Reliable Eye-Blinking Detection With Millimeter-Wave Radar Glasses

Emanuele Cardillo, *Member, IEEE*, Luigi Ferro, *Graduate Student Member, IEEE*, Gaia Sapienza, and Changzhi Li, *Senior Member, IEEE*

***Abstract*— One of the most felt and serious problems of our society involves the capability to enable the communication of people affected by neurodegenerative pathologies. Indeed, the inability to communicate as a consequence of the patient paralysis is one of the main detrimental effects of such diseases. Since the head is the last affected part of the body, an accepted solution to enable the communication considers the detection of intentional eye blinking to be interpreted as messages or commands. In this article, a millimeter-wave (mm-wave) Doppler radar is devoted to this purpose with advantages in terms of size, computational cost, privacy concerns, and immunity to different light conditions, compared with competing optical image-based technologies. Displacement and micro-Doppler signature are measured with a 120-GHz radar to accurately recognize intentional motions. After analyzing the performance dependence on different radar positions, the radar has been integrated into a glass frame. This allowed us to mitigate the effects of random body motion as a consequence of the movements due to both the physiological activity and external factors. This contribution aims to demonstrate the radar's effectiveness as assistive systems to enable the patient's communication.**

***Index Terms*— Assistive devices, biomedical applications, dementia, Doppler radar, eye blinking, microwaves, neurodegenerative diseases, random body motion, smart glasses.**

I. Introduction

THE World Health Organization (WHO) estimated that the number of people affected by neurodegenerative disorders is growing very fast in the last decades, probably due to the increase in life expectancy. In detail, the number of people affected by dementia, which is the main symptom associated with neurodegenerative pathologies and may include memory loss, difficulties with thinking, problem-solving, or language, was approximately 55 million in 2019. Furthermore, the number is expected to increase to 139 million in 2050, according to the last WHO report [1].

Serious physical and psychological, hence social and economical consequences arise, not only for the subject affected by the pathology but also for relatives, friends, and caregivers [2], [3]. Since the body undergoes neurons death and progressive paralysis, the subject loses the ability to communicate by speaking. This disability goes beyond the discomfort due to the limitation of the social activities because also the capability to communicate basic needs as the sense of thirst or hunger is impaired, with serious consequences on the health status and life quality. This scenario has not left indifferent the scientific community, which put a great effort toward finding new technological solutions to enable the subjects to communicate in an alternative way [4]. A limited number of aids are already available, but a great scientific effort is still required to provide an effective solution.

The available assistive devices are mainly based on the detection of either movements or signals of/from the head. This is a direct consequence of the consideration that the head is physiologically the last part of the body being paralyzed during the last stages of the disease. Known solutions rely on the detection of brain signals by means of electrooculography (EOG) and electroencephalography (EEG) [5], [6]. They are often aimed at tracking the eye movement to select a predefined message. Indeed, many systems are equipped with a display, where images depicting basic needs or simple words browse slowly; when the desired image appears on the display, it can be selected by a subject's intentional movement, as an eye blinking. Intentional movements need to be distinguished from unintentional movements; thus, they are usually coded. As an example, an intentional command can be represented by two or three consecutive eye-blinking which can be easily separated from a single physiologic eye blinking. The systems based on EOG or EEG recognize the ocular movement by directly analyzing the brain signals. However, they require contact electrodes placed on the head of the subject. This aspect, common for every contact-based sensor, affects the comfort of the user.

Another commonly used technology for assisting people affected by neurodegenerative pathologies relies on optical sensors, i.e., cameras. Once again, the intentional movement of the eyes, e.g., the eye blinking, can be exploited to communicate a specific command. However, also the task of analyzing images with cameras is not exempt from errors. The low immunity to the surrounding environment characteristics, as the strong dependence on the light conditions, seriously affects the system performance and increases the probability of error [7], [8], [9], [10]. Moreover, cameras raise

Manuscript received 11 September 2023; revised 24 October 2023; accepted 24 October 2023. Date of publication 9 November 2023; date of current version 10 January 2024. *(Corresponding author: Luigi Ferro.)*

Emanuele Cardillo and Luigi Ferro are with the Department of Engineering, The University of Messina, 98122 Messina, Italy (e-mail: ecardillo@unime.it; luferro@unime.it).

Gaia Sapienza is with Tre Ali Onlus, 98124 Messina, Italy (e-mail: gaiasapienza@gmail.com).

Changzhi Li is with the Department of Electrical and Computer Engineering, Texas Tech University, Lubbock, TX 79409 USA (e-mail: changzhi.li@ttu.edu).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TMTT.2023.3329707.

Digital Object Identifier 10.1109/TMTT.2023.3329707

privacy concerns, making this technology barely appealing for private environments.

In this scenario, we are witnessing a massive growth of radar systems employed for biomedical applications [11], [12], [13], [14], [15]. Among the widely known advantages of portable radars, it is worth mentioning that the capability to measure sub-millimeter displacements and to provide peculiar, advanced information as the target micro-Doppler signatures. This set of information is provided with high accuracy, by preserving the privacy of the user and by ensuring a high integrability with the standard technologies. Moreover, radar systems are very robust and reliable against ambient light conditions, which is a distinctive feature if compared with the optical systems [16]. A limited number of examples are available within the scientific literature, whereby radars are employed to recognize eye blinking and head movements [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28]. A context of interest for such a kind of detections concerns the automotive industry, where the head motion and the eye-blinking detection are often exploited to recognize inattentive driver behaviors [20], [21].

In this contribution, the authors propose a millimeter-wave (mm-wave) radar system able to detect the intentional eye blinking performed by users affected by neurodegenerative pathologies. These movements can be interpreted as commands or requests for an assistive system or person. This task is fulfilled by accurately detecting both the displacement and the micro-Doppler signature resulting from the activity of the subject and by subsequently recognizing the movements of interest. Compared with the current competitor technologies, the system shows advantages in terms of size, computational cost, privacy concerns, and immunity to different light conditions. The theoretical feasibility of the proposed solution has been investigated by simulating a possible ideal scenario, and the related measurement has been performed. Afterward, different real aspects affecting the measure have been taken into consideration, e.g., the immunity of the solution from the physiological activity. This is a case of interest, even more so for applications concerning people affected by neurological disease. Indeed, their physiological activity is often characterized by noncorrect, i.e., costal breathing, which involves also the movement of the shoulders and consequently of the head. This might seriously affect the measurement. However, it should be observed that costal and diaphragmatic can be tightly coupled during voluntary breathing [29]. Some examples are the breathing during singing or playing wind instruments. Moreover, the breathing patterns depend on the breathing frequency and individuals. With the purpose to enhance the system immunity to external movements, i.e., random body movements, the radar has been integrated on the glass frames. A measurement campaign has been carried out to demonstrate that this expedient mitigates the effects of random body motion. Moreover, the dependence of the performance on the radar position have been investigated to suggest a suitable radar location on the glass frame. Exploiting electromagnetic signal allows also to place the radar behind the lens thus enabling the system integration on already existent glasses and making the system distribution easier.

