Radar for healthcare: recognising human activities and monitoring vital signs

Radar is typically associated to defence and military applications, such as detection and monitoring of the traffic of ships and aircraft in certain areas. Many of us must have seen for example the antennas near the runways of airports while travelling, rotating to scan the surrounding space and discover airplanes approaching or leaving.

However, in recent years radar has started to gain significant interest in many fields beyond defence or air traffic control, opening indeed "new frontiers in radar", as the title of our special collection of articles mentions. Emerging applications of radar sensing include, but are not limited to, automotive radar (radar on vehicles to help them navigate around obstacles and other vehicles), human gesture identification (radar to identify the complex gestures performed by human users to interact with smart objects without tapping screens or pushing buttons), and healthcare domain (radar to estimate vital signs such as respiration and heartbeat, and to monitor our level of activities at home).

So, radar is ceasing to be only of interest to a niche community of researchers and users in the defence sector, and becoming a relevant subject for a wide audience of students in electronic engineering and computer science, researchers and academics, entrepreneurs and policy makers. Radar sensing intersects and relates to many skills and disciplines, from manufacturing of chips and components operating at the desired frequency to electromagnetic wave propagation, from manufacturing and integration on printed circuit boards (PCBs) to power management, from radar-specific signal processing to machine learning algorithms applied to radar data. For this reason, it is very likely that engineering professionals will have to deal with some aspects of radar sensing as part of the design and development of a larger system, be that a smart vehicle, a mobile phone, a tablet, or a suite of sensors for new smart homes.

In this article, we decide to focus on the healthcare applications of radar systems and radar sensing, which perhaps are among the most innovative and somewhat most different from the traditional, defence-oriented applications that are commonly associated to radar.

New healthcare needs and provision

The adoption of radar sensing and other technologies in the domain of healthcare is related to the new needs in care and welfare provision arising from the rapidly aging population worldwide. Estimates from the World Health Organisation and United Nation analysis report that 30% of the world population will be over 65 by 2050, and in the UK the Office for National Statistics expects the proportion of people over 85 years to double over the next 20 years. With aging, the incidence of multiple chronic health conditions (or "multimorbidity") and the likelihood of critical, life-threatening events such as strokes or falls increase. Statistics from the UK charity Age UK show for example that "falls and fractures in people aged 65+ account for over 4 million hospital bed days each year in England alone, and the healthcare cost associated with fragility fractures is estimated at £2bn a year". The challenges to manage these conditions on an increasing segment of population are combined with budget pressure on public healthcare systems, making potentially unsustainable the traditional approach of intensive care provided in high-specialised hospital structures. Besides the economic argument, prolonged periods in hospitals can also be unpleasant for the patients and their families and come with risks of exposure to antibiotic-resistant bugs and other infections.

Therefore, in recent years, there has been very significant interest in using the most advanced technologies to provide integrated care in private home environments, which is often referred to as "assisted living technologies". This has primarily two objectives.

First, preserving as much as possible the autonomy and independence of older citizens in their own familiar environments, avoiding hospitalisation and the rupture of the familiar routine and daily habits which are very important for the welfare of people.

Second, promoting a "proactive" approach to healthcare, whereby technology can provide continuous reliable monitoring and timely identification of subtle signs related to worsening health conditions, rather than reacting only when there are very serious symptoms.

Why using radar technology then?

What can radar contribute to as a technology for healthcare? Well, radar is good at identifying the presence of people, track them while they move in a certain area, and characterise these movements, from the bulk motion of the whole body, to the smaller movements of individual body parts such as head or limbs, down to the very small movements of chest and abdomen while breathing and even heartbeat. So, radar research has primarily worked in two directions when it comes to healthcare:

- Estimation and monitoring of vital signs such as respiration rate and heartbeat using radar systems and data;
- Monitoring of daily activity patterns using radar data, looking at their regularity and at the time it takes to perform them. This includes ensuring that people perform fundamental activities such as food preparation/intake or personal hygiene, identify anomalies in the normal pattern such as an increased access to the bathroom overnight, and detect any critical event that may occur and require prompt response, such as falls.

Before describing the details of radar systems for these applications, it is worth asking why radar rather than the other technologies proposed in recent years? These include video-cameras (in normal colours or in thermal and depth modalities), wearable sensors either as stand-alone devices worn at the wrist or embedded into smartphones, and sensors embedded in the ambient including acoustic (microphones), pressure (pads over floor tiles), infrared (revealing presence of objects in close proximity), and presence or switch sensors for door, windows, drawers and electric appliances.

