Technical survey about available technologies for detecting buried people under rubble or avalanches

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Abstract

Among all activities carried out in disaster scenarios, such as collapsed buildings, earthquakes, and avalanches, the detection and rescue of buried or trapped people have the priority. The paper aims at presenting the progress in the technological development of electronic devices and systems used to detect people buried under rubbles or avalanches. Many technologies realize detection, but only electromagnetic ones assure best results in terms of speed and accuracy of a relief, working also in a noisy environment. We can divide the methodologies using electromagnetic propagation in the three main. One is based on detection of active or passive electronic devices carried by the victim; the second one detects the body of a person as perturbation of the backscattered electromagnetic wave, due to dielectric discontinuity in the medium; the third case is based on the detection of vital signs. Both last two methodologies can be suitable for detecting people trapped under rubbles that can be free to move, also partially. More frequently, a buried person is motionless, because he is unconscious or the ruins block him. Consequently, the detection of vital signs, such as heartbeat or breathing, is the unique possible only. Performances and limits of each method is presented in the article, together with possible innovations.
Keywords: rescue, people buried and trapped, GPR, avalanche beacon.

1 Introduction

Among main emergency targets in disaster scenarios, such as collapsed buildings, earthquakes, and avalanches, the detection and rescue activities of buried or trapped people assume the priority.

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An important parameter orients the design of a system, dedicated to solve detection issue: the average survival time. This one imposes a maximum delay time within which to conclude the detection operation by means of the adopted system. The survival time of victims buried under rubbles is approximately 72 hours, but this interval can decrease consequently at climatic conditions, pulverization of building material, and type of entrapment. The same survival time decreases to values very short in the case of avalanches. The probability of survival is estimated to decrease from 90 to 40 and 30 per cent, if the buried person is removed from the snow within 15, 30 and 60 minutes, respectively. Technologies, and location methods, including algorithms, together must concur to increase location accuracy, and operation speed. This is particularly necessary in the case of person buried under avalanches. The methodological approaches differ in dependence of target that is detected: the body of the victim, in the sense of shape, or specific identification of a feature; motion of trapped persons, movements induced by heartbeat or breathing, voice and so on that disclose the presence of vital signs.

A network of geophones can detect vital signs of people located in closed structures [1]. Nevertheless, during an emergency following a catastrophic event, its use is inappropriate or more complicate, since it needs quiet operational conditions that are hardly met during emergencies.

Technologies that are more suitable based themselves on radio frequency (RF), like ground penetrating radar (GPR).

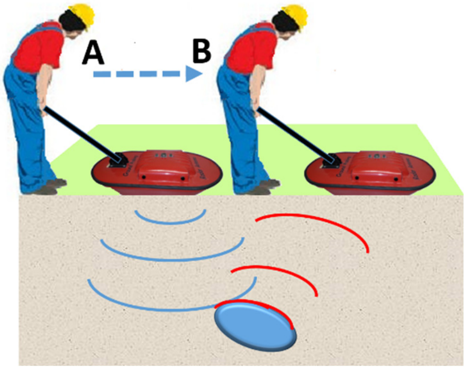

Figure 1: Bistatic GPR system transmits EM waves into the ground and receives signal scattered by discontinuity surface of two contiguous layers of different permittivity and conductivity.

In particular, by means of GPR, it detects objects of interest, such as pipelines, structural concretes, in the context of the survey of many infrastructures: buildings, motorway, etc. GPR uses normally two separate antenna elements: the former is the transmitter and the latter is the receiver. So, the entire antenna system is named bistatic. In the basic operation mode, a GPR system transmits electromagnetic (EM) waves into the ground for a propagation in depth.

The wavelength of the electromagnetic energy and velocity change their value by crossing two contiguous layers of different permittivity and conductivity. If a layer is conductive, GPR energy will get absorbed. If it is a resistive layer, the radio wave is able to penetrate in the same layer.

