mm-Wave wireless radar network for early detection of Parkinson's Disease by gait analysis

Ignacio E. López-Delgado*, Elías Antolinos*, Ignacio Sardinero-Meirás*, Marcos Gómez-Bracamonte*, Julián D. Arias-Londoño*, Elisa Luque-Buzo†, Francisco Grandas†, Juan I. Godino-Llorente*, Jesús Grajal*
*Information Processing and Telecommunications Center, Universidad Politécnica de Madrid.
E.T.S.I. Telecomunicación, Av. Complutense 30, 28040 Madrid, Spain
†Movement Disorders Unit, Neurology Department, Hospital General Universitario Gregorio Marañón, Madrid
Email: *ie.lopez@upm.es*

2023 IEEE Radar Conference (RadarConf23) | 978-1-6654-3669-4/23/$31.00 ©2023 IEEE | DOI: 10.1109/RADARCONF2351548.2023.10149746

***Abstract*—Anticipating the detection of Parkinson's Disease is critical to delay its effects. This paper presents the design of a radar network for the early-detection of Parkinson's Disease analyzing gait impairments. The preliminary results of the radar network show that gait biometrics, and gait asymmetries linked to Parkinson's Disease can be clearly identified in the micro-Doppler signature.**

***Index Terms*—Parkinson's Disease, PD, gait monitoring, LFM-CW radar, wireless, radar network.**

I. Introduction

Parkinson's Disease (PD) is a neuro-degenerative disorder that affects 2% of the population over 60 years old [1]. Its impact is expected to increase as a consequence of the population aging. PD not only affects the quality of life of patients, but also implies a high cost in health systems. Thus, its early detection, treatment and monitoring are critical.

The neuropathological diagnosis is the only unequivocal PD diagnosis. However, it cannot be practiced while the patient is alive [1]. Still, it is possible to perform a reliable PD clinical diagnosis while the patient is alive. After the diagnosis, it is important to monitor the patient to study the effect of the treatment and to prevent risks such as falls. Therefore, the challenge arisen concerning PD is three-fold. First, it is necessary to anticipate the detection of PD to delay its effects (early detection). Second, it is necessary to increase the accuracy of the diagnosis of PD. Third, it is critical to monitor the patients with PD to prevent risks.

In the last few years, new non-invasive trends have appeared in the literature using biometrics to detect and monitor PD. Some of these biometrics are tremors [2]–[4]; gait [2], [5], [6]; speech [7], [8]; handwriting [9]; and eye movements [10]. The technologies presented in this paper focus on the early detection of PD based on gait impairments.

Early detection of PD based on gait impairments should not be limited to a clinical environment, because clinic measurements focus on the patient's capacity, while domestic measurements focus on the patient's performance [6]. The evaluation should be continuous, in a domestic environment.

All the technologies implemented to assess PD diagnosis based on the biometrics present in gait cannot be applied in domestic environments because of their limitations. Inertial Measurement Units (used in [2], [3]) cannot provide continuous measurements because their battery is limited and because they need to be wore. Video-cameras and infra-red sensors (used in [5]) invade the subject's privacy, and are vulnerable at obstacles and low-illumination environments. On the contrary, radar technologies are capable of continuous unobtrusive measurements in low-illumination environments even with obstacles [11].

Radar technology has already been used to monitor gait with promising results [12]–[14]. Radar technology has also been applied to assess the diagnosis of PD by detecting tremors [15] and to continuously monitor PD patients with very remarkable results [6]. However, there are no direct applications of radar technology for early detection of PD.

In this paper it is proposed the design of a radar network for PD early-detection based on monitoring gait impairments. The radar network will determine some metrics associated with PD [16], [17]. The requirements of the system proposed in this paper are evaluated and listed, the node is presented and validated, and the different challenges are identified and discussed.

II. Gait monitoring using radar

Gait is analyzed using the micro-Doppler signature of the target. The micro-Doppler signature represents the velocity of all the moving scatterers of the human body (torso, head, limbs, etc.). The micro-Doppler signature of a person walking towards the radar is shown in Figure 1.

The graphs shown in Figure 1 are obtained using an in-house software presented in [18]. This software simulates a radar sensor measuring people performing different tasks. The recordings are obtained from the CMU Graphics Lab Motion Capture Database [19]. The location and the working parameters of the radar sensor can be configured. Thus, it is possible to consider all the aspects related to gait measurement using radar. Moreover, this software is capable of separating the micro-Doppler signatures of the different body parts.

