Biomimetic Snake Robot for Search and Rescue: A Case Study

Jake Levere
Robotics Engineering
Worcester Polytechnic Institute

Adam Nudelman
Robotics Engineering
Worcester Polytechnic Institute

Shreyas Chandra Sekhar
Robotics Engineering
Worcester Polytechnic Institute

Nick Sipes
Robotics Engineering
Worcester Polytechnic Institute

***Abstract*—The majority of time spent during Search and Rescue operations, following natural disasters, is clearing and navigating rubble in order to hopefully discover pinned or trapped survivors. What this paper proposes is a robot that mimics a snake's motion which can be utilized as an assistive searching tool. This will allow search and navigation through rubble to be significantly more efficient during these missions as well as get to area's that normal methods are unable to get to without first clearing the rubble. Throughout this project, this paper explores the different methods of industry standard devices used for this operation, in addition to the supportive public research papers. This paper also calculates the kinematics and velocity Jacobians of our proposed robot, and shows the forces and torques acting on the joints for a unique motion useful given this scenario. This paper also describes further research goals and methods to enhance the design beyond this initial stage.**

I. Background

According to [1], there have been roughly an average of 50,000 deaths annually from earthquakes since the year 2000 globally. The biggest danger during earthquakes, according to Michigan Technological University [2] as well as Penn State [3] and other places, is the damage to or collapse of buildings. When buildings collapse and people are trapped inside, it is up to the rescuers to find and extract the survivors. It is estimated that of the survivors of urban disasters, 80% are surface victims, meaning that they are not buried. The other 20% of survivors are from the interior of the rubble yet the majority of victims are found inside the ruble [4]. As explained in the Springer handbook of robotics [4], Disaster response is always a race against time, to move as fast as possible to reach all potential survivors and yet move slowly enough to avoid creating additional collapses, damage, risk to rescuers and victims, or contention over airspace.

II. History

The disaster robotics community began to form in 1995 after the Hanshin-Awajii earthquake in Kobe, Japan, and the bombing of the Murrah Federal building on Oklahoma City, United States. The first use of these disaster robots was at the 2001 World Trade Center disaster. There are many types of tasks that robots can perform in disaster situations including but not limited to search, reconnaissance and mapping, structural inspection, medical inspection and intervention and acting as a beacon or repeater for information [4]. Currently, research in disaster robotics has many different types of solutions. One solution is a tethered snake-like robot. This is what the authors of [5] built. They designed a tethered "hairy" robot with an Active Scope Camera. This is the idea behind breaking the robot into two sections, the lower part that propels the robot forward and the upper part that controls the head and thus the direction of the sensors. The authors showed that their system worked reasonably well in three dimensional rough terrain over a distance of five meters. Another system that has been built and tested in the field is the CMU snake robot [6] [7]. This robot is a modular device that is also tethered and is able to move in various three-dimensional motions including rolling, sidewinding, through a pipe, as well as climbing a pipe. This robot was tested in a disaster in Mexico City after an earthquake. During the test, the system was shown to work, though they didn't find any survivors. This team also discovered that most current search methods use a dog's olfactory senses or acoustic sensors to search for survivors. This robot was also quite fast when compared to other snake robots that were researched for this paper, which shows that there is still plenty of potential to increase the speed of snake robots. In [8], the authors define the kinematics and dynamics of their proposed system and design a controller for their robot. This adaptive controller, during their experiments, was able to mostly nearly equal existing controller methods and in some cases, especially switching terrains, exceeded the existing method they tested against. This robot used a passive wheel system and is specifically a planar robot so it has many limitations in real world rough terrain, but it shows that an adaptive controller is possible that could quickly compensate for changes in terrain. [9] is an analysis of the basic kinematics of snake motions and some variations on the basic motion and how those changes effect the way a snake moves in different terrain. The paper also goes into different types of joints and different environments that robotic snakes could be used in as well as some of the design requirements of those environments. In addition, they discuss various innovative snake robots and how they moved along with their own pros and cons.

