Snake Robot Urban Search After the 2017 Mexico City Earthquake

Julian Whitman, Nico Zevallos, Matt Travers, and Howie Choset

***Abstract*— The Carnegie Mellon University Biorobotics Laboratory was invited to bring snake robots to Mexico City to assist with search and rescue efforts in the wake of the September 2017 earthquake. We travelled with the Mexican Red Cross to collapsed building sites, and deployed a snake robot within one building to obtain a camera view in two voids that conventional search cameras could not access. We confirmed that the an open area within the building was unoccupied. In this paper we describe our experiences during the deployment and the limitations of snake robot platform encountered along the way.**

I. INTRODUCTION

On September 19, 2017, a magnitude 7 earthquake struck Mexico City, damaging and collapsing buildings throughout the city. The next day, volunteers working with the Mexican Red Cross invited the Carnegie Mellon University Biorobotics Laboratory to bring snake robots to assist in the Urban Search and Rescue (USAR) efforts. Three lab members flew to Mexico City to support recovery efforts over the period Sept. 21-24. We travelled to collapsed building sites with the Mexican Red Cross, fully deploying the snake robots twice at one site. Our team assisted rescue workers by establishing that an open void within the building was unoccupied. In this paper we describe our experience, outcomes, and improvements for future deployments.

II. SNAKE ROBOT PLATFORM

Rescue robots have the potential to allow first responders to access dangerous or difficult-to-reach locations, carrying sensor payloads like cameras, and potentially delivering supplies or communications to trapped victims. To date, a number of robot platforms have been deployed on search and rescue missions, many of which are summarized by Murphy et. al [1].

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The Robotics Institute, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA, 15213, USA. jwhitman@cmu.edu

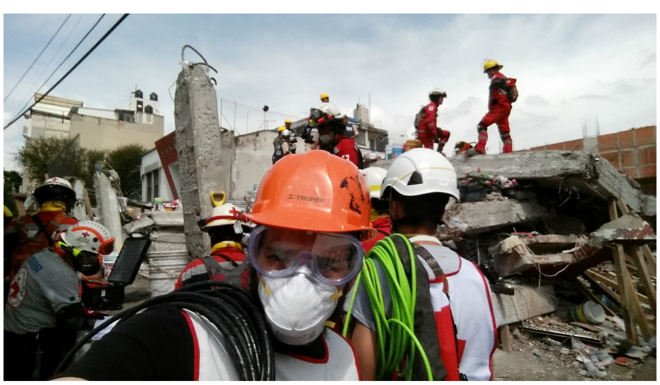

Fig. 1. Carrying the snake robot onto the collapsed building.

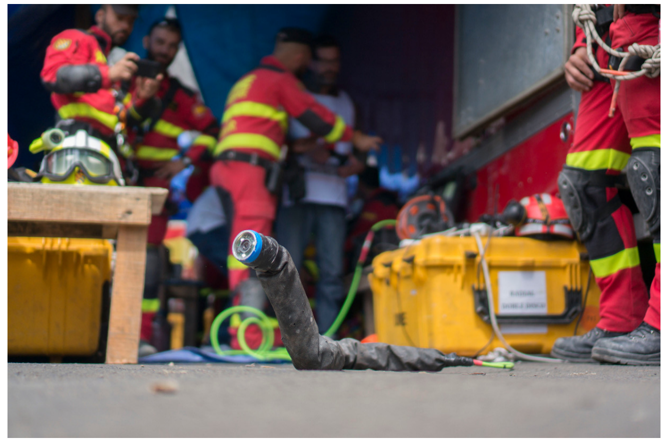

Fig. 2. The Carnegie Mellon University Biorobotics Laboratory deployed a snake robot in a collapsed building in Mexico City after the earthquake in September 2017. The snake robot was demonstrated to rescue workers before deployment.

The Biorobotics Laboratory at Carnegie Mellon University has developed snake robots over the past 20 years. We have iterated on designs to produce a model called the *unified snake robot* or "U-snake" for short, shown in Fig. 3. The body of the robot is composed of a sequence of identical modules. Each joint axis is offset by 90 degrees from the previous, enabling the body to take on three-dimensional shapes that allow locomotion through a variety of terrains. The robot has been extended to as many as 36 actuated joint modules; for the deployments in Mexico City the robot was configured using 16 modules. The 16-module configuration is approximately one meter long and five centimeters in diameter. The robot's head module contains a camera and LEDs. The tail module connects the robot to its power and communications tether via a slip ring. When deployed the robot's body is covered with a rubberized skin to increase traction and protect against dirt and water. Further design and control details are described in [2].

