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SURVEY

Remote Pedestrian Localization Systems for Resource-Constrained Environments: A Systematic Review

ASIIMWE PADDY JUNIOR[1,3], LUIS ENRIQUE DÍEZ[1], ALFONSO BAHILLO[2], AND ODONGO STEVEN EYOBU[3]

[1]Faculty of Engineering, University of Deusto, 48007 Bilbao, Spain
[2]Department of Signal Theory and Communications, University of Valladolid, Campus Miguel Delibes, 47011 Valladolid, Spain
[3]Geospatial Data and Computational Intelligence Laboratory, School of Computing and Informatics Technology, Makerere University, Kampala, Uganda

Corresponding author: Asiimwe Paddy Junior (pjasiimwe@deusto.es)

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ABSTRACT The steady increase in the number of elderly citizens represents a likelihood of an increased burden on the family, government, healthcare, and social services since many of these elderly people cannot live independently without assistance from a caregiver. As such, there is an increase in demand for services in terms of technologies to address the urgent needs of the aging population. Remote monitoring, which is based on non-invasive, non-intrusive, and wearable sensors, actuators, and communication and information technologies, offers efficient solutions that bridge the gaps between healthcare and where elderly people really want to live every day. The rate at which such platforms have been adopted is extremely low in low-developed countries and rural areas, one of the main reasons being the lack or scarcity of some resources that these systems take for granted. In other words, these systems are designed for developed countries but are very much needed in resource-constrained environments as well. This study provides an in-depth, state-of-the-art systematic review of the current outdoor remote pedestrian localization systems to identify their suitability for resource-constrained environments. After checking 35 survey papers from the last ten years to the best of our knowledge, this is the first survey that investigates the suitability of existing pedestrian localization systems for a resource-constrained environment. This study is based on PRISMA guidelines to provide a replicable work and report the studies' main findings. A total of 37 works published between 2012, and January 2023 have been identified, analyzed, and key information that described the devices and tools used, communication technologies, position estimate technologies, methods, techniques and algorithms, and resource optimization strategies currently used by the localization systems was extracted to help us answer our question. The results indicate they are not fit for a resource-constrained environment as most assume the availability of infrastructures such as Wi-Fi, Internet, cellular networks, and digital literacy, among others, for their systems to operate properly, which are limited or not available in the resource-constrained environment described in this review.

INDEX TERMS Elderly, geolocation, constrained-environment, localization, low-power, pedestrian, positioning, systematic literature review, tracking, vulnerable, wildlife.

I. INTRODUCTION

The world's population is increasingly aging [1]. Globally, there were 727 million persons aged 65 years or over in 2020. Over the next three decades, the global number of older persons is projected to more than double, reaching over 1.5 billion in 2050. Old age comes with several non-communicable diseases such as cardiovascular diseases, hypertension, cancer, diabetes, and dementia [2].

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As the number of elderly citizens increases, there is a likelihood that they will represent an increased burden on the family, government, healthcare, and social services since many of these elderly people cannot live independently without assistance from a caregiver. For example, research shows that people with dementia have at least a 60% possibility of getting lost in open areas [3].

In order to save costs, health care policy should shift from institutionalization to aging in place (in the community). As such, there will be an increase in demand for services in terms of technologies to address the urgent needs of the aging population. Remote monitoring, which is based on non-invasive, non-intrusive, and wearable sensors, actuators, and communication and information technologies, offers efficient solutions that bridge the gaps between healthcare and where elderly people really want to live every day [4]. Such technologies, when implemented properly, will not only ensure appropriate quality of life among the elderly persons in their homes but also assist the family and caregivers in providing adequate services to these elderly people in society [5].

These remote monitoring tools can collect many different types of information, but among all of them, we will focus on location information as this can help us to remotely monitor the elderly person's behavior and infer some basic physical activity information related to the health status (step counter, walking speed, fall detection) [6].

In outdoor environments, location estimation has been successfully implemented using Global Navigation Satellite Systems (GNSS) technology. Today, four major Global Navigation Satellite Systems (GNSSs) are fully operational. Global Positioning System (GPS), GLONASS, Galileo, and BeiDou enable worldwide 24/7 positioning. Standalone positioning services reach meter-level accuracies under open sky conditions. This has made GNSS the de-facto standard for many positioning applications [92]. Although GNSS can provide reliable and accurate location data anywhere globally, it is not the best solution for all localization problems.

On the one hand, the use of GNSS is mainly in outdoor environments. This is because GNSS satellites move in Medium Earth Orbit (MEO), and given their low transmission power, GNSS signals often cannot reach indoor environments [7]. On the other hand, GNSS technology has relatively high energy consumption in its typical use case, which aligns poorly with the stringent constraints of battery-powered devices [21]. Therefore, more energy-efficient positioning alternatives like terrestrial Low Power Wide Area Networks (LPWANs), such as LoRaWAN and Narrow-band IoT (NB-IoT), are gaining increasing popularity [92]. Also, in order to mitigate these two challenges, GNSS has been integrated with other technologies such as Wi-Fi, Bluetooth Low Energy (BLE), or Inertial Navigation Systems (INS).

Although many pedestrian localization systems have tried to reduce power consumption, they still assume that other types of resources are available, such as access to electricity to recharge the batteries, communication networks for exchanging data (Wi-Fi, Internet, cellular networks), service providers (coverage), and users with enough economic capacity and digital education to acquire and properly use these devices. In other words, these systems are designed for developed countries, yet they are very necessary for less developed countries and rural areas with limited resources.

Some of the less developed regions include Sub-Saharan Africa, South Asia, the Middle East, North Africa, Latin America, and the Caribbean, among others. For example, Sub-Saharan Africa's rural population for 2020 was 668 million persons, a 1.69% increase from 2019, representing about 60% of the population. Sub-Saharan Africa's care for the elderly is predominantly a family-centered healthcare system. Families provide most long-term care without any organized training or support. This aging population, living in remote regions, has been exposed to the cruelest conditions in resource-constrained environments. Reliance on families alone to provide this care results in inconsistent care quality and particularly puts a heavy burden on girls who are forced to drop out of school to look after the elderly [8]. Moreover, it may be unsustainable given the rapidly increasing number of older people living in rural areas, and having their children living and working in distant urban areas, thus making it hard for them to visit frequently and consequently monitor and check on their health.

The main objective of this study is, therefore, to provide an in-depth, state-of-the-art systematic review of remote pedestrian localization systems with the aim of identifying if they are suitable for resource-constrained environments. For that, different localization algorithms, devices, technologies used for outdoor localization systems, and power-saving strategies will be identified and analyzed. The outcomes of these analyses will provide a clear view of the strengths and weaknesses of various localization systems when applied in resource-constrained environments. In addition, a description of what a resource-constrained environment is will be provided. Hence a great research opportunity that seeks energy optimization strategies as a proposition for future research directions in localization systems suitable for elderly persons.

Several general surveys and reviews exist related to localization systems [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [102], [103], [104], [105], [106], but none focus on investigating if the current pedestrian localization systems are suitable for resource-constrained environments, and to the best of our knowledge, this is the first survey to this end.

This study limits its scope to pedestrian remote location systems designed for outdoor environments, or at least both outdoors and indoors, published in the last decade (from 2012 to January 2023). That is, only indoor localization systems were discarded. This is because people in rural areas mainly live outdoors, working in primary industries such as agriculture, forestry, fishing, and hunting [9], including elderly people who spend most of their time outside their homes. Works that do not mention any power-saving strategy were excluded. Likewise, some types of localization systems that do not fit for pedestrian monitoring in resource-constrained environments, such as power-hungry hybrid systems using cameras or pure inertial localization systems, were also discarded.

The review is based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [10]. We identify, analyze, classify, and discuss the current state of the art in terms of localization devices, techniques, and findings on localization systems reported in the scientific literature indexed in Scopus or Web of Science datasets. In summary, this article, therefore, focuses on the following specific contributions:

(i) Systematically collecting and analyzing research works related to remote outdoor pedestrian localization systems.
(ii) Review the current state of the art in terms of localization devices, techniques, algorithms, and methods that consider the scarcity of resources, mainly power.
(iii) Identifying and describing the communication networks used.
(iv) Identifying and discussing the power optimization strategies employed.
(v) Lastly, we give recommendations for the system(s) or combination of systems suitable for monitoring pedestrians in resource-constrained environments.

The remainder of this work is structured as follows. Section II explains what we mean by a resource-constrained environment and shows how current surveys do not consider the characteristics of this resource-constrained environment. Section III introduces the research methodology used to find the relevant articles and describes the systematic review undertaken. Section IV presents the results from the systematic review. Section V briefly discusses the main findings, current challenges, and recommendations. Section VI presents the conclusions of this review.

II. RELATED WORK

In this section, we will explain what we mean by a resource-constrained environment and show how current surveys about remote pedestrian localization systems do not consider the characteristics of these resource-constrained environments.