III. Motivation

The majority of current technology practices in search, mapping, and inspection is mainly done by flying drones. These drones are rarely able to find the room to penetrate into or move around in a collapsed structure. Two of the most productive tools for search and rescue are rescue dogs and acoustic sensors [6] and the current technology for robotic penetration searches. They are done with either a camera on a stick [6] or what is essentially a long, large endoscope that can handle some complex terrain, however is still tethered [5]. Other research [5], also shows how the head section of a snake robot can be manipulated separately from the body, leaving the body to handle movement and the head to handle search and data collection. Despite a large amount of research being done in the field of rescue robotics, as seen in [6], when it comes to real world situations in the field, penetration robots are currently not extensively used. The benefits of such a robotic system would be able to penetrate into a collapsed structure, semi-autonomously [10] search and map the area while also being able to designate survivors, casualties, the structural state of the collapse [6] [11], as well as relay information back to rescue teams [12] [13]. The snake-like robot was chosen because it has a low cross-sectional diameter coupled with high maneuverability potential. This solves the biggest hurtle with current methods which are either too large to penetrate the rubble or not maneuverable enough to handle complex terrain and the sharp turns necessary. The snake-like robot also minimizes the strain on the rubble and therefore minimizes the risk of penetration. This robot has the potential to be used cooperatively in a ”swarm” to efficiently and more quickly assess the area. In addition, it has the ability to be adapted with different forms of motion depending on the situation. This includes highly specific motions such as climbing a ladder [14], different ”scales” for diverse environments [15], to different drive mechanisms [9] such as passive wheels or cable driven [16] motion. The one downside to this method is the comparatively low speeds [17] [18] that the robot is able to achieve without third party assistance, such as a canine carrier. This report will outline the structure of such a snake robot that could be used in a search and rescue scenario.

IV. Our Methods

A. Derivation of forward kinematics

The cylindrical model in Figure 1 features six decoupled joints representing the revolute joints that moves horizontally with respect to the ground, coupled with another revolute joint directly in-line with the robot, which moves vertically with respect to the ground. The horizontal revolute joints mimic the lateral undulation motion of a snake, while the vertical motion allows for movement in the third dimension. A snake moves by the variable friction of its scales and the ability to push into the ground to create friction. This, in addition to their shifting of weight, encapsulates much of the full motion of a snake. Therefore, without the vertical revolute joint to produce the similar shifting of weight and pseudo-gait motion pushing into the ground to propel the entity in a direction, our configuration would not be an authentic replication of snake serpentine motion. With the Denavit-Hartenberg table in Figure 2, it is also possible to produce a coordinate frame model utilizing the robotics toolbox which is provided by the software in Matlab. In this model shown in the right side

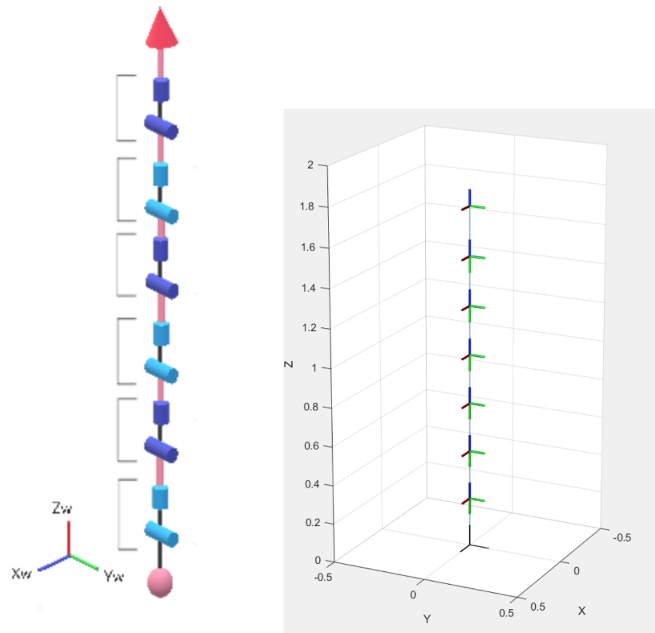

Fig. 1. Robot Joint Structure

Num.	A	Alpha	D	Theta
1	0	0	L	0
2	0	-90	0	0
3	0	90	0	q1*
4	0	-90	L	q2*
5	0	90	0	q3*
6	0	-90	L	q4*
7	0	90	0	q5*
8	0	-90	L	q6*
9	0	90	0	q7*
10	0	-90	L	q8*
11	0	90	0	q9*
12	0	-90	L	q10*
13	0	90	0	q11*
14	0	0	L	q12*

