic devices. In the Unified Modular Snake Robot developed by Carnegie Mellon University [28], an inertial sensor (accelerometer, gyroscope) is used to find the direction of gravity to allow grasping by the top surface of the snake robot. In the modular pneumatic snake robot developed by SINTEF IKT [23], the actuator was pneumatic, and so the chamber pressure was measured through a pressure sensor. To recognize the exploration environment, several kinds of sensors have been attached to snake robots.

Many sensors which are applied in snake robots have been used for increasing driving performance in the constrained terrains. Because overcoming the constrained terrains is the advantages compared to other robots. In the recent research, the force sensor was used for traversing terrain with arch with force feedback. Sensing contact force and internal torque helps to generate the propulsion for overcoming the terrain with arch. Also it's important for determination of 3-D body structure. In these studies, a simple arch obstacle was used [45,68]. Therefore, research about overcoming the complex terrain with many arches should be conducted for using this method in the disaster environment. In the other research, camera was used for applying compensation method The self-localization and path following is hard work, because the head of the snake robot is swinging during the locomotion [69]. This compensation method based on camera should be conducted in rough terrains with complicated path for applicating in disaster environment.

5. KINEMATIC STRUCTURE DESIGN

Various mechanical designs of the skin which touched the ground have been studied to effectively move snake robots. The structure that touches the ground is called the skin of the robot. There are active skin type robots that move their skins to move in desired directions; others are fixed-skin type robots, which induce various motions without driving the skin. This section will covers the fixed structure design and active structure design.

The first one is fixed structure design. To generate various locomotions, living snakes move their bodies in certain ways. With the help of the repulsive force from the ground, they can move in desired directions. Fixed skin-type robots move with certain types of motion by driving various joints in certain ways. Researches have been conducted on robots that move using friction between individual links and the contact surface [11,21,23,47,60,67,70], and a robot that swims on water [55] has also been studied. Furthermore, studies are being conducted to realize more efficient movement by changing the frictional force. A research [71] increased the friction force in a narrow space like pipe environment by changing the shape of the mechanism structure, and a research [72] increased the friction force by adding an additional joint to the link. However, it has been confirmed that if a special structure is borrowed to adapt to the specific terrain, inefficiency appears except for the specific terrain. The snake robots with passive wheels have been proposed to reduce the friction force in the longitudinal direction and to increase the frictional force in the direction perpendicular to the longitudinal direction as shown in Fig. 8(a) [24,30,43,49,61,65,73–75]. In [76], an optimal scale structure was designed to enhance robot movement as shown in Figs. 8(b) and 8(c). Another study was carried out to fabricate the entire body as a single body using soft material, rather than as a multi-link structure composed of rigid links and joints [52,53].

The second one is active structure design. There have also been studies to attach active skin to the robot body using methods different from those delineated in the previous section. Unlike previous robots, robots with active skins do not use undulating motions to move forward, and so they usually have fewer nodes than the robots in the previous section. Some snake robots have nodes that are motorized wheels, such that the robot can move forward as the node rolls [66]. Some have individual nodes composed of spherical omnidirectional wheels; each wheel is rotated to move the robot in the desired direction [38]. Snake robots with actuated wheels on their bodies have also been suggested as shown in Fig. 8(d) [18,35,41]. Circular wheels are effective for robots that must pass through smooth pipes; however, track-type wheels are more effective for smoothly overcoming rugged terrain [55]. Research has also been conducted to attach track-type wheels to robot bodies [39,40,44,51]. These robots can move each of the individual joints via several actuating systems. In addition to controlling the active skin using a motor, a robot that controls the skin using pneumatic system has also been studied as shown in Fig. 8(e) [77]. With this method, it could be reduced the size of the robot, but requires an additional external pneumatic system.

