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A RESCUE RADAR SYSTEM FOR THE DETECTION OF VICTIMS TRAPPED UNDER RUBBLE BASED ON THE INDEPENDENT COMPONENT ANALYSIS ALGORITHM

M. Donelli *

Department of Information Engineering and Computer Science, University of Trento, Polo Scientifico e Tecnologico Fabio Ferrari, Via Sommarive, Trento 5, Italy

Abstract—This work presents a light-weight microwave system for the search and rescue of victims trapped under the rubble of collapsed building during an earthquake or other disasters. The proposed system based on a continuous wave X-band radar is able to detect respiratory and heart fluctuations: the information is extracted from the backscattered electromagnetic field exploiting independent component analysis (ICA) algorithm which provides an efficient noise and clutter cleaning. The proposed rescue radar is compact enough to be mounted onboard of a small unmanned aerial vehicle (UAV) in order to reach inaccessible or dangerous areas. The obtained experimental results show that the proposed detection method is able to successfully locate trapped victims with a reasonable degree of accuracy.

1. INTRODUCTION

Most of the victims of earthquakes, avalanches or other natural disasters in various parts of the world, including the 2011 earthquake and tsunami in Japan, are people trapped under rubble of collapsed buildings. An early detection of survivors can potentially reduce the mortality rate, so the development of survivors detection systems is desirable. Optical and acoustical life detectors are widely used in search and rescue missions. Optical systems present a limited number of degrees of freedom, require expert operators and cannot be used in inaccessible area. Acoustical detectors such as geophones, are

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* Corresponding author: Massimo Donelli (massimo.donelli@dit.unitn.it).

simple to use but they require quiet working environments, a condition difficult to reach especially in critical situations. Recently, microwave life-detection systems has been developed to remotely detect vital life signals for rescue missions [1–6]. Such kind of problems have been efficiently solved considering continuous wave or ultrawideband radars [7] which offer good localization and spatial accuracy. In rescue mission and also in some surveillance operations there is not only the need of detect life signals but also the identification of people in a given area, to facilitate rescue team operations in case of emergencies. This task can be complied with through the wall surveillance techniques [5, 8–11]. This techniques could be effectively used with efficacy for medical applications like the monitoring of the breathing and heartbeat of critical patients in a clinic. All the cited methods consider the backscattered modulated wave generated when an human body is illumined by an electromagnetic wave. The extraction of information associated to breath and heartbeat signals is possible with an appropriate processing of the backscattered wave [6, 7]. The aim of this work is the design and development of a light-weight microwave detection system based on a compact X-band radar to detect victims trapped under rubble and other obstacles. The life signals are extracted from the modulated backscattered wave by the independent component analysis (ICA) algorithm [12–14], a powerful processing technique successfully adopted to analyze mixed signals and adopted recently in order to analyze brain signals and in particular electroencephalographic (EEG) data [15]. The preliminary experimental results, obtained considering a realistic scenario, are quite promising. The main innovation introduced in this work is the post processing of the data with the ICA algorithm, according to the best knowledge of the author it has never be used before for these kind of applications. The use of the ICA permits to clearly identify life signals despite the low power of the system and the presence of interfering signal sources. Moreover the proposed rescue system make use of a remote elaboration unit for the data post processing, to reduce the complexity of the radio frequency sub-system, the power consumption and consequently to obtain a very light and compact radar. The letter is organized as follows. The procedural schema of the system and the description of the application of the ICA algorithm is reported in Section 2. The description of the system prototype, of the experimental setup and of the preliminary experimental result is described in Section 3. Finally in Section 4, conclusions are drawn and areas of future work are examined.

