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ORIGINAL RESEARCH

Monitoring Dressing Autonomy: A Remote Home Care RFID-Based Solution for People with Dementia

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Abstract
The number of elder people with dementia is steadily increasing, and so is the need for solutions to support remote home care and to facilitate "aging in place". People affected by dementia often need assistance with daily self-care tasks such as dressing, eating, and bathing. Our focus is on the dressing activity: we analyze the requirements and propose a system that leverages RFID-based technology to support individuals in dressing appropriately, let the individuals reside at home or in assisted living facilities. The system exploits RFID tags, fixed or ironed onto the person's clothes, and antennas to read and collect data from the tags. The system detects the user's outfit, eventually providing the individual with immediate feedback and alerting the caregiver. We compare two different RFID technologies: one operating at 13.56 MHz (HF)—commonly adopted in the literature—and one at 868 MHz (UHF). An in-depth analysis of the RFID technology for detecting worn clothes is reported, considering the scenario where the antennas are positioned on one side of a door to achieve comprehensive detection coverage of the entire body.

Keywords Dementia · Activities of daily living (ADL) · Dressing · RFID · Remote care · Elderly · Smart environment

Introduction

The number of older adults (65 years or more) has been steadily increasing in recent decades and is estimated to double from 703 million worldwide in 2019 to 1.5 billion in 2050 [1]. The growing aging of the world population requires a change in healthcare by proposing paradigms that promote staying at home for as long as possible. A significant geriatric condition is dementia, a chronic syndrome that causes cognitive disorders, disabilities, and, in severe cases, dependence on relatives or caregivers in carrying out daily activities (Activities of Daily Living, ADL) [2]. In the intermediate stages of cognitive impairment, people with dementia (PwD) can live independently with some support in smart home environments, typically provided by ICT solutions and tools for monitoring the daily activities [3]. The typical approach involves detecting behaviours in PwD from sensor data analysis and integrating this detection with compensatory actions by caregivers. This paradigm is exemplified in systems such as AaIS [4] and BRIDGe [5]. In this way, critical behaviours deriving from cognitive disabilities are detected and properly addressed, while supporting personal autonomy. For example, if a person dresses inappropriately for the current weather, compensatory actions might include: separating heavy clothing from light clothing; using colour labels to suggest what to wear; using texts or symbols to suggest the proper clothing according to the current weather.

The ability to perform everyday activities heavily impacts the quality of life of people with dementia [6]. Dressing is a personal self-maintaining skill for which more than half of people with dementia could benefit from some assistance. Some works have already tackled the challenge of supporting the dressing activity, such as [7–12]: they use different kinds of technologies, ranging from cameras to RFIDs. However, the proposed solutions are in their early stages of

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development or present several limitations (see Sect. Related Work).

The primary goal of this paper is to design a system using passive RFID technology to detect dressing failures in PwD. The system aims to operate in both smart homes and healthcare facilities, addressing a variety of dressing challenges through a user-centered design approach. To meet this goal, we collect data using passive RFID tags and consult experts in dementia to align the technology with users' needs and habits.

We assessed the feasibility of the proposed solution on two prototypes: the first prototype is based on HF (High Frequency) technology operating at 13.56 MHz, a common approach aligned with existing literature; the second prototype is based on UHF (Ultra High Frequency) technology operating at 868 MHz, which has not previously been applied to this task. We performed an in-depth analysis of this technology to investigate its capability to accurately detect multiple tags positioned on different body parts of a walking person, such as shoulders, legs, chest, back, and feet, to understand its effectiveness.

The novelty of this paper lies in three key aspects:

- A comparative analysis of two RFID-based prototypes, one based on HF and one based on UHF. This analysis explores the strengths and limitations of both technologies in monitoring dressing activities.
- Evaluation of the system's performance in static scenarios, where the person is stationary. From a technological point of view, this means assessing the system's capability to read multiple RFID tags at varying distances and analyzing its robustness, limitations, and adaptability to different scenarios.
- Testing in dynamic scenarios, where the clothing is monitored while the person moves through a doorway, allowing for the detection of the direction of movement. From a technological point of view, this means analyzing the system's response time in reading the tags during movement and also evaluating the critical issues related to human body interference with the RFID signals in the dynamic scenario. We observe that the interaction between the human body and RFID tags can be leveraged to detect the direction of the person's movement. This dynamic scenario testing helps to assess the feasibility of using RFID technology for real-time, motion-based monitoring of the dressing activity.

The paper is organized as follows: Sect. Related Work reports related work about the methods proposed in the literature for monitoring basic activities of daily living like dressing; Sect. Design Considerations reports some basic design considerations and describes the approach from the elicitation of requirements to the design of the whole system; Sect. System Description provides the reader with an overview of the system we developed as a validating proof of the approach; two different prototypes based on RFIDs (13.56 MHz and 868 MHz) are reported and pros and cons are discussed; Sect. "Result Evaluation Using UHFTechnology" presents the results obtained with the 868 MHz RFID technology with the static and dynamic scenarios; finally, Sect. Conclusion draws the conclusions and sketches out some future research directions.

Related Work

In this section, we introduce some background considerations and analyze the state of the art; we also consider some requirements from the literature and existing work on deploying the RFID-bases technology to people with dementia.

Supporting Dressing Activity by ICT Solutions

Dressing is an Activity of Daily Living that involves not only physically putting on clothing but also the cognitive processes of selecting appropriate attire based on factors such as weather, occasion, and personal preferences. While the literature presents various approaches for automatically monitoring ADLs, including wearable technologies, IoT-based systems, and smart home monitoring (refer to Baig et al. [13] and Mshali et al. [14] for surveys on wearable, IoT-based, and smart home monitoring systems), these approaches focus on categorizing ADLs performed throughout the day without addressing the quality or accuracy of their execution.

Several proposals concern support to autonomy with a focus on single activities: a major aspect dealt with is that of providing indications on the sequence of actions to be carried out to achieve a goal, such as washing [15, 16] or getting dressed [17].

Various proposals focus specifically on dressing activities to improve independence and efficiency in this daily task by means of technological solutions [18].

Schaad et al. [19] introduce an intelligent wardrobe suggesting clothing options based on sensor data like temperature and weather forecast: the system provides recommendations for choosing the dressing, only; however, it does not verify the selected dressing. Woiceshyn et al. [20] explore the usage of social robots to recommend clothing items from a user's wardrobe, tailored to specific activities. This system continuously learns from individual user preferences, providing assistance and adapting to potential changes in preferences over time. It is important to observe that these solutions provide us with some recommendations *prior* to the dressing process, but do not assess dressing performance quality.

Other researchers have explored several technologies for recognizing dressing failures that occur *during* the activity (Kalimeri et al. [7], Matic et al. [8], Ruiz et al. [9], Burleson et al. [10], Chu et al. [11]) or have conducted post-activity analysis when the individual leaves home (Orr et al. [12]).

Kalimeri et al.'s solution [7] uses only RFIDs, employing Bayesian Networks and Layered Hidden Markov Models (HMM) to detect two dressing failures: forgetting an item or wearing clothes in a wrong sequence. Different RFID antenna configurations were tested, including two antennas near the mirror in perpendicular positions, one on the hanger, and one in the wardrobe. In another experiment, RFID antennas were positioned within the dressing cabin on the side walls (covering shoulder areas) and the back wall (covering the subject's back). Clothing items were tagged with three RFID tags—two on the shoulders and one on the back. Despite some false negatives, the study demonstrated that probabilistic approaches can mitigate RFID technology limitations like noisy or missed readings.

Matic et al.'s Aid-me system [8] combines RFID and computer vision technologies to detect potential dressing failures. Like in Kalimeri et al.'s work [7] three RFID antennas at 13.56MHz are positioned within a dressing booth. They improve accuracy by merging RFID data with image analysis, detecting issues like clothes worn backward, too many layers, and garments not suitable for the temperature, and detecting partial dressing, such as wearing only one sleeve with image analysis. Unfortunately, details about the RFID technology and its limitations are not specified in these papers.

