General Research and Design of Snake Robot for Fault Detection in Confined Space

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***Abstract*—In this paper, the current research status of snake robots at home and abroad is firstly investigated, followed by its key technologies, and finally a design solution suitable for confined space and radiation resistance is proposed.**

***Index Terms*—snake-like robot, radiation resistance, modularization, confined space**

I. Introduction

Similar to submarines, ships, chemical industry and other special occasions with complex structure, narrow space, maintenance difficulties, valves, pipelines are more prone to failure and other characteristics, and easy to cause system failure. Therefore, it is very important to carry out defect inspection, leakage detection, status acquisition and other operational tasks on related equipment to ensure the safe operation of equipment in special occasions. Especially in the nuclear field, for example, inside the silo, a variety of strong radiation, high pollution scenarios, to carry out key facilities, key equipment safety status online monitoring is even more difficult. In this paper, for the submarine depot internal equipment maintenance, detection and other special working conditions, to carry out narrow space fault detection snake robot overall program research and design.

II. Current status of domestic and international development of serpentine robots

Snakes in nature have a strong ability to adapt to complex environments due to their flexible bodies, and can weave through rivers and lakes, deserts, and rugged roads. A group of researchers have designed a variety of snake robots that mimic the structural characteristics of biological snakes [1].

Prof. Hirose of Japan has developed several snake robots that mimic biological snakes since the 1970s. Figure 1(a) shows the ACM III snake robot, which consists of modules with follower wheels that are connected to each other by parallel articulated axes and has a total weight of 28 kg.

Figure 1(b) shows an ACM R5 serpentine robot with small auxiliary wheels, small fin-like follower wheels evenly distributed around each module, and joint connections sealed by bellows for amphibious locomotion capability.

In 2015, the team developed the ACM R8 snake robot, which is configured with active wheels, possesses heel strong driving ability, and is able to cross 60 cm obstacles with strong obstacle-crossing ability, as shown in Figure 1(c).

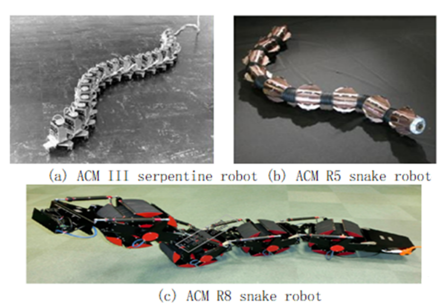

Fig. 1. Serpentine robot series developed by Prof.Hirose of Japan

Domestic snake robot research is later than foreign research institutions, in recent years has also made greater development. Shenyang Institute of Automation in 2009 developed can be realized three-dimensional movement of the snake robot rover II, as shown in Figure 2. The robot has 7 identical modules, with a length of 1.2 m and a diameter of 120 mm. each module has three degrees of freedom, including pitch, yaw and slew,

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and the weight of a single joint is about 1 kg. the rotation torque of a single joint is 3.56 Nm for pitch and yaw, and 1.78 Nm for slew.

Fig. 2. Snake Robot Rover II developed by Shenyang Institute of Automation

The Robotics Research Institute of Harbin Institute of Technology (HIT) developed a rope-driven super-redundant robotic arm prototype in 2016, as shown in Figure 3. The arm has 10 joint segments and 20 degrees of freedom, with a joint diameter of 45 mm, a total length of 1.5 m, and an end load of not less than 2.5 kg. This robot has high degrees of freedom, flexible operation, and strong adaptability to non-structural environments and multiple obstacles. However, it requires high manipulation accuracy of the joints, and because its own structure is driven by ropes, it has a lower load and weaker stiffness, and cannot realize the telescopic function.

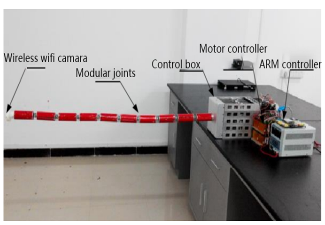

Fig. 3. Rope-driven serpentine robotic arm developed by Harbin Institute of Technology

In summary, with the continuous progress of industrial technology, all countries attach great importance to the development of special robots to carry out inspection, maintenance and repair work in highly radioactive areas.

III. Key Technology of Snake Robot for Fault Detection in Confined Space

As the working environment of the robot is characterised by narrow passages, interlocking pipe networks, confined space, radiant nature, etc., this paper collates the following key technologies for this robot.