Each sensing technology can be evaluated on different metrics. First of all, the quality and accuracy of its information and performance (how good and useful is the information obtainable?), and the field of view and range of action (how far can it sense the environment?). Then other aspects, such as cost (of installation and maintenance), reliability, number of units required, and last but not the least users' perception and acceptance, which are very important for healthcare applications. Will the end-users, potential patients and their families and carers, accept these sensing technologies in their homes, and will they comply with any instructions or procedures they are supposed to follow for the system to work properly? Perceived privacy is a rather important aspect to consider, especially for deployment of the specific sensing technology in potentially sensitive environments such as bedrooms or bathrooms. Any type of camera can be perceived as privacy-invasive but will provide useful information, whereas ambient sensors can be embedded in the built environment but cannot be too informative on their own. Figure 1 provides a summary of this potential dilemma between privacy and information, with a possible classification of assistive living technologies as a function of their perceived privacy and richness of the information provided.

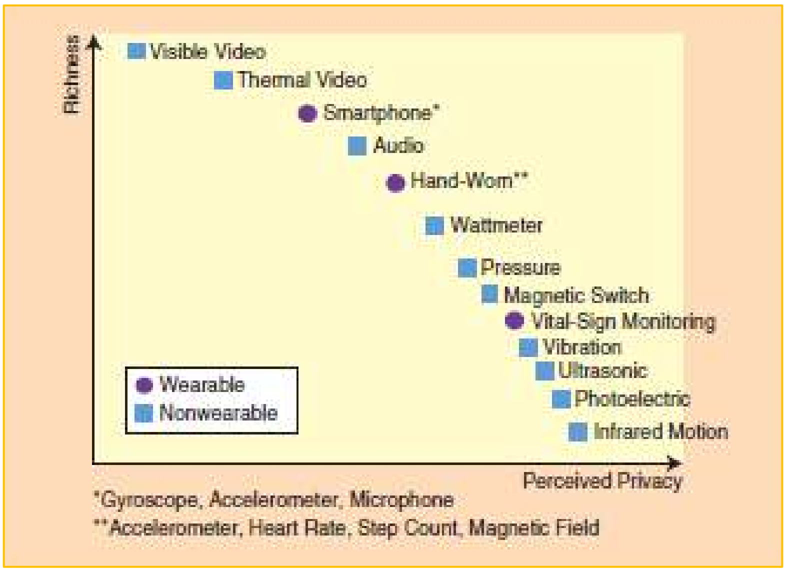

Figure 1 Classification of sensing technologies for assisted living as a function of richness of information and perceived privacy (courtesy of Prof C. Debes et al., from "Monitoring Activities of Daily Living in Smart Homes: Understanding human behavior," in IEEE Signal Processing Magazine*, vol. 33, no. 2, pp. 81-94, March 2016.)*

In this context, radar has two main advantages:

- Unlike cameras, no optical, plain images or videos of the monitored subjects are recorded by radar systems, making them less problematic in terms of privacy. However, the level of information they can provide is still very rich, as we will discuss in the next sections.
- Unlike wearable sensors, radar systems do not require the users to wear, carry, or interact with any additional electronic device or modify their daily routine and behaviour, which is an advantage for acceptance of this technology.

With respect to practical deployment of radar systems, in particular their feasibility in terms of miniaturisation, cost, and infrastructures, we may be in a transition period, where more and more research evidence emerges on their usefulness for healthcare applications, but they are not yet to the point of being mass-produced and widely available like cameras or wearables. Technology development in electronics and market push from the autonomous vehicles sector (automotive radar) is making radar systems more and more compact ("radar on chip"), and driving costs down, as reported by C. Li and collaborators in their recent reviews papers on portable/integrated radar in 2017 and 2018.

Principles of radar systems

The basic principle of any radar system consists of transmitting and receiving sequences of electromagnetic waves, modulated in suitable waveforms. By collecting and analysing the received radar waveforms, one can extract information on the targets of interest that may be present in the area under test and will reflect back to the transmitter part of the radar waveforms. The typical comparison everyone does is with animals such as bats or dolphins, which can emit and receive acoustic waves (ultrasounds) to gain awareness of their surroundings and locate their preys. Similar principles (transmission and reception of waves), but different physical mechanisms (acoustic waves in nature, electromagnetic waves for manmade radar systems).