$$T_{i-1}^{i} = \begin{bmatrix} \cos\theta_i & -\operatorname{sen}\theta_i \cos\alpha_i & \operatorname{sen}\theta_i \operatorname{sen}\alpha_i & a_i \cos\theta_i \\ \operatorname{sen}\theta_i & \cos\theta_i \cos\alpha_i & -\cos\theta_i \operatorname{sen}\alpha_i & a_i \operatorname{sen}\theta_i \\ 0 & \operatorname{sen}\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Fig. 2. Standard Denavit-Hartenberg method

of Figure 1, the representation shows the coordinate frames of each of the overlapping decoupled joints, as well as the end effectors coordinate frame. This model served as a proof that the cylindrical model would in fact be an acceptable structural form. However, with the limitations of the robotics toolbox in Matlab, only data pertaining to the positions and velocities of the end-effector has been able to be calculated and analyzed. Shown in Figure 2, the DH table, in respect to the

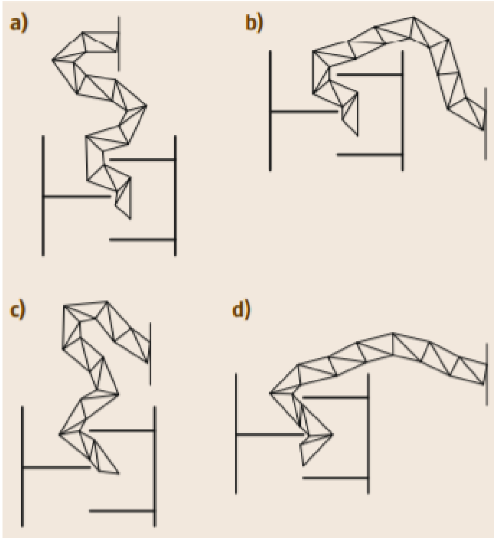

Fig. 3. modal navigation

cylindrical model, can be used to produce the homogeneous transformations. This Homogeneous transformation matrix can produce the exact location and orientation of the end-effector, or the snake robot's head, with respect to the base-link or the tail of the simulated robot. With the positional specifications, it is possible to successfully navigate an obstacle-filled environment. The robot in this research [4], shows how by pushing off from the tail of the robot and orientating the head in a specific way, it is possible to successfully navigate an obstacle. This method is called the "modal approach." With the parameters made in the Denavit Hartenberg convention, along with the calculations made throughout the use of the homogeneous transformations and the Jacobian, figure 4 shows the Matlab produced plots on top and the Simulink outputs below. These plots represent the position and velocity determinations of the snake robot's head. The consistency between the Matlab position and velocity plots along with the Simulink output position and velocity plots, ensures that the model made in Simulink is accurate with our expectations of how the snake robot should operate.

B. Simulink Model Simulation

To analyze the joint input values, with respect to the motions of a snake, it was necessary to construct a Simulink model of the snake robot system to examine the dynamics of the model. This model features identical joint systems composing of two coupled revolute joints with a link twist of 90 degrees. Between each of these joint systems are cylindrical links that make up the body of the snake. The head link has the density of nylon and the body links have the density of aluminum. These physical properties give a realistic mass relationship between the head and the links of the body. Due to the limitations in Simulink when simulating a complex system within an environment, the use of the program called VREP was utilized. The snake model in VREP built by Andres San-

