Experiences of Deploying a Citywide Crowdsourcing Platform to Search for Missing People with Dementia

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ABSTRACT

People with Dementia (PwD) suffer from a high risk of getting lost due to their cognitive deterioration, leading to potential safety hazards and significant search efforts. In this paper, we propose DEmentia Caring System (DECS), an effective crowdsourcing platform to search for missing PwD. Specifically, PwD carry our customized Bluetooth Low Energy (BLE) tags that broadcast BLE packets, which are detected and then uploaded by mobile volunteers via their smartphones. To further enhance search efficiency, DECS deploys BLE gateways as its infrastructure and analyzes PwD's daily spatial-temporal mobility patterns. DECS has been deployed in Hong Kong since 2019, supporting 3,100+ PwD's families with over 45,000 app downloads by volunteers. More importantly, it has successfully served the search for 254 missing cases. This paper reports the unique lessons and experiences learned through our 4-year citywide deployment of DECS.

CCS CONCEPTS

• **Information systems → Location based services**; **Sensor networks**; • **Networks → Location based services**.

KEYWORDS

Crowdsourcing; Searching System; Bluetooth Low Energy.

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1 INTRODUCTION

Dementia is a syndrome characterized by a decline in cognitive abilities that affects a person's daily functioning [15]. According to the latest report from the World Health Organization (WHO), more than 55 million people worldwide live with dementia, and there are nearly 10 million new cases diagnosed annually [40]. People with Dementia (PwD[1]) face a high risk of becoming lost, exposing them to injury vulnerabilities and potentially life-threatening situations due to memory loss and cognitive impairments [6, 31, 31, 42]. Additionally, the impact extends beyond the individuals themselves, exerting significant pressure on their family members and caretakers [43, 44].

To ensure PwD can live normally in society, a supportive system is essential to report their loss, gather clues, and assist caretakers, families, and the police in finding them as quickly as possible when they get lost. Consequently, it has attracted much attention in both academia and industry [36]. Table 1 shows a few operational systems for searching for PwD in different countries. Many systems [2, 5, 19, 39] adopt the straightforward solution by attaching a bracelet to each PwD, which records his/her identity and family information. When PwD are lost, passersby who see the bracelets could scan the bracelets to help locate these missing persons. Such a system relies on volunteers to observe with eyes, introducing additional manual efforts. Moreover, it is difficult to accurately identify who is actually lost, leading to low efficiency in the search process. Other approaches are utilizing devices equipped with Global Position System (GPS) and local network modules, such as smartwatches [35, 49, 54] and smart-tag [20]. While commendable, the reliance on power-hungry GPS devices imposes limitations on their long-term

[1]We use "PwD" to refer to both singular and plural forms of People with Dementia.

Table 1: Search systems for missing PwD. Medical IDs in [5, 19, 39] are usually recorded on bracelets.

Area Served	Project	Method
U.S.	Lifesaver [49]	GPS
U.S.	Safe Return [5]	Medical ID
Canada	Safely Home [39]	Medical ID
China	Yellow Bracelet Action [2]	GPS & QR code
Worldwide	MedicAlert [19]	Medical ID

usability and user convenience, which are especially crucial for PwD with cognitive issues. Another possible solution is generic tracking, such as Apple AirTag [4] and Samsung SmartTag [37], designed for tracking personal belongings instead of human beings. When applied to PwD search, they suffer from serious limitations including limited geographical coverage, user policy violation, poor usability, and a lack of historical trace access (detailed in Sec. 10).

In this study, we propose a novel, effective, and power-saving system called DEmentia Caring System (DECS), to search for missing PwD. DECS relies on angels (volunteers) and angel boxes (customized BLE gateways) to help locate the missing PwD. DECS offers lightweight Bluetooth Low Energy (BLE) tags for PwD to carry throughout their daily activities. When PwD are missing, their caretakers can report the incidents using the DECS's mobile app. Notifications are then dispatched to angels for assistance in the search. When an angel or angel box is in proximity to the missing individuals, the sensed BLE signal along with the angel or angel box's location will be uploaded to DECS. Based on these inputs, DECS employs propagation model techniques [21] to determine the missing persons' locations, subsequently sending them to the caretakers for prompt search. To further enhance the searching efficiency, DECS leverages historical (spatial-temporal) data analytics to provide mobility characteristics (*e.g.,* frequently visiting regions) for hints and prediction.

To facilitate the efficient search, we design DECS with the following unique features. (1) *Customized BLE tags:* Our tags are specially designed for PwD and can be seamlessly integrated into their personal belongings (*e.g.,* crutches, wallets). This mechanism ensures PwD will carry them when going out. Additionally, we are planning to integrate the medical alert bracelet form factor into the system, which might accommodate these forgetful people. In contrast to GPS devices with a mere battery life of 2-10 days, our tags can function effectively for over a year without requiring charging. (2) *Customized angel boxes:* Angel boxes are designed with an enhanced antenna to receive signals broadcast from tags. These boxes can operate around the clock and are strategically placed at bus stations and indoor sites, serving as an integral part of the citywide infrastructure to improve search efficiency. (3) *Spatial-temporal data mining:* DECS uses spatial-temporal data mining techniques to analyze the mobility of PwD based on their trajectory data. These approaches provide valuable insights into their movements, such as stay points and mobility heatmaps. Studies have shown that PwD often revisit familiar regions when they become lost [8]. Therefore, the analysis results can serve as critical clues in searching for missing individuals. (4) *Privacy protection and anti-abusing:* To safeguard the privacy of angels, their identities are randomly generated and changed periodically, preventing easy tracking. Meanwhile, protecting the privacy of PwD involves access control and restricted location data access for authorized personnel, such as caretakers. Furthermore, our system is designed to minimize the risk of improper use by requiring caretakers to provide supporting documentation (medical certificate) for PwD and sign an agreement during registration.

During DECS's 4-year deployment in Hong Kong (HK), DECS has been downloaded over 45,000 times and served 3,100+ PwD. More importantly, DECS has contributed to the successful search of 254 missing cases. To the best of our knowledge, DECS is the first work to offer its unique lessons and insights gained through a city-wide search system. Details are as follows.

- DECS's goal is to ensure a quick and efficient search of missing PwD. Our analysis and validation reveal the importance of quick initial signal scan time (time gap between reporting missing cases and first signal capture), which should be a primary consideration when designing similar systems.
- Recognizing that PwD tend to revisit familiar regions when lost, pinpointing their daily areas can offer vital search clues. Furthermore, the implementation of trajectory prediction can enhance the search process by anticipating potential paths for missing PwD, thereby expediting the search efforts.
- DECS also observes the 80-20 rule, where a small percentage of angels make a significant contribution to crowdsourcing. However, DECS's application requires broad geographical coverage, which cannot be fulfilled by limited active angels. Thus, it is essential to introduce additional hardware, such as the angel box, to complement the geographical coverage of angels.
- Our trace-driven emulation (Sec. 7) validates multiple significant advantages (*e.g.,* shorten initial signal scan time) if we integrate the current DECS with LoRa. These benefits serve as motivation for our next phase of improving DECS, aiming to enhance search efficiency, ultimately contributing to the realization of a dementia-friendly community.
- DECS received positive feedback from 860 caretakers who joined DECS for over a year. Caretakers found the app user-friendly, and PwD are willing to carry our tags.