Exploiting a radar working at the very high frequency of 120 GHz is a critical step to decrease the total system size and to allow the integration with the glasses.

Only a few papers have been devoted to investigating the eye blinking detection for biomedical applications and this is the first contribution whereby a complete analysis is provided, not limited to ideal scenarios but investigating the real circumstances affecting the measurement effectiveness, such as the random body motion effects. To this aim, the investigation of the best sensor location might be very beneficial to those researchers interested in further developing this topic. The applicative field of this technology can be also extended to other human–computer interaction applications, where radar-based systems compete with camera-based devices. As an example, in the field of healthcare services, contactless commands based on the body motion can be exploited to allow a paralyzed subject lying on the bed to switch off/on the light, or to remotely control the electric shutters or to ask an assistive staff for help.

It is worth noting that this is an extended version of [26], which was presented at the 2023 IEEE MTT-S International Microwave Symposium. In this regard, the present contribution extends the conference paper with broader literature study, deeper theoretical description and simulation of the scenario, the higher working frequency of the employed radar involving advantages in terms of decreased size and better integration, the crucial integration on glass frame to suppress the random body motion, the experimental activity taking into account also the presence of random body motion due to the subject activity and external factors, and the performance analysis for different radar positions.

This article is organized as follows. The theory of the employed radar and the challenges related to the eye-blinking detection has been discussed in Section II. Section III shows the experimental setup characterized by the mm-wave radar glasses, studies the performance by varying the radar position, and shows the results related to the body motion suppression. Finally, the performance of the current contribution and of the state-of-the-art works are described in Section IV, whereas the conclusion is drawn in Section V.

II. Theory and Challenges of Eye-Blinking Detection

Conventional Doppler radars often rely on a quadrature architecture. A simplified block diagram has been schematically reproduced in Fig. 1. It exploits two receiving channels, i.e., in-phase (I) and quadrature (Q), in order to fix the null point problem typical of single-channel radars [30], [31]. The transmitted signal, exploited also as a reference for the receiving mixer, is generated by exploiting a voltage-controlled oscillator (VCO). Due to the well-known temperature dependence of the VCO performance, often a phase-locked loop (PLL) circuit is required but this is not the case of this work. The generated signal, after being amplified, is transmitted by the antenna. The transceiver exploited in this work has integrated microstrip patch antennas both in the transmitting and receiving stages. The expression of the transmitted signal $s_{tx}(t)$

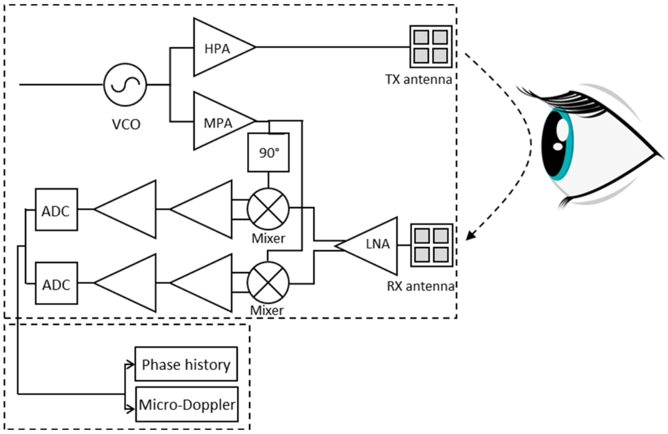

Fig. 1. System block diagram.

might be written as in the following equation:

$$s_{\mathrm{tx}}(t) = e^{j(2\pi f_c t + \phi_0)} \quad (1)$$

where f_c is the operating frequency, and ϕ_0 is the initial phase.

The reflected received signal is again amplified by exploiting a low-noise amplification stage. The down-converted signal $s_b(t)$ after the IQ demodulator can be expressed as in the following equation:

$$s_b(t) = \sigma e^{j\left(\pm\frac{4\pi x(t)}{\lambda} t + \phi_1\right)} \quad (2)$$

where σ is proportional to the strength of the received signal, λ is the wavelength, ϕ_1 is the accumulated phase, and $x(t)$ is the target displacement.

The argument of the arctangent must be enclosed within the interval $(-\pi, \pi)$ but in case of crossings over $(-\pi, \pi)$, the well-known phase unwrapping algorithm can be exploited to correct the results. Moreover, the measured phase difference samples must not exceed the boundary of π for avoiding phase ambiguities. For all the measurements of the present work, the measured speeds are always under the maximum unambiguous speed of 6.3 m/s, to a great extent.

In order to keep the signal processing steps as light as possible for making the radar actually usable on a portable system, only an average removal is applied to the signal $s_b(t)$, before the next phase analysis steps.

The phase of the received signal is also exploited to characterize the micromotions of the target. According to the definition reported in [32], the term micromotion includes any small motions, e.g., the eye blinking, in contrast to the bulk motion of the object. As an example, if the target or any section of the target itself exhibits an oscillatory motion in addition to its bulk motion, an additional frequency modulation will be induced on the reflected signal, thus generating sidebands in addition to the conventional Doppler shift due to the translational motion of the target. The additional Doppler modulation is the micro-Doppler effect.

The micro-Doppler signature is a time-varying frequency shift that can be extracted from $s_b(t)$ due to the frequency modulation induced on the carrier frequency of the received signals.

As an example, the detected harmonic frequencies might be used to recognize vibrations, rotations, and their directions, and these signatures can be further analyzed for classification, recognition, and identification tasks. Contrary to the classic Doppler analysis, time-varying features require complete time–frequency techniques; thus; the fast Fourier transform (FFT) is not suitable for this purpose because it lacks the time-dependent frequency information. On the other hand, the short-time Fourier transform (STFT) is used to compute the instantaneous frequencies for each harmonic component, thus displaying the spectral density of time-varying signals with a spectrogram. In detail, during the STFT processing, a limited time-window is considered instead of the entire measuring time. The FFT is then applied on the time-limited window so that the combined results represent a trade-off between frequency and time. The larger the window size, the higher the frequency resolution but the lower the time resolution. As can be inferred from Fig. 1, the radar will be placed very close to the subject's eye in order to detect the eye-blinking based on different ranges due to the eyelid thickness. The typical eyelid thickness might be considered close to 500 μm, indeed, according to [33], the thickest part of the upper eyelid is just below the eyebrow, i.e., 1127 $\pm$ 238 μm, whereas the thinnest is near the ciliary margin, i.e., 320 $\pm$ 49 μm. However, the presence of the eyelash and different orientations of the radar regarding the eye might result in larger measured displacement, also in the order of 1–1.5 mm. It is worth noting that, in principle, also the detection of the eyeball rotation could be exploited to make the patient able to communicate.