This work was supported by project PID2020-113979RB-C21, DPI2017-83405-R1 and PID2021-128469OB-I00 founded by MCIN/AEI/10.13039/501100011033. The work of Ignacio E. López-Delgado was supported by an FPU Fellowship granted by the Spanish Ministry of Education (FPU20/06405). The work of Elías Antolinos was supported by an FPU Fellowship granted by the Spanish Ministry of Education (FPU18/01525).

Therefore, it is possible to obtain very accurate information about the gait.

There are two main stages that repeat twice in a gait cycle (once per step). They are represented in Figure 1a, and reflected in the micro-Doppler signature. During the stance stage, one foot accelerates while it is elevated from the floor. The velocity of this foot is maximum (5 m/s) when it passes below the torso. The foot decelerates before holding back in the ground. Meanwhile, the other foot remains still, so its micro-Doppler frequency is 0 Hz. In the double support stage, the Doppler frequency of both feet is near 0 Hz because they are on the ground simultaneously. The micro-Doppler signature of the arms is shown in Figure 1c. The hand has the largest Doppler shift, and the shoulders the smallest. The signature of the torso (shown in Figure 1d) represents the velocity of the target.

When all the signatures are analyzed at once (as in real-life measurements) it is obtained the result represented in Figure 1e. The velocity of the foot is the largest, so it is possible to differentiate the gait stages.

There are several metrics present in gait that are related to PD [16], [17]. The data obtained with the radar must be sufficient to calculate these metrics accurately. These metrics are:

- Stride length: distance covered by the foot during a step.
- Step time: interval that begins with heel strike of one foot and ends with heel strike of the same foot.
- Stance duration: interval that begins with heel strike of one foot and ends with toe off of the same foot.
- Double support duration: interval that begins with heel strike of one foot and ends with toe off of the other foot.
- Gait velocity: average velocity. It is represented in the micro-Doppler signature of the torso. Gait velocity is used in [6] to monitor PD patients.

In addition, gait asymmetries are usually associated with PD [20]. These asymmetries are different movements in the right and left sides of the body. The micro-Doppler signature should reflect these asymmetries.

III. Radar network. Requirements and deployment

Prior to analyzing gait in a domestic environment using a radar network to early-detect PD, it is necessary to validate the performance of the network in a controlled environment. Thus, the radar network is designed to measure patients performing the clinical tests currently used to detect PD.

The radar network used for validation will record a patient performing the Timed Up and Go (TUG) test [21] in a hospital room as the one shown in Figure 2. At the TUG test, the patient stands up from a chair, walks 3 m away from the chair, turns around, walks 3 m back to the chair, and sits down.

The radar network proposed for this environment is formed of several nodes synchronized using GPS. In this environment, the location of the nodes is known. The nodes establish a wireless communication with a processing unit. The processing