A. RESOURCE-CONSTRAINED ENVIRONMENT

Anderson et al. [11] define resource-constrained environments broadly (e.g., low-income communities, low bandwidth environments). These environments provide unique constraints (e.g., cultures where people are unfamiliar with or afraid of technology, and environments where power and network connectivity are scarce and expensive). This is different from resource-constrained devices such as IoT devices with limited CPU, memory, and power resources. Resource-constrained environments provide unique infrastructure, and technical, and social constraints that demand innovative design approaches. Most less developed countries in Africa, the Middle East, South Asia, Latin America, and the Caribbean have the same challenges and the need to monitor their aging population remotely but have to do it in constrained environments, as discussed below.

1) LIMITED OR NO ACCESS TO ELECTRICITY

According to the World Bank collection of development indicators, Sub-Saharan Africa has the lowest energy access rates globally. Electricity reaches only about half of its people; roughly 600 million people lack electricity. Only 18% of the rural community have access to electricity coverage. Those with electronic devices like mobile phones that use batteries and require periodic charging travel to town centers with electricity coverage to charge them (about four times a month). These town centers are often in a radius of more than 5 km walking distance from their homes. This parameter is key to the design of the localization system, as the devices being used need the power to operate. Even in areas with electricity infrastructure, there is stagnated supply of electricity (load shedding) due to poor maintenance of power lines, structurally insufficient electricity production on all sources to meet the high power demand, sudden power failures, and downtime, or widespread blackouts. This means that systems depending on electricity will be off for sometimes during these blackouts exposing elderly people that are being monitored.

2) LIMITED OR NO ACCESS TO THE INTERNET

According to Africa's digital infrastructure transformation report 2022 [12], Africa has the lowest number of Internet connections, as fewer than one-third of Africans have access to broadband connectivity. Of the 25 least-connected countries in the world, 21 are located in Africa. Three hundred million Africans live more than 50 kilometers from a fiber or cable broadband connection. At just 36%, Africa's Internet penetration compares poorly with the 63% global average and 92% for Europe. Connection to the stable Internet is a key requirement for most designed remote localization systems and technologies such as assisted GNSS.

3) LIMITED OR NO ACCESS TO CELLULAR NETWORKS

Mobile phones are the key means most people access the Internet, an essential requirement for most designed remote localization systems. Therefore, it is necessary to analyze mobile (cellular) network connectivity to understand the remaining gap. The GSMA's state of mobile Internet connectivity report 2020 [13] shows that while there has been significant improvement in mobile (cellular) network coverage and affordability of devices, 600 million people still live outside of covered areas, 67% of whom are from Sub-Saharan Africa. Rural people move to raised grounds or town centers where masts have been installed to access the stable network to make or receive calls. Also, these rural areas have no fixed networks (landlines) or fiber optics coverage. Cellular networks were used in about 20% of the reviewed papers as a communication network, and mobile phones were the most used devices, especially with commercial systems. The currently designed positioning systems require a stable network to operate.

4) LACK OF DIGITAL LITERACY

The GSMA's state of mobile Internet connectivity report 2021 [14] identifies a lack of literacy and digital skills, such as calling and texting, as well as affordability, as key barriers to mobile Internet adoption. With this report, it is important to note that any system designed to operate in such environments must be in a position to operate without the user's technical intervention (autonomous). The same report identifies the unconnected people as more likely to be poorer, less educated, older, rural, and women, and thus the need to design a low-cost positioning system that fits their purchasing power.

5) LIMITED ACCESS TO HEALTH CARE

Rural access to healthcare remains challenging in less developed regions due to urban bias, social determinants of health, and transportation-related barriers resulting in most health centers being largely understaffed. For most patients in these regions, it takes a major part of the day to reach the nearest hospital facility, which makes it a big deterrent to undergo regular screening and checkups. Even when patients eventually reach a hospital, many a time, due to the high patient load and overcrowding, chances are that physicians are already too busy to give any consultation time [15]. For example, in Uganda, one of the best-ranked countries in Sub-Saharan Africa, more than 70% of households are in a radius of more than 5 km to the nearest health facility, whether public or private. The ratio is only one doctor for every 8,300 Ugandans, and 70% of the doctors' population practice in urban areas, where only 20% of the population lives. This makes the coverage in rural areas much worse: one doctor for every 22,000 people compared to the UK, with 2.8 doctors for every 1000 people. Because of the distance and poor infrastructure, elders find it quite challenging to walk this distance. Thus, a remote healthcare monitoring solution is needed to bridge the gap between households and healthcare providers and easily monitor them in their homes.

6) RURAL TO URBAN MIGRATION

In addition, the inadequate services and limited access to financial capital in the rural areas have driven educated, semi-educated, and working people in South Asia, Latin America, and Africa, among others, mostly youth, to migrate to urban centers and other countries in search of job opportunities, modern-day technology, productivity, entrepreneurship, modernization, social benefits, and services [16]. These urban centers (towns and cities) are often far away from rural communities making it hard to visit frequently and look after their aging relatives. This has necessitated a solution to remotely monitor these exposed elderly people in rural areas with nobody to seamlessly look after them.

7) POVERTY

From the Economic Development in Africa Report 2021 [17], poverty levels declined in most African countries: On average, the proportion of African households with a consumption level below the 1.9$ per day poverty line declined from 40% in 2010 to 34% in 2019. At below 3.2$ per day, the poverty rate fell from 63% to 59%; and at below 5.5 $ per day, it fell from 83% to 80% compared to about 35.28 $ per day for the U.S. This rural population who are primarily in the low-income group and depend upon daily wages, taking a break to visit the hospital is an economic burden. From these statistics, we can conclude that the majority of the households are not in a position to afford the already existing localization solution because of their limited purchasing power.

B. EXISTING SURVEYS ON LOCALIZATION SYSTEMS

This section presents a review of the purpose and scope of existing surveys, showing how they do not sufficiently cover the peculiarities of resource-constrained environments. We could not find review papers specific to our area of interest, i.e. pedestrian localization systems for resource-constrained environments, so we decided to look at the reviews on pedestrian localization systems in general in the last ten years. Some reviews and surveys have been conducted about resource-constrained devices, but as explained in section II-A, there is a difference between resource-constrained environments and resource-constrained devices. Table 1 summarizes the comparison between the 35 survey papers on pedestrian localization from 2012. Most of the surveys offered a comprehensive discussion of localization system technologies, techniques, and methods. Additionally, some authors provided a brief discussion of current challenges from the point of view of indoor and outdoor localization technologies, techniques, environment, devices, coverage, and privacy. Even though it has been noted in the introduction that elderly people in rural areas spend most of their time outdoors, most of the review papers targeted indoor environments only, with only 18% covering indoor and outdoor environments. As discussed in section II-A, there is limited or no access to electricity in rural areas, though 62% of the review papers considered power optimization, and still, it is mainly about IoT devices as none of the reviews looked at resource-constrained environments. Furthermore, only 18% of the review papers considered cloud computing which is emerging as the key platform for localization system data storage, computing, processing, and analytics due to its simplicity, availability, and scalability. Cloud computing helps prolong the tracking device's battery life by transferring all power-hungry activities to the cloud, a major requirement for battery-powered devices operating in a resource-constrained place [7].

The cost of the current localization systems is one of the limitations of their adoption in most environments and

TABLE 1. Comparison of criteria included in existing surveys. HT: Hybrid Technologies; PC: Power Consumption; SW: Size & weight; CC: Cloud Computing; EES: Energy Efficiency Strategies; DL: Digital Literacy; ✓: Considered; ×: Not Considered.