6. CONTROL METHOD

The study about the control method of the snake robot has been studied through various ways. Some studies were conducted to develop the basic locomotion of the snake robot such as lateral undulation, vertical wave, and rolling motion. Also studies for improving driving performance were conducted by adjusting parameters such as amplitude, frequency, and phase lags [40,55]. After then, mapping and navigating algorithms were studied for performing rescue and inspection as shown in Figs. 9(a) and 9(b). In these researches, various sensors such as tactile sensor, ultrasonic sensor, and PIR sensor were used [17,32,58].

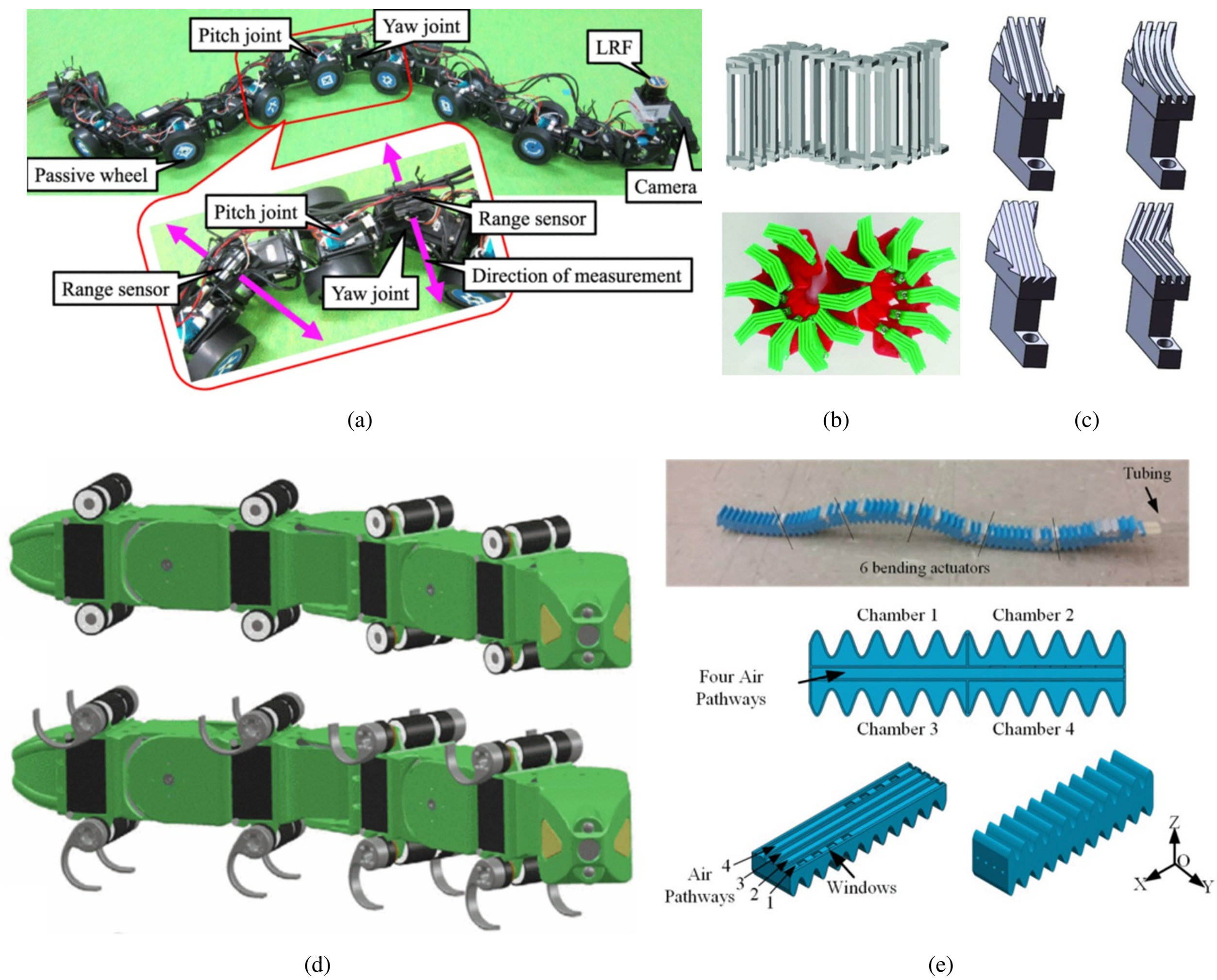

Fig. 8. The kinematic structure design of the snake robot. (a) Snake robot with passive wheels. Courtesy of Southwest University of Electro-Communications [65]. (b) Overall structure of the snake robot with optimal scale. (c) Four types of the scales. Courtesy of Southwest University of Science and Technology [76]. (d) Snake robot with motorized wheels and snake robot with motorized legs. Courtesy of SINTEF [18]. (e) Soft snake robot with the pneumatic actuated module. Courtesy of Michigan State University [77].

Since then, many studies have been conducted to develop special gaits for overcoming terrains with restrictions on movement, such as ladders, stairs, and humps [27,28,38,59]. Recently, studies that combine a reinforcement learning algorithm with an existing control method are being actively conducted to decrease power consumption and improve energy efficiency [67,68]. This section summarizes the recently published studies on the control and describes the pros and cons of the state of art for giving the insight and research trends.

Many studies have conducted about the control based on reinforcement learning. In a study that probabilistically solved the problem of how the angle of the motor should be changed when the snake robot encounters an obstacle based on reinforcement learning, the snake robot was controlled through a dynamically decentralized model. It is a meaningful study because it experimentally verified that the proposed decentralized model is effective in overcoming obstacles compared to the existing centralized control and tried a new control technique in the snake robot. For the high performace, more sophisticated model is essential for overcoming the various obstacles [78]. In other reinforcement learning-based studies, various reinforcement learning algorithms were used to learn gait on a snake robot in a simulator. In addition, the controller that controls the snake robot was tuned to increase energy efficiency through learning, and it was confirmed that the snake robot operates with the most efficient movement [79]. In the paper that attempted to solve the target tracking task of a snake robot using a model-free reinforcement learning algorithm, the controller was trained in a dynamically changing track scenario through a new customized