Ethical Consideration. All the analyses conducted in this paper comply with the agreement established between DECS and caretakers of PwD. No data used in this paper contains personally identifiable information (PII). We never correlate PwD location with their true identities.

2 BACKGROUND AND MOTIVATION

2.1 Dementia Background

Outdoor activity is essential for the PwD, as it offers numerous health benefits and contributes to the preservation of cognitive functions [29]. Unfortunately, PwD suffer from cognitive and functional impairments that may lead to disorientation and the risk of getting lost unpredictably [12, 47]. Even in the presence of caretakers, the sudden onset of illness can inadvertently lead to the departure of PwD from their caretakers [48]. Past studies have reported the likelihood of PwD becoming lost ranges from 46% to 71%, and such incidents can happen during their daily activities [3, 10, 51]. This not only calls for significant human efforts to locate lost PwD, but also leads to severe health threats. According to [46, 48], as many as half of PwD who remain lost for over 24 hours may experience severe injury or even death. To encourage them to participate in outdoor activities [17] and alleviate the potential hazards [27, 45] when PwD get lost, an efficient search platform is required. A report indicates that the proportion of demented individuals who go missing in HK is as high as 27.9% [30].

2.2 Crowdsourcing

Localization techniques have been widely studied and tested in existing literature. For example, GPS is widely deployed for localization and tracking PwD [33]. However, the power-hungry nature inevitably leads to frequent battery recharging and user inconvenience, which could be especially critical for PwD with cognitive issues. Instead, the idea of crowdsourcing offers a potentially long lifetime for sensors by leveraging the contribution of the community. As a metropolitan city, HK's population density ranks among the top three in the world [11]. The high population density offers the potential opportunity of tracking PwD. In addition, crowdsourcing is cost-effective, as it demands little infrastructure deployment. Individuals can contribute to locating missing persons by simply downloading our mobile app, thus facilitating collaborative efforts in search and rescue endeavors. As for the signal choice, we chose BLE devices because of their small size, portability, and wide applicability on commodity smartphones for crowdsourcing.

3 THE DECS SYSTEM

DECS aims to provide location clues and facilitate the search for missing PwD by utilizing crowdsourcing technology. Sec. 3.1 elaborates the workflow of DECS. As discussed in Sec. 3.2, multiple personnel participate and collaborate to enable efficient search. DECS's components are included in Sec. 3.3.

3.1 System Workflow

We illustrate the basic workflow of the DECS system in Figure 1: (1) PwD carry beacon tags in their daily life, which continually broadcast BLE signals. (2) An embedded BLE scanning module in a smartphone app of volunteers and the angel boxes are utilized to receive BLE signals from beacon tags when in proximity. These signals and the associated locations (angels or angel boxes' locations) are then uploaded to a cloud server. Note that the uploading is in an anonymous manner so that no personal information would be used and it would not raise any privacy concerns. (3) Leveraging these data, the localization service in the cloud server employs propagation model techniques [21] to compute and update the location of PwD to their caretakers. The data analysis module collects daily location data and processes it into spatio-temporal trajectory (Sec. 5). When PwD become lost, DECS utilizes these trajectory data to extract their mobility characteristics, offering search hints (*e.g.,* frequently visiting regions, historical mobility heatmap, *etc.*) for caretakers. (4) When caretakers identify that PwD have gone missing, they can report the cases to the server. The loss report management module on the server will then send notifications to angels, prompting them to assist in the search. Caretakers utilize real-time location and searching clues provided by the app to conduct searches, often involving friends and family until the missing person is located.

3.2 Personnel

DECS benefits from the caring community, such as caretakers and volunteer angels, who devote their efforts to support our system. Figure 1 demonstrates the participating entities in DECS's workflow.

People with Dementia (PwD). PwD might get lost due to navigation impairment. To facilitate efficient search efforts, DECS requests that caretakers attach our BLE tags to PwD whenever they are outdoors, as a precaution for potential missing incidents.

Caretakers. A caretaker is responsible for taking care of specific PwD. Through our system, caretakers apply for BLE tags and download our mobile app. After registration and association of a BLE tag to PwD, this caretaker could view the real-time location. In cases where PwD are missing, caretakers can utilize our app to initiate the search. Caretakers also have the option to post additional details (such as height, clothes, and pictures) to facilitate angels' search.

Angels. Angels are volunteers who install our mobile app on their smartphones and search for the missing PwD. When a missing case is reported by the caretaker, DECS will push notifications through the app to angels. If they prefer to assist, they will activate their app to receive BLE packets broadcast from BLE tags. Importantly, angels also have the option to proactively use the app to help locate other PwD who are

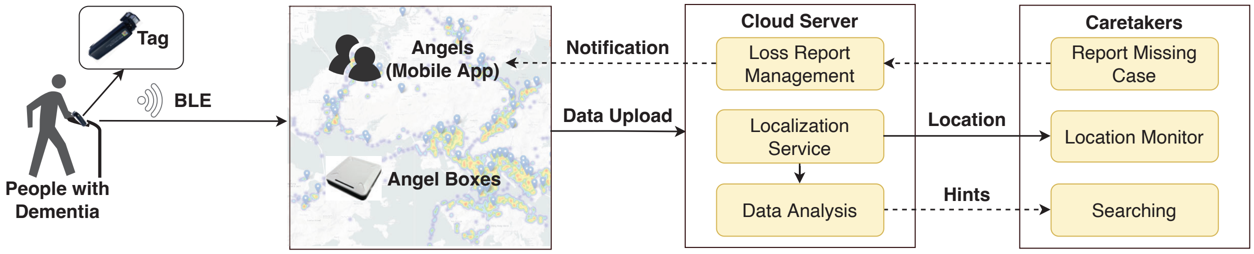


Figure 1: Workflow of DECS. The solid lines represent daily activity monitoring of PwD, while the dashed lines indicate additional actions taken when a missing case occurs.

not currently reported as lost. When the app receives a BLE packet, it will upload the packet along with its current GPS data and anonymous angel ID. Importantly, we generate the angel ID randomly to protect the privacy of the angels and prevent other potential security leaks.

3.3 System Components

In addition to the aforementioned human participants, DECS also has hardware support, including beacon tags, angel boxes, mobile app, and cloud server.

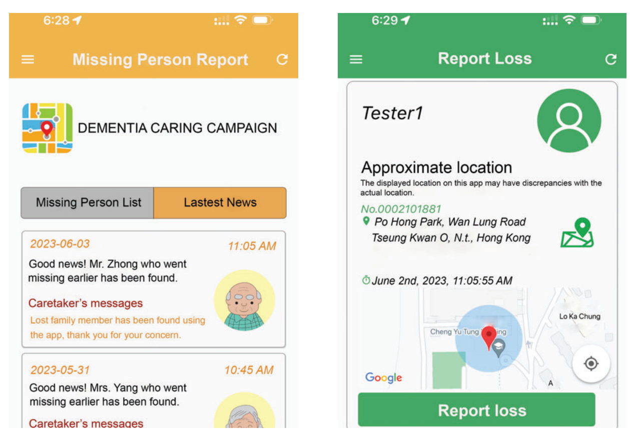
Beacon Tags. Unlike the conventional localization systems [16] that care more about accurate localization/sensing, our primary goal is to ensure reliable search. First, since GPS's high power consumption leads to frequent battery recharging [24], we chose to leverage BLE radios on these tags, which offer a lifetime of around one year without recharging. Second, we designed different types of tags in Table 2 that are lightweight and specifically adjusted to meet the PwD's needs. More design details are included in the next section. By providing different options of beacon tags, caretakers can select the most suitable tag for their dementia families, increasing the chances of them carrying the tag when they go out. Overall, the customization of the hardware based on PwD's living habits is a crucial consideration for the effectiveness and usability of beacon tags for PwD.

