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Human Detection Techniques for Search and Rescue of Trapped Victims Under Debris: A Review

Sajjad Ahmed[1,2*], Ariffuddin Joret[2], Norshidah Katiran[2], and Muhammad Suhaimi Sulong[3]

[1]Quaid-e-Awam University of Engineering, Science and Technology (QUEST) Nawabshah, PAKISTAN

[2]Faculty of Electrical and Electronic Engineering,
Universiti Tun Hussein Onn Malaysia, Johor, MALAYSIA

[3]Faculty of Technical and Vocational Education,
Universiti Tun Hussein Onn Malaysia, Johor, MALAYSIA

*Corresponding Author

Abstract:
This study presents a comparative review study on human detection techniques for search and rescue of trapped victims under debris. Natural calamities are increasingly common as climate change becomes more serious. Search and rescue missions become more and more important to humanity worldwide. Often, time is a crucial factor for an optimistic result of search and rescue operations. Different technology-based techniques are used for human detection, including radar techniques, robotics techniques, drone techniques, gas sensor techniques, optical acoustic/seismic techniques, and infrared techniques. Furthermore, analyzing of advantages and disadvantages of the different types of human detection techniques and the development direction of human detection techniques is presented in this review. At present, there is a need for advanced human detection systems that can support rescue operations, while improving location accuracy and speed in a short period of time.

Keywords:
Radar · Robotics · Drone · Gas sensor · Optical · Acoustic/Seismic · Infrared · Trapped victims · Human detection technique · Debris

1. Introduction

Every year, thousands of humans experience their last breath under the rubble of collapsed buildings due to natural disasters such as earthquakes, flooding, hurricane, and other incidents that turn buildings infrastructure into piles of debris. Among all the operations carried out in natural disasters, such as earthquakes, fires and building collapses, the search and rescue of entrapped victims has priority [1]. Survival rates decline after 72 hours of being trapped under the rubble of the collapsed buildings, and without access to water, most victims are unlikely to survive longer than 120 hours [2]. Human detection techniques and tools find and locate humans under debris based on the victim's senses, such as sight, hearing and smell. The history of revolutionary systems to detect human survivors trapped under the debris starts with the work of Kun-Mu Chen [3] that carries out the concept of detection of buried humans using microwave beams in 1985. The researcher had put their efforts time by time to

*Corresponding author: sajjadbhatti@quest.edu.pk

develop various human detection technologies for disaster situations. These human detection systems are based on many technologies which are discussed here.

2. Human Detection Systems

The signal such as radio frequency reflection, heartbeat, and pulses of humans buried under rubble would become into energy sources like radio waves, light waves, sound waves, infrared rays, and video images. Human detection systems are a kind of acquisition system for different forms of a wave through which signal data is analyzed through sensors and different technologies tools to determine the location of victims buried under rubble.

2.1 Radar Human Detection System

Radar technology has recently gained much attention for detecting survivors under debris [4]. Radar has the ability to penetrate through debris to detect the signal of vital signs or non-invasive techniques such as breathing rate, heartbeat, and pulse rate of the targeted victim. Types of radar detection systems are discussed here.

2.1.1 Continuous Wave (CW) Radar Human Detection System

The approach of continuous wave radar detection system instigates continuous microwave beam on a human body, in result system obtains returned echo signal in form of heart rate, pulse rate, etc. which further process through signal processing technique for extracting of the parameters of the body of life signals. This type of radar is used to measure distance in the frequency domain and the resolution range depends on the frequency domain resolution that can be altered as preferred [5]. The received signal to recognize humans under the ruins from the antenna affects the time variation of the radar to detect the survivor [6]. CW radar based on radar vital signs monitor (RVSM) technology for vital sign detection was discussed in [7].

CW radar with the dual-frequency operation was presented in [8]. The proposed human detection system with low and high-frequency combinations indicated a good potential application for search operations because it exhibited effective carrier interference suppression. The work in [9] developed a human-detection system based on CW radar for the detection of several human targets buried under wreckage. The author developed the Blind Source Separation (BSS) signal processing technique along with a multiple-antenna MIMO configuration for the detection of several human targets simultaneously.