However, during the experimental campaign, no effect has been noticed as a consequence of the eyeball rotation. Indeed, although the eyelid thickness might be similar to the difference between the real radius of the eye and the radius of the eye considered as a perfect sphere, the eye blinking is accentuated by the presence of the eyelash. Moreover, although the radar is very close to the eye, due to the radiation beam aperture, the entire eye falls within the radar field-of-view. This makes the radar unsensitive to the eyeball movement, i.e., there is no range migration for the eyeball. Moreover, due to the wide iris dimension compared to the entire sclera, very evident and unnatural eyeball movement should be required to create a noticeable range difference.

In order to test the feasibility of the solution and provide a preliminary description of the scenario, a possible case study has been simulated. The simulations have been carried out by analytically reproducing the down-converted signal $s_b(t)$; thus, the geometry of radar scenario, as well as the target characteristics and trajectory are not taken into account.

In detail, a possible eyelid movement has been simulated and shown in Fig. 2(a), by considering a typical positive maximum displacement due to the eye closing, i.e., a movement toward the radar, equal to 1.48 mm, occurring in a time frame of 200 ms. The corresponding micro-Doppler signature has been extracted and reported in Fig. 2(b).

From Fig. 2, it is possible to observe the expected displacement and micro-Doppler activity due to the eye-blinking. As an example, Fig. 2(a) highlights a first expected phase of displacement increase, as a consequence of the range

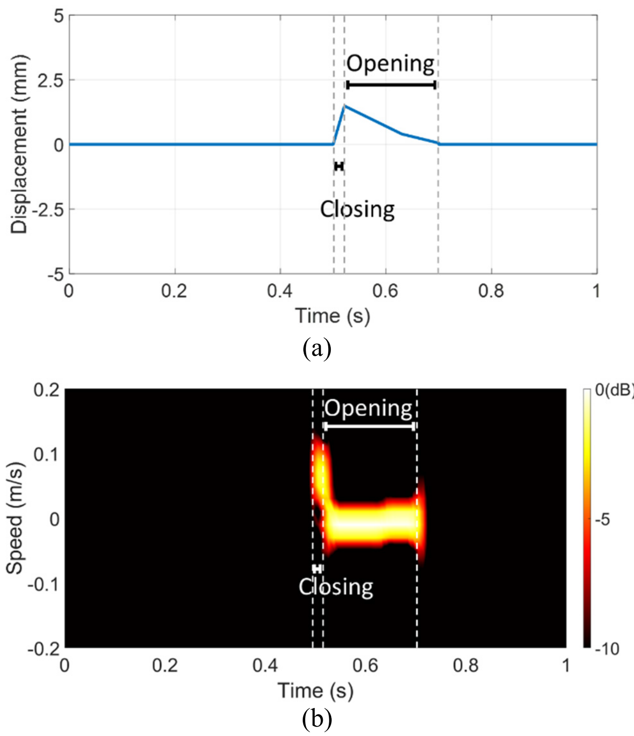

Fig. 2. Simulated (a) displacement and (b) micro-Doppler signature due to the eye blinking.

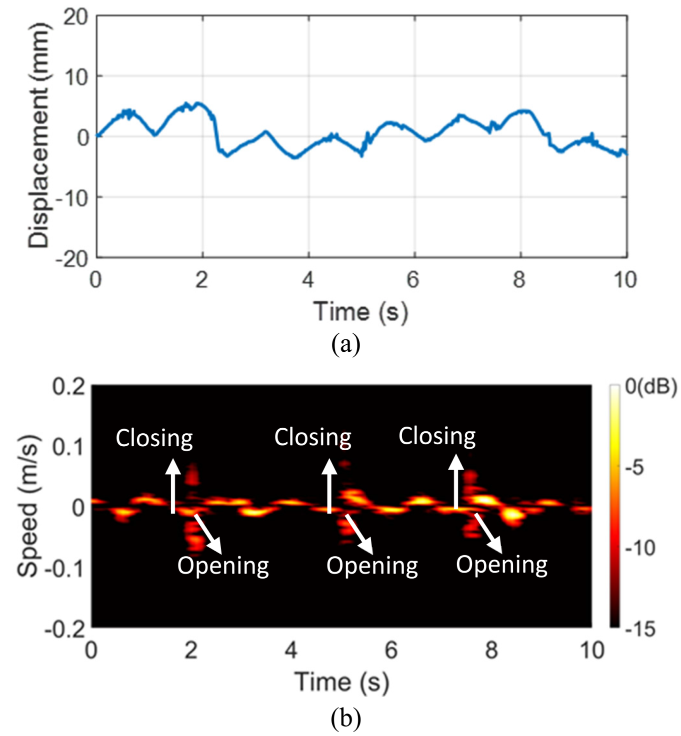

Fig. 3. (a) Displacement and (b) micro-Doppler signature due to the eye blinking during costal breathing. Whereas from (a) it is not possible to notice the eye blinking, it is clearly highlighted in (b).

shift due to the eye closing and a subsequent phase of displacement decrease consequence of the range shift due to the eye-opening. Similar considerations can be made for the micro-Doppler signature of Fig. 2(b), whereby the Doppler strips are effect of the eye blinking. It is worth noting that from both measurements, it is possible to recognize the time when the eye blinking occurs. During the remainder of this article, the micro-Doppler signature will be the key parameter to recognize the eye blinking.

However, the simulated case can be considered a simplified scenario. Indeed, although the target is mostly a paralyzed subject, the effect of the random body motion cannot be neglected and great care should be taken because an additional target movement can easily overcome the tiny eye-blinking extent, thus making the detection very challenging. One of the main aspects to be considered concerns the head motions resulting from the subject's physiological activity [26]. To this purpose, the respiratory activity of a subject can be divided into two categories: diaphragmatic and costal breathing.