Permittivity and permeability influence signal wavelength according to following formula:

$$\lambda = c_{light} \Big/ \left(f \cdot \sqrt{\varepsilon_r \mu_r} \right) = c_{light} \Big/ \left(f \cdot n \right)$$

where λ is the wavelength, c_{light} is the speed of light in vacuum, f is the frequency of EM waves, ε_r and μ_r are the relative dielectric permittivity and the relative magnetic permeability of the medium respectively and n is the refractivity index.

Finally, the variation in EM properties between two contiguous layers generate scattering, and the reflected fractional amount of energy arrives to the receiving GPR antenna, allowing to draw the relative radargram (fig. 1).

2 RF technologies

At first, we can divide the methodologies using electromagnetic propagation in the three main. One is based on detection of active or passive electronic devices carried by the victim; the second one detects the body of a person as perturbation of the backscattered electromagnetic wave, due to dielectric discontinuity in the medium; the third case is based on the detection of vital signs.

Figure 2: A collapsed building realizes a very inhomogeneous environment with stratified slabs and heavy rubble at different inclinations. A GPR detects only motion as signature of trapped victims.

The first procedure occurs more frequently during planned activities, such those planned by skiers and winter hikers. They are conscious to walk in dangerous areas and prudently, or following legacy directives, they bring with them electronic devices, like transceivers. By means of receiver device, a rescuer can locate exact position of a buried person, detecting signal transmitted from the victim. A similar principle inspires other technologies aimed at detecting personal electronic devices, e.g. cellular phone, possibly carried by the victims [2]. Methods based on triangulation can localize mobile phones, but only those ones based on pulse radar system may determine positioning of headsets, radio controlled watches, etc. More general rescue conditions however show how victims do not always carry these electronic devices or that objects are distant from them.

Both last two methodologies can be suitable for detecting people trapped under rubbles that can be free to move, also partially. More frequently, a buried person is motionless, because he is unconscious or the ruins block him. Consequently the detection of vital signs, such as heartbeat or breathing, is the unique possible only.

The reason is mainly due to the fact that the detection based on localization of the discontinuity in the medium of electromagnetic wave propagation can be efficient only in the case of homogeneous medium. Therefore, the method could be suitable for detecting people buried for example under avalanches. In the case of collapsed buildings, the debris show stratified slabs and heavy rubble at different inclinations, such as those shown in fig. 2, realizing a very inhomogeneous environment that makes it impossible to exploit the retrieval of the dielectric contrast features as the only means for detection.

In addition, irregular surface and instability of ruins prevent linear scans of the radar at contact of soil, and impose that the sensor system should locate itself in a static position or on board of an aerial vehicle. Therefore, although its implementation can be complicated, vital signs detection represents method that is more promising for the case of people buried under debris.

2.1 Vital signs detection and moral implications

In case of a survival time very short, there are contrasting opinions on the use of devices that include subsystems for detecting vital signs. At the same manner, the detection device should not include any tool for the identification of a person. In particular, the relief activity should avoid, and eliminate the conflict of interests that could lead to the identification. Moreover, the uncertainty of measurement of vital signs, along with the short survival time, it orients to not to draw up a priority action: first rescue of survivors and then the location of the dead. This is an example of how a bigger potentiality offered by technology cannot be useful in specific situations, because it is refused. While, the same information on vital signs are essential in a different situation, specifically in the relief of buried victims under debris.

2.2 People buried under debris

Quite recently, researchers investigated the performance of radars for monitoring vital signs as heartbeat or breathing [3]. At first, the application field has been prevalently the biomedical engineering: to exploit noncontact measurement method that assures a more comfortable analysis for human patient, avoiding the electrodes applied on the skin. In the simpler implementation, a continuous wave (CW) signal is transmitted towards human subject; the movements of heartbeat and breathing modulate the phase of signal, generating a Doppler shift on the reflected signal, which back to the receiver; and finally the demodulation of the received signal detects vital signs. In order to obtain higher resolution, and thanks to the absence of obstacles between antenna and human body, researchers used Ka (27-40 GHz) [4] and X (8-12 GHz) [5] frequency bands. The same X band allowed to achieve a compact radar system, small enough to mount on board of unmanned aerial vehicle (UAV), and to realize a preliminary experiment of detection of victims trapped under rubble [6]. Unfortunately, vibration and aerodynamic instability of a flying vehicle, together limit accuracy and the validity of the same measure, because of physiological movements that show very low frequency and reduced width of expansion.