2.1.2 Frequency Modulated Continuous Wave (FMCW) Radar Human Detection System

FMCW radar works on the principle of beat frequency which is a difference of transmitted and reflected signals of the target. Further FMCW techniques achieve the velocity, range measurement with less power [10]. FMCW radar technology has broad applications in the field of search and rescue of human beings in disaster conditions. The experimental work of FMCW radar with a frequency range of 1.2-2.2GHz started for detection of targets under snowpack by Y. Yamaguchi, et. al. in the 1990s [11], [12], and [13]. Further in [14], an FMCW radar system was developed for the detection of human targets through the wall structure. Maaref et. al. [15] used FMCW radar equipped with an antenna system for through the wall detection of human subjects.

Non-contact detection of vital signs has rising importance for human localization in disaster rescue, in such case, FMCW radar technology is also considered a fine solution for vital signs detection. FMCW radar technology has previously been presented in the earlier for numerous applications associated to vital signs detection. In [16] and [17] FMCW radar was used for the detection of heartbeat rate with a frequency range of 24 GHz and 9.6 GHz respectively. While in [18] FMCW radar prototype was designed along with a patch antenna system for monitoring of non-contact vital signs. Different systems have been developed by researchers for bringing improvement in vital sign detection. A study in [19] showed the FMCW radar has been used in small displacement detection systems and projection matrix methods for the detection of human vital signs. Another work in [20] also used a small-displacement detection system for monitoring human respiration through FMCW radar.

2.1.3 Stepped Frequency Continuous Wave (SFCW) Radar Human Detection System

The working principle of SFCW radar is simple, it transmits a series of discrete frames linearly to the direction of the target. Furthermore, it offers good target detection accuracy with simple calibration procedures and post-processing techniques [21]. The work in [22] was performed through wall experiments for the detection of human activities by SFCW radar with 93% to 98 % accuracy. Gumbmann et. al. [21] developed a short-range imaging system based on the SFCW approach for the detection of targets with high sweep rates and low ambiguity level. In addition, physical experiments for the detection of human survivors under debris through the SFCW radar approach have been conducted in [23]. The proposed radar system used 100MHz - 1GHz frequency and showed the ability to detect a victim buried under thick debris of one meter.

As this radar system has fine range resolution and Doppler sensitivity for monitoring several human vital signs [24], it has been widely studied for applications such as vital signs monitoring, and object detection behind obstacles [25], [26]. The work in [27] performed real-time experiments for the detection and localization of multiple stationary human targets behind walls based on dual-station SFCW radars. The cross-correlation algorithm was introduced in this work to effectively detect multiple targets and to provide a range pairing mechanism for dual radars.

2.1.4 Ground Penetrating Radar (GPR) Human Detection System

Ground penetrating radar (GPR) is known as a geophysical technique for imaging the earth's subsurface and detecting buried objects. GPR has the ability to resolve many problems where the answers are buried in the earth subsurface. The GPR technique works by transmitting antenna sends radio waves into ground surface or rubble and strike the hidden target, when these waves touch targets with different electromagnetic characteristics, these waves reflected back and received by the receiver antenna. The first patent for a GPR system for tracking hidden objects was filled in 1910 [28] and then the first survey was conducted by using the system for mapping glaciers in 1929 [29]. Nowadays GPR techniques are in focus for research in many applications such as, detection of buried objects, locating of utility, fault detection in the concrete structure, and human trapped detection in the rubble [30], [31].

Locating of humans buried or trapped under debris is a developing field of GPR application. The work in [32] showed GPR-based detection and localization of objects under voids in the rubble of disaster conditions during search and rescue operation. The proposed method with the developed algorithm achieved overall good results considering both real and simulated GPR scans with 93% accuracy. Yuan et. al. [33] developed GPR based new drop–flow algorithm for the detection of underground utilities with a detection rate of 84% and a precision of 78%. In [34] demonstrated GPR numerical modeling and estimations of target response magnitude when buried in a complex subsurface such as encountered in search and rescue situations. In addition, the GPR approach was used for the detection of buried human bodies [35] in order to increase the effectiveness and efficiency of natural disaster victims by conducting simulation and measurement methods.