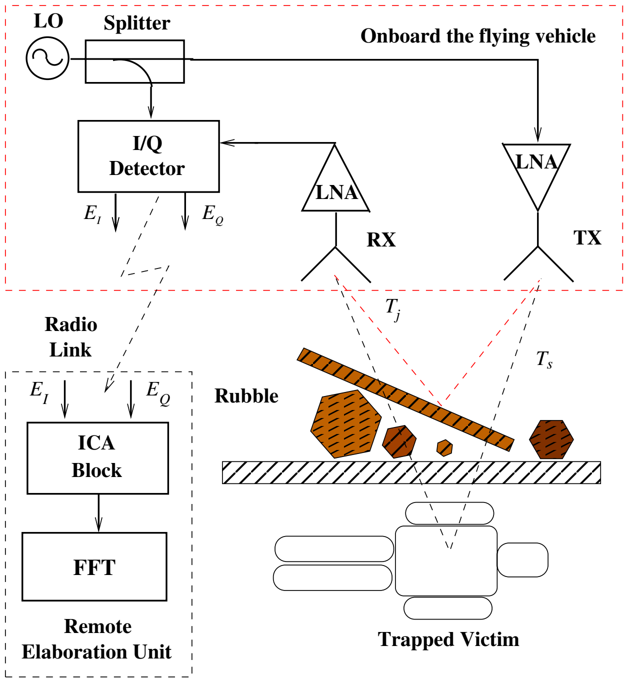


Figure 1. Diagram of the microwave life detection system.

2. MATHEMATICAL FORMULATION

Let us consider the schema of the system shown in Figure 1. The main component is a bi-static continuous wave (CW) radar consisting of a local oscillator which produces a sinusoidal signal of 10.45 GHz, a low noise amplifier, and a two patches array as transmitting antenna. The radar irradiates an electromagnetic wave and collect the reflected signal that contains the breathing and the heartbeat information coming from a human detected target. The backscattered signal is received by a two patches antenna, amplified and led to an I/Q detector. The orthogonal detector is mandatory because the ICA [12] requires a number of observation points equal to the number of the original signals and we exploit I/Q signals as two independent sources of information. Then the output I/Q signals are given as input to a remote elaboration system by means of a low frequency wireless channel. As stated previously the amplitude and the phase of the received backscattered wave are modulated in accordance with the movement of breathing and heartbeat. The information associated to amplitude is generally negligible [6] and only the phase variation is considered. The signal at the receiving antenna can be expressed considering the following relation [4].

$$E_{rx}(t) = A_x \cos\left(\omega_0\left(t - \frac{2R_s(t)}{v}\right)\right) + \sum_{j=1}^{J} A_j \cos\left(\omega_0\left(t - \frac{2R_j}{v}\right)\right) \quad (1)$$

where ω_0 is the angular frequency and v is the propagation velocity of the radio waves, A_x, A_j are the amplitudes associated to life signals and rubble respectively. $R_s(t)$ and R_j are the round trip distance of the survivor and rubble from the radar system. The second term describes the constant contributes due to the rubble and it can be easily removed with a simple filtering procedure while the first term contains informations related to life-signals. The small movement of the survivor body caused by breathing and heartbeat can be seen as a fluctuation around a mean distance R_s and modeled at the output of the orthogonal phase detector as $\varphi_x(t) = (\frac{\omega_0}{v}(R_s + A_b\cos(\omega_b t) + A_h\cos(\omega_h t)))$, where ω_b and ω_h are the frequencies due to the breathing and the heartbeat respectively. A_b, A_h are the amplitudes due to the movement of the chest and heart respectively. The weak received backscattered field, which is a mixture of vital signals, noise and clutter contribute, is amplified down-converted with an orthogonal detector, and processed with an analog-to-digital converter. The I/Q signals at the output of the orthogonal detector are led to a remote elaboration unit by means of a low frequency transmission module. The received signals must be post-processed to separate the life signals from the noise and the clutter contribute. ICA algorithm has been chosen to accomplished this task. The ICA is a method for separating mixed data (such as MRI images [13], biomedical data [15], sounds, telecommunication channels or signals) into underlying informational components. The ICA belongs to a class of methods called blind sources separation (BBS). The classical example is two person speak at the same time in a room. Two microphones, placed in different points inside the room collect a mixture of the two voice signals. From these two signal mixtures, ICA can recover the two original source signals. One of the most important fact about standard BSS methods like ICA is that the number of independent source of information (i.e., the receivers) must be greater than the number of overlapped source signals. For the problem at hands this implies that there must be at least two probes to detect the life signals and for this reason we use an orthogonal detector generating E_I and E_Q these two signal mixtures collected at the output of the orthogonal phase detector and sent to the remote elaboration system for the post-processing could be expressed as:

$$\begin{cases} E_I(t) = a_{11}\varphi_x(t) + a_{12}N(t) \\ E_Q(t) = a_{21}\varphi_x(t) + a_{22}N(t) \end{cases} \tag{2}$$

where $E_I(t) = A_I \cos(\varphi_x(t)) + N(t)$ and $E_Q(t) = A_Q \cos(\varphi_x(t)) + N(t)$, $N(t)$ represents the noise contribution due to the clutter and other interfering sources. The terms a_{11}, a_{12}, a_{21}, and a_{22}, are parameters that depend from the phase shift. The two original signals $N(t)$ and $\varphi_x(t)$ are assumed to be statistically independent at each time instant: for this reason it is possible to estimate the original signals processing the mixed signals $E_I(t)$, $E_Q(t)$ observed at the orthogonal detector. Let us consider the following matricial representation

$$\begin{bmatrix} E_I(t) \\ E_Q(t) \end{bmatrix} = [A] \begin{bmatrix} \varphi_x(t) \\ N(t) \end{bmatrix} \tag{3}$$

After estimating the coefficients matrix $[A]$ and its inverse $[A]^{-1}$, it is possible to obtain the original signals as shown in the following equation

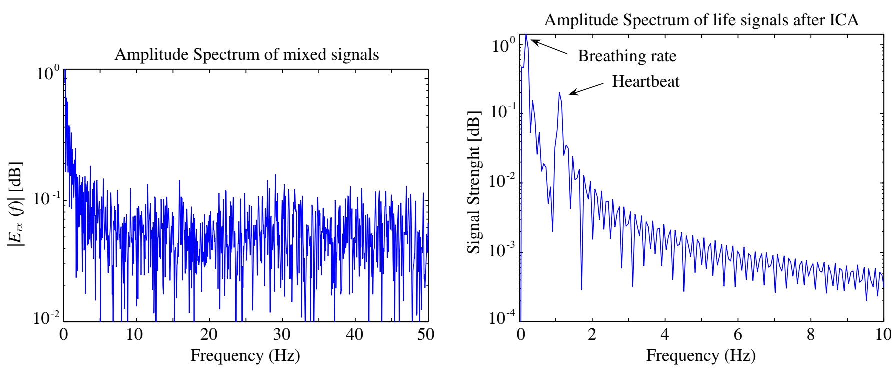
$$\begin{bmatrix} \varphi_x(t) \\ N(t) \end{bmatrix} = [A]^{-1} \cdot \begin{bmatrix} E_I(t) \\ E_Q(t) \end{bmatrix} \tag{4}$$

This goal is accomplished by using the ICA algorithm. After the ICA application, the cleaned signals $N(t)$ and $\varphi_x(t)$ are separated. Only $\varphi_x(t)$ contains information related to the weak life signal while $N(t)$ is negligible. $\varphi_x(t)$ is then further processed with a FFT algorithm in order to estimate the heartbeat and the breath rate.

Figure 2. Photography of the experimental setup.