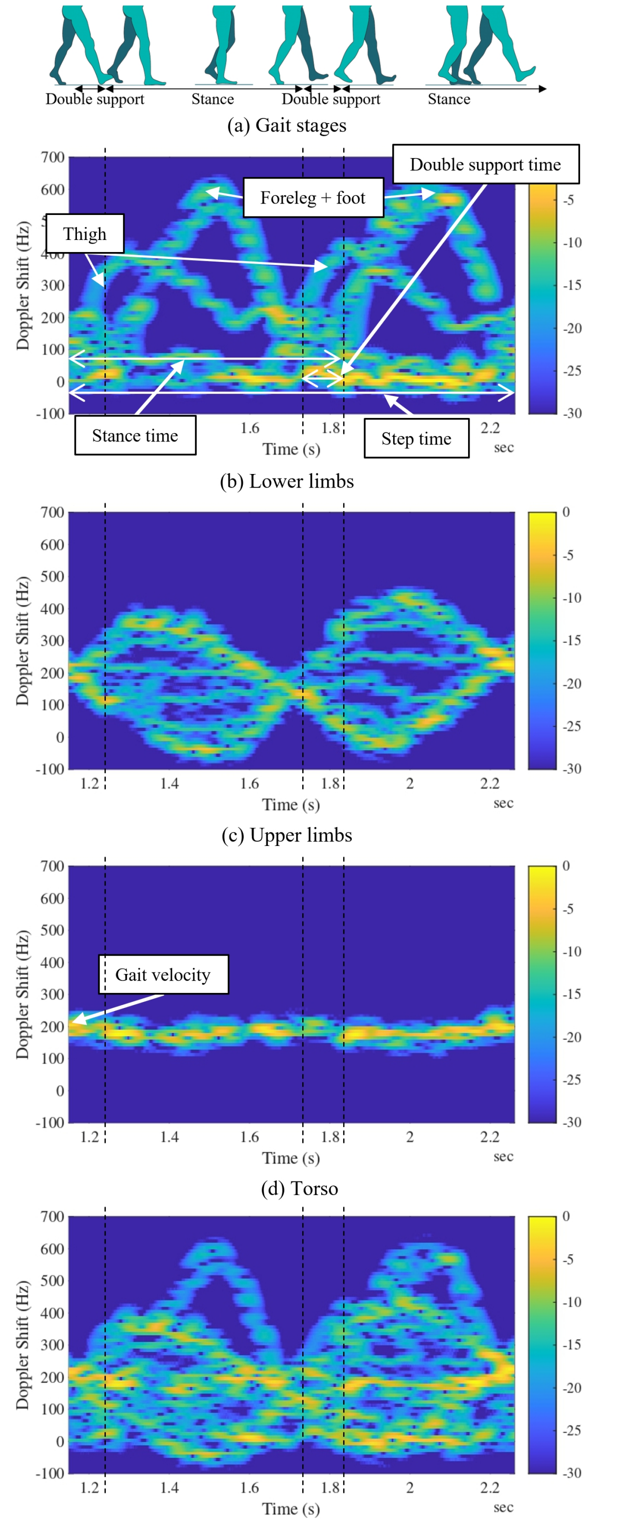


Fig. 1: Simulation of the micro-Doppler signature of the different gait stages (represented in a) focusing on: (b) lower limbs, (c) upper limbs, (d) torso, and (e) complete human body. Some metrics are included in the signatures. It is used the recording of subject 2 of [19]. The radar simulated is a 24-GHz LFM-CW radar with chirp time $T_c = 625\mu$s, and bandwidth $B = 1.4$ GHz.

unit calculates the micro-Doppler signatures from the signals of the nodes, and calculates relevant metrics for PD detection.

The node location is presented in Figure 2. There are two nodes pointing to the target's torso, and two nodes pointing to the target's lower limbs because this improves gait analysis [22]. There are two lateral nodes used to detect asymmetries.

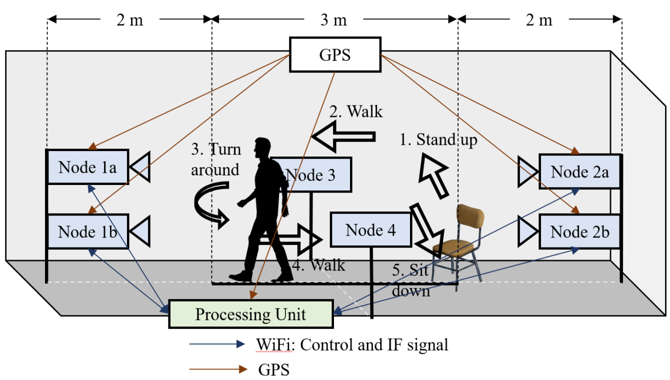


Fig. 2: Measurement environment with a target performing the TUG test. The system must work in small rooms such as the ones in a hospital. All nodes must capture a 1.8 m tall person 2 m away from the node. Nodes 1b and 2b are 0.4 m above the ground, and nodes 1a, 2a, 3, and 4 are 1.2 m above the ground.

The deployment of the radar network benefits from the wireless connection of the nodes with the processing unit. The nodes are synchronized using GPS receivers, as proposed in [23]. The GPS receivers also establish the time reference to synchronize the node frames.