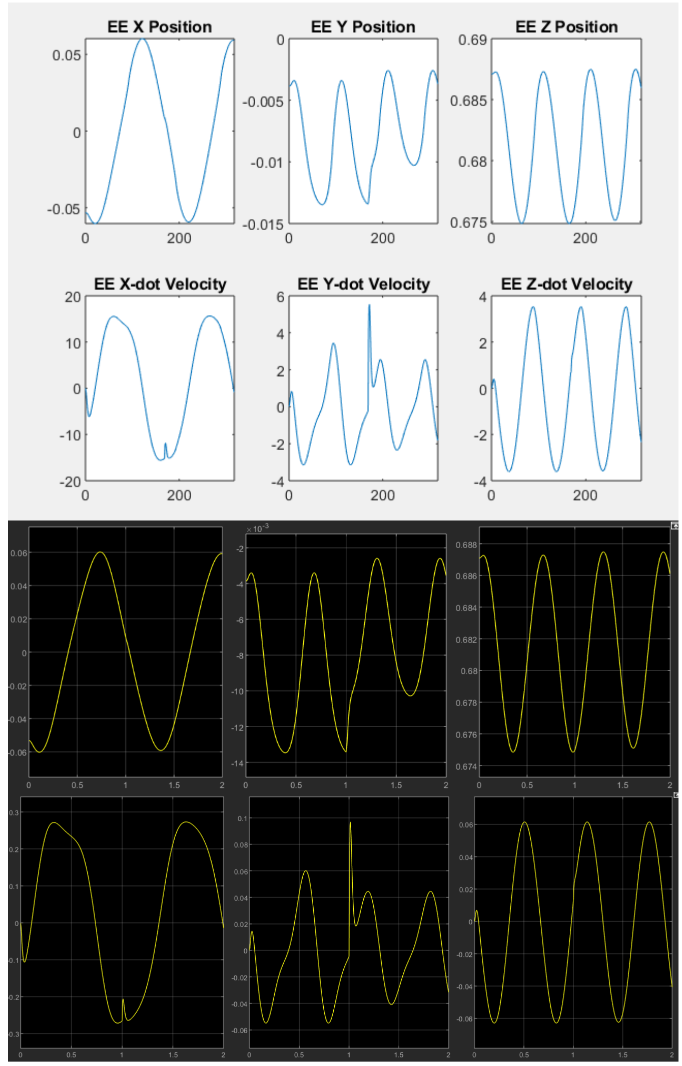

Fig. 4. Matlab and Simulink positional/velocity x,y,z graphs

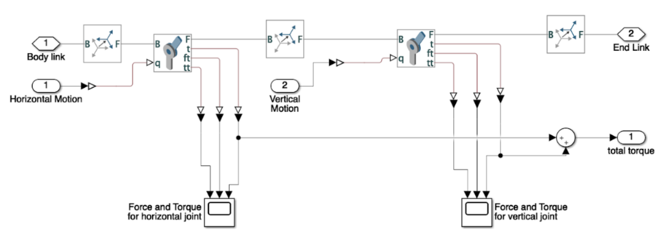

Fig. 5. Simulink Model of the robot

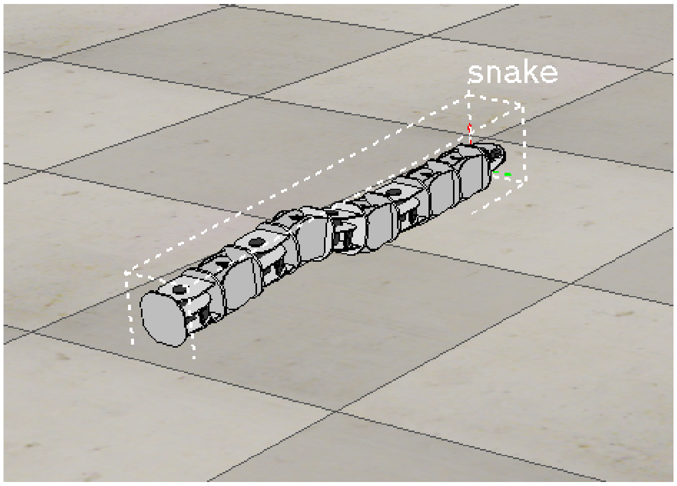

Fig. 6. Robot VREP Model

Millan, has two rotating couplings at each joint similar to that of the snake Simulink model made in this report. Total length of the model was 62cm in length and 10cm in diameter and could sustain 100 N-m torque. In addition, the VREP model featured six links with a visual camera connected to its head. This model was capable of serpentine, rectilinear, circular, and rotational motion. In order to produce a snake robot system capable of forward locomotion, the use of the pre-modeled snake robot [19], similar in build to the snake robot in this report, was analyzed. These functions serve as the input for the Simulink model joints, which outputs the joint torques of each joint system within the snake robot over the course of the lateral undulation motion. The model design allows for easy tuning of parameters such as snake speed (input wave frequency), turning direction (input wave bias), and horizontal and vertical amplitude. Figure 7 and Figure 8 represent the joint torques with only horizontal motion and with horizontal and vertical motion respectively. The horizontal motion follows an irregular pattern because the amplitude increases as the snake digs into the ground, resulting in