Diaphragmatic breathing is the normal respiratory act of a healthy subject. As a consequence of the diaphragm contraction and relaxation, the air passively comes out of the lungs and the upper side of the body is not subject to any related movement. Since the body motion is confined to the chest level, also the head can be considered a stationary target.

On the other hand, a healthy subject might also show a costal breathing. In this case, the intercostal muscle relaxation makes the air leaving the lungs and the head moves as a consequence of the intercostal muscle movements. As investigated in [26], the effect of costal breathing seriously affects the measurement. In many cases, the eye-blinking detection by means of the displacement analysis becomes impossible.

This can be inferred from Fig. 3(a), where the displacement does not allow to detect the eye blinking due to the great extent of the breathing activity compared with the eyelid movements. Indeed, in Fig. 3(a), the eye blinking are present, but they cannot be recognized.

For these measurements, the radar is placed on a holder 3 cm from the healthy subject's face, in order to reproduce the same distance from the radar to the subject for the cases described in the next Section III. The subject has been instructed to blink normally without over- or under-stress the movement.

On the other hand, it is interesting to observe that, despite the small eyelid thickness, the eye movement is characterized by Doppler components higher than those related to the breathing activity. This consideration might be exploited to separate the eye blinking from the breathing activity by exploiting the micro-Doppler analysis. This feature can be verified from Fig. 3(b), where different micro-Doppler components due to the eye-blinking during costal breathing can be recognized based on the longer Doppler strips. This is a very interesting result, since it demonstrates that the micro-Doppler signature can be considered a reliable tool to detect tiny movements also in the presence of disturbing motions.

This issue is particularly relevant for this specific application because subjects affected by neck and upper limb musculoskeletal disorders can lose the natural supporting function of the neck, thus making the effect of the breathing activity on the head more evident.

However, respiratory activity is not the only detrimental body motion effect to be taken into account. People affected by neurodegenerative disorders exhibit an additional

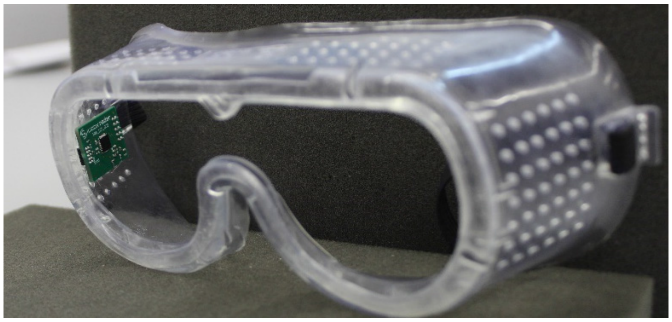

Fig. 4. Photograph of the glasses equipped with the mm-wave radar.

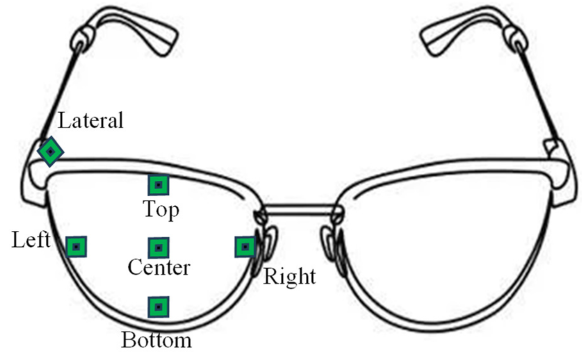

Fig. 5. Radar test positions.

movement-related clinical symptom called myoclonus. It is characterized by involuntary movements caused by muscular contractions or inhibitions [34]. Since myoclonus can make the head move, it must be carefully taken into account in the present analysis to provide a reliable eye-blinking detection.

Moreover, head motion might also be a consequence of external factors. As an example, the subject might be pushed while seated on a wheelchair, with the related vibrations, shakes, and velocity changes affecting the measurement. With the purpose to mitigate the effects of the random body motion, in this contribution, an ad hoc tailored system is proposed and described in Section III.

III. MM-WAVE RADAR GLASSES EXPERIMENTAL SETUP

Fig. 4 shows a photograph of the proposed system. Basically, the idea is to make the radar move with the head as a whole. Therefore, every movement of the head will result in the same movement of the radar with a net zero-Doppler speed between them.

The core of the system is the TRA_120_002, an SiGe 120 GHz highly integrated IQ transceiver with antennas on chip by Indie Semiconductor, formerly silicon radar [35].

It is placed on a compact board of 2.5 × 2 cm and mounted on a demo glass, as shown in Fig. 4. The mm-wave front end is wire connected with a two-stage amplifier realized with internal laboratory facilities, i.e., an S103 Protomat milling machine by LPKF Laser & Electronics, and with an ADC board that enables data processing. The radar is working in continuous wave (CW) Doppler mode at the carrier frequency of 120 GHz. The effective isotropic radiated power (EIRP) is typically −3 dBm. Employing a radar working at a very high frequency is a fundamental step of this project. Indeed, this allows to a noticeably decrease the total system size, particularly concerning the critical space occupied by the antennas, for an effective integration with the glasses.

As an example, in [26], a 24-GHz radar has been exploited for the task of detecting eye blinking and head movement. Although microwave radar showed its effectiveness with the aim of demonstrating the system operation, it might hardly be integrated into the glass frames without affecting the user's comfort.

It is worth noting that, in addition to different working frequencies, this article extends and improves [26] with a deeper analysis of the scientific literature, by providing a complete theoretical analysis and simulations, by analyzing the system performance for different radar positions and by demonstrating the feasibility of the system integration on smart glasses to suppress the random body motion.

Of course, mm-wave radars are not exempt from the technical issues arising from the low maturity level of the current technology, particularly in terms of the maximum range without lenses. However, this is not an issue for such a very short-range application.

A. Radar Position Analysis

A preliminary study has been carried out in order to investigate the performance dependence on the radar position and to suggest a suitable radar location on the glass frame. In detail, the eye blinking has been measured for each of the following radar positions on the glass front frame: center, top, bottom, right, left, and lateral. Different tested radar positions are graphically depicted in Fig. 5. Of course, the center position is less attractive from a practical point of view, but it has been considered as a good reference point.

To provide a quantitative analysis of the performance, the distance between the 0 m/s axis in the micro-Doppler graph and the maximum point of the micro-Doppler strip due to the eye blinking has been selected as a figure of merit.

This choice is corroborated by the thought that the higher the micro-Doppler strip, the clearer is the eye-blinking detection.

As a consequence, an estimate of the micro-Doppler shift might be a good parameter to quantify the detection effectiveness. Fig. 6(a) provides a graphical view of the described parameters' meaning.