The U-snake has been previously deployed in scenarios including for search and rescue training [3], nuclear inspection [4], [5], and archaeology [6]. The robot has also been used for biology and bio-inspired engineering research [7], [8].

The primary benefit afforded by snake-like robots is that they can access confined spaces due to their narrow diameter, yet can also traverse a wide range of terrain challenges

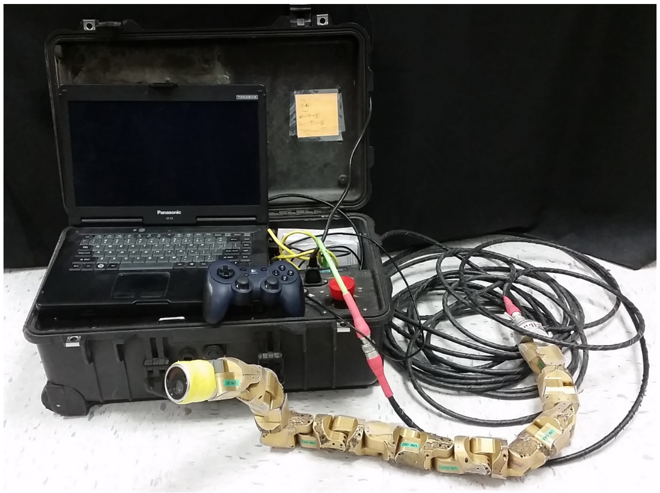

Fig. 3. The "U-snake" robot and its control case with laptop, game pad, and tether.

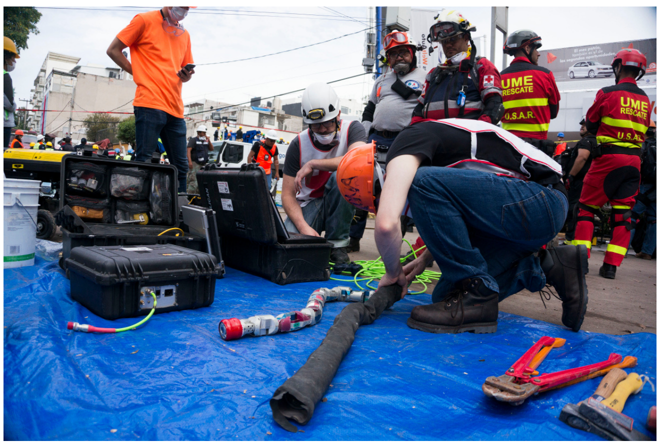

Fig. 4. Setting up the snake robot on a tarp next to the site and testing the control case before deployment.

including climbing trees or poles, piles of rubble, stairs, or flat open regions [9]. In general, each terrain type is traversed via a different locomotive behavior by executing different *gaits*. A gait is a cyclical motion through the space of internal joint angles that produces a net displacement of the robot's body through the world. The wide variety of possible behaviors for a snake robot is larger than in the case of conventional robots. For example, if the robot executes a rolling gait, it will rotate about its backbone [9], behaving like a tracked vehicle [10]. If it executes a crawling gait, however, the pattern of making and breaking contacts [11] acts more like a legged robot. Other gaits, such as those used for climbing poles or moving through pipes are unique to snake-like robots [12].

The U-snake robot is teleoperated using a standard game pad with two joysticks and twelve buttons. Game pad buttons are used to change behavioral parameters, such as speed and amplitude, or to move to preset poses. Combinations of buttons are used to switch between modes, such as sidewinding, pole climbing, or independent manual control of the robot's

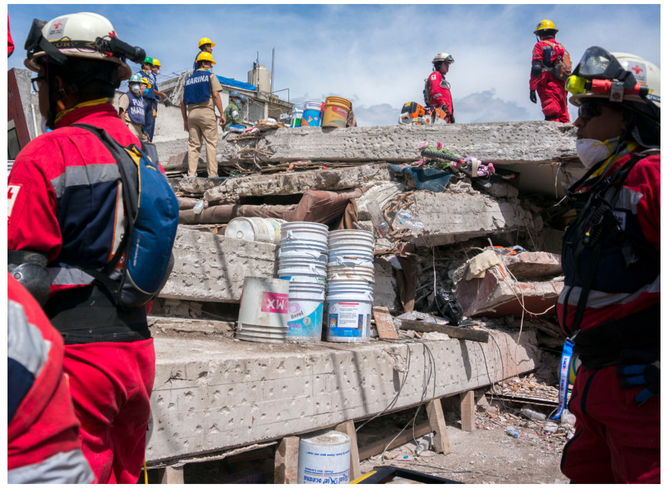

Fig. 5. The collapsed apartment building in which we deployed. Rescue workers searched for voids within the rubble and used dogs and microphones to search for survivors.