IV. Node Design

The nodes must fulfill the following requirements to be able to early-detect PD by analyzing gait:

- Compact system: The sensing is carried out with radars working above 24 GHz to achieve small-sized antennas.
- Low-cost system: The radars are linear-frequency-modulated continuous-wave (LFM-CW) radars. The functioning principle of these radars systems is summarized in Figure 3: the frequency difference between the transmitted and received signals (the beat frequency f_b) is proportional to the distance to the target R.
- Measurement range: The measurements must be carried out in the environment shown in Figure 2. Thus, the field of view (FoV) of the antennas should be $\vartheta \approx 40°$.
- Maximum radial velocity: The micro-Doppler signature must represent all radial velocities below 5 m/s: the highest radial velocity of a person's foot walking towards the radar, as shown in Figure 1.
- Continuous interrogation: To observe the maximum radial velocity, it is necessary to have the maximum update rate, i.e. process all the sweep intervals.
- High SNR: The target must be differentiated from the noise to observe the details of the micro-Doppler signature.
- Wireless communication protocol: The communication between the nodes and the processing unit must be wireless. It is selected Bluetooth.

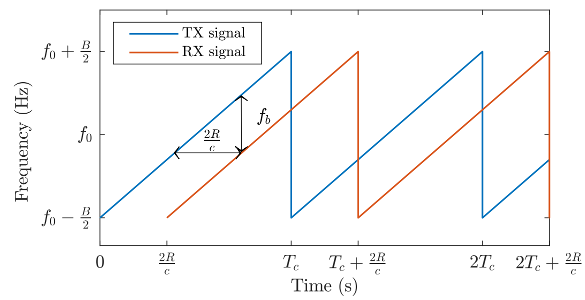


Fig. 3: Working principle of LFM-CW radar. The range of the target R is proportional to the beat frequency f_b: the frequency difference between the transmitted and received signals.

A. Node working conditions

The parameters optimized are the chirp time (T_c), the central frequency (f_0) and the bandwidth (B).

The chirp time determines the maximum micro-Doppler frequency that can be measured ($f_{d\,max}$) [11], which is related to the maximum radial velocity $\nu_{r\,max}$ = 5 m/s ($f_d = 2f_0\nu_r/c$):

$$f_{d\,max} \leq \frac{1}{2T_c} \Rightarrow T_c \leq \frac{c}{4f_0\nu_{r\,max}} \tag{1}$$

where c is the speed of light. Notice that larger chirp times increase the SNR because the integration time increases.

The gain of the antennas of the system is given by the beamwidth. If the central frequency decreases, it is necessary to increase the effective area of the antennas to keep the gain constant.

The target should appear in the region where the noise of the system is flat, above the corner frequency (f_c). Thus, the bandwidth is set so that the minimum range $R_{min} = 2$ m is observed at $f_{b\,min} \geq f_c$, as shown in Figure 4. Considering the relationship between the range and the beat frequency shown in Figure 3, the required bandwidth is:

$$R = \frac{f_b c T_c}{2B} \Rightarrow B \geq \frac{f_c c T_c}{2R_{min}} \tag{2}$$

B. Microcontroller requirements

The sampling frequency f_s is determined by the maximum beat frequency of the IF signal ($f_{b\,max}$) ($f_s \geq 2f_{b\,max}$), which depends on the maximum range of the radar ($R_{max} = 10$ m) as shown in Eq. 3.

$$R_{max} = \frac{f_{b\,max} c T_c}{2B} \Rightarrow f_s \geq \frac{2BR_{max}}{cT_c} \tag{3}$$

The sampling frequency is set to about $f_s = 125$ ksps to reduce the processing burden.

The figures of merit of the node are shown in Table I.

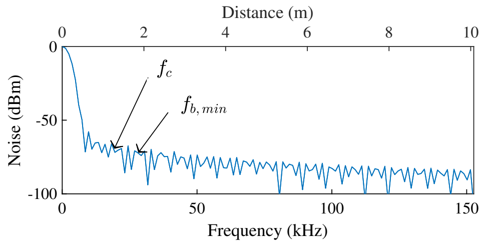


Fig. 4: Noise of the system using the radar MMIC Silicon Radar TRX-024-046 with an FFT bandwidth $B_{\text{FFT}} = 1.2$ kHz, and $N_{\text{FFT}} = 256$ bins. It is selected $f_{b\,min} = 30\text{kHz} \geq f_c$. In the top axis it is represented the distance to the target considering $B = 1.4$ GHz, and $T_c = 625\mu$s.

TABLE I: Node figures of merit.