In their very basic form, radar systems have a transmitter and receiver part to generate, condition, and receive electromagnetic waves, antennas to transmit and receive the radar waveforms, and a digital processing core to manipulate and store the radar data through suitable radar signal processing. Figure 2 shows a few examples of radar systems from our research laboratory at the University of Glasgow used for research in the healthcare domain. They operate across different frequencies, from 5.8 GHz (blue device on the right-hand side) up to 60 GHz (small printed board on top of the second blue device in the middle of the figure). Note the small size of these devices, with the largest ones, the blue boxes, being approximately 15 x 20 x 3 cm, showing how modern radar systems can be easily miniaturised for unobtrusive indoor applications. The acronyms in the picture mean UWB (Ultra Wide Band), CW (Continuous Wave), and FMCW (Frequency Modulated Continuous Wave). These are related to the specific type of waveform transmitted and received by the radar, and you can read additional information if interested in the references at the end of this article.

Figure 2 Examples of radar systems used at the University of Glasgow for healthcare applications such as human activity classification and monitoring of vital signs

Radar signal processing in healthcare: basic principles

The two main applications of radar sensing in the healthcare context are classification of human activities and monitoring of vital signs. Both can be related to the detection and characterisation of movements of body parts of the subject, either large movements of the whole body and limbs while performing daily activities, or very small movements of chest (for respiration monitoring) and internal organs (for heartbeat monitoring or blood pressure).

Once the presence of a subject is detected, the typical signal processing on the radar data aims to characterise these movements in three domains: range (as the distance at which the subject and their body parts are located with respect to the radar), time (as the evolution over time of the position of the subject and any change to their movements), and velocity (as the speed at which these changes happen, whether controlled and regular, or with sudden acceleration and deceleration). Velocity and its changes are typically measured by radar systems through the Doppler effect, which is a change in the frequency of the received radar waveforms (Doppler frequency shift) due to the movement of the target. For example, in the case of someone walking indoor, if the person is walking towards the radar, the Doppler shift will be positive as more electromagnetic wave-fronts will be scattered back to the radar in a unit of time; the opposite, negative Doppler shift, will happen for movements away from the radar.

Measuring velocity therefore means measuring the frequency components of the received waveforms in radar signal processing, and this can be done using Fourier analysis, in particular Fast Fourier Transformation (FFT) algorithms. Figure 3 shows the signal processing chain for an example of data where a person was walking back and forth in front of a radar system. The initial stage of radar signal processing is the temporal sequence of digitised received raw radar data. These are typically organised in a matrix form, where each individual radar pulse will include range bins, digitised samples related to the distance of a possible target, and the sequence of radar pulses will be associated to time, according to the temporal sequence of these pulses. This matrix is typically called Range-Time-Intensity (RTI) matrix. In figure 3, as the person is walking back and forth in front of the radar, a diagonal zig-zag pattern can be seen in the RTI image, with the echo of the person moving away from the radar (range bins increasing over time) and then back towards it (range bins decreasing over time). As mentioned above, FFT can be applied to characterise the velocity of the target through its Doppler effect. If a single FFT is applied across the time dimension of the RTI, that is across the sequence of radar pulses, a new matrix called Range-Doppler (RD) can be obtained. In the example in figure 3, both positive and negative Doppler contributions can be seen as the person was moving towards the radar (positive Doppler) and away (negative Doppler). This matrix characterises the overall Doppler due to the macro-movement of the person, but does not say anything about how the body and its parts were moving over time. To achieve this, a different signal processing technique, called Short Time Fourier Transform (STFT) can be used to generate Doppler-Time patterns also called spectrograms. The STFT performs several FFT on the data using shorter, overlapped time windows, so that each FFT produces a column of the spectrogram over time. The key parameters of this operation are the duration of the short FFT window, the overlap factor, and the type of window (for example Hamming window, a very typical one), as these parameters affect significantly how the final Doppler-Time pattern appears. In the example in figure 3, there is positive and negative Doppler in the pattern; each contribution has a central, more intense signature (red and yellow colour) due to the movement of the torso and main body, and less intense streaks (light blue colour) due to the limbs. When a person is walking, the movement pattern typically presents a bulk movement of the main body and torso, with additional back and forth oscillating movements of the arms. This is what is visible in the Doppler-Time pattern in figure 3. Finally, in the context of human activity recognition, further processing after generating the patterns in figure 3 consists typically in using machine learning to "teach" an algorithm how to classify automatically patterns related to different activities, as different human activities will exhibit different patterns in the three radar domains described so far.