greater friction to propel itself forward. This element is necessary for proper forward motion in the absence of variable friction. These changes cause the spiking and irregularity in the joint torques over the course of the motion. A snake robot would be able to achieve forward motion with this joint torque motion characteristic if it were able to replicate the variable fiction scales that a real snake utilizes to propel itself forward.

V. VREP Model

VREP model had 8 joints in the model and servomotors model Futaba s3003 were used as actuators responsible for the movement of the robot. These servomotors are often used in model airplanes and represent a cheaper alternative to other variants of exclusive use in robotics.

Below were the specifications of Futaba s3003:

- Supply voltage between 4.8 and 6.0 V

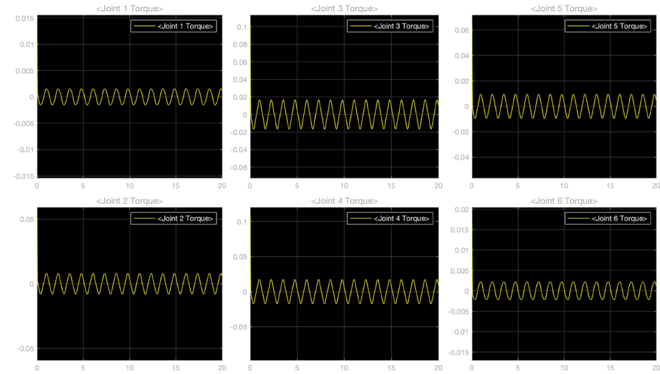

Fig. 7. Joint torques with only horizontal motion

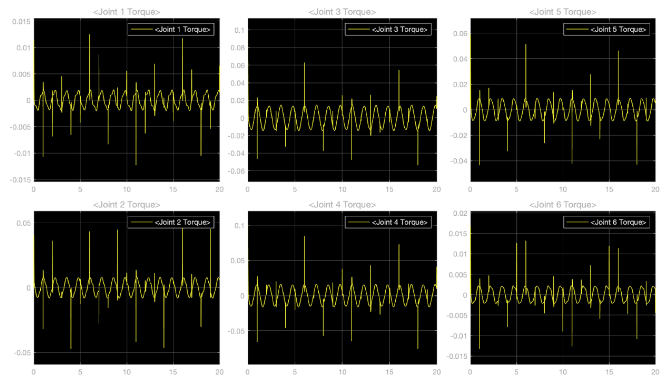

Fig. 8. Joint torques with horizontal and vertical motion

- Torque: 3.2 Kg / cm at 4.8 V and 4.1 Kg / cm at 6.0 V
- Speed of rotation: 0.23 seg/deg
- Dimensiones: 40 x 20 x 36 mm
- Weight: 37 g

The robot locomotion was based on sinusoidal oscillators propagation of two transverse waves along the body of the robot. The movement of the robot was controlled by the parameters of these waves. Wave parameter for Linear, Lateral, Circular and Rotational motion has been specified in the diagram.