Table 2: Three types of beacon tags.

Type	Crutch holder	Button type	Card type
Appearance			
Lifetime	1 year	1 year	1 year

Angel Box. In addition to opportunistic crowdsourcing via angels, we also introduce angel box, a customized BLE gateway that is equipped with a cellular module for data uploading. We embed stronger antennas in the angel box, which can enlarge the scanning range to up to 100 meters. Besides, the box has multiple power supply modes, and they work 24/7 as long as there is a stable supply of electricity, which increases the probability of finding lost people. Our deployment strategy is to complement the areas with little coverage by angels, which could result from multiple factors, such as adverse weather conditions and time of day (*e.g.*, midnight). Currently, angel boxes are deployed at hot spots such as bus stations and shopping malls to increase the chances of detecting missing people. Until now, we have deployed around 100 angel boxes at bus stops, underground shops, and shopping malls in the city.

Mobile App. Our mobile app (Figure 2) contains two modes designed for angels and caretakers, respectively. In the caretaker mode, caretakers could register PwD, apply for tags, and configure tags. Once PwD get lost, the corresponding caretakers will report incidents on the app with a potential description (*e.g.*, height, weight, clothes, and pictures). This will trigger notifications to be sent to angels to enhance the search. For angels, upon receiving a broadcasted BLE packet, the mobile app will upload its status information (*e.g.*, current location) along with the detected beacons and their corresponding received signal strength.



(a) Angel (b) Caretaker

Figure 2: The user interface of our app.

Cloud Server. Our cloud server receives the data uploaded from angels and angel boxes, and tracks PwD. It further analyzes the historical spatial-temporal data to understand the mobility behavior of PwD. Such analysis can provide valuable information for caretakers when searching for missing people. Our DECS adopts multiple strategies for privacy preservation, details in Sec. 8.

4 SYSTEM DEPLOYMENT PHASES

Since DECS's debut in Sep. 2019, we have been improving DECS with several phases, including the proof of concept (PoC) phase and citywide operation. The deployment motivates us to improve DECS in the future phase.

4.1 PoC Phase (2019/09 - 2020/09)

In our PoC phase, we designed DECS and evaluated it on a small scale to verify its feasibility.

Feasibility via Crowdsourcing. To evaluate the feasibility, we recruited 70 volunteers to act as angels and invited 30 caretakers with their dementia families. The testing smartphones comprise 20 iPhones and 50 Android phones of different models. We conducted controlled experiments in 3 districts in HK, including shopping malls, campuses, and various outdoor zones. In these regions, angels and PwD followed their typical activity patterns. The results demonstrated that when angels approached PwD, caretakers could observe the updated positions of PwD within the mobile app. This validation confirms the feasibility of crowdsourcing.

Beacon Tags Design. Initially, we tested two types of commercial beacon tags and gathered valuable feedback from PwD's caretakers. One notable challenge observed was that PwD frequently forgot to carry the beacon tags with them when going out. This feedback served as a key motivator for us to undertake the design of tags specifically tailored for PwD, with a focus on user-friendly features. In addition, we conducted social surveys and consulted with some welfare homes to gather valuable information about PwD.

As a result, we customized three specialized beacon tags (Sec. 3.3). (1) Crutch-type beacon. According to prior studies [14, 55], the majority of PwD in HK are elderly, with more than 60% of them aged 70 or above. Since some elderly PwD have restricted mobility and often utilize crutches in outdoor activities, we developed a beacon tag to be hung on a crutch. This beacon tag is user-friendly since it is lightweight and easy to attach, ensuring convenience for PwD to carry wherever they go. (2) Button-type beacon. In addition, we have developed a button-shaped beacon tag with a keychain attachment, specifically designed for PwD who carry other items regularly. This compact and lightweight beacon tag can be easily hung on items such as keys, ensuring convenience and portability. The discreet design of the circle beacon tag allows PwD to carry it without drawing attention or feeling burdened. Its unobtrusive nature enables seamless integration into their daily routines. (3) Card-type beacon. The last one is a card-type beacon tag, which is very thin and lightweight, leaving a hole in the card so that the user can snap it to other items such as wallets, and bags. By aligning the hardware with the habits of PwD, our beacon tags are tailored to seamlessly integrate into their daily lives, ensuring greater efficacy and usability.

Smartphone Battery Consumption Optimization. To mitigate energy consumption on the smartphones of angel users, we developed multiple dynamic strategies that aim to automatically adjust the acquisition frequency of various signals based on different scenarios. When an angel user scans a beacon signal of a dementia individual who is in normal egression, our app is in *normal* mode to conserve energy. In contrast, when scanning a BLE packet from a missing person, our app turns to *search* mode and automatically increases the scanning frequency of BLE to facilitate quick search.

4.2 Operation Phase (2020/10 - Now)

After our PoC, we deployed DECS across the entire HK. Till now, 3,155 PwD and more than 45,000 angels are using the DECS system.

(I) Advocacy. To attract more participants, we initiated comprehensive online campaigns utilizing social media and websites, alongside meaningful collaborations with community organizations for offline events and exhibitions, including prominent platforms like the Global Innovations in Education Summit (GIES) [22].

To enhance effective search, we have established collaborations with numerous welfare homes, shopping malls, and subway stations. For example, we have partnered with MTR (Mass Transit Railway) to download our application on tablet computers stationed in the customer service centers of all MTR and light rail stations across HK.

(II) In-the-Wild Operation. Figure 3 and Figure 4 show the number of mobile app downloads and registered PwD since Oct. 2020. Until now, our system has been servicing 3,155 PwD. As Figure 3 shows, the mobile app has been downloaded over 45,000 times, specifically 19,472 downloads on iOS devices and 25,566 downloads on Android devices. Both figures illustrate a significant surge in the starting phase. This surge is attributed to the success of publicity activities carried out during the advocacy stage, attracting a substantial number of families with PwD and angel users. In July 2023, the daily average scanned BLE packets is about 46k. This suggests the active participation and engagement of angel users in the system, contributing to the effectiveness of the DECS system in locating and providing support for PwD.

During our deployment, we noticed several constraints of crowdsourcing via angels, including their reduced activity during nighttime, adverse weather conditions, and limited geographical coverage. To complement angels, we have introduced the angel box (Sec. 3.3). This device can be strategically installed in stationary positions or on mobile vehicles, operating round-the-clock. Due to aesthetic consideration, the angel box is designed with a subtle appearance, allowing for discreet placement in building corners, such as installation on shopping mall ceilings or at bus stop service centers. The installation process is intricate and necessitates negotiations with various third-party entities at each site. Nonetheless, we have collaborated with bus companies and several shopping malls with an installment of over 100 angel boxes.