head module. A monitor on the laptop displays the robot's status, e.g., commanded and feedback joint angles, motor currents, a visualization of the robot shape, and a live camera feed rotated to match the direction of gravity at the head (down in the image corresponds to the direction of gravity). Additional menus and options are available on the laptop screen.

Two identical robots and several tethers were transported in a rugged plastic carrying case. The control electronics and laptop control unit were transported in another identical case. One last case contained a spare controller and support equipment including repair tools, tape, scissors, extension cords, and flashlights. The control case and robot are powered by standard AC electrical outlets; the control case contains AC-DC converters for the robot, laptop, and other internal components.

III. PROCEDURE

The Biorobotics team travelled around Mexico City with Mexican Red Cross rescue workers. Our team consisted of Prof. Matt Travers, co-director of the Biorobotics lab, Nico Zevallos, a researcher, and Julian Whitman, a graduate student. In addition to the snake robot equipment, a high-sensitivity microphone and operator unit, as well as a gasoline generator that provided power to the robot were also transported with our team. The group periodically returned to a base of operations to wait for assignments and to arrange logistics among the rescue workers from around the world.

The centralized logistics office maintained detailed maps with locations and status of each site, including estimates of the number of people potentially remaining in each building. These maps were constantly updated based on crowd-sourced information. We were sent to collapsed building sites for which not all people had been accounted.

At each site, the Mexican Red Cross team lead informed the site coordinator about the equipment and capabilities we brought. We unloaded the snake robot and control case,

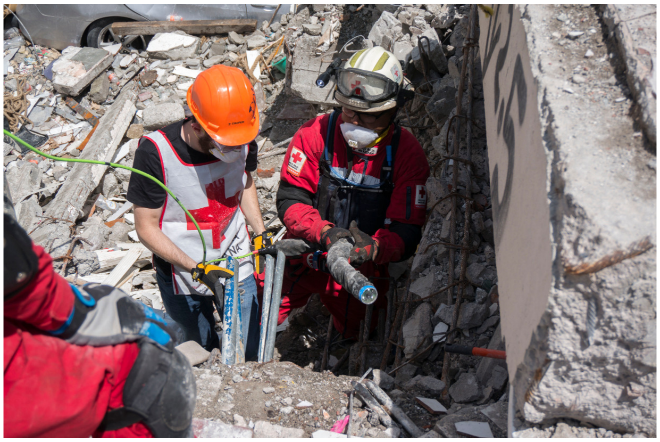

Fig. 6. Inserting the robot into an opening in the roof of a collapsed building with the help of a rescue worker

and set them up on a tarp near the entrance to the active work zone at each site, as shown in Fig. 4. The robot was demonstrated to show rescue workers the robot's size and capabilities (Fig. 2). We waited for between a few minutes and a few hours before either deploying or being dismissed by the site coordinator.

IV. OUTCOMES

The robot was deployed for two drops at one site. We define a *drop* as placing the robot into an individual void or space [13], and a *site* as a single collapsed building. The site consisted of a small apartment building that had "pancaked;" the walls collapsed floor by floor, leaving a stack of layered concrete slabs with some open voids within it, shown in Fig. 5. Rescue workers identified an opening approximately 30 cm in diameter which appeared to lead 10 meters into the interior of the building. We dropped the robot in the void manually and teleoperated the robot into the building. The control case and operator remained on a flat, stable area of the roof (Fig. 9) while a second operator inserted the robot into the opening a few meters away and managed the tether (Fig. 6). A long extension cord connected the robot control case to the generator at the base of the building.

On the first drop, the operator drove the robot down into a hole in the concrete, but reached a dead end. In the process we were able to see through the camera feed a crack exposing blue sky, revealing another nearby opening that would have better access to the interior of the building. The opening was the entry point for the second drop. At the end of the second drop void, we were able to view an open region, and determined that the area was an empty water cistern which could not contain survivors. This information helped the rescue workers decide to dismiss the open area, and encouraged them to proceed with demolition of that part of the building. Both drops lasted approximately five minutes. Views from the robot camera feed are shown in Figs. 7 and 8.