Burleson et al. [10] introduce a system that not only detects dressing mistakes but also provides the user with a real-time feedback. The approach uses computer vision for failure recognition and integrates RFID tags in drawers, an iPod for feedback, and some fiducial markers on garments for context-aware assistance. While the manifold of sensors and technologies of such a solution allows for detecting the user's position and actions in every moment and communicating with them (through colors, audio, music, etc), the approach is very complex to deploy in a real-world environment.

Ruiz et al. [9] propose a computer vision-based method using temporal-relational visual grammars to automatically detect and categorize three dressing failures: wrong dressing order (temporal relationships), partially worn garments (spatial information), and backward dressing (relational relationships). Their system achieves accuracy similar to RFID-based solutions for these errors. Chu et al. [11] use a different clothing system employing a social robot equipped with capacitive sensors, contact switches, an infrared LED, and a RGB-D sensor. This setup monitors the dressing activity and accurately detects partial dressing (e.g., incorrect sleeve placement or unbuttoned shirts) as well as clothes worn inside-out or backward. The overall number of dressing failures that can be detected is limited.

Tan et al.'s Eldercare Toolbox [21] exploits a voice assistant to assist people with dementia: thirteen skills offer step-by-step guidance for various daily activities. For the dressing, caregivers configure the typical routine by selecting clothing items and label drawers with pictures for easy identification. When the assistant is launched, it verbally guides the patient through the selection of clothes based on the configured routine, providing step-by-step instructions. However, there is no guarantee that the correct clothes have been chosen.

Finally, Orr et al. [12] design a basic system to offer feedback as the person prepares to leave home. This system senses an RFID tag in the individual's coat and takes external temperature into account. The system is in its early stage, and it can detect only a single tag embedded in one garment.

Table 1 summarizes the dress detection support systems, highlighting their objectives, employed technologies, deployment complexity, contextual awareness, provision of feedback, and main advantages and limitations: all of these are taken into account in the proposal of the solution we describe here.

We observe that all of the reviewed papers exclusively use HF (High Frequency) RFID technology in their experiments, whereas this paper also explores the use of UHF (Ultra High Frequency) RFIDs. Moreover, most existing approaches focus on environments such as dressing cabins or booths, without considering scenarios in which users move through doorways. The only exception is the work by Orr et al. [12], which examines the use of a single tag placed in a coat. Our work aims to address these gaps in the literature by exploring the use of different types of RFID technology for detecting dressing failures in a more dynamic scenario.

Requirements from the Literature

Several papers address the challenges associated with dressing activities for people with dementia: these challenges must be considered when designing a system for monitoring dressing activity.

Mahoney et al. [22] describe caregivers' experiences across disease stages. Initially, individuals reveal resistance to assistance and time-consuming dressing, with potential mistakes like wearing layers backward. As the disease progresses, individuals may repeatedly wear the same clothes, requiring reminders for weather-appropriate clothing. Advanced stages necessitate caregivers to give detailed step-by-step instructions, including guiding arm placement and foot positioning, often requiring repeated prompting.

Table 1 Recap of relevant papers that tackled dressing support in people with dementia with technological solutions and the main aspects

PAPER	AIM	TECHNOLOGIES	COMPLE- XITY	CONTEXT AWARE	FEED-BACK	PROs	CONs
Matic et al. [8]	Detect dressing failures during the activity	High frequency RFID + computer vision	Medium	Yes	No	Combination of two technologies for better recognition; accurate	Limitations in computer vision elaboration
Kalimeri et al. [7]	Detect dressing failures from data obtained during the activity	RFID	Medium	Yes	No	Noisy and missing RFID problems are overcome using probabilistic approaches	Not online, no feedback
Ruiz et al. [9]	Detect dressing failures during the activity	Computer vision	Low	Yes	No	Accurate; only one non-invasive sensor	Difficult garment recognition; no feedback
Burleson et al. [10]	Detect dressing failures during failures + provide feedback + provide assistance + call caregiver	Computer vision, motion sensor, iPod touch, RFID, fiducial markers on clothes	High	Yes	Yes	Combination of many technologies; gives help in rectifying mistake; if needed, calls the caregiver	Markers (appearance); complex deployment
Tan et al. [21]	Vocal guidance while dressing	Alexa Echo Dot, Amazon Alexa voice service	Low	No	No	Easy to use, non-invasive, low cost, easy setup	Not context-aware: no monitoring, no feedback
Orr et al. [12]	Suggest to wear coat or not	RFID tag, thermometer, motion sensor	Medium	Yes	Yes	Context-aware proposal	A proposal, not implemented
Schaad et al. [19]	Give clothes suggestions	weather station, weather API, Google Calendar, tablet PC, LED in wardrobe	High	Only weather	No	Personalized suggestions from many inputs	Does not monitor performance and final result; Needs interaction
Chu et al. [11]	Detect dressing states	Smart clothing: capacitive sensors, contact switches, infrared LED, RGB-D sensor	High		Not yet	Combination of many sensors; good recognition	No socially assistive robot yet
Woiceshyn et al. [20]	Give clothes suggestions	Social robot	Medium	Only weather	Yes	User motivation; recommendation algorithm takes into account weather, preferences and plans	Does not monitor performance and final result

Mahoney et al. [17] explore technology's potential role in tracking dressing activities. The approach can record dressing time, prompt frequency, and errors, serving as measures for cognitive and functional decline over time. Screens, akin to TV monitors, should be avoided to prevent potential hallucinations. Introduced technology should seamlessly integrate into routines, considering challenges tied to accepting new technology. Other important requirements include the reliability and affordability of the technology.

By explaining the differences between dressing and the basic activities of eating in the everyday life of people with severe dementia, Yokoi et al. [23] highlight that dressing involves conceptual representations like front/back, up/down, and right/left, as well as the order of garment wearing or the understanding that T-shirts are worn from the head, which is cognitively more difficult compared to the eating activity.

Feyereisen et al. in [24] identify many different kinds of failures, by monitoring morning dressing sessions of patients with moderate to severe senile dementia. Failures include choosing inappropriate clothing items, incorrect or partial execution of dressing steps (commonly involving undershirts, shirts, pants, and socks), omitting actions, refusing tasks, and engaging in undressing behaviours.

RFID for People with Dementia

RFID technology has been applied across various domains involving PwD.

Raad et al. [25] introduce an RFID-based solution for real-time monitoring of wandering behaviors in PwD. In their approach, each individual wears an RFID tag attached to their ankle, neck, wrist, or shoulder. Antennas with a coverage range of 7 to 15 ms are placed in the various rooms and at exits. This setup enables the accurate detection of individuals, with higher levels of accuracy when the tag is on the neck and lower levels when the tag is positioned on the shoulder. Lin et al. [26] employ 2.4-GHz bandwidth active tags to localize and detect patients with dementia approaching doorways and hazardous areas, allowing for timely alerts to be sent to caregivers. While this approach provides effective real-time monitoring, the use of active RFID tags may involve higher costs due to the need for battery-powered tags and associated maintenance. In both works, details about the results of the RFID technology are not reported.

Mibu et al. [27] employ passive RFID sensor tags to detect activity anomalies, like leaving garbage or meals, within the living environments of elderly individuals with dementia who live alone. However, practical use of their system faces challenges: increasing the number of RFID tags results in slower reading speeds and unstable readings due to mutual interference. Moreover, the simultaneous use of two antennas causes mutual interference, hindering sufficient sensor data reception. To mitigate these issues, the system recommends using only one antenna and limiting tags associated with objects to three.

Design Considerations

We describe here some design considerations that guided us during the steps of the activities we performed in collecting the requirements.

Requirements from the Interviews with the Experts

To gain a deeper insight into the daily challenges faced by people with dementia and their caregivers, we conducted several interviews with the head and professional staff of Centro Diurno Alzheimer in Trento, Italy, a daycare centre catering to those with mild to moderate dementia [28].