Article	Year	Scope	End-user or Application	HT	Scalability	Autonomy	Cost	Coverage	Accuracy	PC	SW	CC	EES	DL
[18]	2017	Indoor	General	✓	×	×	✓	✓	✓	×	×	×	×	×
[19]	2019	Indoor	General	×	✓	×	✓	✓	✓	✓	×	×	×	×
[20]	2018	Indoor	General	×	×	×	×	×	✓	×	×	×	×	×
[21]	2021	Outdoor	GNSS-Free	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×
[22]	2019	Outdoor	General	×	×	×	✓	✓	×	✓	×	×	×	×
[23]	2020	Indoor	General	✓	✓	✓	✓	✓	✓	✓	×	✓	×	×
[24]	2017	Indoor	GNSS-free	×	×	✓	✓	✓	✓	✓	✓	×	×	×
[25]	2018	Indoor	Shopping Mart	×	×	×	✓	✓	✓	×	×	×	×	×
[26]	2020	Indoor	Multi-resident	×	✓	×	✓	×	✓	×	×	×	×	×
[27]	2020	Indoor	Health	✓	✓	×	×	✓	✓	×	×	×	×	×
[28]	2019	Indoor & Outdoor	Smart city	×	×	×	✓	✓	✓	✓	×	×	×	×
[29]	2018	Indoor & Outdoor	General	✓	×	×	✓	✓	✓	✓	×	✓	×	×
[30]	2019	Indoor	Pedestrian	✓	✓	×	✓	✓	✓	✓	×	✓	×	×
[31]	2019	Indoor	General	✓	×	×	✓	✓	✓	✓	×	✓	×	×
[32]	2021	Indoor	Pedestrian	✓	×	×	✓	×	✓	×	×	×	×	×
[33]	2018	Indoor & Outdoor	General	✓	✓	×	✓	✓	✓	✓	×	×	×	×
[34]	2022	Indoor	Health /Hospital	✓	✓	×	✓	✓	✓	✓	×	×	×	×
[35]	2017	Indoor	General	✓	✓	×	✓	✓	✓	×	×	×	×	×
[36]	2021	Indoor	General	✓	×	×	✓	×	✓	✓	×	×	×	×
[37]	2020	Indoor	Elderly	×	×	×	×	×	×	×	×	×	×	×
[92]	2023	Indoor & Outdoor	General	×	✓	✓	✓	✓	✓	✓	×	✓	×	×
[93]	2017	Indoor	Pedestrian	×	×	✓	×	✓	✓	✓	×	×	×	×
[94]	2014	Indoor	Smart homes	×	×	×	✓	×	✓	×	×	×	×	×
[95]	2016	Outdoor	General	×	×	×	×	×	✓	✓	×	×	×	×
[96]	2015	Outdoor	General	✓	×	×	×	✓	✓	×	×	×	×	×
[97]	2018	Indoor	General	✓	✓	×	✓	×	✓	✓	×	×	×	×
[98]	2017	Indoor	Emergency response	✓	✓	×	✓	✓	×	×	✓	×	×	×
[99]	2017	Indoor	General	✓	✓	×	✓	✓	✓	✓	×	×	×	×
[100]	2015	Indoor & Outdoor	General	×	✓	×	✓	×	✓	✓	×	×	×	×
[101]	2015	Indoor	General	×	×	×	×	×	✓	×	×	×	×	×
[102]	2016	Indoor	General	×	×	×	✓	✓	✓	✓	×	×	×	×
[103]	2016	Indoor & Outdoor	General	✓	×	×	×	×	✓	✓	×	×	×	×
[104]	2015	Indoor	General	×	✓	×	✓	×	✓	×	×	×	×	×
[105]	2015	Indoor	General	×	✓	×	✓	×	✓	✓	×	×	×	×
[106]	2022	Indoor$ Outdoor	General	×	✓	×	✓	✓	✓	✓	×	✓	×	×
Our Review		Indoor & Outdoor	Pedestrian	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

communities. 77% of the existing survey papers considered the cost as one of the requirements in general without clearly defining the real face value in terms of money. Because of income inequality, if cost is not well defined, an affordable product in one area might be expensive in another area.

Active localization entails a device attached to or carried by the target, and because of that, its size and weight can have a significant effect on the movement of the pedestrian being tracked. However, only 10% of the papers looked at those parameters.

In the reviews considered, 14% looked at the independence (autonomy) of the designed systems from the user. But as already discussed in section II-A, digital literacy is lacking in those remote rural areas, and so this requirement needs to be given attention; otherwise, it might lead to application failure.

Also, 62% of the reviews were done without a specific health focus, end-user, or application. Different applications have different requirements and constraints that need to be considered for a positioning system.

Due to the inherent limitations of single position estimation technology, it is important to consider hybridization to provide a better position estimation in all environments. Hybrid systems, as more explained in section IV-D6, are also important in prolonging the battery life of the user devices. Hybridization was considered by 47% of the existing reviews and mostly to improve on the localization accuracy rather than power efficiency, a major challenge in the environments considered for this review.

III. RESEARCH METHOD

This section introduces the procedure and methodology used to identify studies relevant to this systematic literature review. The methodology has been selected for its clear procedure, which can be easily reproduced by other researchers, to comprehensively analyze the published research, identify current trends, and detect the unexplored research lines on a particular topic. As part of the systematic review, we used the PRISMA guidelines [10], consisting of a 27-item checklist together with a flow diagram divided into four parts (identification, screening, eligibility, and included).

A. RESEARCH QUESTIONS

Setting the right research questions is a crucial stage of any systematic review, as it is paramount to identify the analysis's main objectives. We conducted this review with the following main research question (MRQ): Are current pedestrian localization systems suitable for resource-constrained environments? This main question is generic; therefore, we broke it down into the following specific research questions (RQ):

RQ1: What are the resource optimization strategies currently used by the localization systems? The question will help us to identify the technologies, algorithms, and strategies used to save resources, and power will be the main resource we will focus on.

RQ2: What communication technologies are used by the current localization systems? The question will help us to know the different communication technologies as a requirement for remote localization systems: coverage areas, data capacities, and limitations of various networks employed.

RQ3: What are the current position estimate technologies and algorithms used? This research question will allow us to identify the positioning technologies and algorithms, the computing environment (on the edge/on Cloud), accuracy, and position update rate for the systems operating in those environments.

RQ4: How are the devices used in pedestrian localization systems? This research question will help us identify the main characteristics of the user device: mounting point, size, included sensors, commercial or custom-made, and cost.

B. KEYWORDS

The number of research studies relating to indoor and outdoor positioning has increased exponentially over the years, with more applications requiring localization services. Thus, it is important to define clear search queries and strategies to pinpoint the most relevant publications related to the topic of this systematic review. We, therefore, proceed with the identification of keywords related to the research topic and its objectives. The keywords were chosen according to the infrastructure, user, and application. As already mentioned in RQ1, power is the main resource being considered in this review since it is a major challenge for the environments we are considering. Under application, we used keywords tracking, positioning, monitoring, geolocation, and monitoring since they are closely associated with localization, and some authors use them interchangeably. Under the users, we also considered the wildlife keyword since wild animals also live in constrained environments or isolated and remote areas, places requiring the designers of the localization system for the animals in those environments to put into consideration the same challenges mentioned above in II-A.

TABLE 2. Keywords related to the topic research.

Keywords Infrastructure	Keywords User	Keywords Application
Low-power	Pedestrian	Position*
	Wildlife	Tracking
	Dementia	Localization
	Elderly	Geolocation
	Vulnerable	Location
		Monitor*

TABLE 3. Lists of electronic databases searched.

Electronic Database	URL
Web of Science	https://www.webofscience.com/
Scopus	https://www.scopus.com/

Table 2 shows the keywords we have chosen in the research process. The wildcard pattern (* in the queries) means any number of characters. In our queries, we introduced them to identify related concepts with the same prefix (e.g., position, positioning, positions, etc.).

C. QUERY

Once keywords are defined, a rigorous study selection process is carried out by first defining relevant search queries and running them against scientific digital libraries (Scopus and Web of Science in this work) to identify all potentially relevant studies. Table 3 shows the URL and lists of electronic databases searched, and table 4 shows the search queries used. Although the term 'localization' or 'positioning' has been used for a long time, and outdoor and indoor positioning has been studied for many years, we limited this review to articles published in the last ten years (from 2012 to January 2023). We think that ten years is enough time as technology has greatly changed compared to the early 1990s and 2000s. For example, there have been great changes in smartphones and satellite technology in the latest years.

D. STUDY SELECTION

The selection of relevant articles rigorously followed the PRISMA process for study selection. This step includes identifying relevant studies concerning the research questions, removing duplicate records, and defining inclusion and exclusion criteria. Those criteria form the basis for the ultimate decision on which works are included in the qualitative and quantitative synthesis.

TABLE 4. Scopus and Web of Science search queries.

Database	Input Query	No of Articles
Web of Science	TS = (((pedestrian OR elderly OR vulnerable OR dementia OR wildlife) AND (localization OR location* OR geolocation OR tracking OR monitor* OR position*) AND (low-power))) Timespan: 2012-January 2023	472
Scopus	TITLE-ABS-KEY ((pedestrian OR elderly OR vulnerable OR dementia OR wildlife) AND (localization OR location OR geolocation OR tracking OR monitor* OR position*) AND (low-power))	460

1) STAGE 1: IDENTIFICATION

Scopus and Web of Science are important databases that index works from different sources, such as IEEExplore, SpringerLink, Elsevier, Wiley Online Library, etc. Merging the results from all datasets leads to duplicate records that must be removed. Thus, the retrieved records and their abstract, title, bibliography, and metadata are imported in CSV format and stored in MS Excel software. This software was used to remove duplicate records and classify and analyze the studies obtained from search engines.

2) STAGE 2: SCREENING AND SELECTION CRITERIA

Once we have removed duplicate records, we obtain 640 unique registries, which must be filtered to obtain only relevant publications for this review. Thus, we defined the following inclusion criteria (IC) and exclusion criteria (EC).

Inclusion criteria.

IC1: Research works written in English.

IC2: Each article must be related to the localization of pedestrians or wildlife.

Exclusion criteria.

EC1: Research works that do not mention anything about energy consumption, low consumption, low power, low resources, or similar.