In the last period and always more frequently, CW radars are used in the experiments by operating in the instrumental scientific medical (ISM) band, around 2.4 GHz [7, 8]. Moreover, some researchers proposed to utilize L band frequency (1.452–1.492 GHz) still able to detect respiratory and heart fluctuations, and to provide of a clutter cancellation subsystem [9]. Decrease frequency allows a bigger penetration depth of electromagnetic wave, while the resolution in the space is worst. In particular, L band penetrates the rubble for about 0.9 m in thickness, in absence of layers of reinforced concrete slabs or structures mainly made of metallic materials that decrease the penetration depth, and introduce multiple reflections.

In order to evaluate distance between antenna and target position, detect many subject simultaneously, and overcome problems of CW GPR, such as null detection points and co-frequency interference, technology progressed to frequency-modulated continuous-wave (FMCW) radars [2] and ultra wide-band (UWB) pulse radars. From point of general view, increasing sensitivity of GPR system improves the probability of detection, but at the same time, it can produce a bigger number of false alarms. In addition, besides the stationary clutter, there is the nonstationary clutter that is the main source of false alarms. The origins of this last one are different: rescue engines, motion of objects located near the GPR, and so on. They are present in the operative scenario, where take place certainly a frenetic activity, together with interferences sources, like all types of radio source, and cell phones [10]. As consequence of the previous problems and considering the entities of movements, induced by heartbeat and breathing, only the breathing assures a useful signature to detect persons buried under rubbles.

2.3 People buried under avalanches

Traditional methods use dogs and snow-probing teams for searching victims under avalanche, independently if buried people carry or not electronic devices dedicated to transmit their position. Rescuers to line up along a row orthogonal to direction of walk, and step by step they verify the presence of some victim by inserting within the snow the probes.

At present, a skier or winter hiker, which is run over avalanches, can increase his survival probability by using transceivers and eventually by putting on special clothes. Rescuers will use a similar transceiver for localizing transmitter of the victim; the special clothes are for increasing survival time and for allowing rescuers to use a larger time interval for their activities. It will present transceiver in the following subsection. Special clothes are sportive vests, named AvaLung by

Black Diamond Equipment. Thanks to little pipes, a membrane at front that filters fresh air from snow, and an equivalent membrane at back that expels CO_2, AvaLung can increase survival time to over two hours.

The technologies that we will present in the following two subsections are used to detect victims only if they use special devices. The last technology, based on GPR, and described inside the following third subsection, at the contrary allows also detection of buried person without specific electronic devices.

2.3.1 Detection based on active devices

This technology uses active electronic devices: one transceiver per each skier or hiker. Avalanche Beacon, ARVA or more recently ARTVA are the different names with which it is called the same transceiver. It emits low-power pulses that justifies the first name: avalanche beacon. At start, each of participants a hike switches for transmitting the own avalanche beacon. Even if some hikers are run over by avalanche and are buried under snow, their avalanche beacons continue to transmit. Hikers that do not run over by avalanche switch ARVA for operating as receiver, and then they walk on the snowy surface for beginning the search.

Avalanche beacon operates at 457 kHz ±80 Hz international standard frequency, ETSI standard EN 300 718, which shows good penetration depth into the dry snow. The pulse width is in the interval 70–900 milliseconds, with a duty-cycle in the range 10–69%. Avalanche beacons base the operation on detection of the higher intensity of electromagnetic field of transmitted radio wave. There are both models of avalanche beacons: analogue and digital. In order to detect multi targets, the modern digital devices use three antennas, and by means of digital signal processing (DSP) it can evaluate direction and distance of the buried transmitter. Often, digital versions are also equipped with a radio transmitting at higher frequency, which changes in the different countries, i.e. 869.8 MHz in Europe and 916–926 MHz in United States. Nevertheless, Russian, China, and other various countries in Asia and Eastern Europe do not permit the use of this additional frequency named W-Link frequency. By means of this W-Link frequency it possible to detect and transmit vital signs, such as micro-movements and heartbeat.