The first observation concerns the application field: a dressing support system should be used at home or in resident facilities with a high degree of independence by people with mild to moderate dementia to promote their independence. Instead, it is not suited for severe cases who are not self-sufficient and need to be extensively supported by caregivers in everyday activities.

Given the potential disorientation experienced by people with dementia, for any feedback, the system must deploy an easily recognizable and distraction-free interface. Traditional communication methods like messages or phone calls, which are familiar to the elderly, may be more effective than newer, unfamiliar technologies.

Dressing dysfunctions that should be addressed are those considered dangerous for the health and safety of the person, such as clothes unsuitable for outside weather, and mismatching of shoes (especially in terms of heel height or wearing them on the wrong feet). Personal hygiene and appearance should be taken into consideration as well and not only safety: people should get changed when leaving (or entering) the bed, but in case of refusal, it might be fine to dress them over the pajamas to avoid unnecessary stress and arguments. Also, personal appearance might be taken into consideration (for example, stained clothes) but is not that relevant.

Relatives (cohabitants or not, as well as during the COVID-19 pandemics when person-to-person contact was limited [29]) should always be informed about the health conditions of their beloved. They could receive a message or notification in case of dressing failures. Moreover, it could be particularly useful to create regular reports to show yearly, seasonal, and daily trends, and to infer patterns and potential causes of decline or improvement.

Lastly, all monitoring devices should be non-invasive and should not require the person to remember to activate, wear, or operate them.

System Requirements

Based on insights gathered from both literature reviews and expert interviews, we set up a comprehensive list of dressing failures that need to be addressed:

- *Weather inappropriate attire*: selection of clothing and shoes unsuitable for the current and forecasted weather conditions, considering also the next 6 h in the local weather forecast;
- *Improper body placement*: errors such as dressing the wrong way around (mixing right and left sides) and placing clothing items incorrectly on the body (e.g., upper and lower parts). Although less common, we also include the swapping of shoes (right with left) or mixing shoes from different pairs;
- *Repetitive outfit*: wearing the same clothing for several days in a row, without replacing it;
- *Missing essential clothing items*: forgetting to wear essential clothing items required for every outfit, such as underwear (pants). We also extend this category to include necessary objects for specific weather conditions, such as an umbrella on rainy days;
- *Duplicate garment*: accumulating multiple instances of the same clothing type, such as overlapping pairs of trousers.

System Description

We describe here the overall architecture of the system we developed, and the use of the RFID technology, making some evaluations about the power of the antennas and the distance from the antennas for an optimal reading of the tags.

System Architecture Overview

To detect the dressing failures outlined earlier, we choose the RFID technology. RFID tags are cleverly positioned within garments, while RFID readers (antennas) can be positioned along doorframes. These readers monitor the clothing's position and type concerning the door's RFID markers when the person goes through the door.

The entrance door is the primary location for detecting all the garments and accessories worn by the person. However, to capture all the potential scenarios, the system could also be mounted on the bathroom door, which would help verify nighttime attire and provide prompt feedback on the lower layers of clothing.

In both scenarios, depending on the kind of human failure that needs to be detected, it may be important to know the person's direction (entering or exiting the room).

Antennas are mounted on the door and positioned on different heights to discern various categories of clothing related to "shoulders" (shirts, sweaters, etc.), "hips" (trousers, skirts, underpants, etc.), and "feet" (which may encompass socks in specific scenarios). RFID tags are sewn/ironed into the clothes or possibly into particular objects, such as wallets always to be taken when exiting, or items like umbrellas, in case of rainy weather conditions.

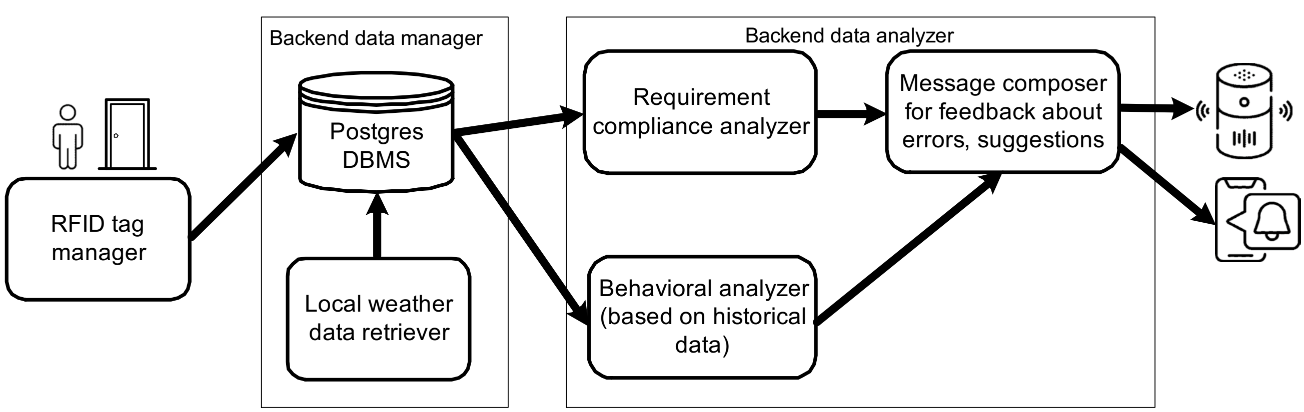

Fig. 1 Overview of the general architecture of the system. Arrows depict the flow of data between the modules. The RFID tag manager captures data from the antennas and stores them in the Postgres database; the backend data manager stores data; the backend data analyzer performs queries over stored data and sends out suitable warning messages to a buzzer/loudspeaker and to mobile phones

Figure 1 depicts an overview of the entire system architecture, the key components and the overall data flow.

Each time the person goes through the door, the RFID tag manager reads all the RFID tags. Data about the worn garments collected by the antennas are sent to a server and stored in a Postgres database, since no data is stored within the tags themselves. The primary tables of the Postgres database include:

(i) Tag(Tag_Id, TagType, Person, Garment, Position) storing respectively the Id of the tag, its type (type 1 or type 2, see Fig. 3), the name of the person bound to the tag, the type of the garment (e.g., coat, shoe, pants), and the position (e.g., left/right, front/back, top/bottom) if applicable;
(ii) Reading(Tag_Id, ReadTime, RSSI) storing respectively the ID of the tag, the timestamp at which the tag is read, and the Received Signal Strength Indicator (RSSI). The RSSI value represents the strength of the backscattered radio frequency field returned by the reader for each tag read. In other words, the passive RFID tag receives the signal from the RF reader and reflects it back. The reader then receives and measures this reflected signal. This measurement is the RSSI (in our system, it is measured in dBm).

The Local weather data retriever module retrieves data about local weather conditions via external weather APIs that provide real-time forecasts and temperature data for the user's location.

Next, the Backend data analyzer queries the Postgres database to perform critical checks related to the subject's attire:

(i) *Garment compliance*: the system ensures that the subject is wearing the correct number and type of garments, checking for instances in which more than one garment of the same type is worn, whether any required types of clothes (or objects) are missing, or if garments are worn incorrectly (e.g., wrong side, upper/lower body misplacement). This task is handled by the Requirement compliance analyzer module.
(ii) *Weather-Appropriate Clothing*: The same module evaluates whether the garments currently worn are suitable for the current weather conditions and forecasts for the upcoming hours. For example, the system can detect if the user is underdressed for cold temperatures or lacks rain protection.
(iii) *Behavioral Patterns*: The Behavioural analyzer module assesses the user's clothing habits by examining historical data on previously worn garments. For example, it detects whether the same item has been worn for consecutive days, which may indicate potential hygiene concerns or signal a need for garment washing.

The results from the analyzer modules are processed and conveyed to the user through the Message composer, which generates feedback on potential errors, suggestions, or reminders. This feedback can be delivered via voice assistants like Alexa or sent to caregivers for further action.

The backend data analyzer components go beyond the main scope of this paper: full details on their design are available in [30].