The behavior used most during the drops was the "roll in shape" gait [9], [12], in which the robot took on a narrow helical shape and rolled forward, such that the body acted as

Fig. 7. A frame from the snake head camera footage while inside the collapsed building, showing that another entry point was visible. Rescue workers can be seen above the channel. The video is rotated to align with gravity.

Fig. 8. A frame from the snake head camera footage, looking down the length of the narrow passage within the collapsed building. The video is rotated to align with gravity.

a large tread. Other gaits like an inch-worming crawl were used to navigate over obstacles. We used the head camera to look around the open region while perched at the end of a channel. The ability to independently control the head to actively re-position the camera and look around corners is beyond that provided by conventional search cameras. The robot was extracted by driving it backward or by turning the robot off so that the joints go limp and then pulling in its tether.

Video was recorded from the robot head camera. When guiding the robot through a narrow passage in a collapsed building, our primary concern was that the tether would become tangled in broken rebar and other debris, and so care was taken to avoid driving the robot through obstacle-dense regions.

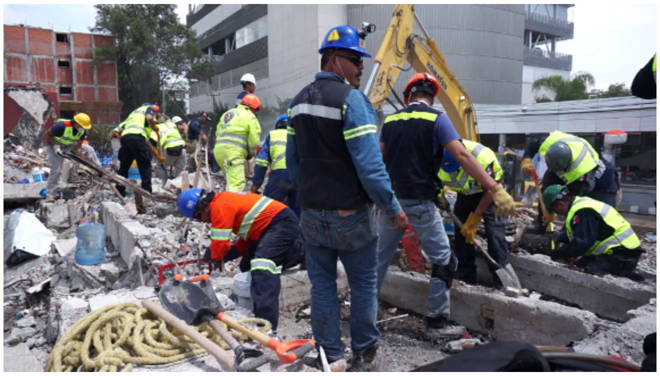

Fig. 9. Workers and construction equipment excavating the site. The robot control station was placed below the camera view.

V. LIMITATIONS AND FUTURE IMPROVEMENTS

The deployment in Mexico City exposed several limitations of our system and highlighted directions for future improvements. Overall we validated the recommendations made by Casper and Murphy [13] after the first use of robots in search efforts during 2001 World Trade Center disaster. Even with the advances made in search and rescue robots over the past 15 years, many of the same concerns and limitations are still applicable. Their recommendations to leverage many sources of sensor information including touch or sound, to create a training and certification procedure for USAR workers using robots, to increase robot portability, and to take advantage of advances in computer vision, are all still relevant. We encountered additional limitations more specific to highly articulated mobile robots.

A. Operator training

The user interface for the U-snake robot can be learned with a brief tutorial and instruction guide. The instructions map button combinations on the robot controller to different behavioral modes and parameter adjustments that can be learned over a few minutes of practice. Users with prior experience playing video games with similar game pads find it intuitive to use. However, to operate the robot efficiently and under difficult time constraints (such as those that typify search and rescue operations) requires practice and experience, as the user must be comfortable with different button combinations and know when a mode change is helpful. As a consequence the robot cannot currently be operated effectively by rescue workers on site, and so was operated by Biorobotics researchers.

The Biorobotics team had no formal USAR training. Had the site been more dangerous, for instance if the building had not entirely collapsed or if aftershocks were occurring during rescue operations, rescue workers may have considered us a liability rather than an asset. Site coordinators may be reluctant to allow robotics researchers on site if space is limited or safety a concern. For future deployments we will work to ensure that the robot is usable with minimal training, and that lab researchers who may be deployed with the robot have some formal USAR training.

B. COMMUNICATION AND LOGISTICS

When the U-snake capabilities were demonstrated, rescue workers were able to understand quickly what the robot was capable of and how it could be used. However, they also extrapolated other capabilities the robot did not have. For example, because the robot has a camera on its head, they assumed it also came equip with a microphone and speakers. They also assumed the robot could carry food, water, or other supplies; in our experience attaching additional payloads to this robot severely reduces its mobility. Translation of the robot's exact capabilities into Spanish ensured that the rescue workers had a reasonable expectation of what the robot could actually do.