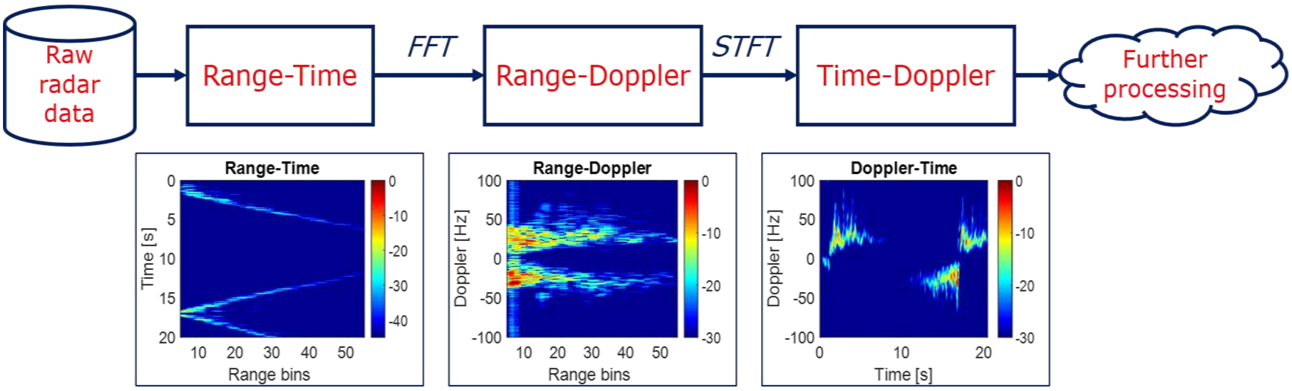

Figure 3 Typical signal processing chain for radar data, with examples of Range-Time, Range-Doppler, and Doppler-Time patterns for a person walking back and forth in front of the radar

Example of results

In this section, we present a few representative results in the context of human activity recognition and monitoring of vital signs. Figure 4 shows some of the environments at the University of Glasgow where the experimental data were collected to generate such results. These range from small laboratory environment (room A), to larger laboratory and experimental area (room B and D), to the large common room labelled as room C.

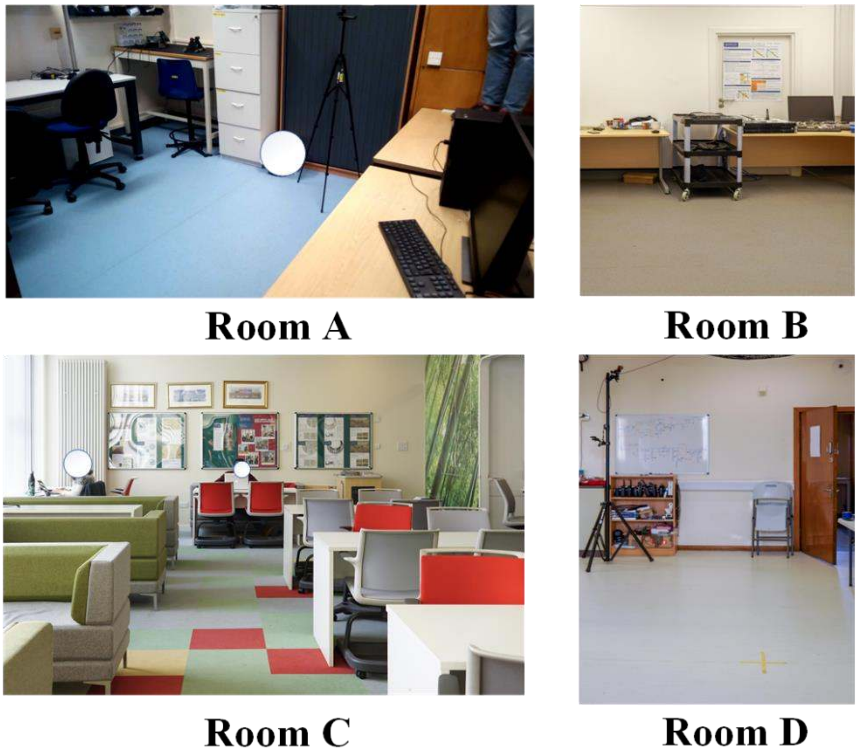

Figure 4 Example of environments (laboratory and common rooms) at the University of Glasgow where the results presented in this section were generated

Figure 5 shows six Doppler-Time patterns for six different activities performed by the same subject while facing the radar, as recorded by a radar system operating in C-band (5.8 GHz) at the University of Glasgow. The six activities are the following: sitting on a chair, standing up from a chair, bending to tie shoelaces, bending to pick up an object, crouching and standing back up, and falling frontally after tripping. It should be noted that the Y axis of the figures is expressed in velocity rather than Doppler shift. Activities that imply movement towards the radar, for example bending down and falling, have all positive velocity in their patterns, and vice versa (for example the “sitting on a chair” scenario, where the subject in this case sat down and leaned a bit back on the chair, hence generating a significant negative Doppler shift). One of the challenges researchers are investigating is avoiding false alarms for fall detection tasks when the subject sits or bends down, as all these activities produce a significant acceleration and therefore sudden velocity signature. Another challenge is coping with the variability of movements and therefore radar signatures with different subjects. Any algorithm will be inevitably trained on a subset of people, but everyone has his or her own characteristic way of moving and performing actions, depending on body type, posture, age, gender, possible disabilities. The capability of capturing the “general, universal features” of the kinematics of human movements irrespective of the changes above is one of the outstanding research questions in this domain.