RFID-Based Prototype

The most critical aspect of the whole system is the correct detection of the worn garments. We opt for the RFID technology, but this choice has to consider several aspects. The proposed application requires passive tags, many tags readable at the same time and at distances greater than a few centimetres (more than 10 up to 1 m), tags attachable to clothing in a simple way and in any position, tags with an acceptable size and suitable material (e.g., not rigid) and tag technology that tolerates the proximity to the human body. In this context, the admissible technologies are HF (High Frequency, for proximity) and UHF (Ultra High Frequency, for long-range). Both have pros and cons:

- UHF tags are generally cheaper compared to LF (Low Frequency) and HF;
- UHF tags, unlike HF tags, are influenced by the presence of water and body tissue;
- UHF technology can be read up to a few meters, while HF technology, based on inductive coupling, is severely limited in the distance (from a few millimetres to 1 m, depending on the size of the antenna and the transmitted power);
- UHF technology can read tens of tags simultaneously while HF is capable of reading only a limited number of tags simultaneously (typically a few units);
- UHF and HF technologies, even if in different ways, are susceptible to the component materials of some objects of everyday life (e.g., metal for HF).

Indeed, the technological limitation of UHF technology in the presence of water, which masks the signal reading, can be turned into an advantage, allowing for the selective reading of tags only when they are visible from the antennas. Consequently, this feature can be exploited to distinguish between the right and left sides.

We also analyze the optimal placement of tags on the body for effective recognition. We propose positioning the tags on some fixed points of the body, minimizing movement interference during walking, and ensuring that other body parts do not accidentally cover them. In particular, we propose the shoulders (2 tags), the back (1 tag), and the front (1 tag) for the upper part of the body; the upper part of the thighs (2 tags) for the intermediate part of the body (at the end of the hands); the ankles (2 tags) for the lower part of the body (see Fig. 2). However, future developments may identify alternative positioning. For example, in the case of underpants or undershirts, where leg and sleeve positioning options are limited, we recommend positioning the tags on shoulder straps for the former and on the front and back for the latter.

The analysis of the technology unequivocally indicates that the currently applicable technology for garment recognition is passive UHF RFID. Since many works in the literature refer to HF (13.56 MHz) technologies (e.g., [7, 8]), we also implement and test this solution (HF) to analyze its applicability.

RFID Technologies

We conduct two different kinds of experiments to assess the feasibility and limitations when deploying HF and UHF tags. We aim to read simultaneously multiple tags, possibly with different orientations with respect to the centre of the antenna, at detecting the left and right tags on a walking

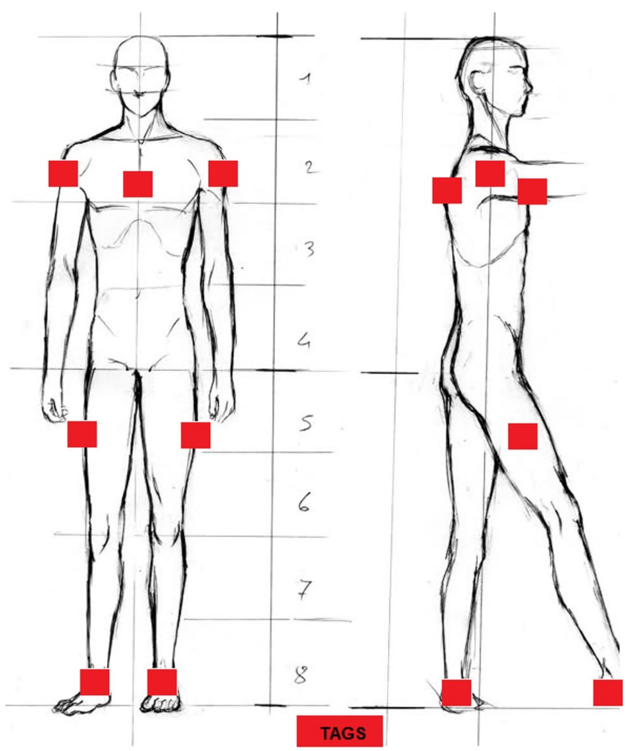

Fig. 2 Positions of RFID tags on a person's clothes on the frontal and sagittal planes

person, and at investigating the effect of the body that masks the tags positioned on the shoulders, legs, chest, back, and feet.

As for the antennas, we deploy a compact, long-range, RAIN RFID reader from the CAEN easy2read product line. The reader has four antenna ports, enabling long-range RAIN RFID portals. Its slim (L 60 mm × W 42 mm × H 7.5 mm) design makes it easy to install in limited spaces. It supports USB interfaces. The reader is compliant with both European and US regulations.

Prototype 1—HF

The test is performed under near-ideal conditions, with a tag perfectly aligned with an RFID reader. We used the most popular readers: the smart card RFID reader 13.56 MHz based on the Philips MFRC522 chip. The experiments confirm that the antennas have a limited read distance that does not exceed 5 cm, even by rising the read gain to 48 dB (RFCfgReg register). By running the default values for the parameters in air, the distance does not exceed about 2 cm [31]. We read up to a few units of tags (tiles) perfectly overlapping and positioned perfectly in contact with the reader; we observe that, presumably, the limit is reached because of the thickness of the used tags and the material. By changing the reading angle of the tag (e.g., positioning the tag perpendicular to the antenna) or introducing misalignment (where the centre of the tag does not match the centre of the reader), the tag is no longer detectable. This effect depends on the positioning of the tag but is consistently observed within a range of a few centimetres—less than 10 cm—from the reader.

Regarding the reading angle, in our experiments, the tags must be in front of the antennas and are not readable at different angles from the vertical (when the tag surface is nonparallel to the reader antenna). This result is in line with the results found in the literature. To solve this problem, Benamanra et al. [32] propose a solution based on serial complementary antennas, called "twisted" antennas, which allow the tags to be read at any angular position. The greater the angle of the tag, the smaller the read radius; even a small angle can cause a decrease in the tag's read radius, and by using an array of antennas, the tag can be read correctly from multiple angles. Given the limitations observed in both the distance between the reader and the antenna and the reading angle, multiple tags are also not well supported. However, one advantage of this solution is that the human body does not generate attenuation.

Furthermore, similar works using the high-frequency band (13.56 MHz), such as Kalimeri et al. [7] and Matic et al. [8], report results where the proposed approach was feasible, considering a particular context (e.g., a narrow booth where the person has to wear his or her clothes with extremely precise relative positions between the tags and the antennas) and simplified; the cited works do not report more complex results such as reading at different angles of the tags, misalignment of the tags with respect to the centre of the antennas, and varying distances.

Prototype 2—UHF

We perform the tests using two embedded antennas in the same container (measuring 71.12 cm × 30.48 cm × 4.24 cm): the flat Panel Antennas Andrew RFID-900-SCA (by Andrew/Motorola, RFID-900-SCA/AN400-CB66203WR, operating at 902–928 MHz, 6dBi, and Dual CP Circular Polarization). The centers of the two antennas are approximately 30 cm apart. The reader deployed is the CAEN Hadron High-Performance 4-port Embedded RAIN RFID. The container is positioned 73 cm above the ground: the centre of the first antenna is approximately 93 cm above the ground, while the second is approximately 124 cm above the ground.

We evaluate the main characteristics of the technology both through static tests, where the tags stand still and in specific positions throughout the test phase, and through dynamic tests, where the tags are worn and the subject walks in front of the antennas at different distances. In each dynamic experiment, the tags are positioned at approximately 136 cm (central shoulder height), 65 cm (thigh), and 13 cm (ankle) above the floor, as in Fig. 2. Two more tags are added at approximately 136 cm, one on the chest and one on the back; these two additional tags are used to detect whether the subject is approaching to or moving away from the antennas.

Result Evaluation Using UHF Technology

We conducted three different test sessions: a static session to test the simultaneous reading of multiple tags under varying distance and antenna power conditions; a first dynamic session to assess the sensitivity of the system in detecting tags worn on several parts of a person's body in motion; and a second dynamic session to analyze effectiveness of the system in detecting anomalies in clothing or carried objects. The following subsections describe these tests.