2.2 Robotics Human Detection System

Nowadays search and rescue using robotics technology is a huge and active field in both academia and industry. Robots are the perfect choice for when it is dangerous to send in humans in search and rescue including disaster situations such as earthquakes, fires, avalanches, minefields, and floods. Rescue robots are based on different sensors technologies such as vision sensors, ultrasonic sensors, heat sensors, laser range finders, electromagnetic wave sensors, and GPS sensors. The robot for rescue purposes is made with a long and thin structure through different tracked vehicles in series, so it can pass through narrow and small spaces. The disaster robot system consists of four structural parts, such as robot, sensor, communication network, and monitoring unit. When humans are trapped inside the rubble, it will be difficult to search and rescue them quickly, in these circumstances mobile robots are used that can enter the building and find if there is any victim there and then send a signal to the rescue team to call for help [36].

According to the work in [37] and [38], the purpose of using robots is to help the first-aid workers by providing them an image of a place that they cannot reach for rescuing of victims if any. The first attempt at real-time robots was used during the World Trade Center disaster rescue mission in New York in 2001 [39]. Since then, worldwide attention in robots for search and rescue operations has grown rapidly. Six remotely-controlled rescue robots were used during the World Trade Center by the rescue team for tracking human victims trapped under rubble. Robots can be easily used and controlled in dangerous situations such as bomb disposal, mining fields, and also for cleaning toxic wastes. In 2019, the development of a human detection robot for rescue operations in natural calamities was presented [40]. The robot model used a radar technique which is based on electromagnetic wave signal reflection for detection of targets which can be controlled through mobile application with Bluetooth module.

Nowadays different technologies are integrated into robots for search and rescue purposed in natural calamities. Cao Xin et. al. [41] presented a robot system based on Internet of Things technology for human detection under debris. Another robot based on image processing and neural networks system was proposed in [42] for human detection in the operation of urban search and rescue. In 2018, a research work was presented [43] where the main focus was on live human detection in battle fields and earthquake site using robots. The robot system was integrated with GPS, GSM, sensors, and camouflage technologies for effective detection. Furthermore, referring to the work in [44] and [45], a robot system had been designed for the detection of survivors during a disaster situation.

2.3 Gas Sensor Human Detection System

The gas sensor is the smallest and cheapest device for detecting people by smell, which could be used in the search for people buried under the rubble of an earthquake or any disaster. Further, gas sensors are considered as tiny electronic rescue dogs which are the size of small computer chips. These gas sensors emit in low concentrations via human breath or skin, whereas it has also been confirmed that the use of gas sensors for human sensing is possible through analysis of changes in carbon dioxide (CO2) and oxygen (O2) in the environment due to human respiration [46]. The gas sensor is capable to determine CO2, propane, and methane. CO2 measurements are used to detect the breathing of living trapped victims. Additionally, CO2, propane, and methane are also used to detect dangerous gas concentrations for human rescuers [47]. The ChemPro chemical detector was used for the detection of selected volatile organic compounds known to be possible signs of human presence under debris [48]. The work in [49] proposes to use a CO2 detector to detect survivors based on particular thresholds.

In 2018, Güntner et. al. [50] developed novel gas sensor arrays to detect acetone, ammonia, isoprene, CO2, and relative humidity (RH) from metabolic tracers emitted from breath and skin, all jointly working as signs of life for tracking entrapped humans. This pilot study shows that such sensor arrays could be quite effective during natural calamity situations for rescuers teams. In the same year, another study was proposed by Zhang et. al. [51]. A CO2 sensor was proposed and tested for detecting living victims trapped under debris. The efficiency of the sensor was evaluated and confirmed through experiments. The gas sensor's performance in detecting living victims under debris was tested in a high-fidelity simulated disaster area. The results show that the CO2 sensor can provide useful information to locate a victim in a disaster. Furthermore, an experimental study on the evolution of chemical plumes created by trapped inside collapsed buildings was conducted in [47]. The results show that gases such as NH3, acetone and CO2 are reliable indicators of active metabolism and these compounds quickly pass through the construction debris with a column of metabolites.