In order to decrease duration of the search activity, and to be certain that all victims have been detected and rescued, it need an efficient search procedure, which is applicable also with a few number of rescuers. It consist in a defined sequence of route that rescuers must make. At first, the rescuer must proceed in the direction from he receives the higher radio wave intensity; after detected the victim he must continue in opposite sense along parallel line scan to previous one and distant from it about 20 m. In the case of multiple victims buried in the same area and one near another, the rescuer should follow a different route named “three circles”. These ones are three concentric circles with ray of 3, 6 and 9 m respectively. The procedure is simple to apply, and assures good results, but it less effective to resolve complex multiple detections of victims, like victims located in the same location at different depths.

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2.3.2 Detection based on passive reflector integrated in the clothes

Since 1973, a less expensive system than avalanche beacon has been introduced. Functioning principle is founded on a passive reflector, i.e. it is not necessary a battery, carried by a skier all times, and a small hand-held transceiver used by rescue team. The reflector, named Recco® reflector, is a tuned resonant circuit, which retransmit with doubled frequency the signal received from transceiver of a rescuer. It uses same principle of more known Radio Frequency Identification (RFID) tag, which is used for many applications such as preventing theft of merchandise. The reflector it is less effective than avalanche beacon, and need at least a transceiver carried by not buried skier. Normally, skiers carry two reflectors, one per each jacket's sleeve or one per each of two boots. The system uses a transmitting signal operating at 917 MHz frequency. Therefore, tuned detector receives a signal at 1834 MHz frequency. At present, modern transceivers operate for receiving both signals ARTVA and RECCO®.

2.3.3 GPR systems

Although about since 1980 researchers investigated on the use of radar for detecting avalanche victims, only since 1994 the research focused on GPR's usage for searching persons buried under snow [11]. Frequency band of standard GPR systems dedicated at the snowy environment's survey is allocated in the range 0.4-2 GHz. Nevertheless, frequencies upper about 0.9 GHz have sufficient spatial resolution for detecting details of human body. In any case, the choice of frequency is a compromise between resolution and penetration depth of radio wave. This last one decreases more and more than frequency increases.

Snow is quite a favourable medium for radio wave's penetration, and differently from the case of debris, we can use the strong scattering generated at interface between the body of buried victim and the snow, which shows characteristic of almost homogeneous medium. In the case of object of finite geometrical dimension and characterized by permittivity and/or electrical conductivity different from those of the snow where it is buried, if the radar moves along a direction, the same object is shown as diffraction hyperbola in the resulting radargram. Characteristic of this hyperbola depends by velocity of radar's motion and by dimension of object. Evidently, the contemporary presence of little debris can complicate the detection of a person. In addition, victims that are run over by avalanches, roll and float in the snow, creating more layer interfaces such as: snow/body, snow/air/body, ice/body, etc. Moreover, the final position of the victim under snow can generate hyperbola of different characteristics.

The very short survival time of people buried under avalanches urged researchers for improving detection reliability, and organization of rescue operation. In order to decrease detection time, it should implement a preliminary characterization of the snowy environment and a scan of territory by means of contiguous and overlapped strips. Both two issues, characterization and scan, can obtain advantages by using aerial vehicle. In the year 2005, researchers proposed the usage of GPR mounted on board of a helicopter [12]. Although many problems arise with the use of an aerial vehicle, this approach signs a big step of the method, decreasing time-consuming of usual operation, which places radar just on the snow. Obviously, it need to consider one added layer at first position between antenna and target, i.e. air/snow/body, air/snow/air/body, etc., imposing to data to interact with three layers as minimum. It need analyse also the influence of distance and orientation of the victim with respect to the flight direction, and of the snow properties [13]. In any case, the adoption of aerial vehicle decreases the time-consuming of total operations. In fact, it simplifies acquisition of data in whole area and allows a preventive extraction of snowpack. The last one is an opportune step, allowing a detection of victims that is independent of buried material, such as underground ice, rocks, and so on [14]. Again, the snow properties, like wetness and density that determine dielectric permittivity and conductivity of the same snow, can be detected more quickly by means of a radar on board of an aerial vehicle [15].