In addition, during the two drops the tether manager and teleoperator had difficulty communicating due to noise from the construction equipment, rescue workers, and the 10-15m between the void opening and the control computer. The tether manager was unable to see the robot camera stream, and did not have clear line of sight to the robot. For future deployments we will investigate a means to more intuitively share more information between the person managing the robot's tether and the teleoperation station, as the tether manager can enhance the robot mobility by strategically pulling the tether to prevent the robot from getting stuck.

C. Deployment speed

The mortality rate of victims trapped within collapsed structures who are not extricated in the first 48 hours after a disaster event are unlikely to survive beyond a few weeks in the hospital [1]. By the time that our team arrived, the rescue workers expressed they were primarily searching for remains and clearing sites for full demolition. While we were not invited by the Red Cross until the day after the disaster, the impact of search and rescue robots in collapsed structures would be maximized in the first 48 hours, so the time to test and pack the robots before leaving must be minimized.

D. Hardware limitations

Some limitations the team encountered were due to the age and in-lab development of the robot. The Biorobotics lab has deployed the U-snake to numerous locations outside of the lab environment, but not tested the full system under a wide range of realistic scenarios. For example, the laptop screen (a rugged laptop designed for outdoor use) was not easily visible in the bright sunlight during the two primary drops. We had to improvise a shade source to clearly see the screen (a plastic bucket held by one of the aide workers, see Fig. 10).

The camera on the U-snake has not been updated recently, and the age of the robot led to some video quality degradation. The robot is also lacking any microphones, speakers, range/proximity sensors, thermal imaging, or gas sensors. These sensors would greatly enhance the robots ability to detect and interact with survivors, or map and localize within the environment. As these robots near their end of life cycle, we plan to replace them with similar platforms containing updated sensor packages.

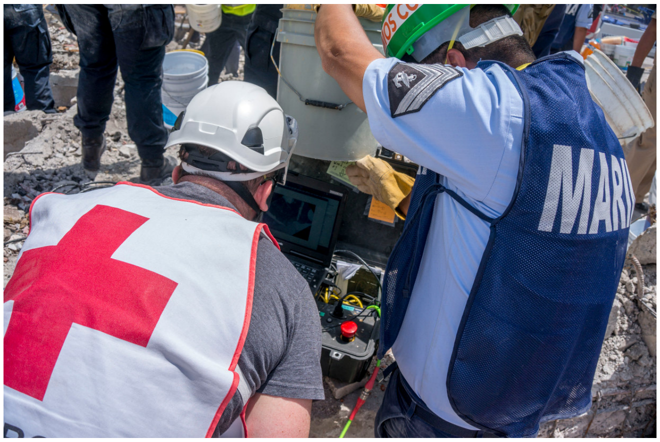

Fig. 10. The bright sunlight made it difficult to view the camera stream, so we improvised to create shade over the laptop monitor.

Fig. 11. Rescue workers on the roof of the collapsed building. We deployed the robot at this site.

Even when the screen is visible, the U-snake camera feed displays only to a single local computer screen. While the teleoperator watches the screen for signs of survivors and potential hazards, they must also pay attention to the robot status, communicate with the tether manager, and physically operate the game pad. In future iterations we will consider including secondary video displays or streaming capabilities such that USAR experts on site can monitor the video feed and watch for signs of survivors with their full attention.

Lastly, the transportation and operation human-to-robot ratios (how many people are needed to deploy each robot) [1] for the U-snake platform could be improved with updated, smaller control electronics that are mounted on a backpack to allow the user to use both hands to climb or crawl while carrying the robot, tether, and control case. The platform had a human-to-robot ratio of 2:1 for operation: one teleoperator and one tether manager. The platform had a human-to-robot ratio of 3:1 for transportation: humans had to carry a case containing the robots and some repair equipment, a case containing the control electronics, and a gasoline generator power source. The platform was *man-portable*, i.e. can be carried a short distance by two people or on a small all-terrain vehicle [1]. Reducing the size of the control case and replacing the generator with a high-capacity battery pack or smaller generator would make the platform *man-packable*, i.e. could be carried by responders over debris, up and down ladders, and into the core of the disaster area. These changes would make it more likely to be used immediately after a disaster.

E. Situational awareness

During deployment we encountered some limitations in operator situational awareness. The U-snake control laptop displays a visualization of the robot in its *virtual chassis frame*, an averaged coordinate body frame that isolates the internal motion of the robots shape changes from external motion [14]. However, the teleoperator does not have a sense for which direction the robot is facing in an inertial frame or where the robot is located relative to the point of ingress. In our experience, when the robot can no longer be seen via line of sight, the GUI/robot visualization becomes critical to situational awareness and effective teleoperation. We will equip future iterations of the robot with range sensors, and use advances in simultaneous localization and mapping to enhance operator situational awareness.