EC2: Works where cameras are used as part of the localization system.

EC3: Works where only INS is used as part of the localization system.

EC4: Research works proposing systems valid only for indoor environments.

In order to select only those works that fulfill all the requirements established in the IC and EC, we proceeded with the manual revision of titles and abstracts for their subsequent tagging with ACCEPTED for accepted articles and REJECTED for rejected records. Overall, we selected around 24% of the total number of studies obtained in the previous stage.

3) STAGE 3: ELIGIBILITY

In this stage, we carefully read each remaining study under the consideration of the main objective of this review and the established IC and EC. If the article reviewed does not accomplish the requirements established in previous steps, it is excluded from this work.

4) STAGE 4: INCLUDED

The studies are categorized according to their conclusions and contributions to the research field (localization systems in resource-constrained environments). This step is the last filter to select only relevant publications for this review.

E. MAIN FIGURES FOR THE PRISMA PROCESS IN THE CURRENT REVIEW

Figure 1 shows the flow diagram and the results after following the process. Through an extensive article search performed using the search engines from two curated scientific digital libraries, namely Scopus and Web of Science, using an equivalent search query, we identified 932 potentially relevant studies concerning the research questions. We identified 460 from Scopus and 472 from Web of Science. When the screening process was carried out, by first removing duplicates, we remained with 640 unique works. We subsequently screened the remaining articles' titles, abstracts, and keywords against the inclusion and exclusion criteria; 124 articles remained. Finally, the remaining works were checked against the eligibility criteria in the eligibility phase to obtain a final set of included articles. We included only 37 articles [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71], [107], [108], [109] in our review for the complete analysis, and this represents about 5% of the initial number.

F. OVERVIEW OF THE SELECTED STUDIES

Although the search queries provided 932 works, only 37 fulfilled all the criteria established in this work and were analyzed (see Figure 1). The distribution over the years of the selected works is shown in Figure 2, where the type of article is also differentiated.

G. DATA EXTRACTION

We collected all the relevant information from the 37 selected studies during this process. This information includes resource optimization strategies currently used by the localization systems (RQ1), communication technologies and networks used (RQ2), position estimate technologies and algorithms used (RQ3), and how the devices are used in pedestrian Localization systems (RQ4). The main outputs of this process are reflected in Section IV.

IV. RESULTS

This section will analyze the key information extracted from the 37 selected studies (see Section III-G) to answer the four defined research questions (see Section III-A)

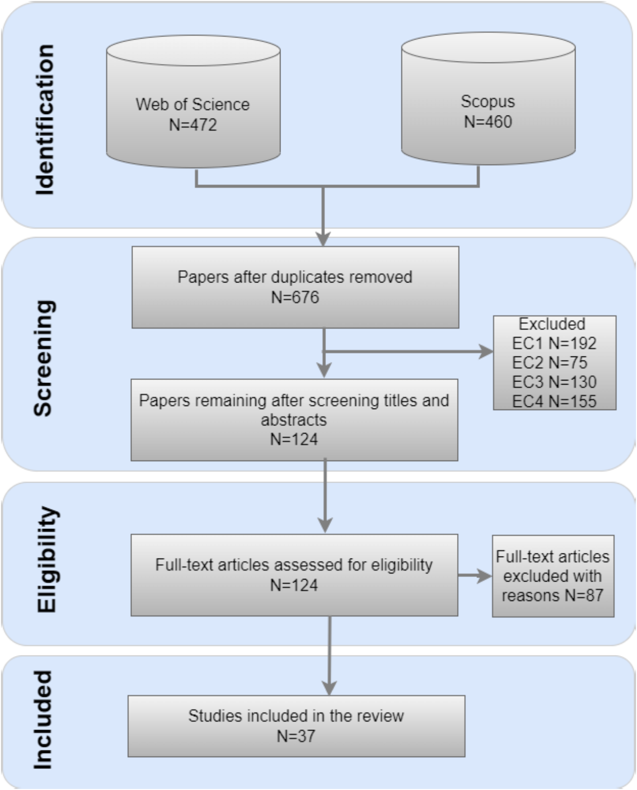

FIGURE 1. PRISMA flow diagram.

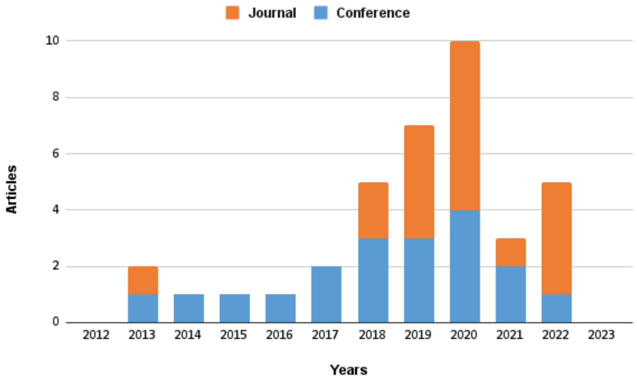

FIGURE 2. Distribution of the articles considered in this review over the years, grouped by type of publication.

A. POWER OPTIMIZATION STRATEGIES

Energy consumption is one of the most significant constraints for remote localization systems in a resource-constrained environment where access to electricity and other resources is limited. The devices need to be powered by batteries and alternative energy sources. This means long battery life and low energy consumption are fundamental points for these systems. Because battery energy is limited, there is a need for power optimization to maximize the life of these batteries up to many years without charging. Different strategies have been found in this review. In this section, we will present the different optimization strategies as deployed by different authors.

a) Localization algorithms, methods, techniques, and technologies

Different technologies have different power challenges, and therefore it is crucial to select the right localization technology after understanding the energy challenges of technology. For example, a standard GNSS technology has a very high power consumption compared to the other technologies, even though it offers the best localization solution for outdoor environments. Technologies such as LPWANs were used by more than 33% of authors for localization and 64% for communication because of their low power consumption, as discussed more in section IV-D4.

Furthermore, techniques such as snapshot as used in [54], [57], [61], and [63], reduce the energy consumption as it determines the position by using a minuscule interval (about 20ms) of GNSS signal that is subsequently processed at the cloud with the help of assistance data to retrieve pseudo-range information and compute the pedestrian position.

b) Devices

With most battery-powered devices being used in building localization systems in this review, it is essential to use low-power devices to maximize the battery life. Most authors in custom-made systems used low-cost and low-energy devices to minimize power consumption. For example, authors in [42], in addition to using LPWAN technologies, used low-power consumption devices such as the Waspmote core processor based on the Atmel ATmega1281. End devices such as Sigfox, LoRa, and NB-IoT are in sleep mode most of the time outside operation, thus maximizing the battery life. The flexibility of choosing what to use makes custom-made devices more power efficient than commercial ones.

c) Duty cycling

Here, devices were turned off or went to sleep mode when there was no signal or when indoors, or when other technologies were being used. For example, authors in [50], [53], [55], [66], and [67] turned off GPS when there was no signal and when indoors to decrease power consumption. For example, in [50], the authors achieve low power consumption by the optimization of the transmitter circuit of an ultra-wideband system together with implementing sleep modes. The proposed power management technique decreased the current consumption from 30 mA in active mode to 6.7 μ A in sleep mode.

d) Location update rate

The update rate is the frequency with which the positions are calculated on the device or at an external processing facility. This rate has a significant impact on the battery life, with high data rates leading to more on-time for the devices and hence high energy consumption.

We categorized the update rate as periodic when updates are regular, or at the specified interval, for example, every after 10sec [42], [107], on request [52] when the update is triggered by the user or by a remote device, and on the event, [46], [51], [52], [60], [62], [66] when the measurement update is initiated by the local device when a specific event occurs, e.g., when a temperature sensor exceeds a critical threshold.