Static Reading of Multiple Tags (UHF)

This test aims to analyze the simultaneous detection of multiple UHF tags, each of them at varying distances and with different levels of transmitted power. We analyzed two sets of UHF tags (see Fig. 3): 10 tags of type 1 (consisting of a label to be ironed on the garment and suitable for laundry); and 12 tags of type 2 (consisting of self-adhesive labels for logistics, containers, etc.). The first type of tags can be used in the dressing monitoring scenario, only; we also considered the bigger tags for comparison, and to validate the methodologies with different types of tags.

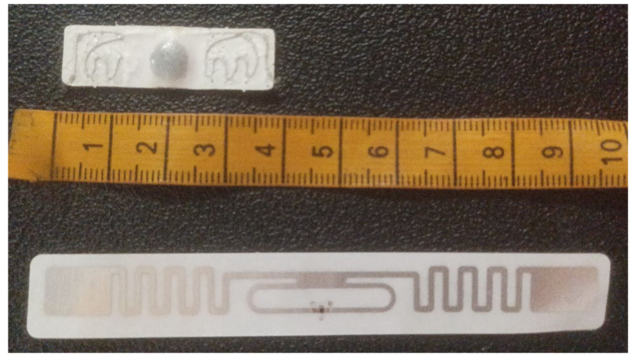

Fig. 3 Deployed tag types: UHF tag type 1 at the top (designed for ironing on garments, suitable for laundry), UHF tag type 2 at the bottom (self-adhesive, tailored for logistics, containers, etc.)

Figure 4 schematically depicts the results of tag reading at various distances: each row refers to one tag. The tags with Tag_Id starting with "54" are of type 1 (see Fig. 3); the tags with Tag_Id starting with "e2" are of type 2 (see Fig. 3).

We perform the experiments by using the tags at varying distances (tag to the antennas: 24 cm, 51 cm, 100 cm, 178 cm, and 295 cm) and at varying power levels (antenna power: 150 mW, 300 mW, 500 mW, 750 mW, 1000 mW, and 1400 mW). We perform every experiment with all tags contemporaneously and repeat every experiment 10 times. Each experiment duration is 10 seconds. Globally, we perform:

10 tests × 5 distances × 6 power levels = 300 experiments with multiple tags

In Fig. 4, each vertical block represents readings at *one* distance, varying in the range 24 cm, 51 cm, 100 cm, 178 cm, and 295 cm; every single column in one block reports the averaged (10 experiments) readability with *different* power levels of the antennas (150 mW, 300 mW, 500 mW, 750 mW, 1000 mW, and 1400 mW); every single row over the blocks reports the detection of the *same* RFID at different distances and at different power levels. A green mark reports a successful detection of the tag at the corresponding distance and power level: a red mark reports a failure in detecting the tag at the corresponding distance and power level. As expected, the probability of successfully reading one tag decreases from 100% to as low as 45% as the distance increases and the power decreases. Fig. 5 summarizes the major results.

In our specific scenario, short distances are needed and all the tags can be read correctly. Nevertheless, the results show that the proposed approach holds applicability also for other scenarios. For instance, the approach can be deployed in gate

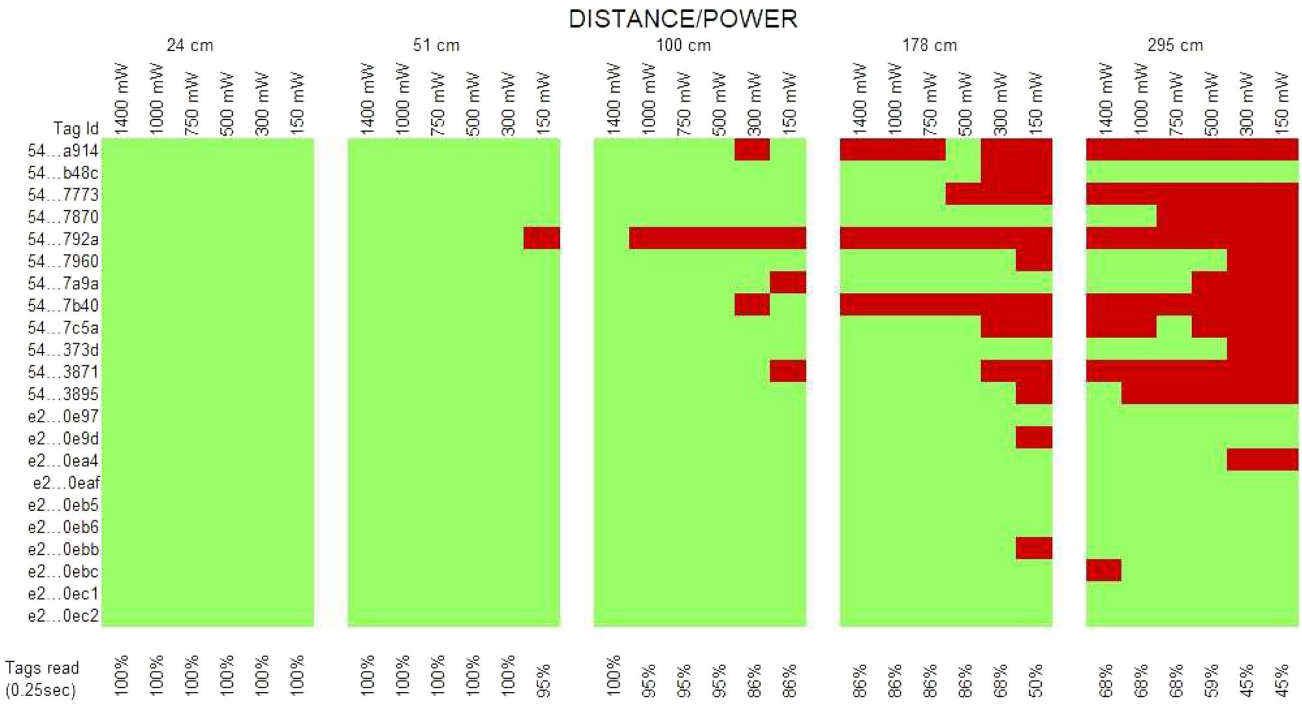

Fig. 4 Static multi-tag reading at different distances and with different power levels for UHF tags. Tags identified with 54. Refer to type 1 tags, tags identified with e2. Refer to type 2 tags, respectively (see Fig. 3). A green mark reports a successful detection of the tag at the corresponding distance and power level: a red mark reports a failure. The higher the distance of the tag from the antennas, the lower the success in reading the tag

control systems to monitor individuals entering or exiting a building: in such cases, redundant tags should be worn to enhance the probability of accurate person detection.

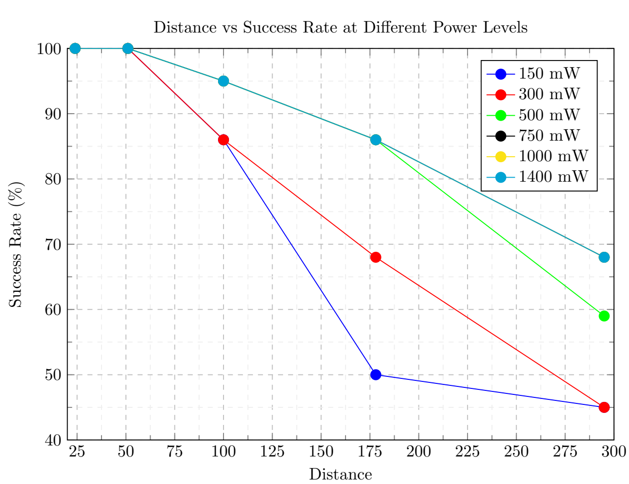

Fig. 5 Data aggregated by distance and power levels for UHF tags of Fig. 4: As the distance of a tag from the antenna increases, the success rate lowers—or more transmitting power is required to achieve better performances

Dynamic Reading of Multiple Worn Tags (UHF)

In each experiment, we consider one walking person at a time. Eight tags of type 2 are positioned as shown in Fig. 2. The person passes by the antenna in both directions (roundtrip: exits the room and then re-enters the room), at a walking speed of approximately 70 cm per second (see Fig. 6).