2.4 Drone Human Detection System

During natural disasters one of the key challenges faced by rescue teams is finding live humans as early as possible, in such conditions drone human detection system is very useful to help first responders in their search to find survivors in the disaster areas. Avalanches, floods, and wildfire are among the most common natural calamities which make search and rescue operations extremely hard for rescue workers [52], in such situations drone system has an advantage over other detection systems. Drone human detection system uses different technologies such as sensors, high-definition cameras, and wireless technology to detect human victims in disasters zone. In 2019, Naji et. al. [53] presented a drone system equipped with standard cameras for life sign detection in disaster zones. The proposed system uses a drone-based computer vision system to detect cardiopulmonary motion caused by periodic chest movement in survivors. The experiment was conducted on eight human subjects and one mannequin at distances of 4-8 meters in different positions where the results obtained have reached 100% accuracy. Another drone system based on the passive infrared sensor (PIR), radio frequency technique, and microcontroller for earthquake rescue operation was reported in [54].

The use of drone technology has made it possible to find survivors at high altitude areas where another detection system was insufficient to find live humans in less response time. A study by Tariq et. al. [55] presented a drone system named "DronAID" for human rescue purposes in natural calamities. The drone system used a monitoring unit integrated with a camera and sensor to detect the presence of human subjects buried under the rubble. Another study by Lee et. al. [56] developed a drone system based on an infrared camera and lidar sensor for human rescue in disaster situations. The experiment was conducted in limited lighting and unknown building structure to highlight the real-world issues that may occur in practical search and rescue operations.

2.5 Optical Human Detection System

An optical system for human subject detection under debris can be referred to as a system that helps rescuers visually search the location and the vital status of a victim inside the rubble. To be capable of reaching further into void space, the optical camera is generally fixed on a telescopic rod. The rescue team then tries, as with the search camera, to access the void with the fiber optic camera through holes and openings in the debris. Information on the inside of the rubble can then be vision by the operator on the video screen. The dimension of a fiber optic search camera is compact in relation to other visual rod-based detection systems which makes the fiber optic system able in accessing smaller voids and openings. Additionally, for a better vision in darkness, the optical camera is often offered with a light source and the system gets no interference from other sources.

The key features related to the design of optical detection systems are sensor sensitivity, sensor size, and image processing algorithm. In [57], researchers have developed a prototype of an optical sensor network for rescue operations for urban search and rescue (USAR). The proposed devices use the positioning of visible (VIS) and infrared (IR) range cameras to obtain images of signs of life and detection of dangers. At the time of the design and development of the prototype, special care has been taken to select the appropriate optical components and image processing algorithms. Furthermore, the development of optical sensors in 2017 has been reported for detection applications [58]. In addition, Zarco et. al. [59] developed an electro-optical detector to rescue humans during natural calamities. The designed optical detection system consists of commercial pyloric quantum sensors and a Cassegrain antenna which detect humans on the basis of the infrared radiation discharged by the human body under debris.

2.6 Acoustic / Seismic Human Detection System

An acoustic/seismic system works as an amplifier of seismic activity, this system consists of sensors that are capable to detect vibrations and sounds that are not detectable by the rescuer. These sensors are connected through a cable to an amplifier with special indicators. The rescue team place the sensors in the rubble and observe the sensor's response by listening in their earphone to determine the happening of sound and seismic activity, if there is a live victim there must be some kind of sound or motion that causes vibrations in the rubble. These vibrations are detected by an acoustic system for the localization of live victims. Nowadays many commercial acoustic/seismic detection systems are available in the market; one of them is delsar human detector system which is worldwide used by rescue teams for trapped victims under the rubble of collapsed structures.

The work in [60] has shown an efficient technique based on passive acoustic sensors for the detection of human vital signs in concealed structures. The proposed method used a geophones network and a signal processing algorithm for detecting and recognizing vital signs. A series of experiments have been carried out as preliminary results, confirming the promising performance of the proposed method. Furthermore, Cao Hui et. al. [61] proposed acoustic/seismic human detection and position system for trapped victims in earthquakes. The positioning method is the basis of the research and development of the acoustic vibration life search and positioning system. Considering the difficulties and time requirements of on-site rescue, a fast search method for energy tracking is proposed.