For example, the authors in [60] combined periodic and on-event categories to minimize power consumption since a high update rate results in high power consumption and vice versa. Also, some devices have regional regulations limiting the maximal payload size and the airtime a transmitter is allowed to use. For example, LoRaWAN devices in Europe must respect a duty cycle limit of 1 % and a maximal payload between 51 bytes and 222 bytes depending on the used spreading factors (SF) [73].

e) Cloud computing

Cloud computing emerges as the key platform for localization system data storage, processing, and analytics due to its simplicity, availability, and scalability. Cloud computing minimizes the energy consumption by the devices by taking away one of the most power-hungry activities, i.e., data process, to determine the user position in the cloud, where sufficient energy, processing power, and clock and ephemeris data are available in virtually unlimited quantity. For example, under GNSS technology, authors [51], [52], [53], [55], [56], [58], [59], [60], [62], [64], [65], [66], [67], [68], [69], [107], [108] designed systems that send GNSS coordinates (PVT) to the cloud for user access and other authors [54], [57], [61], [63] further reduce the power consumption by sending the raw measurements (snapshots) to the cloud for the PVT determination. The cloud-based method also decreases the localization latency by providing storage, computational, and processing power. Therefore, received data will be accessible for real-time positioning and monitoring.

f) Communication network

Since most efficient localization technologies use cloud computing and in this review, we are looking at remote monitoring, it is very important to select a low-power communication network. More than 90% of the papers in this review used the cloud for processing and user access. Communication technologies such as cellular and Wi-Fi are high power consumption networks, and this explains why more than 64% of the authors in this review used LPWANs such as LoRaWAN and Sigfox.

g) Hybridization of technologies

Hybridization, as discussed more in section IV-D6, involves the combination of two or more localization technologies. The hybrid method takes advantage of the strengths of one system. It combines it with another system that has strengths where the first system exhibits inhibitions to compensate for the limitations of single model positioning technologies [35]. For example, authors in [62], [63], [64], [65], [66], [67], [68], and [69] combined GNSS, a global technology, with other technologies such as Wi-Fi, INS, and BLE to minimize the relatively high energy consumption in its typical use case. This is done by turning off GNSS receivers when not in use or places with no access to satellite signals. For example, the authors in [62] enhanced the battery life by 50% compared to GNSS alone by combining GNSS+Wi-Fi+INS.

h) Network architecture

Different authors came up with different architectures to minimize power consumption. For example, the authors in [49] used a hybrid tree topology to create a layered hierarchical layout with a cluster head that coordinates communication and concatenates the data to be forwarded to the central system via LoRaWAN and thus reducing the power consumption. Instead of direct LoRaWAN connectivity as in star topology, utilizing data concatenation at the cluster head drastically reduced the overall energy overhead. Packet concatenation is proposed as an alternative to reduce the packet header energy cost and decrease overall latency in this study.

i) Sampling rate

High energy efficiency can be achieved by reducing the sampling rate of sensing users' locations. A typical location-based application usually updates the user's location only if the distance to the last valid location sample is larger than a certain threshold [66]. Therefore, a fixed and frequent GNSS location sampling policy probably introduces a significant amount of unnecessary GNSS samples and thus increases power consumption. For example, in [62], the authors combined GPS with INS (accelerometer) to determine when the pedestrian was stationary and reduce the sampling rate. In [66], authors select location-sensing methods between Wi-Fi and GPS and reduce the sampling rate by utilizing the information from the acceleration sensor and orientation sensor.

B. COMMUNICATION TECHNOLOGIES

Most remote energy-efficient localization technologies require exchanging data with a network to determine the device's position from the cloud. Different authors have used different communication technologies to minimize power consumption and lower costs in this review. This section provides a brief overview of those communication technologies. Table 5 gives a summary of some of the properties of communication technologies considered in this review, and these include data rates, bandwidth, energy consumption, and range.

1) CELLULAR NETWORKS

Cellular networks operate on different frequency bands, including the 0.9, 1.8, and 2.8 GHz bands. They are based on open, global industry standards, use licensed spectrum, and are always operated by wireless network providers. Cellular networks offer high bandwidths, low latency, high reliability, and good coverage [32]. However, they are not suitable for energy-constrained devices. Because of that, the GSMA has

TABLE 5. Comparison of RF communication networks used in this literature review.

	Sigfox	**NB-IoT**	**LoRaWAN**	**WiFi**	**ZigBee**	**Bluetooth**
Standards	Sigfox	3GPP	LoRa Alliance	IEEE 802.11	IEEE 802.154	Bluetooth SIG
Modulation	BPSK	QPSK	CSS	DSSS, OFDM	DSSS, QPSK	GFSK
Frequencies	ISM:433MHz, 866MHz, 915MHz	Licensed under LTE	ISM:433MHz, 866MHz, 915MHz	ISM:2.4GHz, 5GHz	ISM:868MHz, 2.4MHz	2.4GHz
Coverage	10-40Km	1-10Km	5-15Km	10-100m	10-100m	10-100m
Bandwidth	100Hz	200Hz	125KHz, 250KHz	20MHz,40MHz, 80MHz,160MHz	2MHz	1MHZ
TX Limit	140 Packets per day	Unlimited	Duty Cycle Limit	Unlimited	Unlimited	Unlimited
Max Data Rate	100bps	200kbps	50kbps	Gbps	250kbps	2Mbps
Private Deployment	No	No	Yes	Yes	Yes	Yes
Energy Consumption	Extremely Low	Very Low	Extremely Low	High	Low	Low
Security	Low	High	High	Low-High	High	Low-High

introduced two additional LTE standards: NB-IoT and LTE-M. Even though NB-IoT and LTE-M are primarily designed for LPWAN use cases to provide moderate energy efficiency, the rollout of these networks is still in its early stages, with patchy or no coverage in many regions.

Research studies in [47], [53], [57], [60], [62], and [63] used cellular networks as the communication network, which represent 18% of the reviewed papers. All the studies used GSM networks which are pervasively available in most countries but have high energy consumption. GSM networks have cell sizes of up to 35 km, and GSM far outreaches the coverage of WLAN, and WPAN [74].

2) LPWAN

LPWAN technologies include LTE-M, NB-IoT, Sigfox, and LoRaWAN. LTE-M technologies were not used in any studies in this review. LPWAN is increasingly gaining popularity in industrial and research communities because of its low power, long-range, and low-cost communication characteristics. It provides long-range communication up to 10-40km in rural zones and 1-5km in urban zones [77]. In addition, it is highly energy-efficient (i.e., 10+ years of battery life) and inexpensive, with the cost of a radio chipset being less than $2 and an operating cost of $1 per device per year [33].

These promising aspects of LPWAN have prompted recent experimental studies on the performance of LPWAN in outdoor and indoor environments, as seen in this review (more than 70%). These properties make the LPWAN technology a perfect candidate for resource-constrained environments.

Many factors should be considered when choosing the appropriate LPWAN technology for application, including quality of service(QoS), battery life, latency, scalability, payload length, coverage, range, deployment, and cost. The respective advantages of Sigfox, LoRa, and NB-IoT in terms of IoT factors are demonstrated in figure 3 and briefly explained in the following paragraphs.

Sigfox, LoRaWAN, and NB-IoT end devices are in sleep mode most of the time outside operation, which reduces the amount of consumed energy, i.e., long end-devices lifetime. However, the NB-IoT end device consumes additional energy because of synchronous communication and QoS handling, and its OFDM/FDMA access modes require more peak current [33]. This additional energy consumption reduces the NB-IoT end-device lifetime compared to Sigfox and LoRaWAN. NB-IoT offers the advantage of low latency. Owing to QoS and cost tradeoff, NB-IoT is preferred for applications that require guaranteed quality of service, and in contrast, applications that do not have this constraint should choose LoRaWAN or Sigfox.

The significant utilization advantage of Sigfox is that an entire city or village can be covered by one base station (i.e., range >40 km). By contrast, LoRaWAN has a lower range (i.e., range <20 km), and NB-IoT has the lowest range and coverage capabilities (i.e., range <10 km).

In terms of payload length, NB-IoT allows the transmission of data of up to 1600 bytes. LoRaWAN allows a maximum of 243 bytes of data to be sent. Sigfox proposes the lowest payload length of 12 bytes, limiting its utilization on various applications that need to send large data sizes. In addition, the deployment of NB-IoT is limited to LTE base stations. Thus, it is not suitable for rural or suburban regions that do not benefit from LTE coverage.

The NB-IoT specifications were released in June 2016; thus, the amount of commercial applications has been limited up to now. However, the LoRaWAN and Sigfox ecosystems are mature and are now under commercialization in various countries and cities. LoRaWAN has the advantage of being deployed in 42 countries versus 31 countries for Sigfox [78]. In addition, one significant advantage of the LoRaWAN ecosystem is that it is available in Africa.

In summary, figure 3 shows a clear difference in performance between licensed and unlicensed technologies. The licensed technology (NB-IoT) offers better QoS, payload length, latency performance, and scalability than unlicensed (LoRaWAN, Sigfox). Unlicensed technologies are cheaper, with a better coverage range and battery life.

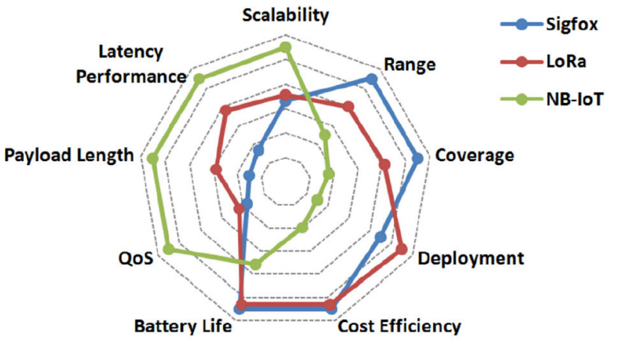

FIGURE 3. Respective advantages of Sigfox, LoRa, and NB-IoT in terms of IoT factors. [33].

TABLE 6. Different costs for LoRaWAN, NB-IoT, and Sigfox [78].