The activities in figure 5 were performed and collected as individual “snapshots”, with each activity separated from the others. In figure 6, the Doppler-Time pattern of a sequence of six activities performed continuously, one after the other, is presented. The six activities are drinking a glass of water while standing, picking up an object from the floor, sitting on a chair, standing back up, walking back and forth, and falling frontally. The first four activities are fundamentally performed without much bulk movement of the body, hence the Doppler signature is concentrated around the 0 Hz value, whereas the positive and negative contributions due to walking back and forth are visible between 20s and 30s, with the final strong positive Doppler signature due to the fall at the end of the recording. This figure introduces an additional challenge for research into activity recognition using radar signatures, which is the processing of a continuous stream of activities (and therefore data), where finding the transitions between them can be very challenging.

Another new application of radar systems and signal processing is the analysis of gait and locomotion parameters, in order to identify any change or degradation of mobility metrics and capabilities. Figure 7 shows as an example the Velocity-Time patterns for two subjects who are walking normally and walking with a limp on one leg. The two patterns are rather different, with a more or less symmetric Doppler signature due to the legs for normal walking, and an asymmetric pattern for the limping case. Further research is being undertaken to extract more precise gait parameters from these signatures, for example periodicity of the gait, mean velocity and acceleration, length of the strides, as these can have clinical value in assessing health conditions of patients at risk.

Finally, figure 8 shows an example of how radar can be used to monitor respiration rates of human subjects, which can be useful to assess respiratory conditions during sleep or the insurgence of further health conditions related to problems in breathing. In this example, a subject was sitting facing the radar at about 60 cm and simulating different respiration rates: 10 normal inhaling/exhaling cycles, followed by holding breathe for a few seconds, a deep exhaling, and finally a few cycles of fast breathing. The experimental setup is shown in figure 8, with a chair where the subject was sitting and the laptop controlling the radar and the radar (occluded by the laptop in this case) facing the subject. The distinction between the different respiration rates and regimes is quite clear in the Doppler-Time pattern, and the periodicity and regularity of respiratory movements can be extracted from these data. Ongoing research within the radar community aims to validate monitoring of respiration rate on longer distances and more realistic condition, as well as extending capabilities to the monitoring of heartbeat and blood pressure. Outstanding challenges include investigating how robust the algorithms for radar-based vital signs monitoring are, in particular the effect of different orientation of the subject (frontal, back, side view, lying down rather than sitting) and the presence of layers of clothing (those worn by the subject themselves or the presence of bed linen, blankets or curtains for instance).