A. Design of a snake robot mechanism for flexible movement in confined space environments

Narrow passages, intertwined pipe networks, and tight spaces pose serious challenges to the snake robot's locomotion, spatial accessibility, and obstacle-crossing ability [2].

B. Radiation Resistant Technology for Snake Robot Motors and Drives in Radiation Environments

Servo motors and actuators are the core components of the control and drive systems of serpentine robots, and high-energy rays can cause failure of the electronics, seals and lubrication materials in the motors and actuators, leading to rapid degradation and destruction of performance [3].

C. Path tracking and supple control of snake robots in confined space environments

For narrow space and inaccessible area, it is difficult to operate the robot by manual remote control for path tracking, and improper operation may cause damage to piping system, instrumentation and other facilities, which threatens the ship's vitality and maneuverability [4] Therefore, in order to improve the adaptive motion capability and safety, the autonomous path tracking algorithm and adaptive supple control algorithm of the snake robot are one of the key technologies and technical difficulties.

D. Visual sensing optical circuits and radiation-resistant technologies for electronics

The proper functioning of the vision system determines the ability of the intelligent snake robot to perceive the environment and perform tasks. Therefore, improving the radiation resistance of the vision sensor and minimizing the radiation noise generation on the image is also one of the key technologies.

In this paper, we will form a research on the design scheme of snake robot for the above key technologies.

1) overall design concept: Serpentine robotic systems can replace personnel to enter the confined space of the reactor compartment or high-radiation areas to carry out environmental, critical equipment inspection, monitoring, fault detection and identification, maintenance operations. The Intelligent Snake Robot System for Fault Detection in Confined Spaces consists of a tracked carrier vehicle, and a snake robot, as shown in Figure 4. One of the tracked carrier vehicles provides transportation, energy, and communication relay services for the serpentine robots and has a coarse detection function. The serpentine robot is connected to the belt carrier by cables that provide energy to the serpentine robot and transmit information for real-time monitoring. The snake robot adopts a separated design, the snake robot more sensitive to radiation devices (such as drives, controllers, sensor processing module, etc.) are all integrated and placed outside the pile cabin, and radiation shielding [5]. The snake robot machine is developed based on bionics and modularization ideas, and consists of several joint modules, 2 adsorption modules (2 hand claws) connected in series, as shown in Figure 5. It can mimic the movement of snakes and inchworms, with a variety of gaits such as peristalsis, telescoping, twisting, flipping and switching, and can move smoothly on the wall, in and out of the pipeline, and is suitable for movement in non-structured small spaces, with a strong obstacle-crossing ability and easy maintenance.

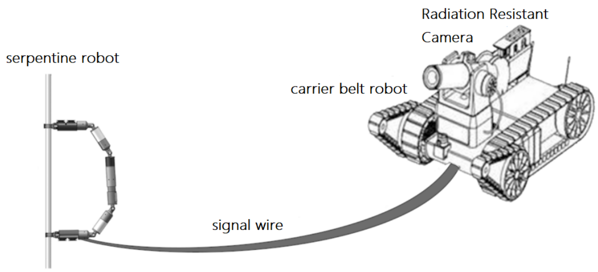

Fig. 4. Intelligent Snake Robot System

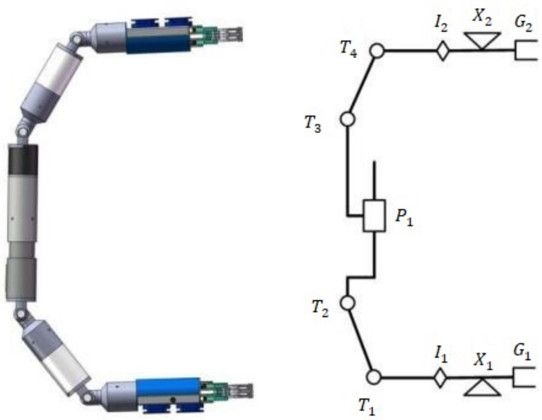

Fig. 5. Snake Robot Structure Solution

2) Robot Body Design: Intelligent snake robots face two basic problems of configuration synthesis and scale synthesis in the design stage. Configuration synthesis is to seek the specific structure of the mechanism, including the number of moving pairs, the form of moving pairs and the connection relationship, under the given task requirements, design variables and constraints. Scale synthesis is to design the optimal or sub-optimal mechanism parameters according to the workspace, obstacle-crossing ability and load capacity, etc., when the mechanism configuration has been determined.

a) modular design: Modular design is a well-established design method in robot design, modular robot consists of a group of modules with the same connection, these modules are independent of each other, easy to disassemble and easy to maintain. These modules can be assembled into modular robots of different functional types to suit different task requirements. Depending on the work environment and task requirements, the proposed modularized design of the intelligent snake robot contains the following modules: swing module [6], slewing module, telescoping module, and adsorption and gripping module, as shown in Figure 6.

b) Configuration Optimization and Scale Optimization: In this project, an optimisation approach is used to select the snake robot configuration with the best overall performance.