Serpentine motion could be obtained controlling the sinusoidal oscillators waves. The robot could be made to executes displacements in a similar way to snakes in their natural environment.

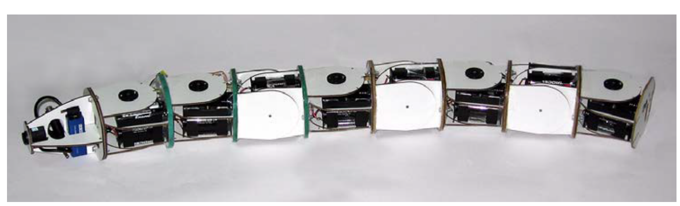

Fig. 9. Snake model in VREP used for research

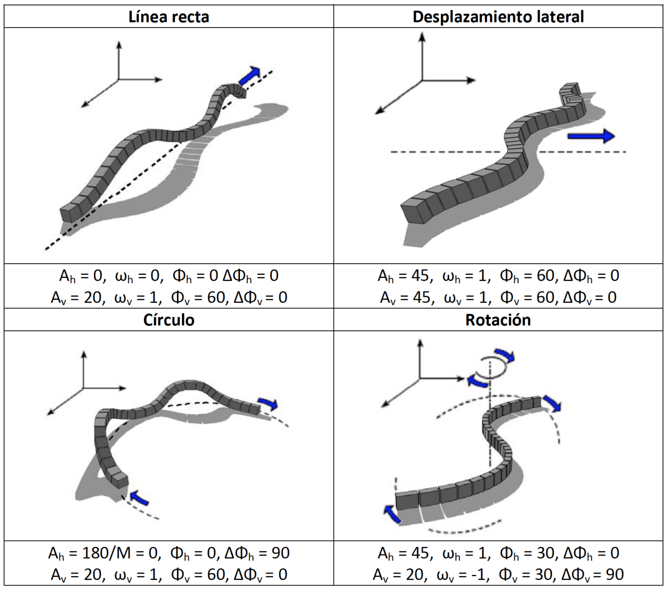

Fig. 10. Mostion simulation

VI. Impact Statement

The proposed work is innovative because it captures the various possible ways to navigate in a random environment. It also can potentially prove to quicken search operations, greatly assisting rescue workers in the process of saving lives. In addition, this solution fills in the gaps the other currently in use rescue devices by allowing the device to handle more difficult terrain, tighter spaces, and further distances from it's point of entry. The Kinematic analysis of the robot will better characterize the true motions of the robot and the Force/Torque analysis will aid in deciding the optimal hardware required for such a robot. The physically accurate model will serve as a basis for research and development for real-world scenarios as well as a comparison to existing systems.

VII. Current Research and Future Work

As mentioned before, the comparatively low speeds [18] [17] of the snake-robot are a negative aspect for this solution, however here are some ways of at least partially overcoming it. As discussed in [18] [20], the mobility of the snake-like robot alone is limited but the robot can be paired with another platform to move the snake robot into position for insertion. Some suggestions are using dogs [18] or aerial robots to transport the snake robot to the nearest insertion point. This allows for safer and quicker response times for the snake robot to get into position. Once the snake robot is in the rubble, the relatively low speeds shouldn't be much of a hindrance due to the fact that sudden motions are potentially dangerous to the integrity of the rubble as well as the need to take time to search and gather data. Another solution to the lower speeds of the snake robot is to use multiple snake robots [13] and have them cooperate and communicate [12]. [11] using multiple devices with sensors mounted to them in order to show that the dispersed system does work and allows for data to be passed from device to device passing data back to the rescue responders. Both [12] and [13] show how swarm robotics with cooperative communication, greatly increases the effectiveness of a system. This, along with optimization of the snake robot processes by using semi-autonomous systems [10] [21], would allow for much quicker knowledge of the cite as well as marking access points, danger points, structural issues, survivors and more. As seen in [5] [14] [15] [22] [8]. complex terrain is able to be traversed using snake robots. In [6] the authors mention that the red cross responders often rely on acoustics rather than vision for searches. This is often due to the low visibility making it necessary for light sources to be used in order to use visible light spectrum cameras. Infrared is also not reliable due to the variability in disaster areas where often there are fires, steam or other heat sources that would interfere. To compensate for these issues, utilizing various and diverse sensors would be necessary. [6] also said that dogs are still the standard for search and rescue. [23] showed that it is possible to create a sensor that replicates a dog's nose for the purposes of search and rescue and this type of sensor could significantly enhance the benefits of an array of search and rescue robots. These concept can be adapted to the snake robot that is discussed in this paper as primary sensors in order to work in tandem with its exceptional obstacle traversal abilities.