3. EXPERIMENTAL RESULTS

In this section, a preliminary experimental result is reported in order to assess the capabilities of the proposed rescue system. The test site is a hollow pipe of concrete with a diameter of 1.5 m and a thickness of 0.15 m. A person is located inside the concrete pipe, and the flying vehicle with has been used to place more close as possible the onboard rescue system is positioned on the top of the pipe at about 1.3 m from the victim chest as shown in Figure 2. The schema of the experimental prototype is shown in Figure 1. The signal is generated by means of a low power compact SAW oscillator able to generate a microwave signal at 10.45 GHz with a power of 5 mW. The signal is amplified and then transmitted by means of a two elements patch antenna array. The backscattered field is collected with a similar receiving antenna array. The transmitting and receiving arrays are arranged on the same dielectric substrate and they have been designed to avoid mutual coupling and keep VSWR $<$ 2 in transmitting as well as in receiving mode. The received backscattered signal is amplified and down converted with an orthogonal detector in order to obtain two signals sources for the ICA algorithm. Then the down converted backscattered signals are transmitted with a 400 MHz AUREL transmitting module toward a remote elaboration unit which provide the post processing by applying the ICA algorithm. Figure 3(a) shows the mixed signals: the life signals are too much weak to be



(a) (b)

Figure 3. Experimental results. Frequency spectrum of the measured (a) mixed signals noise plus signals life obtained from experimental setup, (b) signals life extracted after the application of the ICA algorithm.

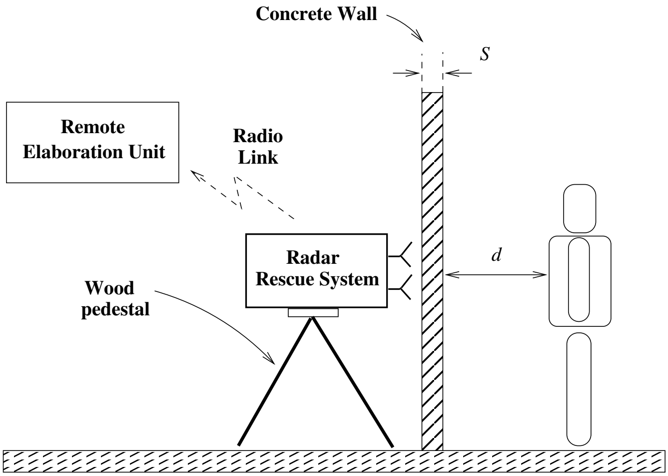


Figure 4. Schema of the last experimental scenario.

clearly identified because the strong corruption due to the noise, the clutter and other interfering signals. Figure 3(b) put in evidence how the life signals are efficiently detected after the application of the ICA algorithm and the FFT. The frequency spectrum clearly indicates a breathing rate of 0.2 Hz (or 12 breath/minute), whereas the heartbeat is 1.11 Hz (or 67 beats/minute). The heartbeat measure has been compared with a finger pulse monitor to verify experimental results. As can be noticed from the data reported in Figure 3(b), the ICA provided an efficient separation of the original signals. Thank to ICA all the noise contributions have been removed and the life signals clearly identified despite of the corruption due to the clutter and noise. To further assess the robustness of the proposed rescue system, the last experiment deal with a scenario in which a person is placed behind a concrete wall. In particular the rescue system has been placed next to the concrete wall by means of a wood pedestal, the person is standing behind the concrete wall, the thickness of the concrete wall is about $S = 20\,\mathrm{cm}$. The distance between the concrete wall and the person's chest was $d = 150\,\mathrm{cm}$. Figure 4 shows the considered experimental scenario. The data have been acquired to send to the remote elaboration unit and post processed with the ICA algorithm in order to remove the clutter and then processed with a FFT algorithm. Also in this experiment for the sake of comparisons, the heartbeat has been monitored with finger pulse monitor in order to verify the experimental data. Also in this scenario the system is able to correctly detect the life signals, in particular the breathing rate was 0.17 Hz (or 10 breath/minute), whereas the heartbeat is 1.16 Hz (or 70 beats/minute). Also in this experiment the system is able to correctly detect and identify the life signals with a reasonable degree of accuracy despite the low intensity of the interrogating signal.