3 Discussion

Comparing technologies presented previously in this paper:

- RECCO® system operates properly only if transmission path goes through air and snow media. If along the path there are: metals, body, and debris, the reflector is useless. This is the reason of two reflectors placed in opposite sides, to increase the probability of detection.
- Avalanche beacon is fast and accurate, but its use is limited to a particular scenario, and to particular figures of victims: only snowy environment and only people opportunely equipped with a transceiver.
- Although its use is not diffuse at present, GPR and, more in general, radar technology show a larger flexibility in terms of application in different scenarios, and very important consider the detection of passive targets.

Obviously, different scenarios require a change of operating frequency band of the GPR, and detection method specific, as a variant of the basic principle. However, results of the research say of a promising technology that has improvement margin again. The last ones are progressing to obtain significant results, and they are specific for each application field. The synthetic Table 1 lists main problems of the GPR, unresolved or insufficiently resolved, and divided per scenarios: people buried under debris and avalanches. The same Table 1 puts in evidence links to results in contiguous research activities that may be source of alternative and new methodologies.

In particular, the characterization of the environment may improve significantly performance of detection. In the case of snowy environment: the state of snow, depth and state of ice under snowpack, shallow rocks and/or debris under snow, and so on, all have relevant influence on resulting radargram, and on its interpretation. Meteorological data and continuous survey of the territorial area increase accuracy and decrease time of elaboration of detection during the emergency. In the survey of a wide area, the monitoring of how the environmental characteristics change in the time can be hard and expensive. A solution can be to use aerial vehicles for performing the survey activities. The size of a GPR, which operates in the frequencies useful for characterizing the snowpack and the layers in the depth, require the use of vehicle of size, and loading capacity that are appropriate, and thanks to greater manoeuvrability, helicopters are preferred. However, it need to take into account the cost of each mission and even the obligation to submit flight plan to the relevant authorities. Only by reducing the size and weight, you could use drones, with huge benefits in terms of frequency of detection, reduction of mission costs, and ease of setup operations. This is perhaps the most anticipated technological leap. Currently the use of drones was essentially limited to the radars operating in the X band. Recently, it was announced in the literature a life detection system that operates at microwave frequency, in L band, on board a quad-rotor, which is used to identify the survivors who are buried under the rubble, but we need more details to accept it as a new solution, in my opinion.

Table 1: Problems and solutions.

Scenario	**Problem**	**Solution/suggestion**	**Research field**
Debris	False alarms.	Constant false alarm ratio (CFAR) and clustering [16].	Adaptive algorithm – Ultra wide band (UWB) radar.
	Tiny body movements and position of different individuals.	Self-injection-locked (SIL) [17].	See-through-wall (STW)-through-the-wall (TTW)
	Noises (interferences, stationary and nonstationary clutters).	Pseudo-noise radar.	UWB radar.
Avalanches	Radargram analysis may fail because of the presence of multiple interactions between the probing wave and the scenario.	Tomographic imaging methods [18].	Inverse scattering procedure.
All scenarios	Characterization of the environment.	Improve data fusion.	Remote sensing and other methods of environmental data detection.

In the year 2014, were produced some commercial GPR, including in particular the model of the Gepard GPR OKM, which are hand-held GPRs and interesting. So, in a near future, their use on board the UAV is predictable. The voltages used and the power required by the system are designed for the use in combination with a tablet Android PC and thus are not oriented the purpose referred to above.

Nevertheless, the size and weight content to operate at frequencies between 60 and 300 MHz, convince of the opportunity to invest in research in this area.

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