Description of the task or requirement: intelligent snake robots need to be able to perform certain functions or tasks,

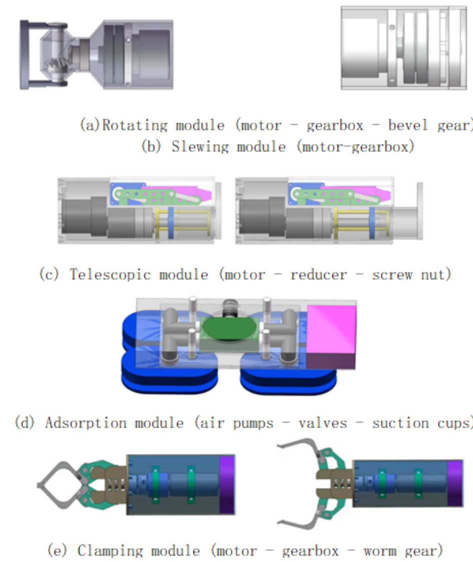

Fig. 6. Modular design of the snake robot

such as being able to move around the outer wall of a large build, move around the outside of a rough pipe, move around the inside of a pipe, move around the outer wall and the pipe, and other functions. Due to the different tasks [7], the number of degrees of freedom of the snake robot configuration is required.

The description of the modular robot is divided into three levels, namely the module layer, the assembly layer and the configuration layer, and the relationship between the three is shown in Figure 7. Since the assembly layer can clearly describe the connection and assembly relationship between modules, the object optimized in the configuration layer is the collection of assemblies of the modular robot. The intelligent snake robot configuration optimization consists of three elements: design variables, objective function and constraints, described as follows:

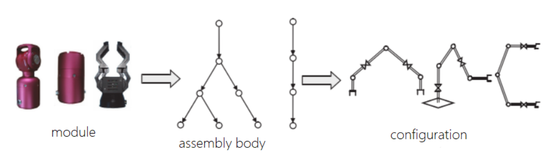

Fig. 7. Relationship between modules, assemblies, and configurations of a robot

Intelligent snake robots are connected in series and do not have a ring structure, so a directed tree (table) can be used to describe their configuration, so a design variable can be described by a directed tree structure or an assembly matrix.

Robot metrics are evaluated as degrees of freedom metrics, workspace metrics, condition number metrics, or maneuverability metrics, among others [8].

Constraints are used to limit the robot configuration, e.g., the snake robot has to be configured with at least three degrees of freedom for spatial motion, at least one telescopic module for creeping inside the pipe, grippers have to be configured on the end, etc.

3) Research on radiation-resistant motors and drives: High-energy rays can cause failure of robot mechanics, electronics, seals and lubrication, resulting in rapid degradation and destruction of robot system performance [9]. Therefore, the design of radiation protection for robots is an urgent challenge to be solved.

As the core component of the robot control and transmission system, the stable operation of the motor in the nuclear radiation environment plays a decisive role in the performance and life of the robot. Improving the radiation resistance level of motors used for robots operating in nuclear environment is of great significance for the development of emergency disaster relief robots in nuclear power plants.

The research line taken to improve the nuclear radiation resistance of the motor is shown in Figure 8 [10].

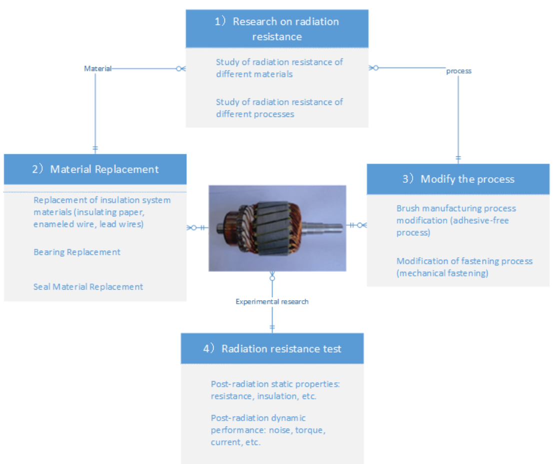

Fig. 8. Radiation Resistant Servomotor Research Route

4) Research on Robot Motion Control Strategies: Intelligent serpentine robot should be used in the pile cabin and other space is narrow, pipeline, equipment layout is complex, the accident situation is generally out of sight operation, can not observe the robot's overall operation process, remote control operation is difficult, improper operation may cause damage to the pile cabin equipment, the control strategy of the serpentine robot is the key issue of this project. This project intends to carry out research on the autonomous motion planning and motion control of snake robots to improve the autonomous decision-making ability and adaptive motion ability of snake robots in complex environments.