From the inset of Fig. 6(a), it is also interesting to observe the different phases of eye closing and opening, in which the first one is physiologically faster than the second one. Fig. 6(b) shows the average value of different measured micro-Doppler shifts for the different radar positions.

Although the measurements are repeatable, the average value was considered to avoid differences related to each single eye-blinking act and not to different positions. It is worth noting that the system performance barely depends on the radar position because the eye blinking can be always detected, with a slight improvement by using the top/bottom positions. This is a very interesting observation because it allows to

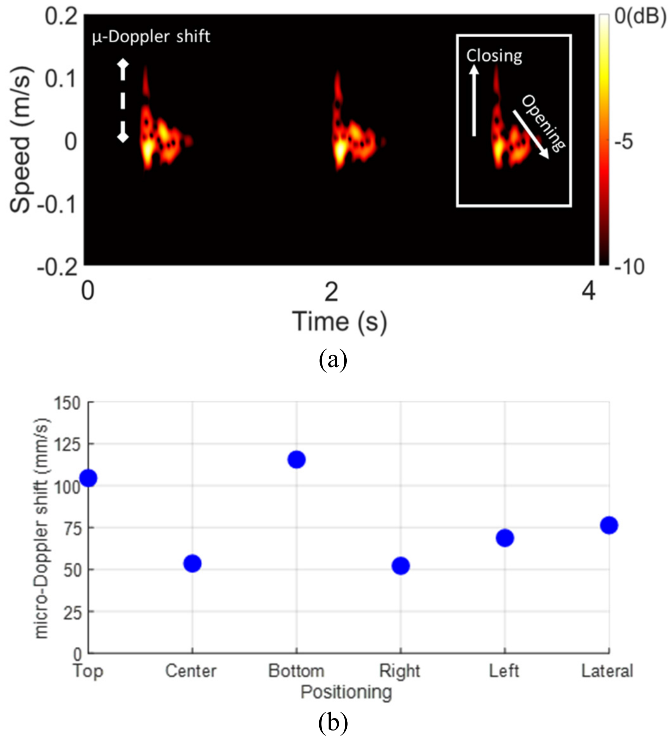

Fig. 6. (a) Micro-Doppler shift evaluation and (b) average of different measured micro-Doppler shifts for different radar positions.

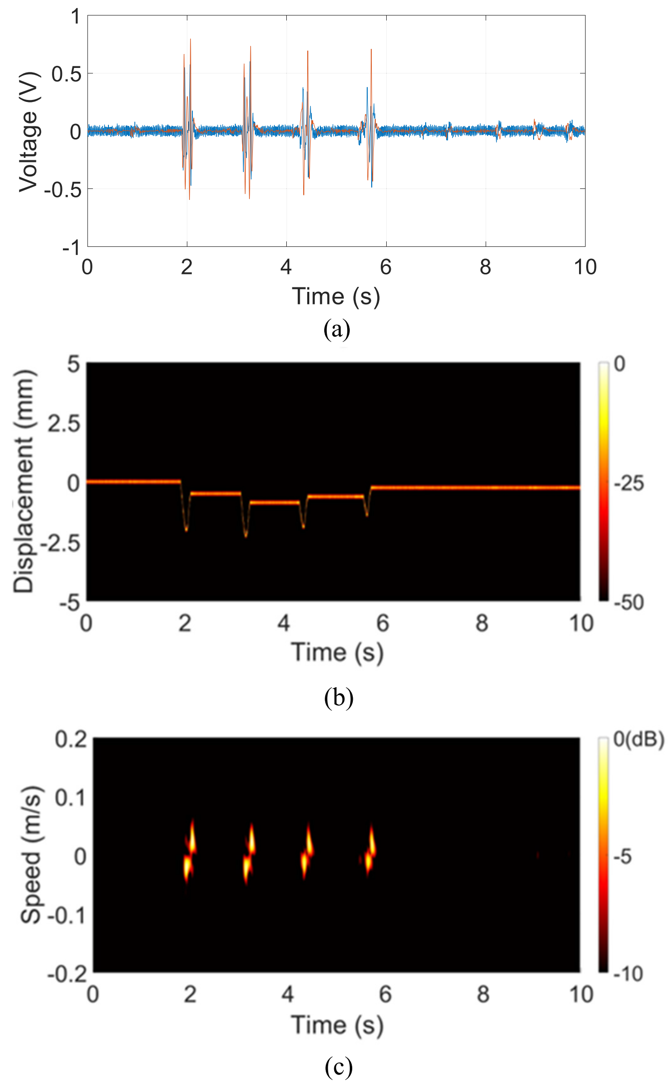

Fig. 7. (a) In-phase and quadrature signal, (b) displacement, and (c) micro–Doppler signature due to the eye blinking during costal breathing. The measurement is performed with the radar placed on the glass frame.

select the radar position based only on design or mechanical considerations by maintaining the performance unchanged. Although the radar is very compact, the performance has been tested also when placed in the lateral position. This can be very beneficial to leave the subject field of view empty, which reduces the discomfort for the user. Since the results highlighted that this position represents a good trade-off between measurement effectiveness and user comfort, it has been maintained for the next measurements. The variance of the measured micro-Doppler shift for the case of the selected lateral position is 0.04 mm/s, whereas the average value is 76.4 mm/s. As already discussed, exploiting a detection system based on electromagnetic sensing also gives the opportunity to place the radar behind the lens, thus allowing an easier system integration on already existent glasses. Examples of the detection effectiveness behind the lens have not been reported for the sake of brevity.

B. Body Motion Mitigation

Fig. 7 shows the results concerning the eye-blinking detection with the mm-wave radar glasses during the interesting case of costal breathing.

According to the analysis reported in Section III-A, the radar is placed in the lateral position also shown in Fig. 4. It is interesting comparing these results with those reported in Fig. 3. Indeed, it is possible to observe from both the displacement and micro-Doppler signature that the detrimental effect of the random body motion has been suppressed, even maintaining the same radar-eye distance of 3 cm. The four eye blinking can be straightforwardly located from both the displacement and the micro-Doppler signature. For the sake of clarity, it should be noted that different format of the graph in Fig. 7(b) is due to a different data analysis required to show a zero displacement when the eye is not blinking. Indeed, in this time window, the body movement is completely suppressed, and the target appears stationary thus the amplitude of the IQ signals is very close to 0 with a resulting random extracted phase history. The processed data reported in this format solves this issue.