We perform all the measurements for every power value of the antennas: 150 mW, 300 mW, 500 mW, 750 mW, 1000 mW, and 1400 mW. One experiment requires the person to pass (go and back). To validate the experiments, we deploy three volunteers out of the four authors: the volunteers' height is in the range 165 ÷ 175 cm. Globally, we perform:

2 pass. × 6 power levels × 3 volunteers = 36 experiments with multiple tags

Due to space constraints, we report only selected results.

We focus here on one experiment with one person. Figure 7 depicts the obtained results with a power value of 300 mW when the person goes through the door in both directions, doing a roundtrip. The X-axis represents time, while the Y-axis represents the normalization of the aggregation of the RSSI (Received Signal Strength Indicator) detected by each tag during a temporal interval of one second.

Fig. 6 Experiment scenario. a) On the left: the person exits the room wearing RFID tags (the white labels on the clothes); the antennas are visible on the right-hand side of the figure, hanging on a coat rack. b) On the right: the person enters the room; the antennas are on the left-hand side of the figure, hanging on a coat rack

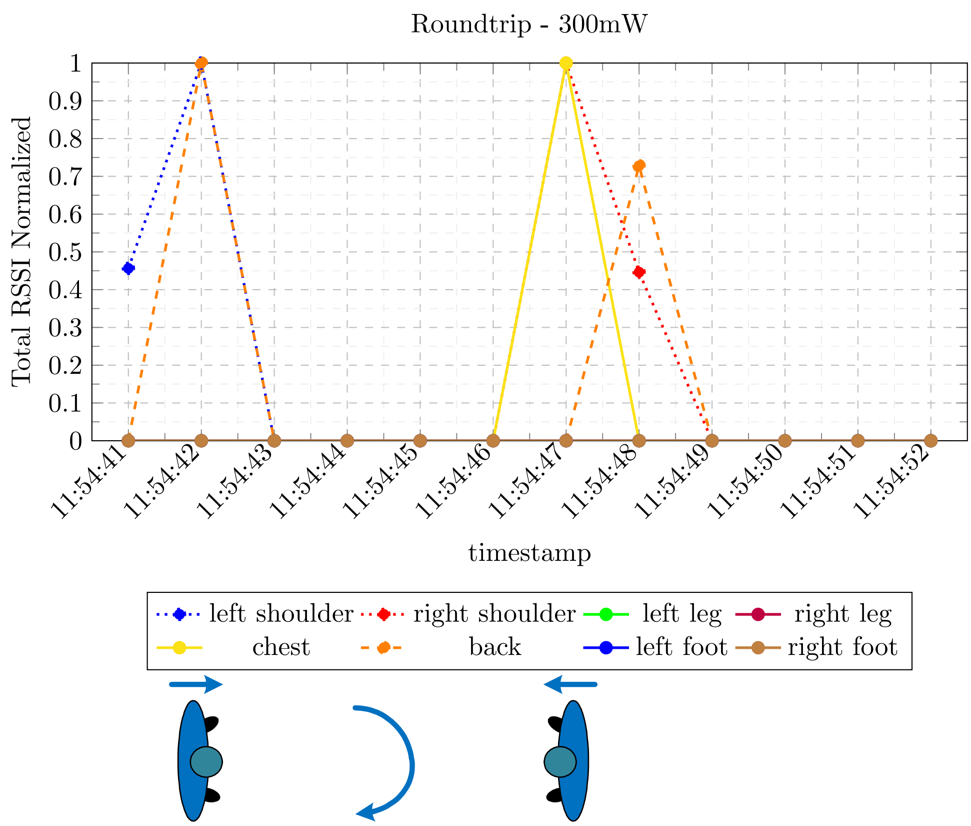

Fig. 7 Detection of the eight tags with power 300 mW and antennas positioned at 93 cm and 124 cm above the ground. The person completes a roundtrip passage, leaving the room at 11:54:42 and re-entering the room at 11:54:47. The antennas are positioned at an average height of 75 cm above the floor: the tags positioned on the legs and feet are not read

When reading the tags, the system records the following data: the tag id, the timestamp, and the RSSI value. The latter represents the effectiveness of reading the tag. To make the impact of reading more understandable, we normalize the RSSI values of each tag compared to its values detected during the experiment. In Fig. 7, at 11:54:42 a.m.

the left shoulder and the back tags are detected, revealing that the person is exiting the room with the antennas on their left-hand side. Next, the person returns to the room, and at 11:54:47 a.m. the tags on their right shoulder and chest are detected. Just one second later at 11:54:48 a.m., the person comes back again into view of the antennas. The same pattern of passing by the antennas can be detected also by 150 mW and 500 mW power values. Even if very sparse, these tag reading values are compatible with the movement of the person.

We observe that with the deployed height of the antennas, the RSSI values read for the shoulders are higher compared to the values read for the legs. Feet tags could not be detected with low power values and therefore are not reported in the diagram. We recall that only the tags that are not masked by the body can be detected.

Increasing the power value to 1400 mW results in the reading of a greater number of tags, as shown in Fig. 8. Again, the pattern with the initial detection of the chest, followed by the back, is visible. The left leg and left shoulder can be seen between the chest and the back readings when the antennas are on the left (on the left-hand side in Fig. 8). Similarly, on the right-hand side of Fig. 8, the right leg and shoulder are detected, followed by the detection of the right foot.

As shown in the previous figures, tags positioned on the lower part of the body can only be partially detected with high power levels: to achieve their detection, antennas should cover the individual's entire height. To address this limitation, we perform additional experiments by positioning the container with antennas on the floor, specifically with antennas positioned at 20 cm and 51 cm above the floor. Figure 9 depicts that with this setup, both feet are observable in both directions, with those closer to the antenna container resulting in higher RSSI values. Instead, tags positioned on the upper part of the body are not detected.

Finally, Fig. 10 depicts the results of another type of experiment: the person, standing in front of the door, rotates in place. The figure illustrates how the readings of the tags positioned on the left and right sides are alternately detected and masked by the body as the person rotates. This experiment demonstrates the system's ability to handle tag readings under dynamic and continuous motion conditions in any direction. This experiment exemplifies what happens if a person changes their mind and retraces their steps, which typically occurs as one realizes that they have forgotten something before leaving home.

Dressing Failure Analysis

Based on the experiments performed with different power settings and passage scenarios, the collected data provide us with sufficient information about several aspects.

The major tests performed under the conditions above, refer to the most frequently observed failures in garment selection. We consider here the following test types:

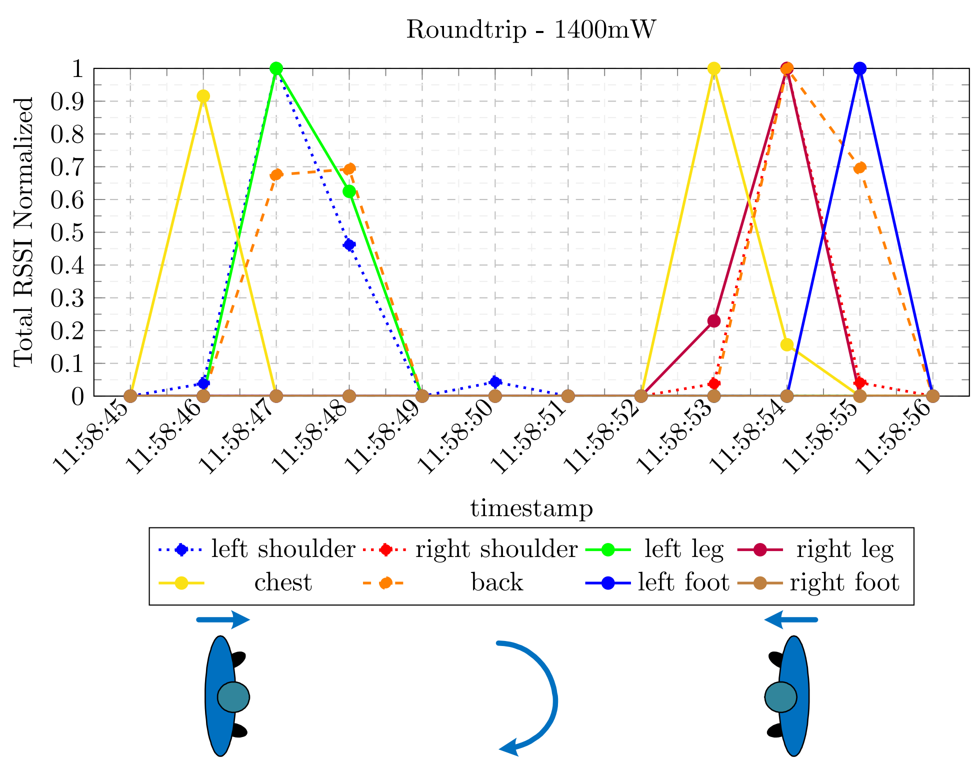

Fig. 8 Detection of the six tags with power 1400 mW. The person completes a roundtrip passage, leaving the room at 11:58:47 and re-entering the room at 11:58:54

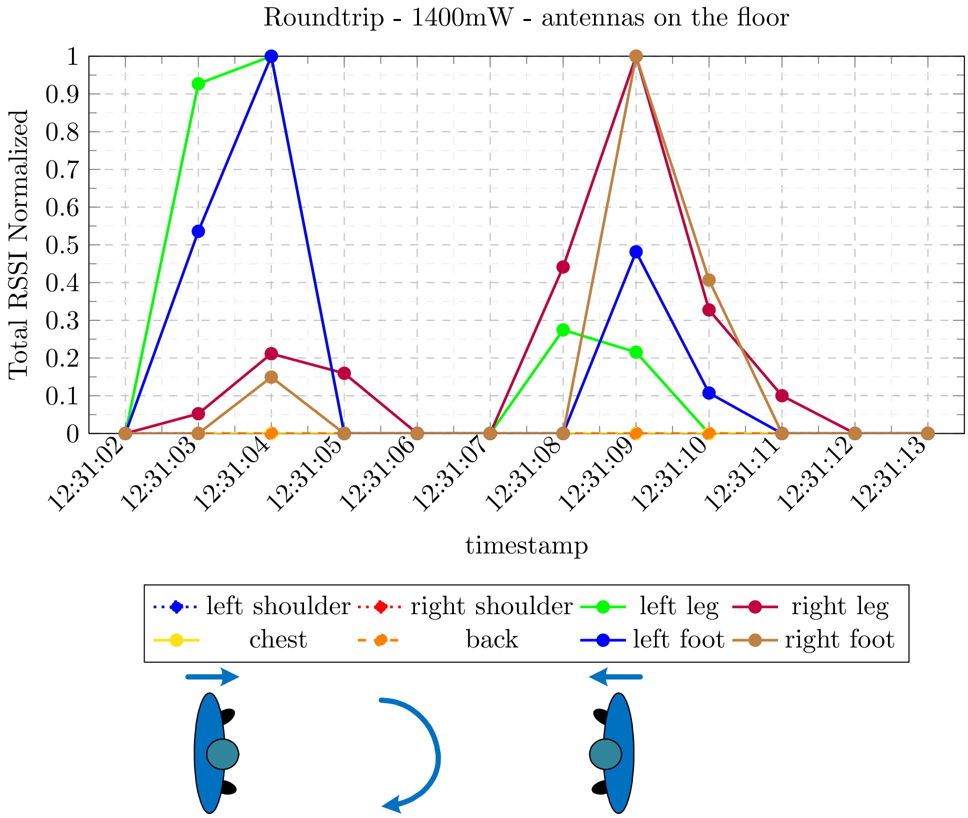

Fig. 9 Tags detection with a power 1400mW: the antennas are positioned at 20 cm and 51 cm above the floor. Tags on the chest, on the back, and on both shoulders are not read. The person completes a roundtrip passage, leaving the room at 12:31:04 and re-entering the room at 12:31:09

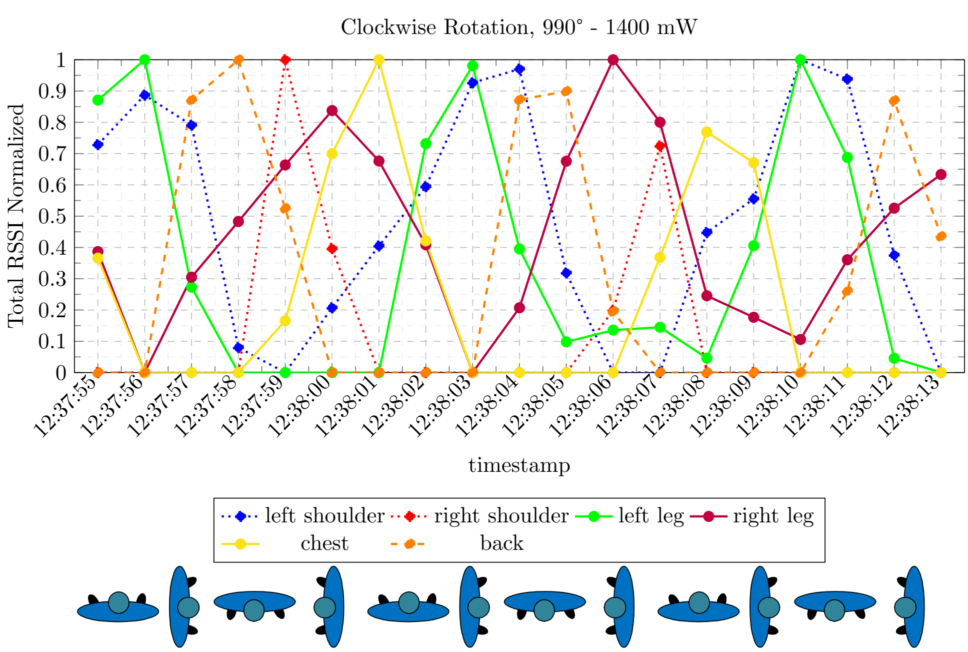

Fig. 10 Tag detection with a power 1400mW as the person rotates in front of the door. Readings alternate between the left and right tags during rotation

i. weather and climate inappropriate clothing (e.g., heavy/light clothing): for example, the person wears a heavy jacket and a heavy shirt in summer or does not wear a coat in winter. In our tests, we identified different types of fabrics and assessed whether the type of fabric is unsuitable for a given temperature and weather condition;

ii. improper body placement (e.g., different shoes): for example, the person wears two shoes not from the same pair. In the tests we perform, the person wears one brown shoe and one black shoe;

iii. unchanged clothing (e.g., same underwear): for example, the person has worn the same underwear for several days. In the tests we performed, the person has worn the same trousers for some days consecutively;

iv. missing essential clothing items (e.g., no wallet): for example, the person leaves home without their wallet, containing the documents and some pocket money. In the tests we perform, the person doesn't pick up the wallet.