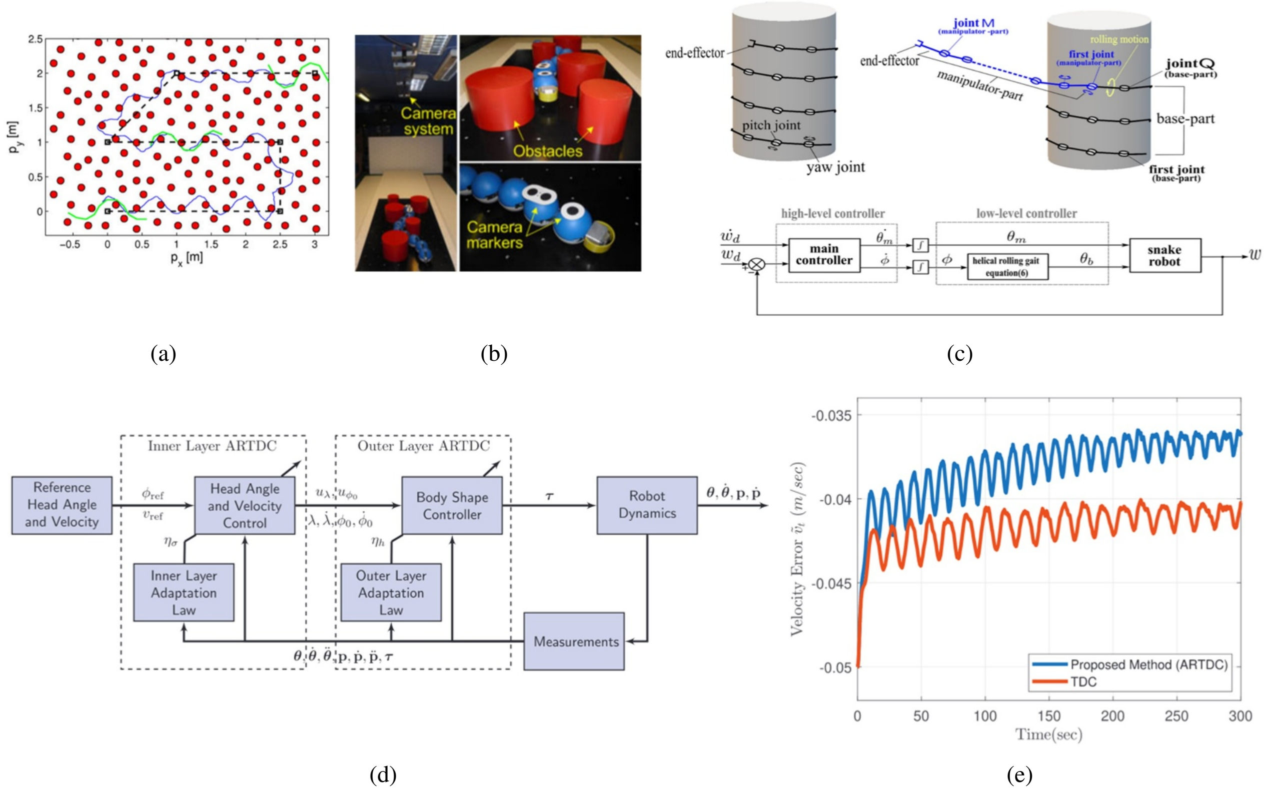

Fig. 9. Control method for snake robot. (a) Navigation algorithm for locomotion. (b) Avoiding obstacles using sensor fusion systems. Courtesy of SINTEF ICT [17]. (c) The strategy of locomotion and control method for helical rolling locomotion. Courtesy of Kyoto University [81]. (d) Control diagram of dual adaptive-robust time-delayed control. (e) Performance comparison graph for two control models. Courtesy of SDU Robotics [83].

reward function. As a result, it was proved that the reinforcement learning-based controller has superior performance in terms of tracking accuracy compared to the traditional model-based controller. These are simulation result, therefore the experiment is necessary to validate the simulation result. Also, matching the simulation's parameters such as dimension, friction should be processed before experiment [80].

Some studies have conducted about the control method to travel inside a pipe or the outer surface of the pipe. In the study of the snake robot operating inside the pipe, a trapezium-like traveling wave was mathematically modeled, and the control of the snake robot was performed by constructing a matrix for angle and motion direction. Through this algorithm, the speed of the snake robot was increased greatly, and the efficiency of power consumption was improved by compensating the number of amplitude links according to the pipe width [71]. In another study on pipe motion, a full-body manipulation control of a snake robot moving along the outer surface of a pipe using a helical rolling gait was studied. In full-body manipulation, they divided the manipulation part and the helical part to perform helical rolling locomotion as shown in Fig. 9(c). And through this, rotational ability was improved even without a rotation actuator in the end effector. There are some limitation on motor torque and pipe material for hanging on the pipe. Therefore, the status of snake robot's base part should be changed or the material of the pipe should be changed [81].

In addition to reinforcement learning-based control and control for driving inside a pipe, research on various control methods has been conducted. In a study using a CPG-based controller, although the dynamics of the snake robot are not analyzed, the control angle of the snake robot's joints was calculated through CPG and the joint was moved to promote the snake robot [82]. In the paper that proposed a new control method called dual adaptive-robust time-delayed control, which is a mixture of the existing adaptive robust control and time delay, the angle and force of the robot head and the body shape were controlled separately through the proposed method. In addition, the stability of the proposed system was judged using the Lyapunov function, and an appropriate gain value was derived mathematically. As a result, the simulation showed improved performance in terms of velocity error compared to the control method using only time delay control as shown in Figs. 9(d) and 9(e) [83].