In order to test the technique in the presence of more intense and irregular movements, like those related to clinical symptoms, e.g., myoclonus, the capability of the system to detect eye-blinking has been tested. The subject performed randomly horizontal, vertical, and rotating head movements, as graphically represented in Fig. 8. As a matter of fact, these are intense sample movements that can be considered worst cases in this article. Again, the eye blinking is detected, as shown in Fig. 9. The characteristic micro-Doppler signature has been exploited as a key indicator of different eye blinking. To test the reliability of the measurements, the experiment

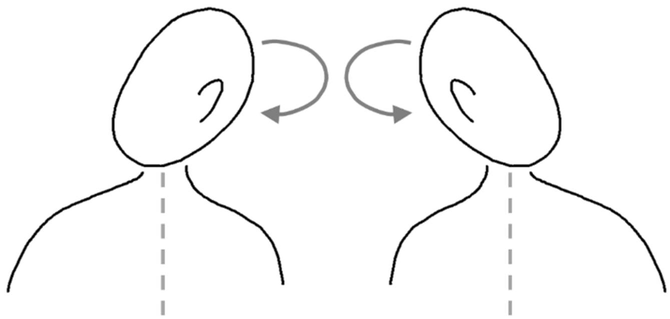

Fig. 8. Head movements during eye blinking.

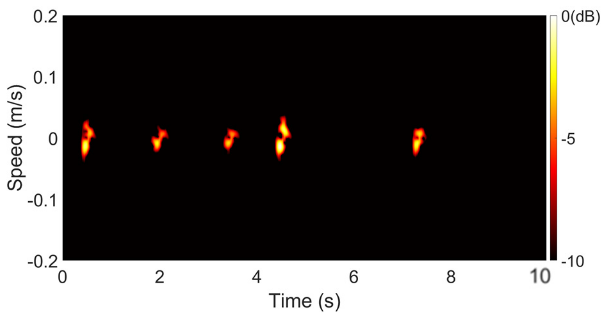

Fig. 9. Eye-blinking detection during random head movements.

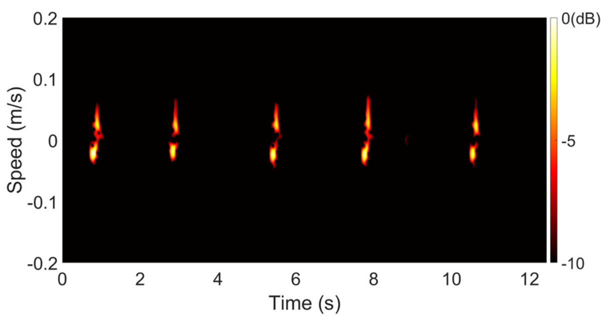

Fig. 10. Eye-blinking detection during random wheelchair movements.

was repeated 50 times with a success rate of eye-blinking detection equal to 100%. It is worth noting that, the capability to properly classify and recognize the movement is usually attributed to detection algorithms which are not within the aim of the present contribution, and thus will not be described. However, the success rate of the detection algorithm is strictly related to the signal-to-noise ratio of the eye-blinking points compared with the others. In detail, the signal-to-noise ratio of the results reported in Figs. 9 and 10 is 10 dB. This is of course not the case of the radar mounted on a fixed platform, which is, indeed, greatly affected by random body motion effects and might barely be classified or detected. Since it has been explained that the head can move also as a consequence of external factors, the eye-blinking detection has tested with the subject seated on a moving chair in order to reproduce the case of a wheelchair during its motion. As in the previous case, the eye blinking is properly detected and shown in Fig. 10.

Also in this last case, despite the movement of the whole body, the system allows to isolate and recognize the desired motion due to the net radial motion between the radar and the eyes.

IV. Performance Discussion

In the scientific literature, some research groups attempted to address the problem of detecting the eye-blinking by exploiting a radar.

In [21], only preliminary results were reported concerning a radar system able to detect the eye blinking and rotation in a laboratory environment. Compared with the present contribution, only a few measurements in a static scenario have been reported, without any attempt to suppress the random body motion effect. Also in [22], a frequency-modulated continuous wave (FMCW) mm-wave radar was tested to detect the eye-blinking. However, it required complex postprocessing techniques and only a simple case has been studied with the subject's face and eyes kept very stable in front of the radar. On the other hand, the present work analyzes the eye-blinking detection for different respiration patterns and during the head motion. Yang et al. [23] proposes a compact sensor based on spoof localized surface plasmons aimed at detecting eye blinking and heartbeats by pointing the sensor toward the temporal region of the subject's head, thus exploiting the motions of the skin. Once again, the tests have been performed on a stationary subject, without focusing on a more realistic scenario.

Cardillo et al. [25], [26] reported a preliminary analysis on the possibility of detecting the eye-blinking under very stable measurement conditions and by testing only the effect of respiration, respectively. As described in Section III, due to different working frequencies, this contribution describes the radar integration on the glass frames with system performance analysis for different radar positions and proposes a system configuration able to suppress the random body motion.

In [27], a 5-GHz radar has been exploited with the same purpose. However, the detected signals were affected by low-frequency noise that, in turn, made the detection challenging. The issue was addressed by applying complex processing techniques to distinguish the desired eye movement. The systems proposed in [20] and [28] were devoted to detecting drowsy driving and suffered from the in-cabin clutter. The issue was solved by applying different processing algorithms. Compared with [20], [27], and [28], the present contribution solves the random body motion issue without applying any complex signal processing algorithms.

The distinctive contributions of this work rely on the thoroughness of the reported analysis. A very high-frequency radar has been exploited, thus facing the issues arising from the low maturity level of the current technology but exploiting the advantages in terms of system compactness.

The proposed study has been carried out by paying attention to practical issues related to both real scenarios and the peculiar condition of subjects affected by neurodegenerative pathologies. An analysis of the system's performance dependence on different positions and its reliability against possible random body motion has been performed.

The results have been provided by exploiting different Doppler radar features, for the capability to detect displacement and extract micro-Doppler signatures without additional processing steps that may increase the computational cost.

It should be noted that an analytical comparison between the present results and those reported in the literature is not feasible. Indeed, this is the first work where the eye-blinking detection has been investigated in the presence of heavy random body motion, and a cost-effective solution has been provided without employing complex signal processing algorithms.

V. Conclusion

In this contribution, an mm-wave radar system is employed with the aim to enable the nonverbal communication of subjects affected by neurogenerative pathologies. In detail, intentional eye blinking can be interpreted as messages or commands for an assistive device/person. After a preliminary analysis of the performance for different radar positions, the experiments of the system with a 120-GHz radar integrated into the glass frames demonstrated the capability to suppress the effects of the random body motion.