The control scheme of the intelligent snake robot is shown in Figure 9, which contains six parts: path planning, path tracking, gait planning, trajectory planning and motion control [11].

5) Irradiation-resistant machine vision research: Most of the serpentine mobile robots are out-of-sight operations, the operator can not observe the robot's position, status and the surrounding environment. The operator is aware of the robot and the environment information is completely dependent

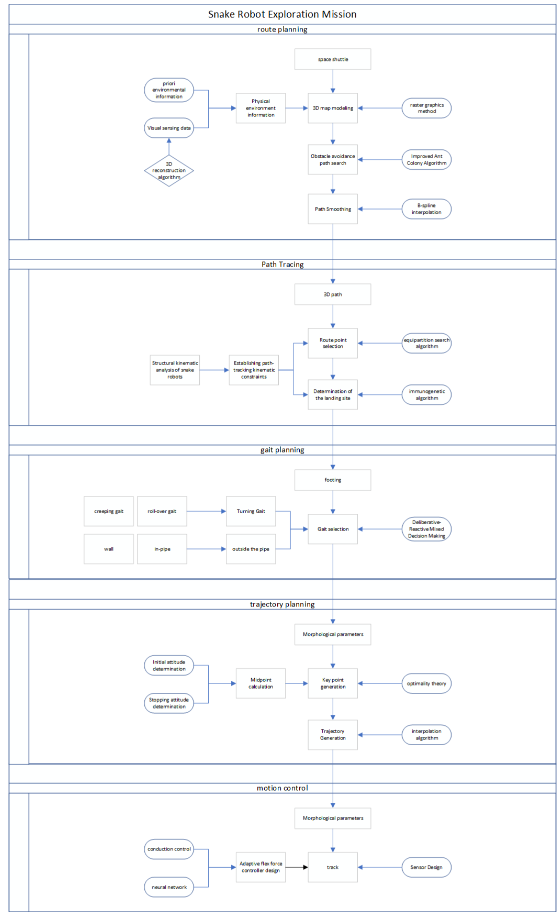

Fig. 9. Schematic diagram of the snake robot control scheme

on the robot with sensors, vision sensors are all kinds of mobile robot movement and execution of the function of the most important sensors, the camera is almost all the mobile robot will be equipped with sensors, the scene of the image information is the operator in the field of vision outside the control of the robot is the most intuitive and the most in line with the cognitive habits of the scene information.

According to the overall program, the vision sensing system assumes the function of an important part of the body of the snake robot, and at the same time, it is also the belt-carrying function component of the snake robot. The former is mainly embodied in assisting the completion of the robot's motion and control functions, while the carrier belt function is determined according to the application of the robot, and is closely related to the specific environment and the characteristics of the operating object.

Figure 10 shows the main research content and key technology decomposition block diagram of the snake robot visual sensing system. According to the difference in radiation levels, the optical path and electronics of the visual sensor to take the optimization of the design, based on the visual sensor function module, respectively, in the optical path design to increase the periscope structure, radiation-resistant optical fibers; in the electronics design of the CCD / CMOS photoreceptor

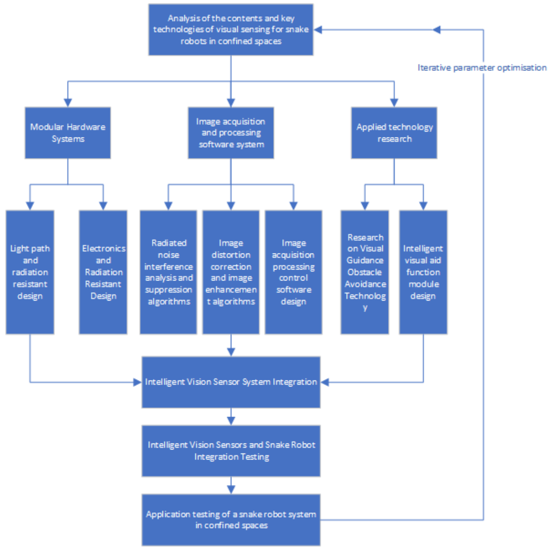

Fig. 10. Block diagram of visual sensing system research content and key technology decomposition

components and the subsequent acquisition and processing circuits for the design of the split [12]. The introduction of radiation-resistant optical fibers can move the photoreceptors back to reduce radiation noise and reduce the weight of shielding materials; the electronics module to take a split design can be shielded and reinforced with the least amount of shielding materials for the electronics module that is most susceptible to damage by radiation. Figure 11 shows the proposed optical path and electronics design ideas. In the