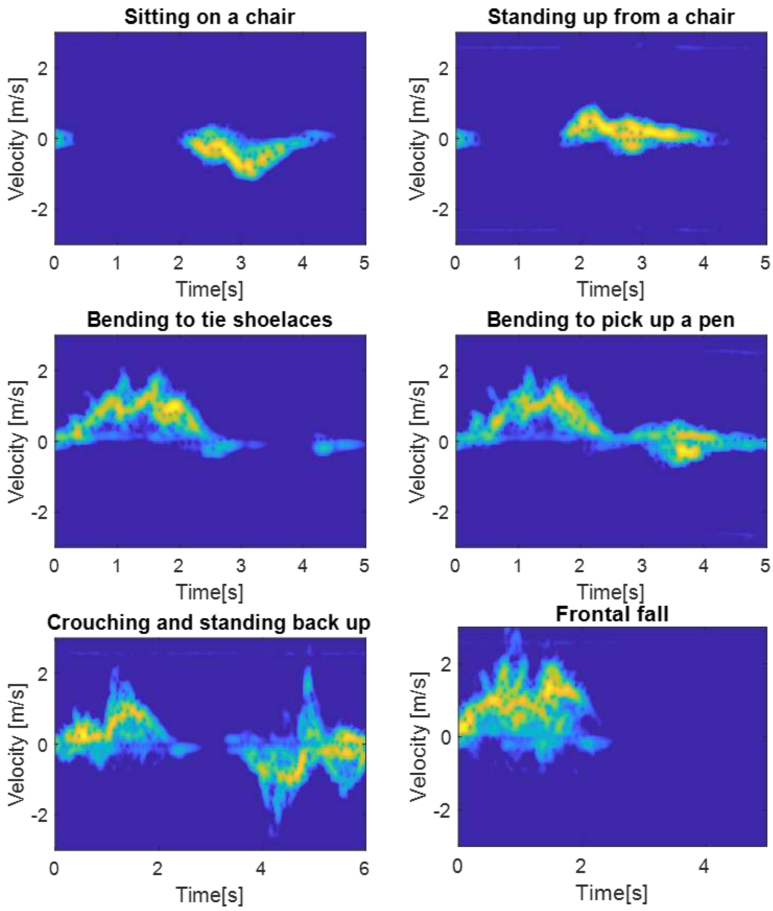

Figure 5 Example of six Velocity/Doppler-Time patterns for six human activities recorded by radar

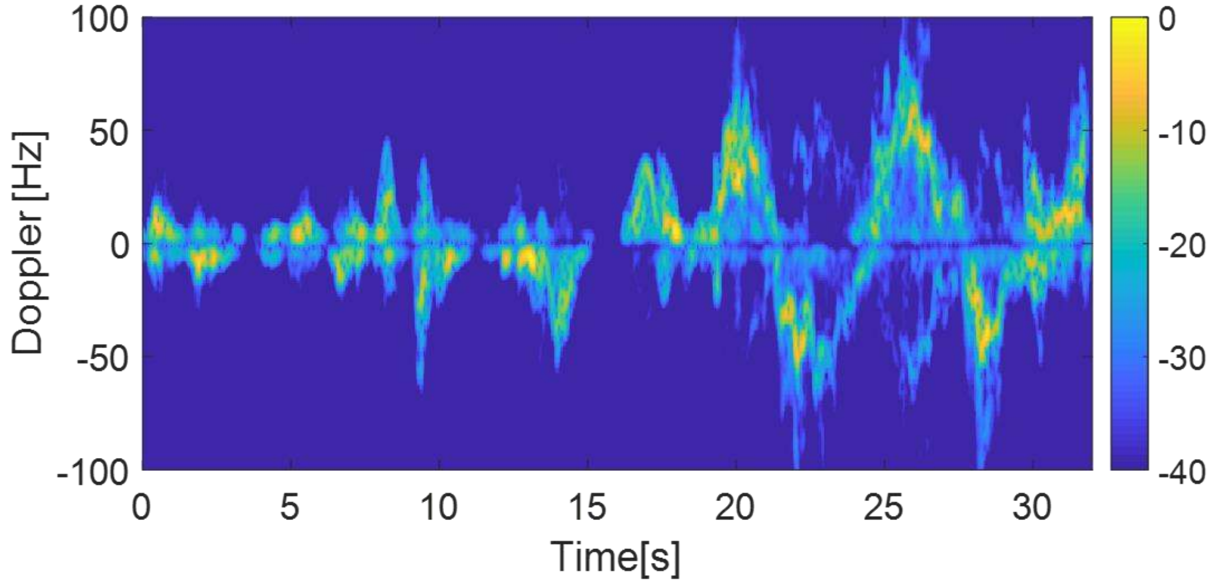

Figure 6 Doppler-Time pattern for a sequence of six activities performed by a subject; these are: drinking a glass of water while standing, picking up an object from the floor, sitting on a chair, standing back up, walking back and forth, and falling frontally