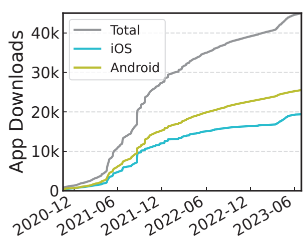


Figure 3: App downloads.

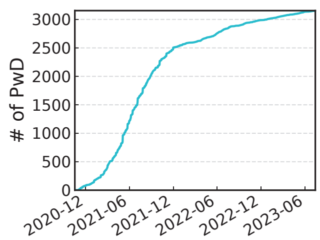


Figure 4: Number of PwD.

4.3 Future Phase

Our 4-year deployment motivates us with the following improvement in our next phase. (1) We plan to enhance search efficiency by integrating LoRa on our customized tag and leveraging HK's existing urban LoRa infrastructure gateways. This evolution will empower us to provide faster response time and broader coverage, ensuring a more effective and efficient approach to locating PwD. Our preliminary trace-driven emulation demonstrates the potential significant improvement in Sec. 7. (2) We are negotiating with more entities for additional deployment of angel boxes.

5 DAILY TRAJECTORY ANALYTICS

This section analyzes the *daily* trajectories of PwD to understand their spatial-temporal features, which will be leveraged to improve our performance for searching *missing* PwD (Sec. 6). Our dataset covers 3,155 PwD from Oct. 2020 to now.

5.1 Trajectory Description

The dementia trajectory record includes an encrypted user ID u, the location represented by latitude and longitude *(lat,lon)*, and the collected timestamp t. Due to the limitation of crowdsourcing, trajectories of PwD might be disconnected and include several disconnected segments.

Specifically, a user trajectory is represented as a sequence of positions: $Tra = \{(\ell_1, t_1), ..., (\ell_i, t_i), ..., (\ell_n, t_n)\}$, where position $p_i = (\ell_i, t_i)$ indicates the user location $\ell_i = (lat_i, lon_i)$ at time t_i.

5.2 Trajectory Processing

Trajectory Denoising. Trajectory points could be affected by angels' location errors due to environmental factors. To mitigate this issue, we choose to filter out large trajectory deviations. Our idea is to calculate the PwD's moving speed - if the speed at a particular position exceeds a predetermined threshold, we identify it as noise and exclude it from the trajectory. This threshold is designed to accommodate different moving speeds, accounting for both walking and vehicle-related movements.

Stay Point Detection. Existing literature has discovered that PwD tend to revisit their familiar spots [8]. A stay point refers to a specific location where an individual with dementia spends a notable amount of time before moving to another place. In the context of analyzing PwD's trajectories, stay points are identified as clusters of consecutive data points within a defined spatial and temporal proximity. These clusters represent instances where PwD remained relatively stationary, indicating a familiar or frequently visited spot. The detection of stay points allows for the understanding of an individual's regular haunts or routine stops, contributing to insights into their mobility patterns and behavior. To detect stay points, we adopt a spatial-temporal clustering algorithm to extract stay points from PwD's trajectories.

Given two consecutive points p_i and p_{i+1} where $1 \leq i < n$. If the calculated distance is below a certain threshold, we add p_{i+1} to the cluster that p_i belongs to; otherwise, p_{i+1} is added to a new cluster. Once all points are evaluated, we further analyze each cluster's dwell time, which is calculated as the maximum time interval between positions in the cluster. If the dwell time of a cluster with more than two positions exceeds a threshold value, we define the cluster as a stay point, represented by the average location of all points belonging to this cluster.

Trajectory Segmentation. In addition to separated stay points, PwD could transit from one stay point to another, leading to a transiting trajectory. Given a trajectory, if the position sequence $\{p_i, p_{i+1}, \cdots, p_j\}$ forms a stay point, we split the trajectory as two segments, $\{p_1, p_2, \cdots p_i\}$ and $\{p_j, p_{j+1}, \cdots p_n\}$. Since DECS is a crowdsourcing system, PwD's trajectory might not be observed temporarily, we further partition a segment based on time interval. If the time interval between two consecutive points p_i and p_{i+1} is large enough (*e.g.,* more than 30 minutes), the two points are assigned to different segments.

5.3 Spatial-Temporal Characteristic

Mobility Visualization. Our system could generate several heatmaps to visualize the mobility of PwD. Figure 5 presents the stay points visited by PwD, with darker colors indicating more people visit. The heatmap allows us to identify popular areas for PwD, which include downtown areas with high foot traffic, as well as country parks in the northeast of HK.

Figure 6 presents the heatmap of an individual's stay points, highlighting the areas he/she frequently visits. Darker colors in a particular location indicate a higher frequency of visitation by the person. The mobility heatmap of PwD

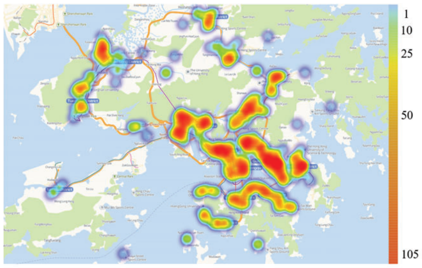


Figure 5: A heatmap of overall stay points.

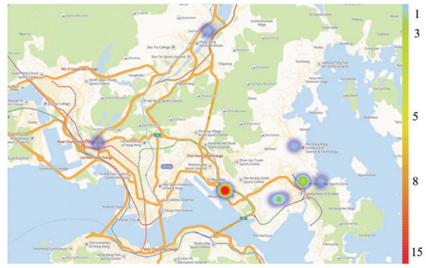


Figure 6: An individual with dementia's stay point heatmap.

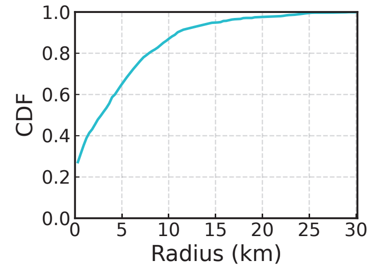


Figure 7: Mobility radius of PwD.

is a powerful tool for enhancing their safety and well-being, as it can provide clues to speed up the search and also offer valuable information for his/her caretaker.

Mobility Radius Detection. Mobility radius of an individual is defined as the average distance between one's stay points and his/her most frequently visited location (*i.e.,* primary location). This metric is often used to analyze the mobility and lifespace of PwD [8, 9]. By understanding an individual's mobility radius, researchers and caretakers can identify potential challenges and opportunities for support, as well as track changes in their condition over time.

To determine an individual's most frequently visited location, we utilize the DBSCAN algorithm [18] to cluster his/her stay points, identifying the cluster with the greatest dwell time as the primary location for further analysis. Compared to other clustering methods (*e.g.,* K-Means and Hierarchical Clustering), DBSCAN possesses robustness against noise and can automatically determine the number of clusters based on data density and connectivity. This eliminates the necessity for manual tuning or reliance on assumptions about the number of clusters, offering both convenience and flexibility.