Parameter	Value
R_{min} (m)	2
R_{max} (m)	10
$\nu_{r\,max}$ (m/s)	5
ϑ (°)	40
Central frequency f_0 (GHz)	24
Bandwidth B (GHz) (Eq. 2)	1.4
Chirp time T_c (μs) (Eq. 1)	625
Sampling rate f_s (ksps) (Eq. 3)	125
Continuous interrogation	Yes

V. Implemented design

There are several commercial radar sensors that can be applied for PD early detection analyzing gait. There are also commercial *evaluation boards* that integrate such radar sensors with microcontroller units (MCU) that sample the IF signals, and communicate with a processing unit. The figures of merit of some of these evaluation boards are shown in Table II.

The radar MMICs Silicon Radar TRX-024-046 and Infineon BGT24MTR11 are the only ones that satisfy the bandwidth requirements [24], [29]. The systems SiRad Easy and Distance2Go use these MMICs respectively. They are equipped with MCUs with enough sampling rate. However, the interrogation is not continuous, i.e. some repetition intervals are lost [25], [30]. As a consequence, the micro-Doppler resolution is not sufficient for gait analysis. Moreover, the FoV of the antennas is too narrow for gait analysis. In conclusion, there are not commercial nodes that could be used for PD detection.

It is implemented a specific node for early PD detection. The schematic is shown in Figure 5a. This node is based on the MMIC Silicon Radar TRX-024-046 [24], and the IF signals are sampled with the MCU ST STM32WB15CC [31]. The node is configured with the parameters in Table I. The node samples the IF data, preprocesses it, and sends the captured samples to a processing unit via Bluetooth without losing interrogations. The micro-Doppler signature is represented real-time at the processing unit. The only drawback is the FoV of the antennas. The antennas are the ones of the SiRad Easy system, so the FoV is too narrow [25].

The MCU samples the I and Q channels. The sampled throughput is 3 Mbps (12-bit ADC at 125 ksps [31]). The majority of commercial MCUs (including the STM32WB15CC) cannot handle a real-time acquisition and retransmission throughput above 680 kbps. That is the reason why the majority of the commercial solutions cannot perform continuous interrogation.

Some pre-processing techniques are performed in the MCU before the wireless transmission to achieve real-time continuous interrogation. These pre-processing techniques are:

1) FFT of the I, Q channels to obtain the range-time matrix.
2) Selection of the bins where the target is present (between 2 and 6 m) [11].
3) Coherent summation of the selected bins.

After applying these pre-processing techniques, the throughput is reduced to 102 kbps without losing useful information.

The pre-processed data is sent via Bluetooth to a PC. The PC computes the Short-time Fourier transform to obtain the micro-Doppler signature of the received added bins using a 100 ms window. During this time it is assumed that the gait of the target does not experience any major changes. The micro-Doppler signature is filtered to remove the DC components (all static targets). Finally, the micro-Doppler signature is represented real-time in the processing unit.

VI. Results

It is simulated and measured a human target walking towards a node placed 1.2 m above the ground in the environment shown in Figure 2. The target was recorded and simulated walking normally, and emulating gait impairments related with PD. The resultant micro-Doppler signatures are shown in Figure 6.

The gait velocity can be calculated filtering the micro-Doppler signature of the torso. It is possible to isolate the micro-Doppler signature of the torso because it reflects the most. The stride length, step time, stance duration and double support duration can be extracted from the signature of the legs (Figure 6b). To calculate these metrics automatically, the processing techniques introduced in [14] will be applied to the recordings of subjects with and without PD.

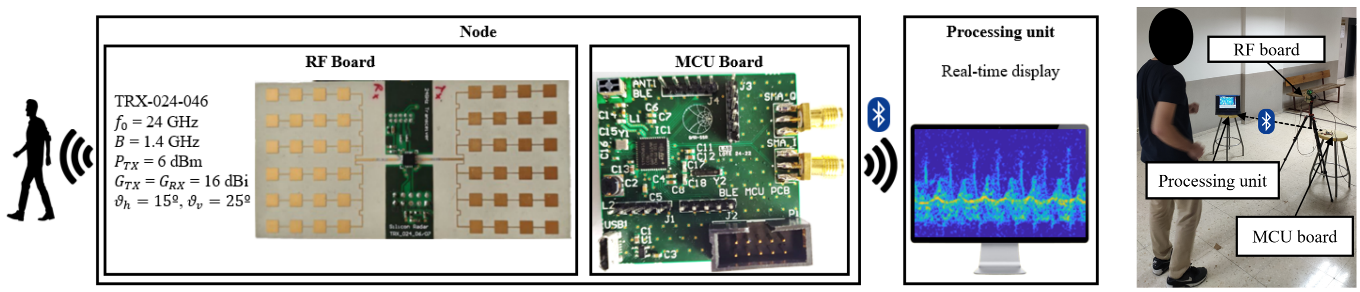
Gait asymmetries are also observed in the micro-Doppler signature. When the asymmetries are present in the lower limbs, they can be evaluated by comparing the metrics stride length, step time, and stance duration of the different legs. When the asymmetries are present in the upper limbs, it is observed a *void* in the micro-Doppler signature of the limb which is not moving. The comparison of the *voids* generated in simulation and in measurements is shown in Figure 6c.