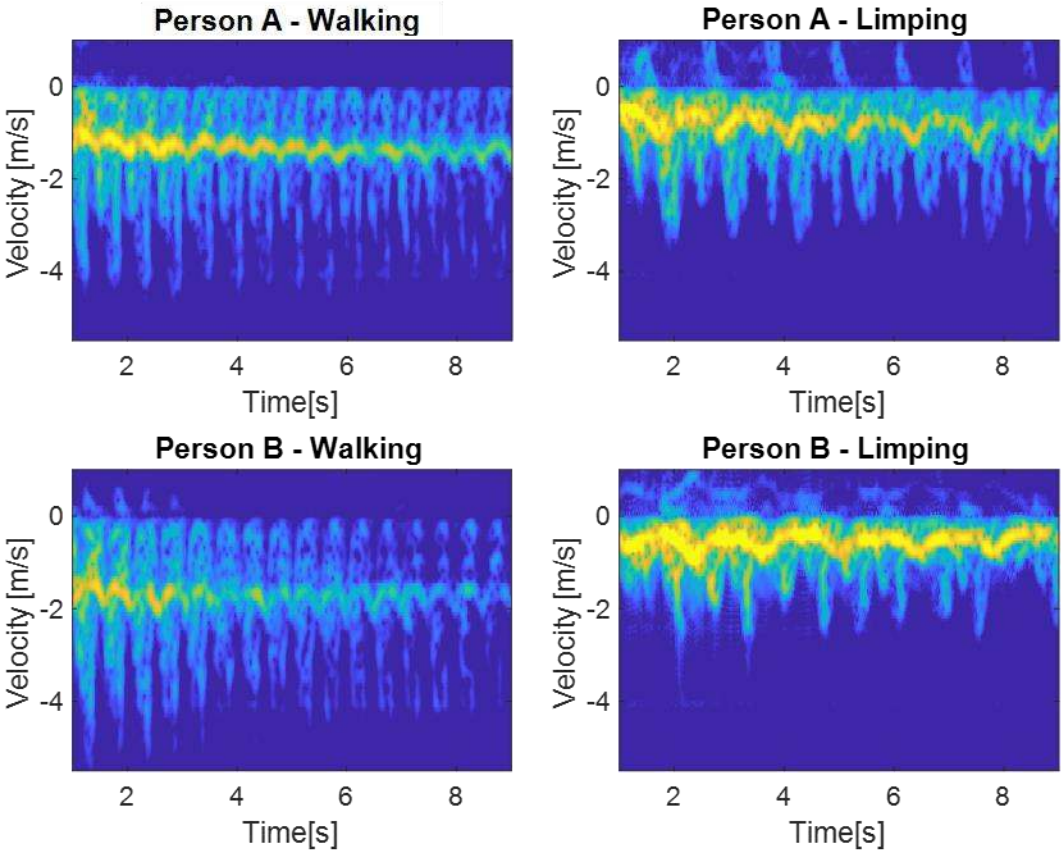

Figure 7 Velocity-Time patterns for two subjects walking normally and limping as recorded by a C-band radar

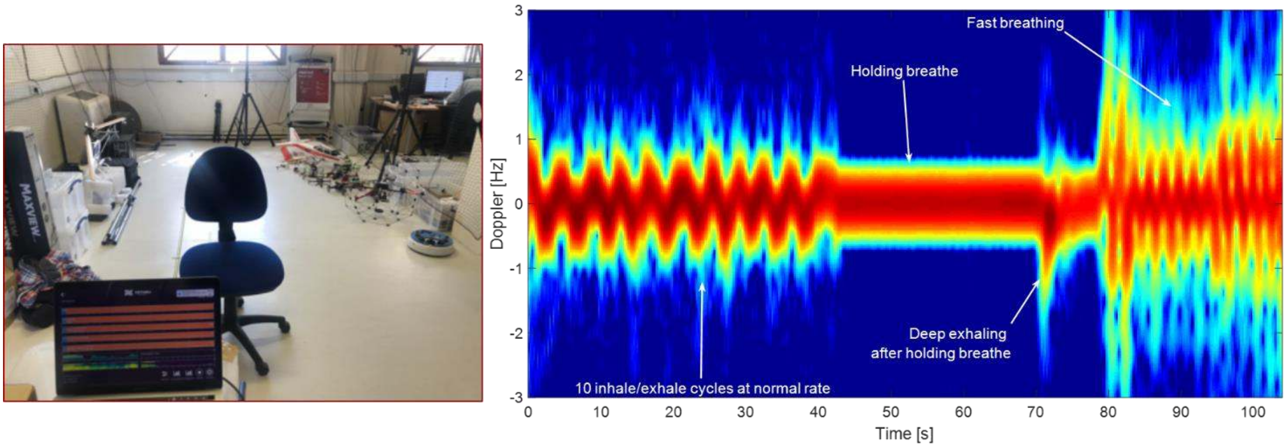

Figure 8 Doppler-Time pattern for a person sitting on a chair at 60 cm from the radar and simulating different respiration rates

Conclusion

Although typically associated to large-scale, defence-related usage to monitor ships and aircraft, radar has been used in the past few years for a number of short-range, civilian applications. In particular, in this article we have discussed and presented some examples of radar used to support healthcare provisions, to help monitor vital signs of patients at risk and their daily activities, a useful proxy for their more general physical and cognitive well-being. Differently from cameras and wearables, radar does not collect sensitive images of the people monitored and does not require users to wear, carry, or interact with new devices that may be perceived as intrusive; it can therefore have significant advantages in terms of users' perception and compliance.

We have shown a few experimental results of the different radar signatures for different human activities, as well as an example of radar data tracking the respiratory rate of a monitored subject. The collection and full understanding of these data will be key to develop innovative signal processing and machine learning algorithms to automatize monitoring, and consequently timely and proactive diagnostic for future healthcare provision.