Based on the clustering results, we calculate the mobility radius for each person with dementia based on their stay points and primary location. We visualize the cumulative distribution function of all users' mobility radius in Figure 7. Notably, the data reveals that over 20% of dementia users exhibit no outdoor activity, while approximately 60% have a mobility radius of less than 5 km. These findings provide critical insights into the mobility patterns of PwD and may inform the development of targeted interventions to improve their quality of life.

Temporal Distribution of Outdoor Mobility. We analyze the temporal distribution of outdoor mobility among PwD. To capture the distribution, we divided each day into 24 hours. We identified instances of outdoor activity by individuals who visited a location more than 50 meters away from their primary location during a given time slot. Our findings, presented in Figure 8, reveal that outdoor activity is more prevalent during the daytime than at night, with

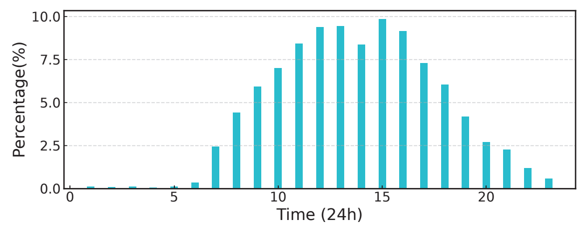


Figure 8: Temporal distribution of dementia mobility.

the highest frequency occurring between 11:00 and 17:00. Notably, there is a drop in activity at 14:00, which may be attributed to afternoon napping. After 17:00, the frequency of outdoor mobility significantly declines, suggesting that many individuals may prefer to engage in outdoor activities earlier in the day.

6 DEPLOYMENT RESULTS

In this section, we evaluate the DECS's performance in the real world by analyzing its search of 254 PwD during its 4-year deployment. This section will first investigate the successful cases, followed by the angel behavior analysis, angel box verification, user feedback, and energy consumption.

6.1 Successful Search

During its operation, DECS has served the search of 254 PwD. A successful search is characterized by the safe retrieval of the lost PwD. Specifically, after a caretaker reports a missing individual through our system, DECS generates location hints to assist the caretaker. Upon the safe retrieval of missing PwD, this caretaker confirms the successful search through our system. Detailed analysis is as follows.

Search Duration Distribution. The search duration $\Delta t2$ in Figure 9 is the time difference between when a caretaker actively reports a case of missing dementia and the time when this caretaker acknowledges finding this missing person. Figure 9 illustrates the entire process of a missing case. Once a caretaker reports the missing person ($T1$), DECS sends a notification to angels. The *initial signal received* ($T2$) denotes the moment when the missing person's tag is detected for the first time in this search. With the help of DECS,

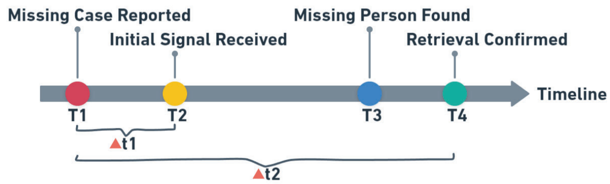


Figure 9: Timeline of searching missing PwD.

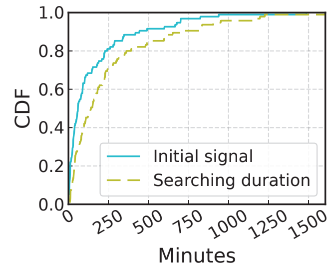


Figure 10: Duration distribution.

the caretaker locates the missing person at $T3$, followed by the confirmation at $T4$. However, it's possible that some caretakers might not promptly respond to the system after locating the missing individual, leading to delayed reporting of the recovery time. To address this issue, we have filtered out six exceptional data points from the analysis. The search duration is a very critical factor in ensuring PwD's safety and well-being, as prolonged search times can increase the risk of adverse outcomes, such as falls, or other accidents [28]. A faster search not only reduces the missing PwD's health risks but also alleviates the incurred labor cost.

Table 3 summarizes the search duration distribution for all missing cases. Remarkably, 58% of reported cases were successfully resolved within less than 2 hours, suggesting DECS's efficient search and help to serve the dementia community. Detailed search duration distribution is depicted in Figure 10. According to a prior study [31], only 15% missing cases were found within less than 6 hours, and the search for the missing person could take more than one week. Although direct comparisons between DECS and previous systems are nearly impossible, DECS effectively facilitates efficient search to serve PwD and their families. Compared with traditional search methods (*e.g.,* using social media), DECS offers multiple unique features, including an extensive network of angels and the infrastructure deployment of angel boxes, which enhance the initial signal scan time and expedite the search procedure, as discussed later. Additional designs, such as spatial-temporal mining, further contribute to DECS's efficient search.

Table 3: Distribution of searching duration.

Duration (hour)	< 2	2 - 4	4 - 6	6 - 12	12 - 26
Ratio (%)	58	16	7	8	11

Initial Signal Scan Time. The initial signal scan time $\Delta t1$ is defined as the gap between the time that the missing case is reported to DECS and the time that DECS first collects the missing PwD's signal. The median response time is 59.22 minutes shown in Figure 10.

There is a strong positive Pearson correlation of 0.86 between initial signal scan time and searching duration, indicating a significant relationship between the time it takes for the initial signal scan and the overall duration of the search and recovery process. This high correlation underscores the importance of improving the initial signal scan time as it directly impacts the efficiency and effectiveness of the entire search process. To further validate this, we participated in a few searches. Caretakers directly utilize location clues provided by DECS to search the nearby areas manually, while they often seek assistance from the missing PwD's friends and family to speed up the search procedure.

■ **Lesson 1.** *The robust Pearson correlation (0.86) between initial signal scan time and search duration emphasizes their close link in the search for missing PwD. Enhancing initial signal scan time significantly affects overall search efficiency. Overall, the initial signal scan time is crucial for quickly finding missing PwD and should be prioritized in similar systems design.*

The Impact of Indoor and Outdoor Activities on the Search Duration. We classify all missing cases into three categories based on their activities at the time of disappearance: those solely engaged in indoor activities, those solely involved in outdoor activities, and those participating in both indoor and outdoor activities. These activity groups exhibit varying influences on the search duration, with median search times of 137 minutes for indoor activities, 150.5 minutes for outdoor activities, and 198.5 minutes for cases involving both indoor and outdoor activities. Indeed, cases involving both indoor and outdoor activities present the greatest search difficulty.

■ **Finding 1.** *Cases involving both indoor and outdoor activities exhibit longer search times compared to those solely outdoors. This is attributed to HK's metropolitan features characterized by complex, high-density building layouts, which can complicate search efforts due to the diverse range of indoor and outdoor activities.*

Relationship between the Lost Trajectory and Daily Stay Point. By analyzing the mobility patterns of missing PwD and comparing them to their daily behavior, we conducted a distance difference analysis between their location at the time of going missing and their nearest daily stay point. The average error in this comparison was approximately

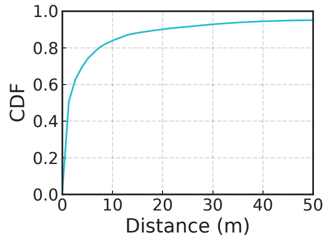


Figure 11: The distance between PwD's trajectory when lost and the location of their usual activities.

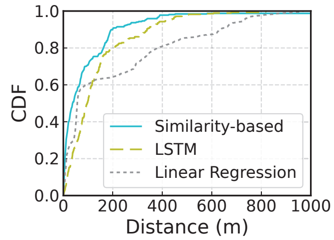


Figure 12: Error of trajectory prediction.