7. APPLICATION

Snake robots have a thin body and can perfom various motions, so it can be used in exploration robots for disaster areas. Entering in disaster areas is difficult for people, but snake robots can enter easily. Especially, snake robots have an advantage in pipes. Therefore, research about the snake robots that can pass through pipes has been conducted actively. The researcher studied the wave motion of snake robots, used to move up and down through straight pipes as shown in Figs. 10(a) and 10(b) [84].

In recent papers, researches on movements of snake robots along the insides and outsides of various shapes of pipes have conducted actively. Therefore, the ability of exploration of pipes which is the important advantage of snake robots will increase [21,30,62,67]. There is a snake robot that can move up and down along the outside of a pipe, as shown in Fig. 10(c) [31]; another snake robot can move along the inside of a pipe [30]. In addition, research on mobile manipulation using the redundant degrees of freedom was also conducted [85]. The robot overcomes the pipe environment and could close the valve.

Avoiding the obstacles is important tast for the snake robots in the disaster spots. To allow robots to avoid obstacles efficiently, researchers have actively studied the application of cameras and sensors [34,35,65]; they have studied mapping using sensors to explore [64]. Furthermore, there have been many studies on applying feedback control systems to snake robots to allow them to use sensors to avoid obstacles autonomously in disaster spots as shown in Figs. 10(d) and 10(e) [29,39,41,51].

Also, researchers have conducted studies on snake robots that can overcome special obstacles such as stairs and ladders as shown in Fig. 10(f) [21,32,33,41,73]. OT-4 snake robot can climb stairs by using vertical waves [39,40,44,51]. To reduce the frictional force when a snake robot hits the surfaces of obstacles, researchers studied snake robots whose bodies were cylindrical or spherical, allowing them to avoid obstacles easily [24,86]. The KULKO robot has a spherical body shape and this snake robot can sense the environment by tactile sensing and can use body shape adapts to the environment [17]. Also, a robot in which a snake robot and a mobile robot cooperate is being studied [81]. This robot could perform tasks in various environments by utilizing the strengths of each robot, but it is difficult to implement because it is a multi-