VII. Conclusion

This paper presents the design of a radar network for the early-detection of Parkinson's Disease analyzing gait impairments in a controlled environment. The basis of the network are defined, and the nodes are tested, obtaining results that show the calculation of gait biometrics and the detection of asymmetries related with PD.

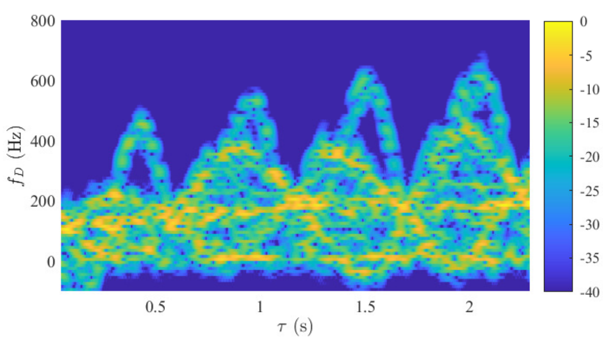
TABLE II: Comparison of the commercial evaluation boards integrating radar MMICs at 24 GHz and MCUs to sample the IF signals recorded. They are analyzed the figures of merit required to analyze gait to detect PD.

System	MMIC	B (GHz)	MCU	f_s	Interrogation	Wireless	FoV	Ref.
SiRad Easy	TRX-024-046	3	STM32F303RE	5	Discontinuous	Yes	Insuffcient	[24], [25]
Sense2GoL	BGT24LTR11	1.3	XMC4700	2.2	Discontinuous	No	Insuffcient	[26], [27]
uRAD	BGT24LTR11	1.3	Arduino	1.2	Discontinuous	Yes	Insuffcient	[26], [28]
Distance2Go	BGT24MTR11	4.5	XMC4700	2.2	Discontinuous	No	Insuffcient	[29], [30]
Our design	TRX-024-046	1.4	STM32WB15CC	1.5	Continuous	Yes	Insuffcient	[24], [31]

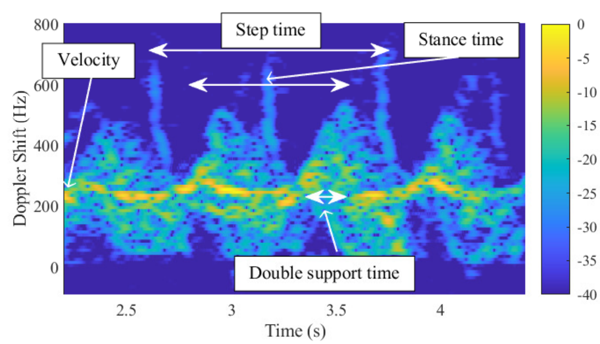


(a) (b)

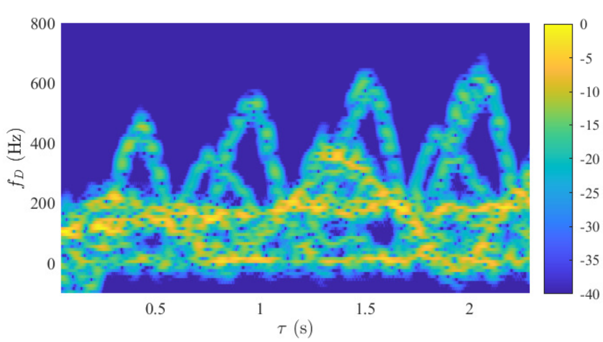
Fig. 5: (a) Node and processing unit schematics, with the different boards of the node: RF board with the MMIC and antennas, and MCU board for signal conditioning and acquisition. (b) Real-life measurement: the MCU board samples the IF signals, and transmits them to a processing unit via Bluetooth.