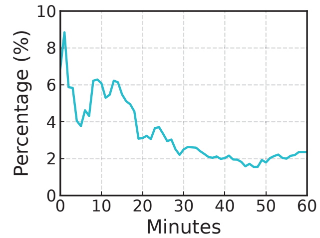


Figure 13: Angel growth rate after sending notification.

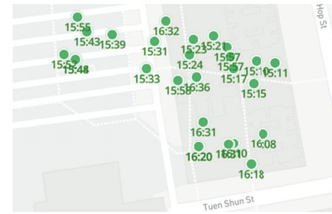


Figure 14: A case study with all locations of the lost PwD during the missing period.

33.31m, as shown in Figure 11. We observed a long tail of errors reaching up to 9.8 km, accounting for 3.06% of cases, attributed to limited daily activity data for missing PwD. The sparse data may lead to larger discrepancies between their location at the time of going missing and their nearest daily stay point, resulting in the observed variability in the error distribution. Overall, the analysis indicates a strong inclination for PwD to revisit familiar areas when they become lost. Therefore, gaining a comprehensive understanding of the areas they typically visit can provide valuable clues and significantly enhance the efficiency of search and rescue efforts. By prioritizing search operations in these familiar areas, caretakers, communities, and search teams can optimize their resources and increase the likelihood of locating missing individuals promptly and safely.

Trajectory Prediction. To reduce search efforts, we propose a similarity-based algorithm to predict the potential trajectory of missing PwD. Denote a set of historical trajectories as $\{Tra_i\}_{i=1}^N$ and the trajectory collected after the individual was reported missing as $\hat{Tra} = \{\hat{p}_1, \hat{p}_2, \cdots \hat{p}_n\}$, where n is the number of uploaded locations in $\hat{Tra}$. Our proposed algorithm evaluates the distance between $\hat{Tra}$ and Tra_i and selects the top k similar trajectories as candidates for prediction. For each location $\hat{p}_j$ in $\hat{Tra}$, its distance to Tra_i is defined as the distance to its closest location in Tra_i:

$$dis(\hat{p}_j, Tra_i) = \min_{p_u^i \in Tra_i} dis(\hat{p}_j, p_u^i) \tag{1}$$

$dis(\hat{p}_j, p_u^i)$ is the Euclidean distance between the two locations. Then the distance between $\hat{Tra}$ and Tra_i is defined as:

$$dis(\hat{Tra}, Tra_i) = \frac{1}{n}\sum_{j=1}^{n} dis(\hat{p}_j, Tra_i), \tag{2}$$

Next, when Tra_i is among the top-k similar trajectories, we leverage it to predict the subsequent positions of the missing PwD. Given the most recent location ($\hat{p}_n$) of the missing PwD, we will search Tra_i to find the nearest location, denoted as p_c^i, and obtain the subsequent predictions as $\{p_{c+1}^i, p_{c+2}^i, \cdots, p_m^i\}$. Our algorithm will utilize each of the top-k similar historical trajectories for prediction and provide them to caretakers to facilitate search.

This predictive model evaluates all missing cases, and the distance error distribution is shown in Figure 12. The mean distance error is 159.8m. Indeed, the vast majority (99.3%) of prediction errors are less than 500m, which can be attributed to the fact that PwD often follow familiar daily routes. However, there are still some long-tail errors that arise due to the sparse nature of the daily trajectories of PwD. This scarcity of data can lead to larger prediction errors in certain cases. We compared our similarity-based algorithm with the widely-used location prediction techniques of LSTM and Linear Regression. As evidenced by the comparison in Figure 12, our proposed approach outperforms both baseline methods in terms of prediction accuracy.

■ **Lesson 2.** *Given that PwD often revisit familiar areas when lost, identifying their daily areas can provide crucial search insights. Additionally, employing trajectory prediction can further expedite the search process by predicting the potential trajectory for missing PwD.*

6.2 A Case Study

In addition to statistical analysis, we also conducted a case study to illustrate the entire search process, starting from the caretaker's initial report of the loss to the caretaker's confirmation of successful retrieval. An 83-year-old PwD left his apartment in the morning but did not return home as usual [26]. Consequently, this PwD's caretaker reported the missing case through our system at 2:25 pm ($T1$ in Figure 9) and received the PwD's location updates 45 minutes later ($T2$). Detailed location updates with time are visualized in Figure 14. This caretaker visited locations provided by DECS and successfully found the missing PwD. This retrieval is confirmed via DECS at 4:38 pm ($T4$).

During the search period, four angels anonymously contributed 18 updates, and one angel box contributed 13 updates. Notably, angels cannot recognize and directly find the missing individuals because they remain unaware of the specific missing PwD unless their caretakers provide public pictures in our app. Overall, this search duration ($\Delta t2$) is around 2.2 hours, with an initial signal scan time ($\Delta t1$) of 45 minutes. We observed that, apart from the actual search time, two factors could lead to longer searching duration: (1) the time it took for the caretaker to reach the location provided by DECS, and (2) a temporal gap between the retrieval of the missing PwD ($T3$) and the confirmation of retrieval ($T4$). In addition, we also recognized that this PwD frequently engaged in outdoor activities near the locations where he went missing.

6.3 Angel Behavior Analysis

The Impact of Notification. When a caretaker reports a missing case, the server sends a notification to angel users. We compare the proportion of online angels before and after the notification is sent at the same time interval, as shown in Figure 13. Immediately after sending the notification, the online count increases by 8.95%. However, this gradually declines to around 2% over time. In conclusion, while notifications do prompt an initial increase in angel engagement, their impact on user participation appears limited.

■ **Finding 2.** *Reliance on notifications alone results in low user conversion rates, prompting the need to explore alternative methods for stimulating conversions.*

Participation Level. In the first hour after the missing person notification was sent, online angel users were categorized according to their level of involvement in the search efforts. The classification was based on the number of times each user participated in searching for missing cases. Among the angel users, there were four individuals who actively participated in the search of over 50 missing cases, indicating a high level of dedication. Furthermore, 73 angel users engaged in a moderate number of searches, ranging from 20 to 50 cases, showcasing their commitment to assist with multiple searches. Additionally, there are 1,797 individuals, each involved in fewer than 20 searches. This classification provides insight into the diverse levels of engagement among angel users within the critical first hour following the notification of missing cases.

■ **Lesson 3.** DECS *also notices the 80-20 rule, where a small percentage of angels offer a dominating contribution. However,* DECS*'s application nature calls for wide geographical coverage, which can not be satisfied by a few active angels. Further measures (*e.g., *rewards) are necessary to encourage more citizens to contribute to creating a dementia-friendly society.*

Correlation between App Downloads and Missing Case. Angel users can receive a notification when a missing case occurs. Over the course of DECS's 4-year operation, we have recorded the days when notifications were sent due to missing cases and compared them with days when no missing cases occurred. Surprisingly, the average daily app download count (62.35) is higher than the daily download count (41.99) on days without missing cases. This observation leads us to speculate that existing angels, upon receiving notifications, may encourage their friends and family to download the app to aid in the search efforts.