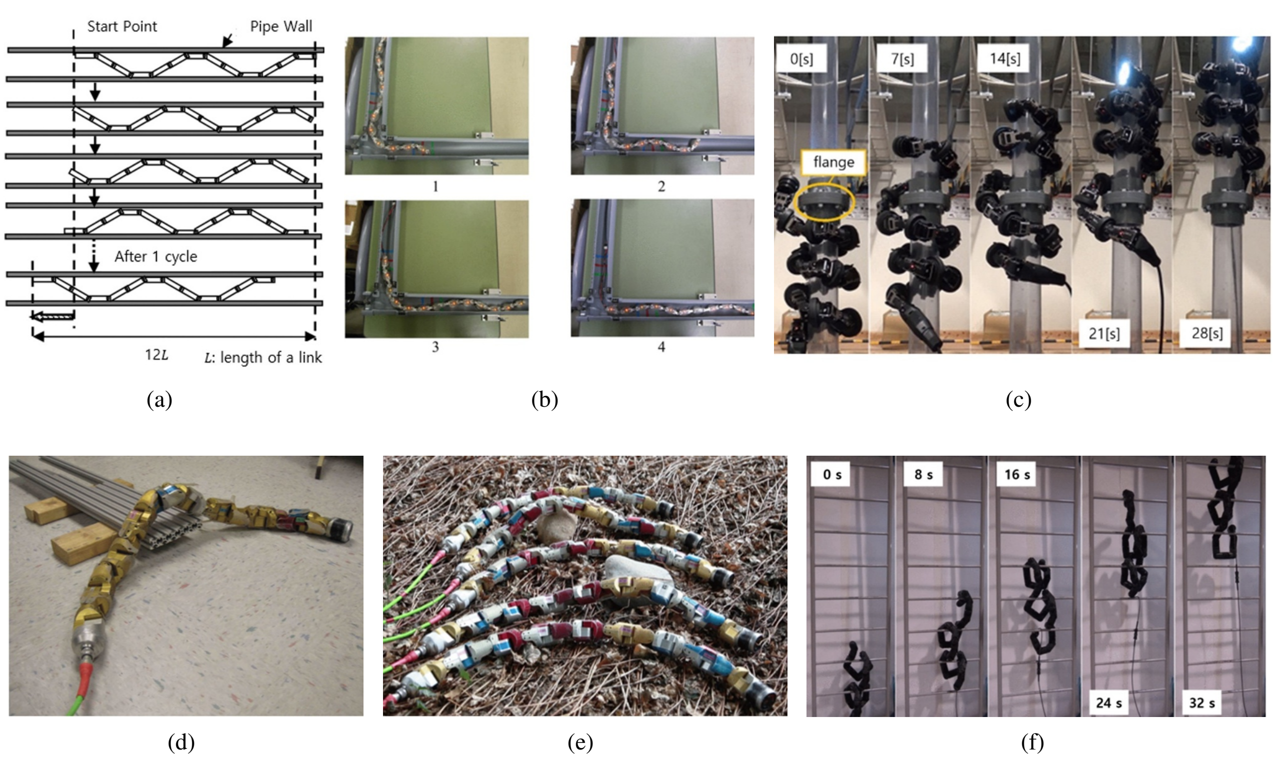

Fig. 10. Application of snake robot in various terrain. (a) Principle of the pipe locomotion. (b) T-shaped pipe experiment. Courtesy of Okayama University [84]. (c) Snake robots that move up and down along pipes. Courtesy of Kyoto University [31]. (d) Rolling motion for moving over the humb. Courtesy of Carnegie Mellon University [29]. (e) Snake robot that can overcome the stone. Courtesy of Kyoto University [32]. (f) Snake robot that can climb the ladder. Courtesy of Kyoto University.

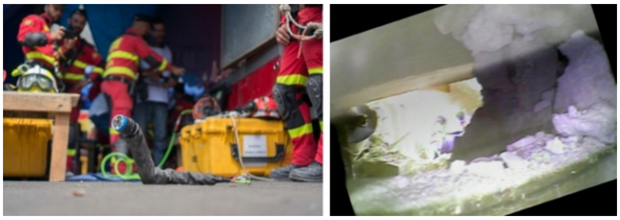

Fig. 11. U-snake robot in Mexico earthquake. Courtesy of Carnegie Mellon University [63].

agent system.

As a result of the previous study, a U-snake robot [63] took a role in exploring an isolated environment created by an earthquake. The robot camera showed the scene of the disaster, allowing isolated people to be rescued, as shown in Fig. 11. This robot contributed to lifesaving in the 2017 Mexico earthquake. Snake robots will not only explore disaster situations but also rescue lives in the future. In addition, if researches will be conducted in various ways, snake robots can be utilized in various fields such as surgical robots and manipulator.

8. CONCLUSION

Snake robots have advantages over wheeled robots in overcoming irregular terrain. To maximize these advantages of snake robots, we described about trends of motion, actuators, sensors, kinematic structure design, control method and applications in this paper as shown in Table 2. In the motion section, we looked at how many snake robots can conduct basic types of motion such as sine wave, side winding, and rolling motions. Sine wave motion is a common type of snake locomotion; side winding is special locomotion of desert snakes. Rolling motion can be used to climb trees or turn over the robot body. Snake robots have high degrees of freedom, and so can produce various types of locomotion. There are also studies on motions that can overcome staircases and ladders. In the actuator section, DC or servo motors were discussed in the development of snake robots. Some snake robots are actuated by smart materials like SMA and IPMC. In the sensor section, we discussed how snake robots use many kinds of sensors to carry out exploration in obstacle environments. These sensors include range sensors, cameras, and force sensors. There are two kinematic structure designs

Table 2. Summary of the physical development of the snake robots.