Communication Network	Spectrum cost	Deployment cost	End-device cost
LoRaWAN	Free	>$100/gateway >$1000/base station	>$20
NB-IoT	> $500 M /MHz	>$15000 /base station	$3-$5
Sigfox	Free	>$4000/base station	<$2

From the cost aspects in terms of the spectrum (license), network/deployment, and end-device, Sigfox, and LoRaWAN are more cost-effective than NB-IoT, as shown in Table 6. In the following, Sigfox, LoRaWAN, and NB-IoT are discussed in terms of their technical aspects in regard to this review.

a) Sigfox

Sigfox is an LPWAN network operator that offers an end-to-end connectivity solution based on its patented technologies. Sigfox deploys its proprietary base stations equipped with cognitive software-defined radios and connects them to the back-end servers using an IP-based network [33].

Sigfox uses unlicensed ISM bands, for example, 868 MHz in Europe, 915 MHz in North America, and 433 MHz in Asia. Even though it uses unlicensed band frequencies, it's a closed network and is not available without permission from the network service provider. Sigfox services are currently not operational in Africa.

Sigfox uses the frequency bandwidth efficiently and experiences very low noise levels, leading to very low power consumption, high receiver sensitivity, and low-cost antenna design at the expense of maximum throughput of only 100 bps. The number of messages sent over the uplink is limited to 140 messages (twelve bytes each) and four downlink messages (eight bytes each)per day [73].

Sigfox can communicate over ranges of up to 10km in urban areas and up to 50km in rural areas. In this review, Sigfox was used in three studies [41], [45], [61].

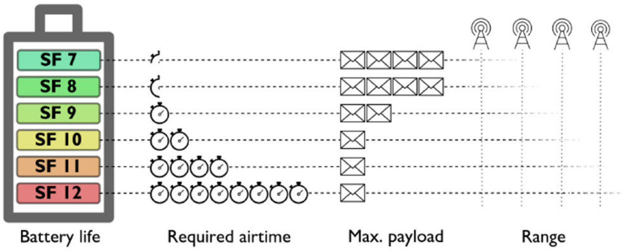

FIGURE 4. The SF of a LoRa signal affects the energy consumption, required airtime, maximal payload size, and the achievable communication range of a transmission [73].

For example, authors in [45] ran an experiment on an LPWAN tracking platform based on Sigfox and achieved a maximum range of 20km.

b) LoRaWAN

LoRaWAN is a physical layer technology that modulates the signals in the sub-GHz ISM band. LoRaWAN provides for long-range communications: up to three miles (5km) in urban areas and up to 10 miles (15km) or more in rural areas under LoS circumstances. A key characteristic of the LoRaWAN-based solutions is ultra-low power requirements, which allow for the creation of battery-operated devices that can last for up to 10 years [67].

Bidirectional communication is provided by the chirp spread spectrum (CSS) modulation that spreads a narrow-band signal over a wider channel bandwidth. The resulting signal has low noise levels, enabling high interference resilience, and is difficult to detect or jam.

LoRaWAN uses six spreading factors (SF7 to SF12) to adapt the data rate and range tradeoff. The spreading factors of a LoRaWAN signal affect the energy consumption, required airtime, maximal payload size, and the achievable communication range of transmission [73], [79] as shown in figure 4. For example, a higher spreading factor allows a longer range at a lower data rate expense and vice versa. The LoRaWAN data rate is between 300bps and 50kbps, depending on the spreading factor and channel bandwidth [21], [73].

The authors in [38], [39], [40], [41], [42], [43], [44], [49], [52], [54], [55], [56], [58], [59], [65], [67], [68], [69], [70], [71], [108], and [109] used LoRaWAN as a communication network representing 64% of all the studies in this review. For example, [49] developed a wildlife monitoring system leveraging BLE and LoRa. The range from transmitter at a transmit power of 4dBm, BW of 125KHz, and SF of 12 under a flat rural environment (open field) was 15.7km. From the experiment, high transmission power results in higher received signal strength, increasing the reception range.

c) NB-IoT

Narrow Band IoT (NB-IoT) was introduced by the 3rd Generation Partnership Project (3GPP) in 2016 [33], [78]. Unlike Sigfox and LoRaWAN, NB-IoT operates in licensed spectrum and synchronous communication. Therefore, it provides higher traffic reliability and is preferred for IoT systems that need guaranteed QoS. The NB-IoT communication protocol is based on LTE, and it can reduce its power consumption by reducing LTE protocol functionalities.

It has a frequency bandwidth of 200KHz and uses OFDMA for downlink and SC-FDMA implemented for uplink communication. It has a 250kbps data rate for downlink and a 20kbps data rate for uplink.

One of the main advantages of this standard is its compatibility with traditional cellular networks. Therefore, it can work in LTE or GSM under licensed frequency bands. In this review, NB-IoT was used in two studies [51], [107] and only for communication.

3) WLAN (WI-FI) COMMUNICATION TECHNOLOGIES

Wi-Fi technology is a tempting approach since Wi-Fi access points are readily available in many environments. However, this is not the case for resource-constrained environments. The range can be scaled up to 1km, which Wi-Fi typically covers outreaches that of Bluetooth or UWB, and another advantage of using Wi-Fi is that LoS is not required. In this review, Wi-Fi [46], [63], [66] was used in only three studies as a communication network.

4) WPAN COMMUNICATION TECHNOLOGIES

WPAN solutions such as BLE, ZigBee, and UWB provide short and medium-range communications and signal-range coverage of up to 300m in free space. In this review, BLE and UWB were used for communication by authors in [49], [50], and [64], respectively. Since ZigBee and BLE operate in unlicensed ISM bands, they are vulnerable to interference from a wide range of signal types using the same frequency, which can disrupt radio communication.

For example, [49] developed a wildlife monitoring system leveraging BLE and LoRaWAN. The range from transmitter under a flat rural environment (open field) was up to 200m for BLE.

C. CHARACTERISTICS OF USER DEVICES

User devices were used to perform different functionalities that include data collection, data transmission, and localization. The main focus of our characterization is to show external usability attributes associated with the use of specific user devices. These include the mounting point, cost, size, and weight. We also identify user devices that are commonly used together and also if they are commercial or custom-made.

1) COMMERCIAL OR CUSTOM DEVICE

In this review, commercial devices represent only 18% of the user devices used by different authors, and all are smartphones. 82% of the reviewed work used custom devices. Arduino and Raspberry Pi account for 25% and 11%, respectively, of the development boards and platforms used to build custom systems. 50% of the reviewed work gives a partial description of the development platforms used, with 14% not giving any description of the platforms or boards used to develop the systems they used to conduct their experiments. Not knowing the platforms used to make their systems makes it hard to replicate and validate the results. The use of custom devices is attributed to the need for tailored solutions that require technologies like LoRaWAN and combinations (hybridization) such as GNSS + LoRaWAN that commercial devices do not usually provide.

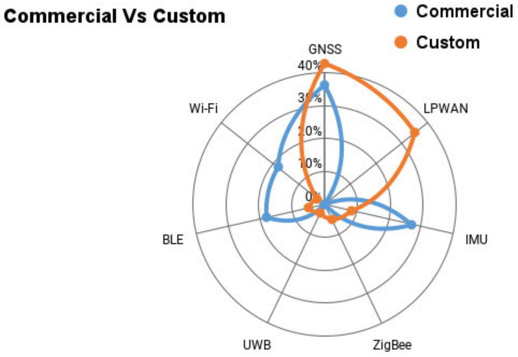

FIGURE 5. The spider graph shows the comparison of the different devices used in the commercial and custom systems.

In figure 5, a descriptive analysis of existing commercial and custom devices is derived as follows: 18% of the commercial devices include Wi-Fi technology, while only 3% of the custom made include it. Similarly, for BLE, 18% of the commercial devices, and 6% of the custom made include it. This phenomenon, where a commercial device's existence is more prominent compared to its custom device usage, is also true for GNSS and IMU. The implication is that there may be no need for the development of custom devices using such technologies. On the contrary, technologies such as LoRaWAN and UWB are not prominent in commercial devices. Our study results show 0% for both technologies under commercial devices and 33% and 3% for custom devices, respectively. This trend shows that there is a need for further development and testing of these technologies in the custom setting before the commercialization takeoff.

2) COMMON SENSORS USED

Overall, 56% of the studies in this review used GNSS sensors [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69]. GPS receivers were the most used type of GNSS constellation at 70%, with 30% using multi-constellation receivers covering GPS, GLONASS, and Galileo on a single chip. LPWAN technologies are increasingly gaining popularity in industrial and research communities because of ultra-low power, low cost, and long-range properties. In this review, LPWAN technologies were used for both localization and communication. 33% of the studies in this review [38], [39], [40], [41], [42], [43], [44], [45], [46], [69], [70], [71], [109] used the LPWAN technologies for localization and 64% for communication purposes. LoRaWAN [38], [39], [40], [41], [42], [43], [44], [46], [69], [70], [71], [109] was the most preferred for both localization and communication because it uses open standards, and also operates in Africa in relation to Sigfox [41], [45], and was used in only two papers. WPAN technologies were used in 21% of the reviewed studies. The WPAN technology included BLE sensors [46], [47], [49], [68], UWB [65] and ZigBee [48], [50].