4. CONCLUSION

A compact X band radar system, mounted onboard of a flying vehicle UAV has been used to successfully detect victims trapped under rubble. The system extracts the respiratory and beat heart fluctuations from the backscattered electromagnetic field. This task has been accomplished by applying the ICA to the backscattered data. A first preliminary test has been carried out on a person located inside a hollow concrete pipe to simulate a realistic configuration. The experimental results demonstrate the potential of the proposed system in a realistic rescue scenario. Further investigations, currently under development, will be devoted to integrate this system with modulated scattering technique (MST) probes in order to add identification capabilities similar to [9] at the developed rescue system.

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REFERENCES

1. Bell Hadj Tahar, J., J. C. Bolomey, and M. Cauterman, "Microwave life detector for buried victims," *Proc. 23rd European Microwave Conference*, 509–514, Madrid, Spain, Sep. 6–12, 1993.
2. Akiyama, I., N. Yoshizumi, A. Ohya, Y. Aoki, and F. Matsuno, "Search for survivors buried in rubble by rescue radar with array antennas — Extraction of respiratory fluctuation," *IEEE International Workshop on Safety, Security and Rescue Robotics, SSRR 2007*, 1–6, 2007.
3. Loschonsky, M., C. Feige, O. Rogall, S. Fisun, and L. M. Reindl, "Detection technology for trapped and buried people," *IEEE MTT-S International Microwave Workshop Wireless Sensing, Local Positioning, and RFID, 2009, IMWS 2009*, 1–6, 2009.
4. Arai, I., "Survivor search radar system for persons trapped under earthquake rubble," *2001 Asia-Pacific Microwave Conference, 2001, APMC 2001*, 663–668, 2001.

5. Wang, Q., Y. Li, T. Wu, C. Foxm, Q. Fang, et al., "Life signal extraction in through the wall surveillance," *Proceeding IEEE International Conference on Engineering Biomedical and Biological Society, ICBPE'09*, 1343–1346, 2009.
6. Chen, K. M., D. Misra, H. Wang, H. R. Chuang, and E. Postow, "An X-band microwave life-detection system," *IEEE Trans. Biomed. Eng.*, Vol. 57, No. 6, 607–702, 1986.
7. Baboli, M., A. Sharafi, and E. Fear, "A framework for simulation of UWB system for heart rate detection," *IEEE Trans. Biomed. Eng.*, Vol. 56, No. 9, 1200–1209, 2009.
8. Wu, C. W. and Z. Y. Huang, "Using the phase change of a reflected microwave to detect a human subject behind a barrier," *IEEE Trans. Biomed. Eng.*, Vol. 55, No. 1, 267–2272, 2008.
9. Donelli, M. and D. Franceschini, "Experiment with a modulated scattering system for through the wall identification," *IEEE Antennas and Wireless Propagation Letters*, 20–23, 2010.
10. Dehmollaian, M. and K. Sarabandi, "Refocusing through building walls using synthetic aperture radar," *IEEE Trans. Geosci. Remote Sensing*, Vol. 46, No. 6, 1589–1599, 2008.
11. Zhang, W. and A. Hoorfar, "Two-dimensional diffraction tomographic algorithm for through-the-wall radar imaging," *Progress In Electromagnetics Research B*, Vol. 31, 205–218, 2011.
12. Lee, T. W., *Indipendent Component Analysis: Theory and Applications*, Kluwer Academic Publishers, 1999.
13. Molgedey, L. and H. G. Schuster, "Separation of a mixture of independent signals using time delayed correlations," *Physical Review Letters*, 3634–3637, 1994.
14. McKeown, M. J., S. Makeig, C. G. Brown, T. P. Jung, S. S. Kindermann, and T. J. Sejnowski, "Spatially independent activity patterns in functional magnetic resonance imaging data during the stroop color-naming task," *Proceedings National Academy of Sciences of the United States of America*, 803–810, Feb. 1995.
15. Bell, A. J., T. P. Jung, and T. J. Sejonowski, "Independent component analysis of electroencephalographic data," *Advances in Neural Information Processing Systems*, Vol. 1, 145–151, 1996.