Name	Year	Motion	Sensors	Actuator	DOF of joint	Kinematic structure design
Wu *et al.*, Ritsumeikan University [74]	2010	Sine wave	/	Servo motor	2	Fixed
Baba *et al.*, Okayama University [30]	2010	Helical curve rolling	Camera	Servo motor	2	Fixed
Maity *et al.*, CSIR [50]	2011	Sine wave Side winding Rolling Caterpillar locomotion	IR sensor	Servo motor	1	Fixed
Shin *et al.*, Korea Atomic Energy Research Institute [21]	2011	Pipe climbing Sidewinding Rolling	Gyro sensor	DC motor	2	Fixed
Liljebäck *et al.*, SINTEF [16,17]	2012	Sine wave	Encoder Force sensing resistors	Servo motor	1	Fixed
Wright *et al.*, Carnegie Mellon University [28]	2012	Rolling	IMU Temperature sensor	DC motor SMA	2	Fixed
Liljebck *et al.*, SINTEF [18]	2014	Sidewinding	Force/torque sensor	Servo motor	1	Active
Zhen *et al.*, Carnegie Mellon University [29]	2015	Rolling Hump	Tactile sensors	Servo motor	1	Fixed
Komura *et al.*, Tokyo Institute of Technology [66]	2015	Forward motion Rolling	Force sensor	DC flat motor	2	Active
Branyan *et al.*, Oregon State University [52]	2017	Sine wave	/	Servo motor	High	Fixed

Table 2. Summary of the physical development of the snake robots (continued).

Name	Year	Motion	Sensors	Actuator	DOF of joint	Kinematic structure design
Nana *et al.*, Southwest University of Science and Technology [76]	2018	Helix structure	/	DC motor	1	Fixed
Malayjerdi *et al.*, Center of Excellence on SCIIP [20]	2018	Sidewinding	Force sensor	Servo motor	2	Fixed
Takemori *et al.*, Kyoto University [31]	2018	Side winding Rolling	/	DC motor	2	Fixed
Singh *et al.*, Visvesvaraya National Institute of Technology [38]	2018	Caterpillar locomotion	Encoder	DC motor	1	Active
Whitman *et al.*, Carnegie Mellon University [63]	2018	Sidewinding Pole climbing Manual control of head module	Camera	Servo motor	1	Fixed
Manzoor *et al.*, Mirpur University of Science and Technology [82]	2019	Sine wave	GPS	Servo motor	1	Active
Qi *et al.*, Michigan State University [77]	2020	Caterpillar locomotion	Pressure sensor	Pneumatic actuator	High	Fixed
Dear *et al.*, Columbia University [87]	2020	Sine wave	/	Servo motor	1	Fixed
Virgala *et al.*, Technical University of Košice [72]	2020	Concertina locomotion	Optical distance sensor	Servo motor	1	Fixed
Virgala *et al.*, Technical University of Košice [71]	2020	Trapezium-like wave	3D camera Distance sensor	Servo motor	1	Fixed
Kakogawa *et al.*, Ritsumeikan University [88]	2021	Sine wave	Encoder	Servo motor	1	Fixed
Inazawa *et al.*, Kyoto University [89]	2021	Rolling	Camera	Servo motor	1	Fixed
Takemori *et al.*, Kyoto University [90]	2021	Sidewinding Rolling Sinus lifting Passing a hole	Position sensor Current sensor	Servo motor	1	Fixed

of snake robots that help generate propulsion: fixed structure design and active structure design. Passive wheels or scales are fixed structure designs that produce robot locomotion. Unlike fixed structure designs, active structure designs look at the actuators. There are motorized wheels or track-type wheels. In control section, control methods for implementing basic motion such as lateral undulation, vertical wave were conducted previously. Also, mapping and navigating algorithms for rescue and exploration were conducted by utilization of various sensors. Recently, the researches based on reinforcement learning algorithm have been conducted actively for improving energy efficiency and power consumption. In applications, snake robots are used for the exploration of irregular terrain with obstacles because, compared to wheeled robots, snake robots can overcome many environments such as stairs and trees. Also, the developing trend of technology is divided by the year range as shown in Fig. 12.