References

[1] WHO. (2022). *World Report on Vision Webpage on The World Health Organization*. [Online]. Available: https://www.who.int/publications/i/item/9789241516570

[2] M. B. Bachli et al., "Evaluating the reliability of neurocognitive biomarkers of neurodegenerative diseases across countries: A machine learning approach," *NeuroImage*, vol. 208, pp. 1–13, Mar. 2020.

[3] N. P. Oxtoby and D. C. Alexander, "Imaging plus X: Multimodal models of neurodegenerative disease," *Current Opinion Neurol.*, vol. 30, no. 4, pp. 371–379, Aug. 2017.

[4] C. K. Behera, J. Condell, S. Dora, D. S. Gibson, and G. Leavey, "State-of-the-art sensors for remote care of people with dementia during a pandemic: A systematic review," *Sensors*, vol. 21, no. 14, p. 4688, Jul. 2021.

[5] T. Wibble, T. Pansell, S. Grillner, and J. Pérez-Fernández, "Conserved subcortical processing in visuo-vestibular gaze control," *Nature Commun.*, vol. 13, no. 1, p. 4699, Aug. 2022.

[6] W. Deng, J. Huang, S. Kong, Y. Zhan, J. Lv, and Y. Cui, "Pupil trajectory tracing from video-oculography with a new definition of pupil location," *Biomed. Signal Process. Control*, vol. 79, Jan. 2023, Art. no. 104196.

[7] E. Cardillo, C. Li, and A. Caddemi, "Heating, ventilation, and air conditioning control by range-Doppler and micro-Doppler radar sensor," in *Proc. 18th Eur. Radar Conf. (EuRAD)*, London, U.K., Apr. 2022, pp. 21–24, doi: 10.23919/EuRAD50154.2022.9784461.

[8] E. Cardillo, L. Ferro, C. Li, and A. Caddemi, "Microwave radars for automotive in-cabin detection," in *Proc. Annu. Meeting Italian Electron. Soc.*, Feb. 2023, pp. 75–80.

[9] C. Waddington and J. Kofman, "Analysis of measurement sensitivity to illuminance and fringe-pattern gray levels for fringe-pattern projection adaptive to ambient lighting," *Opt. Lasers Eng.*, vol. 48, no. 2, pp. 251–256, Feb. 2010.

[10] L. Ren, L. Kong, F. Foroughian, H. Wang, P. Theilmann, and A. E. Fathy, "Comparison study of noncontact vital signs detection using a Doppler stepped-frequency continuous-wave radar and camera-based imaging photoplethysmography," *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 9, pp. 3519–3529, Sep. 2017, doi: 10.1109/TMTT.2017.2658567.

[11] L. Wen, Y. Gao, C. Gu, and J. Mao, "PhysioChair: A dual-frequency radar system for noninvasive and continuous detection of physiological signatures," *IEEE Sensors J.*, vol. 22, no. 8, pp. 8224–8233, Apr. 2022.

[12] Z. Fang et al., "Wide field-of-view locating and multimodal vital sign monitoring based on X-band CMOS-integrated phased-array radar sensor," *IEEE Trans. Microw. Theory Techn.*, vol. 68, no. 9, pp. 4054–4065, Sep. 2020.

[13] P.-H. Juan, C.-Y. Chueh, and F.-K. Wang, "Distributed MIMO CW radar for locating multiple people and detecting their vital signs," *IEEE Trans. Microw. Theory Techn.*, vol. 71, no. 3, pp. 1312–1325, Mar. 2023, doi: 10.1109/TMTT.2022.3216577.

[14] Y. Yuan, A. Y. Chen, and C. M. Wu, "Super-regenerative oscillator-based high-sensitivity radar architecture for motion sensing and vital sign detection," *IEEE Trans. Microw. Theory Techn.*, vol. 69, no. 3, pp. 1974–1984, Mar. 2021, doi: 10.1109/TMTT.2021.3053972.

[15] S. Dong, Y. Li, J. Lu, Z. Zhang, C. Gu, and J. Mao, "Accurate detection of Doppler cardiograms with a parameterized respiratory filter technique using a K-band radar sensor," *IEEE Trans. Microw. Theory Techn.*, vol. 71, no. 1, pp. 71–82, Jan. 2023, doi: 10.1109/TMTT.2022.3184019.

[16] E. Cardillo, C. Li, and A. Caddemi, "Radar-based monitoring of the worker activities by exploiting range-Doppler and micro-Doppler signatures," in *Proc. IEEE Int. Workshop Metrology Ind. 4.0 IoT*, Jun. 2021, pp. 412–416.

[17] E. Cardillo, L. Ferro, and C. Li, "Microwave and millimeter-wave radar circuits for the next generation contact-less in-cabin detection," in *Proc. Asia–Pacific Microw. Conf. (APMC)*, Nov. 2022, pp. 231–233.

[18] D. Bresnahan and Y. Li, "Driver head motion monitoring using a mm-wave FMCW radar," in *Proc. IEEE Texas Symp. Wireless Microw. Circuits Syst. (WMCS)*, May 2021, pp. 1–4.

[19] D. G. Bresnahan and Y. Li, "Classification of driver head motions using a mm-wave FMCW radar and deep convolutional neural network," *IEEE Access*, vol. 9, pp. 100472–100479, 2021.

[20] Y. Shu, Y. Wang, X. Yang, and Z. Tian, "An improved denoising method for eye blink detection using automotive millimeter wave radar," *EURASIP J. Adv. Signal Process.*, vol. 2022, no. 1, pp. 1–12, Dec. 2022.

[21] L. Ma, Y. Ye, C. Gu, and J. Mao, "High-accuracy contactless detection of eyes' activities based on short-range radar sensing," in *IEEE MTT-S Int. Microw. Symp. Dig.*, May 2022, pp. 266–268.

[22] Y. Wang, Y. Shu, and M. Zhou, "A novel eye blink detection method using frequency modulated continuous wave radar," in *Proc. IEEE Int. Workshop Electromagn., Appl. Student Innov. Competition (iWEM)*, Guangzhou, China, Nov. 2021, pp. 1–3, doi: 10.1109/iWEM53379.2021.9790529.

[23] X. Yang, S. A. Kurt, Q. Zeng, X. Tian, M. Zhao, and J. S. Ho, "Non-contact mmWave physiological sensor in eyewear based on spoof localized surface plasmons," in *IEEE MTT-S Int. Microw. Symp. Dig.*, San Diego, CA, USA, Jun. 2023, pp. 975–978.