For proper implementation of our proposed snake robot, if it were to be created, servos or stepper motors would be the desired driving force. This is due to their high precision in rotation, which is necessary for finely tuned movement for the snake robot's motion. The robot may be equipped with passive wheels or a sheathe-like capsule so that it can achieve variable friction, producing the serpentine motions necessary. Soft robotics may also yield promising results such as [17], however their lack of accuracy in actuation can be problematic.

VIII. Conclusion

With the results found in both the mathematical calculations in Matlab as well as the dynamic analysis simulation within Simulink, this report serves as a strong basis for further work of snake robot experimentation. The usefulness in the calculations performed could, in future works, be used to help navigate a robotic snake in an obstacle-filled environment. A simple implementation of our snake robot created from servos could prove useful in testing motions. With the various tests and research done in this report through the accumulation of successful data gathered and information over past research done, can prove to jump start a tangible robotic system for future studies to be used in practical situations.

References

[1] H. Ritchie and M. Roser, "Natural disasters," 2018. [Online]. Available: https://ourworldindata.org/natural-disasters#deaths-from-disasters

[2] "What are earthquake hazards." [Online]. Available: http://www.geo.mtu.edu/UPSeis/hazards.html

[3] C. J. Ammon, "Earthquake effects." [Online]. Available: http://eqseis.geosc.psu.edu/~cammon/HTML/Classes/IntroQuakes/Notes/earthquake_effects.html

[4] B. Siciliano and O. Khatib, *Springer Handbook of Robotics*, 2nd ed. Springer, 2016.

[5] Y. Yamauchi, T. Fujimoto, A. Ishii, S. Araki, Y. Ambe, M. Konyo, K. Tadakuma, and S. Tadokoro, “A robotic thruster that can handle hairy flexible cable of serpentine robots for disaster inspection,” *IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, July 2018. [Online]. Available: https://ieeexplore-ieee-org.ezproxy.wpi.edu/document/8626018

[6] E. Ackerman, “What cmu’s snake robot team learned while searching for mexican earthquake survivors,” October 2017. [Online]. Available: https://spectrum.ieee.org/automation/robotics/industrial-robots/cmu-snake-robot-mexico-earthquake

[7] H. Choset. Carnegie mellon modular snake demo — engadget expand 2013. youtube. [Online]. Available: https://www.youtube.com/watch?v=oat582SaTko

[8] G. Wang, W. Yang, Y. Shen, and H. Shao, “Adaptive path following of snake robot on ground with unknown and varied friction coefficients,” *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, October 2018. [Online]. Available: https://ieeexplore-ieee-org.ezproxy.wpi.edu/document/8594466

[9] S. Hirose and H. Yamada, “Snake-like robots [tutorial],” *IEEE Robotics & Automation Magazine*, March 2009. [Online]. Available: https://ieeexplore-ieee-org.ezproxy.wpi.edu/document/4799450

[10] J. Vilela, Y. Liu, and G. Nejat, “Semi-autonomous exploration with robot teams in urban search and rescue,” *IEEE International Symposium on Safety, Security, and Rescue Robotics*, October 2013. [Online]. Available: https://ieeexplore-ieee-org.ezproxy.wpi.edu/document/6719366