In the future, snake robots are expected to be used not only as exploration robots but also as medical robots in robot-assisted surgery, and as lifesaving robots. The mechanism of avoiding obstacles is important for performing medical applications or lifesaving applications. In robot-assisted surgery, choosing a kinematic structure design that is not harmful to the organisms is also an important topic. Among the currently published studies, there are many cases in which the kinematics of the snake robot are approached mathematically and experimentally verified. Also, there are studies that developed by approaching dynamics mathematically, but there are few cases where

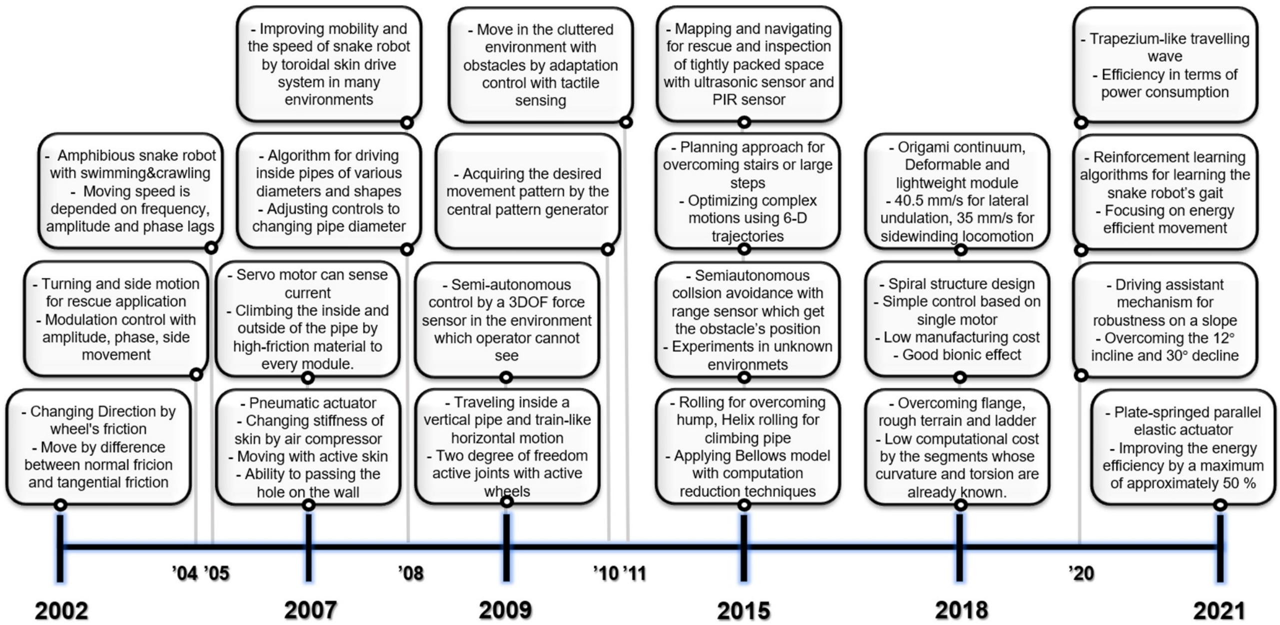

Fig. 12. Developing trend of the snake robot's technology.

they have been experimentally verified. If these parts are supplemented and combined with various control methods currently used in snake robots, the robot will be controlled more precisely and the robot's performance will be improved.

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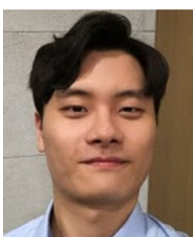

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