Three volunteers among the four authors performed the tests. At every test, the volunteer passes through a door (distance of about 25 cm from the antennas) at a normal walking speed (about 0.7 m/sec), and wears the garment required for the test. Without compromising the generality of the approach, we assume that one experiment features only one failure: i.e., no two concurrent failures (e.g., heavy jacket in summer time *AND* different shoes, or no wallet *AND* the same pants for a long period) exist. Every test is repeated twenty times: 10 times with correct clothing or object carried along and 10 times with non-compliant clothing or object not carried along. Globally, we perform:

$$20 \text{ tests} \times 4 \text{ test types} \times 3 \text{ volunteers} = 240 \text{ experiments}$$

Table 2 summarizes the experiments. Every volunteer repeats the experiment 20 times: thus, a detection of 20 failures per test type and per person reveals a 100% success in failure detection. The experiments consist of detecting the tags and evaluating the failures in the dressing. Out of the 20 experiments, 10 are carried out in a manner compliant with what is expected (for example, dressed according to the season, pants changed, leaving home carrying along a wallet, etc.) and 10 experiments are carried out in a non-compliant manner. Since the system can only detect or not detect the tags and, based on the detection, identify the person's condition, one test can only respond with "passed" or "not passed". For example, if the person is not dressed correctly, and if the tags are detected, the system determines the non-compliant condition of the person, and the response to the test is "passed". If, instead, the person does not carry a wallet or the system does not detect the tag, the two conditions are indistinguishable, and the system returns the test as "not passed".

During the experiments, the tags are positioned on the shoulders and the back of the clothes for the upper body (jacket, shirt, sweater, etc.), on the thighs and the back of the waist for the middle part of the body, at the calf level for the socks, and in the heel or instep area for the shoes. The redundancy of the tags makes it possible to detect 100% of the clothes.

The detection of the shoes and one single object (like the wallet) is less reliable and more error-prone. For example, considering the wallet, it is difficult to detect a tag positioned in the back pocket of a trouser compared to the same tag positioned in a jacket pocket or handbag. Furthermore, we experience that if some coins are in the wallet, the tags are detected with greater difficulty or may go completely undetected.

Moreover, positioning the antennas too high above the floor could result in an incorrect detection of the shoes of the person.

To give an idea of the data analysis performed on the collected data, listing 1 depicts an example of a simple SQL query to check if the tag of a "heavy wool jacket" has been read during summertime, i.e., from May 15th to Sep 30th. Since we want to consider all the events that occurred during the last 10 s, i.e., we do not want to consider the entire history from when the system was switched to the ON position, we use the EPOCH construct to extract the seconds from the duration built upon the difference between the current timestamp and the timestamp at which the tag was read. Full details about the rule-based system can be found in [30].

```
exists select *
  from Tag join Reading on Tag_Id
  where Tag.Garment = "heavy wool jacket" and
        Reading.ReadTime between "15-May-2023" and "30-Sep-2023" and
       EPOCH(CURRENT_TIMESTAMP - Reading.ReadTime) < 10
```

Listing 1 Query to detect a weather inappropriate garment (heavy wool jacket in summer time)

Table 2 Results of correct detection of failures in dressing. Every person repeated the experiment 20 times

Test type	Detected failures person 1	Detected failures person 2	Detected failures person 3	Overal detection (%)l
Heavy jacket	20	20	20	100
Shoes	16	18	12	77
Same pants	20	20	20	100
Wallet	10	8	12	60

Listing 2 depicts an example of a simple SQL query to check if the subject has been wearing two trousers at the same time: i.e., we have two separate read values from two separate tags belonging to "trousers", and the tags are read within a time interval of less than 2 s.

```
exists select *
  from Tag as T1 join Reading as R1 on Tag_Id,
       Tag as T2 join Reading as R2 on Tag_Id
  where T1.Garment = "trousers" and T2.Garment = "trousers" and
       T1.person = T2.person and
       R1.Tag_id <> R2.tag_Id and
       ABS(EPOCH(R1.ReadTime - R2.ReadTime)) < 2
```

Listing 2 Query to detect double trousers worn by the person

The proposed solution detects the correct tags even with low to medium power levels. In the scenario tested within this study, where antennas are positioned near the door to monitor individual passages, the recommended power level is a minimum of 300 mW.

The proposed solution has also been tested to detect multiple tags simultaneously and, therefore, identify the clothing and footwear worn by individuals. Experiments including tags on underwear, inside the wallet, and on multiple clothing layers provide the same results, revealing that there is no relevant interference among the tags. Consequently, one can perform a comprehensive assessment using a set of rules that verify the suitability of attire for the current weather conditions, detect the absence of essential clothing items, patterns of outfit repetition, and duplicate garments.

By positioning at least three antennas close to the doorframe, one can detect tags on the entire body; also, by mounting the antennas on one side only of the door like in our experiments, and attaching the tags on different sides of the garments, one can distinguish the left and the right tags.

Finally, besides monitoring dressing behaviours, the experiments confirm that the proposed solution can also be used to detect the direction of a person's movement and the timing of going through the door. If a person is wearing at least two garments with right/left tags, and if one of them is reversed, the detected data would be inconsistent. Furthermore, as depicted in Fig. 8, when a person approaches the door, the chest tag is detected before the back tag; again, if one garment is reversed, an inconsistency would be detected.

Limitations

The experiments have been performed under controlled conditions and with a limited number of volunteers. These conditions may not fully represent real-world situations, potentially leading to variations in the system's performance when applied practically.

Several additional limitations, both on the technological and on the experimental side, can be detected:

- Tags inherent variability: the response of the tags (RSSI) is not uniform. In particular, even when placed at equal distances and power levels, certain tags may exhibit weaker signals or be barely detectable. Although those tags do not affect the validity of the work or the system's performance in detecting clothes, they can represent an element to pay attention to;
- Tags positioning: all clothes must be tagged and some limitations may arise in tag positioning compared to the optimal positioning as depicted in Fig. 2. For example, underwear (T-shirts) may not have sleeves for proper tag attachment;
- Multiple tags: the system uses multiple tags to detect the right, left, front, and back sides of clothing; such a multi-tag approach increases the system's costs in terms of DB management, maintenance, and data entry;
- Additional dressing failures: the proposed approach might not detect all potential dressing failures. For example, cases where individuals have dressed in the wrong sequence (e.g., wearing underwear over outer clothing or putting shoes on before pants), cannot be detected;

- Body concealment: there might be some cases of concealment if the tags on the clothing are covered by the hands while walking;
- Synchronization: the proposed system requires using four antennas placed on one side only and one control unit that synchronizes the antennas; careful synchronization is needed to avoid interference and ensure reliable tag detection. The deployed control unit is capable of managing up to four antennas. We highlight that antennas do not need to be on both sides of the door. However, to enhance the system reliability by placing antennas on both sides of the door, it becomes necessary to implement additional synchronization measures and consider using supplementary hardware components or different types of antennas.

Conclusion

In this paper, we describe the core RFID-based system that lays the foundation for a dressing monitoring system tailored to meet the needs of individuals with mild to moderate dementia living independently. We explore the feasibility of the proposed solution by implementing and testing two RFID-based prototypes. The HF prototype demonstrates some limitations in read distance and multi-tag detection; the UHF prototype, on the other hand, exhibits very promising results for its applicability. Static experiments with multiple readings at various distances, and with different power levels, provide a thorough evaluation of the system's capabilities in extended scenarios. Dynamic experiments show that the prototype can detect clothing and footwear and determine movement direction and the time of going through the door.

The proposed solution goes beyond the current state of the art to support the activity of dressing, applicable in scenarios involving elderly people and people with mild to moderate dementia living autonomously. The system can contribute to the maintenance of more autonomous living and facilitate ageing in place. Collecting data on dressing behaviour enables understanding of dressing patterns, detecting potential problems of incorrect dressing, e.g., wearing clothes that are too light or too heavy for the detected temperatures, and monitoring personal care and hygiene. In addition, data collection allows one to both detect behaviour drifts and generate reports for caregivers, which are important for providing targeted care and interventions.

Looking ahead, our future work aims to enhance the efficacy of the system by optimizing tag positioning to minimize their number while maintaining high accuracy. Experimentation involving a broader sample of subjects is needed to validate the system's performance and usability across a diverse range of individuals in real-world scenarios. Finally, the safety and ethical aspects of the deployment of the solution are also to be investigated.

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Code Availability The source code is available upon request to reviewers, only.

Declarations

Conflict of interest The authors declare that there is no Conflict of interest.

Ethics approval No ethics approval is required.

Consent to participate Not applicable.

Consent for publication Not applicable.

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