6.4 Angel Box Analysis

DECS's crowdsourcing influenced by the activity range of angels, some areas have limited data contributions from these users. To address this deficiency, we introduced angel boxes as hardware to complement the angel users' data. Analyzing the data from June to July 2023, focusing on a 100-meter radius (sensing distance) around the angel boxes as the center, we observed that angel users collected 1333 data, while all the angel boxes collected 14195 data, accounting for approximately 91.4% of the total signals. Specifically, during the nighttime (11:00 pm - 5:00 am), angel users contributed 36 data points, and angel boxes contributed 929 data points. Therefore, the data contribution rate from angel boxes during nighttime was as high as 96%. This indicates that the coverage of the angel box complements that of the angel effectively, especially during the nighttime, providing a significant amount of additional data to enhance the search and rescue capabilities.

■ **Finding 3.** *Our angel box infrastructure effectively complements the geographical coverage of angels, contributing to a significant amount (91.4%) of total signals within the angel boxes' sensing range. This contribution is even more pronounced during nighttime.*

6.5 User Feedback

We now investigate the preference of all users to further optimize the DECS system and better promote the establishment of a dementia-friendly community.

Tag Preference. Until now, a total of 4,707 beacon tags have been applied by individuals participating in the DECS system, and the distribution of tag types is shown in Table 4. Card-type beacon tags are the most widely used due to their slim and lightweight design, making them easily portable in a wallet or attached to a keychain for convenience. However, surprisingly, crutch-holder devices are the least utilized among PwD, despite the high proportion of elderly individuals among them.

Questionnaire Feedback. The aim of this study was to gather information on the experiences of these caretakers with the DECS system and assess the effectiveness of our systems. Figure 15 depicts the collected feedback from 860

Table 4: Beacon tags distribution.

Type	Crutch holder	Button type	Card type
Ratio (%)	14.9	37.9	47.2

caretakers who had been using DECS system for over a year. Our questionnaire contains 5 multiple-choice questions ranging from 5 (strongly satisfied) to 1 (strongly dissatisfied). The detailed questions are as follows: 1. how do you feel about the size and thickness of tags; 2. how do you feel about the weight of tags; 3. what is your degree of satisfaction with the tag's durability; 4. what is your degree of satisfaction with the support provided by system-related personnel; 5. please select your level of satisfaction with the DECS system.

Additionally, 73% of caretakers found the mobile application intuitive for users. Furthermore, over 80% of caretakers reported that their families (PwD) were willing to wear the tags both during and after this public welfare project.

■ **Finding 4.** DECS *has received positive feedback from caretakers of PwD across various aspects, including the portability and high durability of tags, as well as the user-friendly mobile app. This feedback underscores the success of its design and deployment as a search system for PwD.*

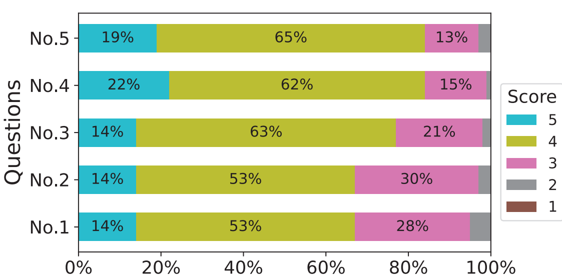


Figure 15: System service feedback.

6.6 Mobile App Power Consumption

The battery consumption of the mobile app was evaluated through controlled experiments using a VIVO smartphone. In the first experiment, our app is in the *search* mode and continuously searches for 3 hours, leading to a battery level drop of 23%. When our app is in the *normal* mode, a similar 3-hour experiment results in a 14% battery consumption. As a baseline, leaving phones idle for 3 hours still led to a surprising 9% decrease in battery life. The detailed result is shown in Table 5. Considering the average participation duration (*e.g.,* less than 1 hour), DECS's app generally requires tolerable energy consumption.

7 TRACE DRIVEN EMULATION

Due to the nature of searching for PwD, it is very difficult for us to compare different systems under the exact settings.

Table 5: Power usage of DECS.

Power mode	1 hour	2 hour	3 hour
Search mode	8%	16%	23%
Normal mode	5%	10%	14%
Idle mode	2%	6%	9%

Table 6: Trace-driven emulation summary.

	Baseline	Emulation	
Systems	DECS	DECS V2	AirTag
Search failure	N.A.	0	18%
Initial signal scan time	Fig. 10	1 - 50s	N.A.
Avg. loc. update interval	201s	24s	246s
Signal continuity	76%	100%	N.A.
Easy accessibility	Yes	Yes	No

As a result, we turn to leverage trace-driven emulation to thoroughly analyze the performance of DECS, DECS V2 (existing DECS + LoRa, the goal of our next phase), and the well-known AirTag.

7.1 Methodology

During the DECS operation, it has served the search of 254 missing cases. For these cases, we leverage their trajectories to conduct trace-driven emulation, covering over 10 districts in HK with a walking distance of 189.6 km. Specifically, testers were equipped with DECS V2 tag and an AirTag. Testers also adopted smartphones to record their actual location using GPS as the ground truth. They were instructed to mimic the behavior of PwD, including walking speed, and retrace the trajectories during the period of their reported disappearance. Meanwhile, the performance of the AirTag was recorded using video capture within the "Find My" app, since Apple does not provide API for direct access.

7.2 Performance Analysis

Search Failure. We define cases in which no location updates are received in these trajectories as search failures. In DECS V2, no instances of search failure occurred, which can be attributed to the comprehensive deployment of more than 300 LoRa gateways by the Electrical and Mechanical Services Department (EMSD) across all 18 districts of HK. In contrast, it is noteworthy that there was no location update in 18% of cases using AirTag, indicating search failures in these instances. This was due to the absence of nearby iOS users with Bluetooth enabled in these test cases.

Initial Signal Scan Time. Recall from Sec. 6.1 that the distribution of the initial signal scan time is shown in Figure 10: the median response time is 59.22 minutes. However, with the integration of LoRa technology (DECS V2), the initial signal scan time can be significantly reduced to within 50 seconds. As for AirTag, we lack the authorization to access

Bluetooth data, coupled with situations where location updates are not received, thus preventing us from inferring the timing of the initial signal scan. Nevertheless, the integration of LoRa technology in DECS V2 leads to a substantial reduction in the initial signal scan time. Importantly, leveraging the existing infrastructure of LoRa gateways, LoRa signals can be quickly received even in the absence of people nearby.

Average Location Updates Interval. We computed the average time gap between location updates in the DECS missing trace, resulting in an average location update interval of 201 seconds for DECS and 24 seconds for DECS V2. By incorporating the LoRa signal, the average location update interval in the DECS missing trace was reduced. In comparison, the average location update interval for AirTag is 246 seconds.

Signal Continuity. We define consecutive signals as those with intervals of less than 60 seconds between them. Signal continuity is vital for efficiently tracking missing individuals, as it ensures consistent monitoring and timely response by maintaining a real-time update on their location. During the period of the missing trace, we calculated the duration of continuous signals to determine their proportion. The continuous signal duration accounted for 76% in the case of DECS and 100% for DECS V2. Due to Apple's limited data sharing policies, we are unable to access BLE data, resulting in a lack of capability to determine the continuous signal pattern of AirTag. LoRa signals are highly stable and were consistently present throughout our trace-driven emulation.