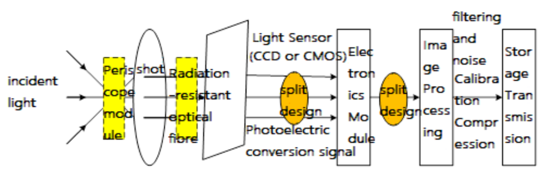

Fig. 11. Proposed Optical Path and Electronics Design Ideas

snake robot intelligent visual sensor software design research, in addition to the interface, display, control and other functions that want to integrate with the robot control platform, in the research work is mainly the algorithm design, including: radiated noise interference analysis and suppression algorithms; image distortion correction and image enhancement algorithms.

a) Radiation noise interference analysis and suppression algorithms: in the radiation noise interference analysis, first of all need to be based on different radiation types, radiation dose (rate), materials for the study of the radiation mechanism, the photoelectric signal and radiation-induced information to screen. Charged particles and high-energy rays cause ionization damage, performance degradation, and even failure of photoelectric conversion semiconductor devices, information acquisition equipment, electronic components, and circuit boards inside vision sensors. The single-particle effect, the total dose effect of ionizing radiation, and the displacement effect induced by the radiation environment are the main causes of degradation and even failure of materials and devices. By conducting radiation tests in different radiation and light environments, analyzing the test results, and referring to the literature research and theoretical research results, the radiation noise response mechanism is determined and screened by the software and hardware system, which in turn improves the usability of the video sensing image. Figure 12 shows the schematic diagram of the proposed radiation noise test program (platform). Under different irradiation conditions and

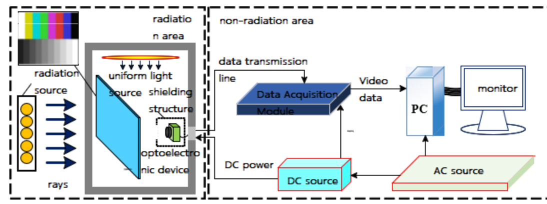

Fig. 12. Schematic diagram of radiated noise test program (platform)

annealing conditions, the output data of CCD/CMOS were collected under shading and non-shading conditions, and the raw data were collected before, during and after radiation under the conditions of adjusting parameter settings such as integration time and gain. The conversion relationship between analog level signals and digital signals was obtained according to EMVA Standard 1288, and the ionization charge collection of CCD/CMOS was calculated as a function of the total γ-*photon* [13]dose during the integration time.

Design of the same single radiation source radiation conditions of color natural light image pattern radiation response experiments, the use of standard light sources and video test card, the collection of the same radiation conditions and parameter settings in different image background values in the radiation damage after the original data and then analyze the noise response.

The main characteristics of noise in radiometric images are: irregular distribution and size of noise in the image; There is a correlation between the noise and the image; The noise is superimposed. Starting from the whole of the image, it is proposed to use local statistics to convert the noise into gray values and then achieve the purpose of noise reduction; because the smooth area with uniform gray scale corresponds to the low frequency component of Fourier transform, and the edge details with frequent gray scale transformation correspond to the high frequency component of Fourier transform. By filtering out the high frequency components of the image a smooth image is obtained. It is proposed to validate the research work by adopting a suitable low pass filtering algorithm for noise reduction.

b) Image aberration correction and image enhancement algorithms: the use of radiation-resistant optical fiber, a better solution to the problem of radiation, high temperature resistance, but the fiber optic bundle imaging there are certain problems: first of all, by the fiber optic drawing process and the weight of the imaging bundle weight constraints, the number of fiber optic filaments can not be too large; secondly, the presence of cladding in the fiber optic bundle around each fiber optic filament, these claddings in the image will leave false edges, both problems will be the clarity of the observation and the subsequent image processing, detection of a greater impact.