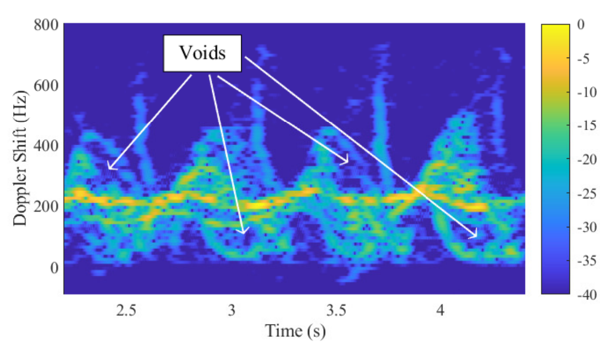
(a) Simulation symmetric gait



(b) Measurement symmetric gait



(c) Simulation asymmetric gait (emulating PD)



(d) Measurement asymmetric gait (emulating PD)

Fig. 6: Micro-Doppler signatures of (a) and (b) a person with symmetric gait (healthy), (c) and (d) a person with asymmetric gait, emulating PD. (a) and (c) are simulations carried out using the techniques presented in [18], using the recording of subject 2 of [19]. (b) and (d) are measurements carried out with the radar node designed placed 1.2 m above the ground using the configuration shown in Table I.

The design has been made with the objective of evaluating gait to early-detect PD, but can be extrapolated to other scenarios. For instance, once implemented in a domestic environment, the system presented could be applied for monitoring progression, and medication response to diseases with symptoms present in gait, such as PD and Amyotrophic Lateral Sclerosis.

References

[1] R. Balestrino, et al. "Parkinson disease," European Journal of Neurology, vol. 27, pp. 27-42, 2020.

[2] S. V. Perumal and R. Sankar, "Gait and tremor assessment for patients with Parkinson's disease using wearable sensors" ICT Express, vol. 2, pp. 168-174, 2016.

[3] M. Delrobaei, S. Memar, M. Pieterman, T. W. Stratton, K. A. McIsaac and M. S. Jog, "Towards remote monitoring of Parkinson's disease tremor using wearable motion capture systems" Journal of the Neurological Sciences, vol. 384, pp. 38-45, 2018.

[4] A. Salarian, H. Russmann, C. Wider, P. R. Burkhard, F. J. G. Vingerhoets and K. Aminian, "Quantification of Tremor and Bradykinesia in Parkinson's Disease Using a Novel Ambulatory Monitoring System," in IEEE Transactions on Biomedical Engineering, vol. 54, no. 2, pp. 313-322, Feb. 2007

[5] A. Zanela et al., "Using a Video Device and a Deep Learning-Based Pose Estimator to Assess Gait Impairment in Neurodegenerative Related Disorders: A Pilot Study" Applied Sciences, vol. 12, no. 9, p. 4642, May 2022.

[6] Liu, Y et al. "Monitoring gait at home with radio waves in Parkinson's disease: A marker of severity, progression and medication response," Science Translational Medicine, vol. 14, no. 663, p. eadc9669, Sep. 21, 2022.

[7] J.I. Godino-Llorente, S. Shattuck-Hufnagel, J.Y. Choi, L. Moro-Velázquez, J.A. Gómez-García, "Towards the identification of Idiopathic Parkinson's Disease from the speech. New articulatory kinetic biomarkers," PLoS ONE. vol. 12 no. 12, pp. 1-35, 2017.

[8] L. Moro-Velazquez, J.A. Gómez-García, J.I. Godino-Llorente, J. Villalba, J. Rusz, S. Shattuck-Hufnagel, N. Dehak. "A forced gaussians based methodology for the differential evaluation of Parkinson's Disease by means of speech processing," Biomedical Signal Processing and Control, vol. 48, pp. 205-220. 2019

[9] P. Kraus, et al. "Kinetic tremor in Parkinson's disease - An underrated symptom," Journal of Neural Transmission, vol. 113 no. 7, pp. 845–853. 2006.