Read more about this

1. M. G. Amin, Y. D. Zhang, F. Ahmad and K. C. D. Ho, "Radar Signal Processing for Elderly Fall Detection: The future for in-home monitoring," in *IEEE Signal Processing Magazine*, vol. 33, no. 2, pp. 71-80, March 2016.
2. E. Cippitelli, F. Fioranelli, E. Gambi and S. Spinsante, "Radar and RGB-Depth Sensors for Fall Detection: A Review," in *IEEE Sensors Journal*, vol. 17, no. 12, pp. 3585-3604, June 2017.
3. C. Li, P. Mak, R. Gómez-García and Y. Chen, "Guest Editorial Wireless Sensing Circuits and Systems for Healthcare and Biomedical Applications", plus additional papers in this special issue, in *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, vol. 8, no. 2, pp. 161-164, June 2018.
4. J. A. Nanzer, "A Review of Microwave Wireless Techniques for Human Presence Detection and Classification," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 65, no. 5, pp. 1780-1794, May 2017.
5. “Radar for Indoor Monitoring: Detection, Classification, and Assessment”, M. Amin (editor), CRC Press, September 2017, ISBN 9781138746091
6. “Stimson's Introduction to Airborne Radar - Electromagnetics and Radar, 3rd edition”, G. W. Stimson, H. D. Griffiths (editor), C. J. Baker (editor), D. Adamy (editor), The Institution of Engineering and Technology, SciTech Publishing, ISBN 9781613530221
7. http://www.radartutorial.eu/index.en.html, free website with basic resources on radar, accessed in January 2019
8. C. Li *et al.*, "A Review on Recent Progress of Portable Short-Range Noncontact Microwave Radar Systems," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 65, no. 5, pp. 1692-1706, May 2017.
9. J. Lin, C. Li, C. Chang, T. Tsai, D. Zito, and S. Chang, “Editors’ Choice – Review – Semiconductor integrated radar for sensing applications”, *J. Solid State Sci. Technol*., 2018 volume 7, issue 7, Q3126-Q3142
10. J. Le Kernec *et al.*, “Radar signal processing for sensing in assisted living”, *IEEE Signal Processing Magazine,* March 2019.
11. “*World Population Aging 2017 Highlights*”, report by UN United Nations, available online at http://www.un.org/en/development/desa/population/publications/pdf/ageing/WPA2017_Highlights.pdf (accessed in March 2019)
12. “*Falls Prevention Exercise – following the evidence*”, A. Charters, Age UK, June 2013.

Acknowledgement

The authors acknowledge support from the UK EPSRC (grant EP/R041679/1 INSHEP) for this work on radar for healthcare applications.

About the authors

Francesco Fioranelli (francesco.fioranelli@glasgow.ac.uk) has been an assistant professor at the University of Glasgow since April 2016. He received his PhD degree in electronic engineering from Durham University, UK, in 2014, and was a research associate at University College London prior to joining the University of Glasgow. He has co-authored more than 50 papers in international conference proceedings and academic journals on various applications of radar systems. His research interests include multistatic and distributed radar sensing, application of machine learning to radar data for classification in healthcare and security, characterization of radar signatures of vehicles and UAVs, wind farms, sea clutter.

Julien Le Kernec (julien.lekernec@glasgow.ac.uk**)** received the B.Eng. and M.Eng. degrees in electronic engineering from the Cork Institute of Technology, Ireland, respectively, in 2004 and 2006, respectively, and the Ph.D. degree in electronic engineering from University Pierre and Marie Curie, France, in 2011. He held a post-doctoral position with the Kuang-Chi Institute of Advanced Technology, Shenzhen, China, from 2011 to 2012. He was a Lecturer with the Department of Electrical and Electronic Engineering, The University of

Nottingham Ningbo China, from 2012 to 2016. He is currently a Lecturer with the School of Engineering in the Systems, Power and Energy Group, University of Glasgow. His research interest includes radar system design, software defined radio/radar, signal processing, and health applications.

Syed Aziz Shah (Syed.A.Shah@glasgow.ac.uk) is currently working as a research associate at School of Engineering, University of Glasgow, UK. He received his PhD degree in Wireless Sensing, MS degree in Wireless Networks and Electronics, and BS degree in Electronics Engineering from Xidian University China, Linkoping University Sweden and COMSATS University Pakistan, respectively. His research interest include radar sensing for health applications, radar technology, wireless sensing, machine learning wireless network, antennas and propagation