Considering the cladding region in an image as the defective information of the image, it can be transformed into an image defect repair problem, and the three mainstream techniques for image defect repair are: image repair based on partial differential equations, image repair based on anisotropic interpolation model, and image repair based on texture synthesis. Among them, the repair method based on partial differential equations is too slow; the texture parameters are difficult to calculate considering the effect of periodic honeycomb-like edges, and the method based on texture synthesis is difficult to be applied, and the anisotropic interpolation needs to compute the direction vector of the boundary of the defective region and iteratively repair it inwardly, whereas it is a honeycomb-like periodic breakage in the fiber optic image, and the difference in the regional transmittance of which destroys the reliability of the direction vectors of the cladding boundary.

IV. Summary

In this paper, for the submarine compartment internal equipment maintenance, detection and other special working conditions, to carry out narrow space fault detection snake robot overall program research and design, including robot body design, irradiation-resistant motor drive program, robot motion control strategy program, irradiation-resistant machine vision program. The intelligent snake robot can be completed in the reactor compartment and other complex environments for nuclear safety critical equipment damage, leakage, dose rate levels, etc. to detect, for the typical environment safety important systems, equipment condition monitoring and detection to provide technical support.

References

[1] Shijie Song, Cong Huang, Yuyang Zhao, and Dawei Gong. Discrete-time optimal control for partially unknown nonlinear systems with asymmetry input constraints. In *2023 9th International Conference on Control Science and Systems Engineering (ICCSSE)*, pages 80–85, 2023.

[2] Minglei Zhu, Sébastien Briot, and Abdelhamid Chriette. Sensor-based design of a delta parallel robot. *Mechatronics*, 87:102893, 2022.

[3] Shijie Song, Minglei Zhu, Xiaolin Dai, and Dawei Gong. Model-free optimal tracking control of nonlinear input-affine discrete-time systems via an iterative deterministic q-learning algorithm. *IEEE Transactions on Neural Networks and Learning Systems*, pages 1–14, 2022.

[4] Cornell Wright, Aaron Johnson, Aaron Peck, Zachary McCord, Allison Naaktgeboren, Philip Gianfortoni, Manuel Gonzalez-Rivero, Ross Hatton, and Howie Choset. Design of a modular snake robot. In *2007 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 2609–2614, 2007.

[5] P. Liljebäck, K.Y. Pettersen, Ø. Stavdahl, and J.T. Gravdahl. A review on modelling, implementation, and control of snake robots. *Robotics and Autonomous Systems*, 60(1):29–40, 2012.

[6] Pavel Prautsch, Tsutomu Mita, and Tetsuya Iwasaki. Analysis and control of a gait of snake robot. *Transactions of the Institute of Electrical Engineers of Japan. D, Journal of Industrial Applications Division*, 120(3):372–381, 2000.

[7] Minglei Zhu, Cong Huang, Shijie Song, and Dawei Gong. Design of a gough–stewart platform based on visual servoing controller. *Sensors*, 22(7):2523, 2022.

[8] Minglei Zhu, Cong Huang, Zhiqiang Qiu, Wei Zheng, and Dawei Gong. Parallel image-based visual servoing/force control of a collaborative delta robot. *Frontiers in Neurorobotics*, 16:922704, 2022.

[9] I. Erkmen, A.M. Erkmen, F. Matsuno, R. Chatterjee, and T. Kamegawa. Snake robots to the rescue! *IEEE Robotics & Automation Magazine*, 9(3):17–25, 2002.

[10] Jindong Liu, Yuchuang Tong, and Jinguo Liu. Review of snake robots in constrained environments. *Robotics and Autonomous Systems*, 141:103785, 2021.

[11] František Trebuňa, Ivan Virgala, Miroslav Pástor, Tomáš Lipták, and Ľubica Miková. An inspection of pipe by snake robot. *International Journal of Advanced Robotic Systems*, 13(5):1729881416663668, 2016.

[12] S.I. Roumeliotis, G.S. Sukhatme, and G.A. Bekey. Fault detection and identification in a mobile robot using multiple-model estimation. In *Proceedings. 1998 IEEE International Conference on Robotics and Automation (Cat. No.98CH36146)*, volume 3, pages 2223–2228 vol.3, 1998.

[13] A. A. A. Razak, A. H. Abdullah, K. Kamarudin, M. A. A. Bakar, J. E. M. Salih, B. Ilias, S. A. A. Shukor, F. S. A. Sa'ad, and M. H. Mustafa. Development of mobile robot in confined space application. In *2017 IEEE 13th International Colloquium on Signal Processing & its Applications (CSPA)*, pages 190–195, 2017.