INS systems which commonly integrate sensors such as accelerometers, gyroscopes, magnetometers, and barometers were used in 18% of the studies [62], [64], [66], [67], [68], [70]. These navigation sensors were used only to complement other technologies such as GNSS [62], [64], [66], [67], [68], [70] or Wi-Fi [66] as stated in **EC3**. This is because of the progressive accumulation of errors over a period of time during motion, and it also gives a relative position.

WLAN devices [62], [63], [66] were used in 9% of the works reviewed for localization and communication purposes. The authors who used Wi-Fi leveraged on the existing infrastructures, and these do not exist in resource-constrained environments and thus limiting the adaption of the technology.

Hybrid systems were used in 33% of the studies, and the most popular combinations of hardware found in the literature were GNSS with INS [62], [64], [66], [67], [68].

3) MOUNTING POINTS

Whereas the mounting point has an effect on the performance of the localization system, only 40% of the reviewed studies mentioned the mounting points used. All authors who used commercial devices mentioned the mounting points. Commercial devices come with already designed and packaged morphology that makes them restrictive and easy for it's designed for mounting points. Even though the authors who used custom devices had an opportunity to redesign and meet the targeted points as identified from different mounting points adopted, only 26% mentioned their mounting points. The most common mounting points for commercial devices were hands [62], [66], pockets [70], bracelets [46], and clothes [47], [64], but in addition to these mounting points, the authors who used custom devices explored different points like a collar [44], [48], [49], [58], animal ear [108] and walking sticks [38]. Not knowing the mounting points makes the adoption of these systems challenging, especially with the group of people and environment being dealt with. It also makes it hard to replicate the system and validate the results.

4) SIZE AND WEIGHT

Although the size and weight of a user device are essential requirements for tracking systems, only 10% of studies reviewed mention the size and weight of the systems used in their experiments. Tracking applications, in particular, are constrained by size and weight, limiting the range of species that can be tagged. The authors in [48] and [61] give a thorough explanation of the total size and weight of their developed system. For example, the authors in [48] suggested that a tracking device placed on an animal should ideally be less than 5% of the animal's body mass. Even though their study was done on animals, size, and weight have a similar constraint on the choice of tracking application to adapt for pedestrians as well. The authors in [61] and [108] designed small, lightweight, low-power electronic tracking tags of 2.6g and 30g total weights, respectively, which is far less than the average weight of a smartphone today. On average, a phone weighs around 200g.

5) COST

The cost of the user devices or systems used is very important since we are looking at resource-constrained environments, as explained in section II-A. Even though our literature search was biased toward systems designed for constrained environments, only 40% of the reviewed studies considered the cost of their designed systems as an essential requirement. Costs were minimized by using low-cost hardware, architecture designs, technologies, and algorithms and also utilizing the already existing infrastructures. The cost of a smartphone with localization capabilities is approximately $200 or more. Most designed custom user devices are estimated to cost $100-$500. Though for both cases, these costs cover the user device, there is an assumption of existing infrastructure on which these devices operate, such as Wi-Fi, satellites, cellular networks, and the Internet. Table 7 represents the summary of technologies, cost, and weight descriptions.

D. LOCALIZATION TECHNOLOGIES AND METHODS

This section covers the overview of the technologies, algorithms, methods, and principles used for localization. Table 8 gives a summary of the localization technologies used in the reviewed articles in terms of accuracy ranges, coverage, throughput, percentage of the technology in the devices used, and advantages and disadvantages of each technology. In this review, localization technologies can be divided into Radio Frequency(RF) based or inertial-based.

RF-Based Navigation Technologies

RF-based systems are the most adopted systems for localization. This is because they offer a good balance of coverage and accuracy in comparison to other wireless technologies such as infrared or ultrasonic-based localization systems [32]. Examples on RF-based navigation technologies include: Wi-Fi [62], [63], [66], Bluetooth [46], [47], [49], [68], ZigBee [48], [50], UWB [65], GNSS [51]- [69], [107], [108], and LPWANs [38], [39], [40], [41], [42], [43], [44], [46], [69], [70], [71], [109]

RF localization methods often leverage wireless network infrastructure that is initially deployed for communication purposes (e.g., LPWANs, Wi-Fi). They translate signal characteristics such as RSS and Time of Flight (ToF) and combine these estimates to determine the location of a wireless device or object.

Many localization methods exist, and generally, their performance depends on error sources such as end-device-related

TABLE 7. Different costs and weights of the devices.

Technology	Spectrum cost	Deployment cost	End-device cost	Weight
Sigfox	Free	> $4000/base station	<$2	<100g
LoRa	Free	>$100/gateway, >$1000/base station	$3-$5	< 200g
NB-IoT	>$500M/MHz	>$15000/base station	>$20	<100g
BLE	Free	$5–$30 per tag	∼ $5 receiver/reader	<100g
UWB	Free	>$45 per tag; >$290 per anchor	Expensive laboratory equipment	> 100g
Wi-Fi	Free	$20–(more than $50) per Access Point	> $10	50g-200g
GNSS	Not free but already defined	Billions of Pounds (but already existing)	$1-$100 (e.g., u-blox LEASH ∼ $50)	<100g
INS	Free	$> \$10 * n$	$10-$100	< 100g

errors like motion diversity, environment-related errors, for example, Non-Line of Sight (NLoS), gateway-related errors like network geometry and time synchronization, and data-related errors that are mainly associated with fingerprinting localization [72].

Localization can be done on either a unilateral or multilateral level [73]. In unilateral systems like GNSS, a device calculates its own location based on the measurements it receives from multiple terminals (i.e., satellites or terrestrial network infrastructure). Multilateral systems work the other way around: the location of a transmitting device is located by combining the measurements of multiple receivers. Due to the limited downlink capacity and star topology of LPWANs, it makes more sense to apply the latter.

The RF localization methods used in this review can be roughly divided into the following two categories: time-based positioning methods, such as time of arrival (ToA) and TDoA, and RSS signal-based positioning methods, such as fingerprinting and signal strength ranging methods.

a) RSS signal-based positioning methods

Ranging methods

Signal strength ranging methods use RF propagation loss models to calculate the distance between a transmitter and its receivers. Generally, such models take the distance between transmitter and receiver as well as the transmitted power and the frequency into account to determine the RSS [41]. The location of a transmitter can be calculated with trilateration or multilateration when the distances to at least three receivers are estimated. A common multilateration technique is to derive an equation system from the receiver locations as well as the estimated distances from the transmitter to the receiver and solve this system with a least-squares approach.

Fingerprinting

Fingerprinting, also known as scene analysis, is a pattern-matching localization method that estimates the location of a wireless device without having any knowledge of the location of the receivers. This method consists of an online step and an offline step. In the offline step, someone collects training data in the area where they want to locate their devices. Messages must be transmitted from known locations all over the area of interest to build a representative training database. In the online step, RSS measurements of newly received transmissions are matched to the fingerprints in the training dataset to estimate a transmitter's location, e.g., by applying a k-Nearest-Neighbors (kNN) analysis [41], probabilistic methods, maximum likelihood estimator (MLE) [40], decision trees, etc.

Fingerprinting has a better positioning accuracy and performance when compared with ranging methods and more especially if used in small ranges. However, these fingerprint-based methods require a wide survey of the environment to build a database and update the database regularly to reflect changes in dynamic environments and complex signal fading of different environment situations (e.g., weather changes). It is even more unsuitable when the object being tracked moves in areas much larger than the considered area during the offline phase, and this is very likely with the objects and the environments being considered in this review.

b) Time-based methods

For time-based localization methods, the distance between a transmitter and a receiver is estimated by measuring the ToA between them.

Time of Arrival (ToA)

Similar to the RSS-ranging. ToA applies trilateration/multilateration to the estimated distances between a transmitter and at least three receivers [41], [73]. However, ToA relies on the basic principle that the distance between a receiver and a transmitter can be related to the propagation time between them. Therefore, this method requires very precise synchronization between the transmitter and its receivers, for example, through additional GNSS hardware. This level of synchronization is often impractical for IoT devices and networks, so ToA can be ruled out as a worthwhile localization method for most applications.

Time Difference of Arrival (TDoA)

Contrary to ToA algorithms, a transmitting device does not have to be synchronized with the gateways to implement TDoA localization. Hence, there is no need to add synchronization hardware that would drain the battery. With a network of precisely synchronized gateways, the location of a transmitter can be calculated based on the TDoA relative to a reference gateway. To eliminate location ambiguity, at least three hyperboles are needed, and the transmitter location is estimated at their intersection. This means that the time measurements from at least four receiving gateways are required.