[11] E. Whitmire, T. Latif, and A. bozkurt, “Acoustic sensors for bioboic search and rescue,” *IEEE Sensors*, November 2014. [Online]. Available: https://ieeexplore-ieee-org.ezproxy.wpi.edu/document/6985475

[12] Y. Liu, G. Nejat, and J. Vilela, “Learning to cooperate together: A semi-autonomous control architecture for multi-robot teams in urban search and rescue,” *IEEE International Symposium on Safety, Security, and Rescue Robotics*, October 2013. [Online]. Available: https://ieeexplore-ieee-org.ezproxy.wpi.edu/document/6719367

[13] Z. Yang, X. Zhang, and X. Weng, “Search and rescue system based on the dispersed main-extension robots,” *IEEE 3rd International Conference on Communication Software and Networks*, May 2011. [Online]. Available: https://ieeexplore-ieee-org.ezproxy.wpi.edu/document/6014299

[14] T. Takemori, M. Tanaka, and F. Matsuno, “Ladder climbing with a snake robot,” *IEEE/RJS International Conference on Intelligent Robots and Systems*, 2018 October. [Online]. Available: https://ieeexplore-ieee-org.ezproxy.wpi.edu/document/8594411

[15] N. Zhu, H. Zang, B. Liao, D. Liu, J. Tuo, T. Zhou, and Q. Wang, “The effect of different scales on the crawling rate of bionic snake robot,” *WRC Symposium on Advanced Robotics and Automation*, August 2018. [Online]. Available: https://ieeexplore-ieee-org.ezproxy.wpi.edu/document/8584156

[16] D. Xu, E. Li, and Z. Liang, “Kinematics and statics analysis of a novel cable-driven snake arm robot,” *Chinese Automation Congress*, October 2017. [Online]. Available: https://ieeexplore-ieee-org.ezproxy.wpi.edu/document/8242808

[17] C. Branyan and Y. Menguc, “Soft snake robots: Investigating the effects of gait parameters on locomotion in complex terrains,” *IEEE/RSJ International Conference on Intelligent Robots and Systems*, October 2018. [Online]. Available: https://ieeexplore-ieee-org.ezproxy.wpi.edu/document/8593404

[18] A. Ferworn, C. Wright, J. Tran, C. Li, and H. Choset, “Dog and snake marsupial cooperation for urban search and rescue deployment,” *IEEE International Symposium on Safety, Security, and Rescue Robotics*, November 2012. [Online]. Available: https://ieeexplore-ieee-org.ezproxy.wpi.edu/document/6523887

[19] A. San-Millan, “Diseo, construccin y control de una serpiente robtica,” 05 2012.

[20] L. Marconi, S. Leutenegger, S. Lynen, M. Burri, R. Naldi, and C. Melchiorri, “Ground and aerial robots as an aid to alpine search and rescue: Initial sherpa outcomes,” *IEEE International Symposium on Safety, Security, and Rescue Robotics*, October 2013. [Online]. Available: https://ieeexplore-ieee-org.ezproxy.wpi.edu/document/6719381

[21] K. Paap, T. Christaller, and F. Kirchner, “A robot snake to inspect broken buildings,” *IEEE/RSJ International Conference on Intelligent Robots and Systems*, August 2000. [Online]. Available: https://ieeexplore-ieee-org.ezproxy.wpi.edu/document/895277

[22] R. Edlinger, M. Zauner, and W. Rokitansky, “Intelligent mobility - new approach of robot mobility systems for rescue scenarios,” *IEEE International Symposium on Safety, Security, and Rescue Robotics*, October 2013. [Online]. Available: https://ieeexplore-ieee-org.ezproxy.wpi.edu/document/6719318

[23] A. Teo, H. Garg, and S. Puthusserypady, “Detection of humans buried in rubble: an electronic nose to detect human body odor,” *Proceedings of the Second Joint 24th Annual Conference and the Annual Fall Meeting of the Biomedical Engineering Society] [Engineering in Medicine and Biology*, October 2002. [Online]. Available: https://ieeexplore-ieee-org.ezproxy.wpi.edu/document/4799450