[10] J.A. Gómez-García, L. Moro-Velazquez, J.I. Godino-Llorente, "Analysis of video-oculographic registers for the discrimination of Parkinson's disease," Summer School on Neurorehabilitation, Spain, September 2018

[11] M. G. Amin, Radar for indoor monitoring: detection, classification, and assessment, 1st ed. CRC Press, 2018 pp. 121-198

[12] B. Jokanovic, M. Amin, and F. Ahmad, "Radar fall motion detection using deep learning", 2016 IEEE Radar Conference, pp. 1–6, 2016.

[13] A. K. Seifert, M. G. Amin and A. M. Zoubir, "Toward Unobtrusive In-Home Gait Analysis Based on Radar Micro-Doppler Signatures," IEEE Transactions on Biomedical Engineering, vol. 66, no. 9, pp. 2629-2640, Sept. 2019.

[14] A. K. Seifert, M. Grimmer and A. M. Zoubir, "Doppler Radar for the Extraction of Biomechanical Parameters in Gait Analysis," IEEE Journal of Biomedical and Health Informatics, vol. 25, no. 2, pp. 547-558, Feb. 2021.

[15] G. Blumrosen, M. Uziel, B. Rubinsky, D. Porrat, "Non-contact UWB Radar Technology to Assess Tremor," XII Mediterranean Conference on Medical and Biological Engineering and Computing 2010, 2010.

[16] J. S. Kawalec, Mechanical testing of foot and ankle implants, 1st ed. Woodhead Publishing, 2017 pp. 231-253

[17] A. Mirelman, P. Bonato, R. Camicioli, T.D. Ellis, N Giladi, J.L. Hamilton. C. J. Hass CJ, J. M. Hausdorff. E. Pelosin and Q. J. Almeida, "Gait impairments in Parkinson's disease," Lancet Neurology, vol. 18, no. 7, pp. 697-708, Jul. 18, 2019.

[18] A. F. García-Fernández, O. A. Yeste-Ojeda and J. Grajal, "Facet Model of Moving Targets for ISAR Imaging and Radar Back-Scattering Simulation," IEEE Transactions on Aerospace and Electronic Systems, vol. 46, no. 3, pp. 1455-1467, July 2010.

[19] Carnegie Mellon University "Graphics Lab Motion Capture Database" cmu.edu. http://mocap.cs.cmu.edu/ (accessed Oct. 18, 2023).

[20] M. Godi,I. Arcolin, M. Giardini, et al. "A pathophysiological model of gait captures the details of the impairment of pace/rhythm, variability and asymmetry in Parkinsonian patients at distinct stages of the disease," Nature Scientific Reports. vol 11, p. 21143, Oct. 27, 2021.

[21] D. Podsiadlo and S. Richardson, "The timed "Up & Go": a test of basic functional mobility for frail elderly persons." Journal of the American Geriatrics Society vol. 39, no. 2, pp. 142-148, 1991.

[22] F. Wang, M. Skubic, M. Rantz and P. E. Cuddihy, "Quantitative Gait Measurement With Pulse-Doppler Radar for Passive In-Home Gait Assessment," IEEE Transactions on Biomedical Engineering, vol. 61, no. 9, pp. 2434-2443, Sept. 2014.

[23] H. Yulin, Y. Jianyu, W. Junjie, and X. Jintao, "Precise time frequency synchronization technology for bistatic radar," Journal of Systems Engineering and Electronics, vol. 19, no. 5, pp. 929-933, 2008.

[24] Silicon Radar GmbH, "TRX-024-046," v.1.3. Oct.6, 2021.

[25] Silicon Radar GmbH, "SiRad Easy r4, siRad Easy & SiRad Simple," v.2.5. Nov.19, 2021.

[26] Infineon Technologies AG, "BGT24LTR11N16," rev.1.3. May.8, 2018.

[27] Infineon Technologies AG, "24 GHz radar tools and development environment user manual," v.1.1. Feb.07, 2020.

[28] uRAD by Anteral, "uRAD Arduino," v.1.2. Jul.20, 2022.

[29] Infineon Technologies AG, "BGT24MTR11," rev.3.1. Mar.25, 2014.

[30] Infineon Technologies AG, "Distance2Go - XENSIV 24 GHz radar demo kit with BGT24MTR11 and XMC4200 32-bit ARM Cortex - M4 MCU for ranging, movement and presence detection," v.1.1. May.05, 2020.

[31] ST Microelectronics, Inc., "STM32WB15CC," DS13258 Rev 7. Aug., 2022.