F. Importance of mid-level autonomy

The U-snake interface and game pad allow operators to reliably drive the robot over uniform terrain. However, the current platform relies heavily on operator experience to navigate using manual controls through certain types of obstacles, such as large rocks. The operator must also choose which gait parameters to adapt based on joint angle and current feedback displays and the real-time camera feed. This limitation emphasizes the importance of a *middle layer of autonomy* between high level path planning or teleoperation directives and low level joint controls. Our current and future work will allow the robot to decide to change gait types or execute obstacle navigation maneuvers autonomously [15], [16]. We have also developed proprioceptive gait compliance techniques for snake robots [17], [18] allowing the robot to blindly adapt its shape to locomote more effectively through unstructured terrain. We will implement behaviors that are far more adaptable to unstructured environmental features on future versions of snake-like platforms.

VI. CONCLUSIONS

Our U-snake robot urban search deployment was useful on-site, as we assisted in establishing the vacancy of a void within a collapsed building. At some sites, rescue teams asked us where they could purchase the same or similar platform, noticing its capabilities beyond those of standard search cameras. We benefited from the experience by observing the platform's performance successes and limitations. We conclude that there is significant "last-mile" development and testing, beyond having a functional robot, that could make the platform usable by non-experts and maximize its impact at disaster sites.

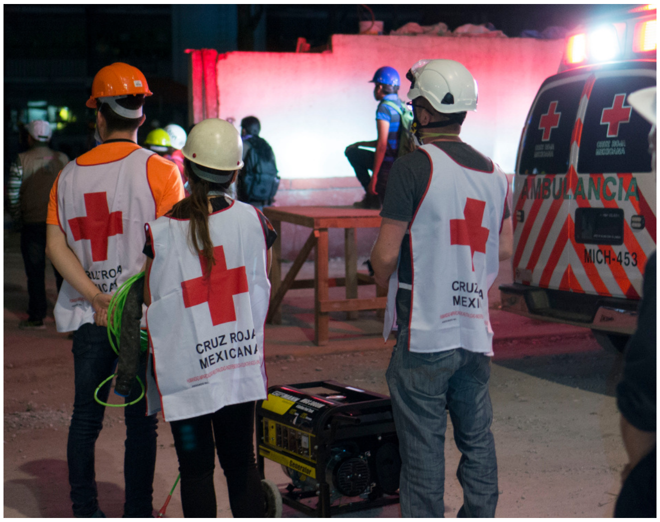

Fig. 12. At this site, we unloaded the robot and generator from the ambulance and prepared for deployment, but were not requested to deploy.

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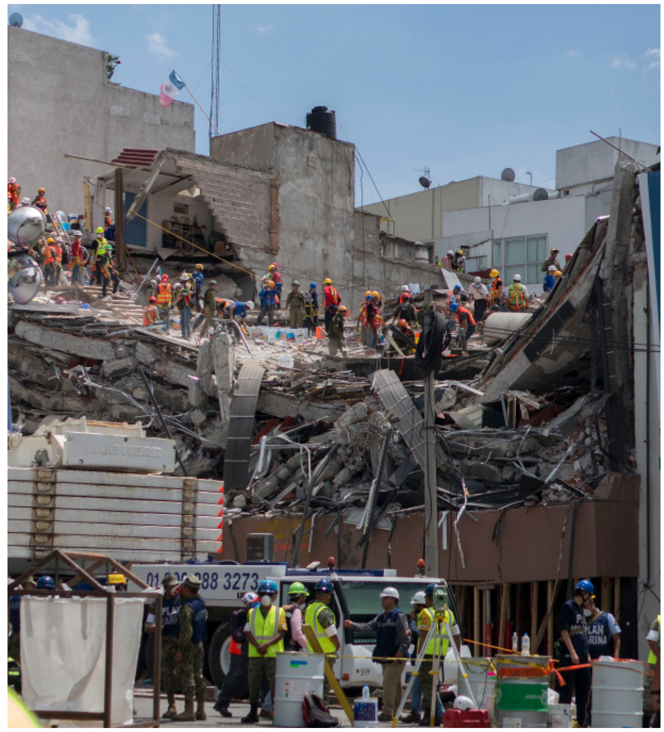

Fig. 13. Rescue and demolition workers on the site of a collapsed building.

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