[24] E. Cardillo, G. Sapienza, and A. Caddemi, "Sistema di rilevamento di movimenti (system for motion detection)," IT Patent 102 022 000 010 118, May 16, 2022.

[25] E. Cardillo, G. Sapienza, C. Li, and A. Caddemi, "Head motion and eyes blinking detection: A mm-wave radar for assisting people with neurodegenerative disorders," in *Proc. 50th Eur. Microw. Conf. (EuMC)*, Utrecht, The Netherlands, Jan. 2021, pp. 925–928, doi: 10.23919/EuMC48046.2021.9338116.

[26] E. Cardillo, G. Sapienza, L. Ferro, C. Li, and A. Caddemi, "Radar assistive system for people with neurodegenerative disorders through head motion and eyes blinking detection," in *IEEE MTT-S Int. Microw. Symp. Dig.*, San Diego, CA, USA, Jun. 2023, pp. 979–982, doi: 10.1109/IMS37964.2023.10187979.

[27] Y. Kim, "Detection of eye blinking using Doppler sensor with principal component analysis," *IEEE Antennas Wireless Propag. Lett.*, vol. 14, pp. 123–126, 2015, doi: 10.1109/LAWP.2014.2357340.

[28] J. Hu et al., "BlinkRadar: Non-intrusive driver eye-blink detection with UWB radar," in *Proc. IEEE 42nd Int. Conf. Distrib. Comput. Syst. (ICDCS)*, Bologna, Italy, Jul. 2022, pp. 1040–1050, doi: 10.1109/ICDCS54860.2022.00104.

[29] M. Higashino, K. Miyata, and K. Kudo, "Coordination dynamics of thoracic and abdominal movements during voluntary breathing," *Sci. Rep.*, vol. 12, no. 1, p. 13266, Aug. 2022, doi: 10.1038/s41598-022-17473-9.

[30] B.-K. Park, O. Boric-Lubecke, and V. M. Lubecke, "Arctangent demodulation with DC offset compensation in quadrature Doppler radar receiver systems," *IEEE Trans. Microw. Theory Techn.*, vol. 55, no. 5, pp. 1073–1079, May 2007.

[31] C. Li, V. M. Lubecke, O. Boric-Lubecke, and J. Lin, "A review on recent advances in Doppler radar sensors for noncontact healthcare monitoring," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 5, pp. 2046–2060, May 2013.

[32] V. C. Chen, *The Micro-Doppler Effect in Radar*, 2nd ed. Norwood, MA, USA: Artech House, 2019.

[33] K. Hwang, "Surgical anatomy of the upper eyelid relating to upper blepharoplasty or blepharoptosis surgery," *Anat. Cell Biol.*, vol. 46, no. 2, pp. 93–100, Jun. 2013, doi: 10.5115/acb.2013.46.2.93.

[34] J. N. Caviness, "Myoclonus and neurodegenerative disease—What's in a name?" *Parkinsonism Related Disorder*, vol. 9, no. 4, pp. 185–192, Mar. 2003, doi: 10.1016/S1353-8020(02)00054-8.

[35] *Datasheet_TRA_120_002 120-GHz Highly Integrated IQ Transceiver with Antennas on Chip in Silicon Germanium Technology*, Silicon Radar GmbH, Frankfurt, Germany, Nov. 2018.

Emanuele Cardillo (Member, IEEE) received the M.Sc. degree in electronic engineering from The University of Messina, Messina, Italy, in 2013, and the Ph.D. degree from the University Mediterranea of Reggio Calabria, Reggio Calabria, Italy, in 2018.

He is currently an Assistant Professor with The University of Messina. His current research interests are focused on the microwave electronics field, mainly on compact radar systems for short-range applications, design of active and passive planar hybrid microwave integrated circuits (HMIC), linear and noise modeling of microwave field-effect transistors, linear and noise microwave measurements, and realization of HMIC circuits and systems and nanosatellites.

Dr. Cardillo served as a member of the organizing committee of the International Workshop on Integrated Nonlinear Microwave and Millimetre-Wave Circuits (INMMIC 2015). He serves as a TPC Member for the Radio and Wireless Week (RWW) and the Mediterranean Microwave Symposium (MMS) 2022. He was a recipient of the "IEEE SENSORS JOURNAL Best Student Paper Award" (2017/2018) and the "IEEE Microwave Theory and Techniques (MTT-S) Award" (2018). He is the Chair of the Technical Committee "Microwave and Millimeter-Wave Radar Sensors" of the IEEE Sensors Council Italy Chapter.

Luigi Ferro (Graduate Student Member, IEEE) received the B.Sc. degree in electronic engineering from The University of Messina, Messina, Italy, in 2018, and the M.Sc. degree in electronic engineering from the University of Catania, Catania, Italy, in 2021. He is currently pursuing the Ph.D. degree at The University of Messina.

He worked as an Electronic Designer with the University of Catania and as a Research Collaborator with The University of Messina, in 2021 and 2022, respectively. His current research interests are focused on the microwave electronics field, mainly on compact radar systems for short-range applications.

Gaia Sapienza received the B.Sc. degree in speech therapy and the M.Sc. degree in science of healthcare professions and rehabilitation from The University of Messina, Messina, Italy, in 2010 and 2012, respectively.

She is currently a Speech Therapist with Tre Ali Onlus, Messina, where she is also a Freelancer. She has more than ten years of experience as a speech teacher, in particular concerning neurodegenerative disorders, autism, communications disorders, and down syndrome.

Changzhi Li (Senior Member, IEEE) received the B.S. degree in electrical engineering from Zhejiang University, Hangzhou, China, in 2004, and the Ph.D. degree in electrical engineering from the University of Florida, Gainesville, FL, USA, in 2009.

He is currently a Professor with Texas Tech University, Lubbock, TX, USA. His research interests include biomedical applications of microwave technology, wireless sensors, and RF/analog circuits.

Dr. Li is a Fellow of the National Academy of Inventors (NAI). He is a Distinguished Microwave Lecturer of the IEEE Microwave Theory and Techniques Society (MTT-S), in the Tatsuo Itoh Class of 2022–2024. He is currently an Associate Editor of the IEEE JOURNAL OF ELECTROMAGNETICS, RF AND MICROWAVES IN MEDICINE AND BIOLOGY. He was a recipient of the IEEE MTT-S Outstanding Young Engineer Award, the IEEE Sensors Council Early Career Technical Achievement Award, the ASEE Frederick Emmons Terman Award, and the IEEE-HKN Outstanding Young Professional Award.

Open Access funding provided by 'Università degli Studi di Messina' within the CRUI CARE Agreement