2.7 Infrared Human Detection System

An infrared human detection system can be used in searching for sunless and hazy situations, and help rescuers quickly and accurately detect living things buried in debris or hidden in cloudy dust with vision capabilities in the darkness. The working principle of the infrared human detection system is very simple when an infrared beam is directed at some part of the earthquake debris covering a victim, the beam penetrates the debris to reach the victim. Infrared (IR) systems are widely used to measure distances for different applications. It uses a reflected light signal to calculate the distance from an object [62]. Snake eye detector and visual detector are commercially available human-detection systems that are widely used in rescue missions. These devices based on infrared sensors on the outgoing and flexible cable, gather the information from the rescue location and convert it into video images, which will aid the rescuers to rapidly inspect whether there is a victim alive or not. An IR detection system for the detection of humans buried under debris has been developed in [63]. The designed IR detection system can detect and measure the heartbeat signals of the trapped victim. An experimental result shows that the developed prototype is economical and effective and not only detects signs of human, but also the identification of trapped victims. The work in [64] and [65] shows a passive infrared (PIR) sensor-based detection system is developed for the detection of live human subjects. Both detection systems are cost-effective, user-friendly, and semi-autonomous with robotics support.

3. Advantages and Disadvantages of Human Detection Systems

Table 1 shows a comparison of human detection systems that can be applied in search and rescue operations. Based on this table the technique can be divided into 7 categories where all the techniques applied are based on an electromagnetic wave, sound wave, gas, or optical signals.

Table 1: Human detection system technique comparison

Technique	Human Detection Systems	Advantages	Disadvantages
1	Radar human detection system	UWB, deep penetration capability and target accurately inspecting	Limited detection in long range and poor in multi-target detection
	Continuous Wave (CW) Radar	Simple design, low cost	Low resolution range and sensitivity to outside interference
	FMCW radar	Simple design, solid-state transmitters and good in short range resolution	Poor in long range target detection and external interference from power source
	SFCW radar	It has quality of low-probability-of-intercept radar (LPIR) and good in resolution	Require more acquisition time and poor in long range target detection
	GPR	Deep penetration capability and low cost	Difficulty in linear scan due to piles of debris and rubble material has cluttered heterogeneous nature it makes difficult to recognize victim
2	Robotics human detection system	Robots can get into locations that humans cannot because of small size, high heat, and environmental toxicity	Costly, more improvement required in design, sensor, decoding behavior, algorithms and communications links
3	Gas sensor human detection system	High sensitivity, compact size and low cost	It has increased airflow which makes difficult to use in open environment, still no commercial product is lunched. Experiments are only conducted in laboratory
4	Drone human detection system	Reduce the rescue time, search a larger area in a shorter time period and reach at high altitude and hard areas	Limited communication range, not enough precision in navigation

5	Optical human detection system	Inexpensive, low power consumption	Image visibility is narrow, skilled operators are required and cannot be used in inaccessible location
6	Acoustic / Seismic human detection system	Penetration through metal objects and sensitivity to detect slow motion	Limited range, ineffectiveness in concrete, and inability to detect unconscious victims
7	Infrared human detection system	Rescue victim in narrow spaces, low cost and portable	Low penetration, to know the condition of the victim, holes are needed to place the probe at the disaster site

4. Conclusion

A comparative review-based study into human detection techniques for search and rescue of trapped victims under debris has been performed in this paper. A detailed summary of a Radar human detection system, Robotics human detection system, Drone human detection system, Gas sensor human detection system, Optical human detection system, Acoustic/Seismic human detection system, and Infrared human detection system, with different research techniques have been presented. At present, the research of human detection systems is mainly based on integrated sensor technology. Human detection-based search and rescue needs a wide range of information because of difficult and changing environmental conditions such as high altitude zones, hot weather, low visibility, loud sound, power failure, and other sceneries that happen during natural calamities. In search and rescue operations, time is considered a critical factor as lives are in danger. To handle such scenarios human detection system must base on multi-sensor technology which can search a huge area within a very short spell of time with better accuracy, measurement, and fine resolution. In order to acquire the entire information of live human subjects within the environment of the disasters zone, the drone technique is brought into the human-detection system. Drone technology can be integrated with other modern techniques such as swarm intelligence, machine learning, and 5G networks for gathering comprehensive and secure information of survivors during natural calamities.

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