Easy Accessibility to Historical Trajectory. Both DECS and DECS V2 record the trajectories of PwD to analyze their mobility patterns. This enables the prediction of potential paths when they go missing, providing additional clues for locating them. AirTag, however, does not offer trajectory data directly in Find My.

■ **Lesson 4.** *The integration of LoRa in the existing system can significantly reduce the initial signal scan time, enhance signal continuity, and decrease location update interval. These advantages motivate us to improve* DECS *in the next phase to improve the search responsiveness and efficiency.*

8 ANTI-ABUSE & PRIVACY PRESERVATION

Abuse Prevention. Implementing measures to ensure the proper and ethical use of the DECS system is crucial for preventing abuse. Requiring caretakers to provide a medical certificate and undergo a review by relevant departments helps validate the need to use the tags for PwD. Besides, caretakers need to sign an agreement, which outlines the guidelines, usage restrictions, and consequences for any unauthorized or misuse of the tags. We will consistently monitor the usage of the tags and capitalize on the mobility pattern of PwD to detect any unusual or suspicious activity. Any unauthorized utilization of the tags will be reported to the appropriate authorities (relevant caretakers) for verification. We will also hold some activities to train all personnel involved in this system on the importance of respecting the privacy and dignity of PwD. Ensure that they understand that the beacon tags should only be used to help PwD.

Privacy Preservation. Privacy considerations are essential for maintaining the trust and security of individuals using the DECS system. To protect the privacy of the angels, their IDs are generated randomly and vary over time, ensuring that they cannot be easily tracked. Similarly, protecting the privacy of PwD is of utmost importance. Access control measures are implemented to restrict access to the search system and location data of PwD, allowing only authorized personnel such as caretakers to access the information. Furthermore, secure data storage and transmission methods are employed, encrypting the data during both storage and transmission processes, thus preventing unauthorized access to sensitive information. These privacy measures are implemented to ensure the confidentiality and protection of individual's personal data in the DECS system.

9 DISCUSSION

In this section, we discuss angel positivity during the process of the system operating and improve our system for future deployment with different aspects.

Angel Positivity. During DECS's deployment, we have stimulated angels' motivation by the following methods: (1) We partner with companies to offer coupons or other rewards to angels. (2) We also encourage angels' participation to create a sense of community and belonging by organizing regular activities where angels can share their experiences and feedback. Through the activities, we also promote our systems to more potential volunteers.

Future Work. Aiming at more efficient search, we plan to improve DECS in the following aspects. (1) Beacon tag upgrade. We will upgrade our tag by integrating LoRa and evaluate its impact in the real world. Additionally, we will combine our tag with a medical alert bracelet to provide health information for emergency care. (2) More deployment of angel boxes. We will deploy more angel boxes at more fixed locations, in addition to mobile buses and taxis. By doing so, DECS will leverage mobile angel boxes with known traces to further facilitate the search of PwD. (3) New application scenarios. In addition to PwD, we plan to expand our DECS to a broader community, *e.g.*, mentally incapacitated persons (including mild psychological disorders and autism), as well as outdoor enthusiasts such as hikers. (4) Until now, we have not found malicious behaviors. In practice, adversaries might generate fake positions to mislead the search. We will investigate countermeasures to ensure DECS is reliable under attacks.

10 RELATED WORK

Localization and Tracking. There has been significant research on the use of IoT tracking systems to monitor the movements and location of people. With the advances in IoT devices and sensing technologies, multiple signals can be used to track PwD, such as GPS [34, 53], video [13], WiFi [25], and BLE [56]. A straightforward way to track PwD is by using IoT devices (*e.g.,* smartphones, smartwatches) with GPS and network modules for uploading. However, GPS's power-hungry nature imposes a significant challenge for a long device lifetime. WiFi sensing is commonly used in indoor environments. However, it requires high energy consumption and deployment in many outdoor areas. Compared with existing approaches, our solution uses a crowdsourcing approach to extract the location of PwD. Its tag design avoids GPS and employs low-energy BLE modules. DECS leverages crowdsourcing with the help of angels and angel boxes, whose locations are available. Thus, our solution is economical, power-saving, and can cover both indoor and outdoor environments.

Spatial-Temporal Data Analytics for PwD. Much research has focused on studying the mobility of PwD's devices, often using life space as a measure of their movement within a geographical area [50]. Traditional assessments rely on questionnaires [32, 41, 50], but these can be limited by memory issues or cognitive impairments. Recent studies have used GPS data for mobility analysis [7, 8, 52], yet they are often limited by small datasets collected over short periods, such as in the case of Bayat et al. [8], which collected data on the mobility of 7 PwD's devices over a period of 4 weeks. In contrast, our study is the first to investigate PwD's devices mobility using a large spatial-temporal dataset. It covers over 3,100 individuals across four years in a mega city, providing a comprehensive view that can guide tailored interventions and support services.

Tracking via AirTag. AirTag is usable as a finder for wallets, bikes, and other personal belongings. However, when applied to tracking PwD, it presents several practical limitations. (1) AirTag could have unwanted tracking and cause abuse issues [1, 23, 38]. (2) AirTag leads to potential disruptions. For instance, if PwD carry AirTags and move around, it may trigger 'AirTag Found Moving with You' notifications on nearby iOS devices, potentially causing disruptions to individuals in proximity. (3) AirTag's tracking functionality relies on the presence of nearby iOS users and the result is exclusively available to iOS devices, which limits its performance. (4) Historical trajectories are helpful in estimating their locations in the event of missing persons (Sec. 6.1). However, AirTag lacks a publicly accessible API for retrieving historical data. Whereas, DECS has unique features dedicated to the PwD search (see Sec. 3) and takes several measures to prevent for preventing abuse (see Sec. 8). Besides, the design of DECS began in 2019, followed by DECS's deployment in 2020, earlier than AirTag's launch in 2021.

Real-World Searching Systems. The development of real-world searching systems aimed at locating PwD who may wander has gained significant attention in recent years. Several initiatives and technologies have been introduced to address this critical issue. For instance, [49] employs devices with GPS to track individuals at risk of wandering. Similarly, [19] and [5] offer personalized identification bracelets with emergency response services for tracking PwD who go missing. Unlike many existing solutions, DECS leverages the widespread use of smartphones to create a crowd-sourced network of angel users who assist in locating missing individuals. This community-driven approach harnesses the power of existing infrastructure and user engagement.

11 CONCLUSION

In conclusion, this paper presents a city-wide deployment and operation study of an innovative search system for PwD. By leveraging BLE and crowdsourcing technology, the proposed system offers a power-saving and reliable solution that can be used in both indoor and outdoor environments. The study demonstrates that the system is effective in rescuing missing PwD. Moreover, the extensive data analytics on the spatial-temporal data collected from the search system provides valuable insights for future research in dementia care. With over 3,100 PwD using the system and more than 40 companies and 70 communities collaborating with it, the system has shown great potential to expand its reach and impact on a larger scale. The regular seminars held to promote the system have also contributed to raising awareness and educating the public about dementia care. Overall, this system offers a promising solution to improve the safety and well-being of PwD and their families, while fostering the development of dementia-friendly communities.

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