In the following, different localization technologies are discussed in terms of their technical differences and known performance characteristics.

1) SATELLITE (GNSS)

More than half of the research works included in this review used satellite technologies for localization [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69]. Satellite systems have global coverage, and free-of-charge provision of absolute positioning solutions [63]. It provides extremely precise, robust, ubiquitous positioning and timing information independent of telecommunication network infrastructure that connectivity-based technologies lack.

There are currently four GNSS constellations in operation: GPS (USA), GLONASS (Russia), BeiDou (China), and Galileo (Europe). In this review, BeiDou was not used. GPS constellation [51], [52], [53], [54], [55], [58], [60], [61], [64], [65], [66], [67], [107], [108] was the most used for satellite navigation and localization.

In traditional GNSS-based localization approaches, the concept of ToF is exploited to estimate the location of a receiver. When a radio signal leaves a satellite antenna, the current time is included in the message, enabling the receiver to compute the travel time and convert it into a distance measurement, incorporating clock errors. When distance measurements of four different satellites are available, the position of the GNSS receiver on Earth can be estimated using tri/multilateration techniques. Depending on the characteristics of the GNSS receiver and the processing method, different accuracies were obtained.

a: DEVICE VS CLOUD

Most of the studies that used GNSS technologies for localization used the position, velocity, and time (PVT) (latitude and longitude) directly offered by the GNSS receiver (local chip), and the data was transmitted to the cloud for the final computations and user access. In these studies [51], [52], [53], [55], [56], [58], [59], [60], [62], [64], [65], [66], [67], [68], [69], [107], [108], an accuracy range between 2.5m and 7.5m was achieved.

Contrary, the authors in [54], [57], [61], and [63], which represents 12% of the studies estimated positions (PVT) using snapshot positioning algorithm that allows ultra-low-power, reasonably accurate global position determination using very short (few milliseconds) sequences of GNSS data (snapshot). Special GNSS receivers are used to capture the GNSS signals, and then the dataset (logged data) can then be post-processed remotely (cloud) to achieve a good estimate of position. For example, accuracies of 6m [54], 14m [57], 27.7m [61], and 25m [63] were achieved from snapshot lengths of the recorded signal of 20ms, 10ms, 4ms, and 20ms respectively.

b: SINGLE VS MULTIPLE GNSS CONSTELLATIONS

The accuracy performance is a function of the satellites-to-receiver geometry quantified by the Geometric Dilution of Precision (GDOP) factor. A large number of satellites in view results in a better GDOP (improved position accuracy) and higher signal availability, particularly in urban environments where the LoS to the satellite might be partially obscured by buildings.

More than 70% of studies used single (GPS) constellation receivers [51], [52], [53], [54], [55], [58], [60], [61], [62], [64], [65], [66], [67], [107], [108]. The studies in [56], [57], [59], [63], [68], and [69] used multi-constellation receivers. The module had GPS, GLONASS, and Galileo constellations. Multi-constellation receivers are more costly and also consume more power [7].

The accuracy ranges achieved show no correlation between the obtained accuracy and the number of constellations used. For example, the authors in [51] achieved an accuracy of 2.5m using only GPS receivers, and authors in [61] achieved 27.7m using multi-constellation receivers.

c: SINGLE VS DUAL FREQUENCIES

Processing GNSS signals in multiple (dual) frequencies provide significant positioning accuracy and also provides better protection against local disturbances such as interferences or multipath. However, this high performance comes at the cost of an increase in overall energy consumption and high cost compared to single-frequency receivers [7].

Studies in [54], [59], [61], [63], and [67] used L1 (1575.42MHz) single-frequency receivers, and the rest of the authors don't mention the carrier frequencies and bands used.

2) WLAN (WI-FI)

Wi-Fi can be used to estimate the location of a mobile device within this network and is the most well-known approach for indoor positioning systems (IPS). The use of Wi-Fi signals is a tempting approach since Wi-Fi access points are readily available in many indoor environments, and it is possible to use standard mobile hardware devices [74].

The Wi-Fi infrastructure, like other RF infrastructures, supports fingerprinting-based systems, which have been a research trend because it is much more accurate compared to other techniques. For example, the authors in [62] used Wi-Fi signal fingerprinting algorithms based on RSS information of Wi-Fi access points collected using a smartphone and achieved an accuracy of 7.57m.

Contrary, the authors in [63] used Wi-Fi Round Trip Time (RTT) ranging method to measure the travel time between the rover (device) and the Wi-Fi router. The recording and processing of Wi-Fi RTT readings were done using an API in an Android smartphone. A maximum likelihood position was calculated using a least squares multilateration algorithm and Kalman filtering to optimize the estimate. The authors

TABLE 8. Summary of the localization technologies and their known performance characteristics. Tech: Technology; % use: Percentage use; MT: Maximum Throughput; PC: Power Consumption; LA: Localization approach used; VH: Very High; L: Low; M: Moderate; EL: Extremely Low.

Tech	% use	Accuracy	Maximum Range	MT	PC	Technique	LA	Advantages	Disadvantages
GNSS [51]–[69], [107], [108]	56%	2m-10m	Global, Outdoors	-	VH	Trilateration	ToA, TDoA	Global, widely-available	Only outdoors, high power consumption.
Wi-Fi [62], [63], [66]	9%	m-level	Outdoor:250m, Indoor:50m	600Mbps	M	Fingerprinting, Wi-Fi ranging	RTT, RSS	It is widely available, low-cost, and often does not need dedicated infrastructure.	Good-accuracy localization methods based on fingerprinting require extensive training and relatively low accuracy.
Bluetooth [46], [47], [49], [68]	12%	m-level	up to 100m	24Mbps	L	Proximity, Trilateration, Fingerprinting	AP ID, RSS	Widely available, ultra-low-power protocol stack suitable for the IoT.	Low accuracy. Significant challenges to real-time localization.
UWB [65]	3%	cm-level	up to 300m	460Mbps	M	Trilateration	TDoA, ToA, RSS	High accuracy and precision, moderate costs. It can penetrate a variety of materials, including walls, and is immune to interference from other signals	Not widely available (yet), and needs dedicated infrastructure.
LoRaWAN [38]–[44], [46], [69]–[71], [109]	32%	TDoA: 20-200m RSS: 1000-2000m	Urban:5km, Rural:20km	37.5kbps	EL	Tri/ Multilateration, Fingerprinting	RSS, TDoA	Ultra-low-power, low-cost, long-range, designed for resource-constrained environments and sensor networks. Wide reception range. It is an Asynchronous communication that allows the end nodes to be in sleep time most of the time. Operates in Africa	Low accuracy. Low data rates
Sigfox [41], [45]	6%	Range of hundreds of meters	Urban:10km, Rural:50km	100bps	EL	Tri /Multilateration, Fingerprinting	RSS, TDoA	Wide reception range and low energy consumption	It uses unlicensed frequency, but it's a private network. It does not operate in some parts of the world
ZigBee [48], [50]	6%	3m-5m	10m-100m	250kbps	M	Proximity, Trilateration, Fingerprinting	AP ID, RSS	low-power consumption	it is not readily available on the majority of the user devices, Low data transmission rate.
Inertial [62], [64], [66]–[68], [70]	18%	2m	-	-	L	Dead Reckoning	PDR	Cheap. No need for infrastructure	Accumulative errors, and it also gives the relative position

achieved an accuracy of 1.5m under optimal conditions (a static device with no nearby obstructions) in a room. One of the potential limitations of Wi-Fi ranging is multipath, which may limit the accuracy of the position indoors.

The authors in [66] achieved an accuracy of 3.1m, but the methods and localization algorithms used are not mentioned. Not knowing the localization algorithms and signal measurement or signal properties used makes it hard to replicate and validate the results. In all three studies, smartphones were used as user devices, and already existing indoor Wi-Fi infrastructures were utilized.

3) WPAN

A wireless personal area network (WPAN) is a type of personal network that uses wireless communication technologies to communicate and transfer data between the user's connected devices. Unlike a WLAN, a connection made through a WPAN involves little or no infrastructure or direct connectivity to the world outside the link. This allows small, power-efficient, inexpensive solutions to be implemented for a wide range of devices.

WPANs such as BLE and UWB offer high penetrating power, low-power consumption and transmission, good positioning accuracy, and little or no interference and multipath effects for indoor environments compared to other IPS and technologies like Wi-Fi. Still, they are not suitable for outdoor environments because of their limited range (10m-300m), and they are expensive to scale.

a) ZigBee Technologies

ZigBee is a wireless technology standard regarded as a low-rate WPAN. It is mainly designed for applications that demand low power consumption but do not require large data throughput. The signal range coverage of a ZigBee node is up to 100m in free space, but in indoor environments, typically 20m to 30m [73].

ZigBee technologies for localization were used in just two papers [48], [50]. The authors in [50] used the RSS method to estimate the distance between two or more ZigBee sensor devices. They used the ranging method (multilateration) for position determination and the weighted least mean square method as an estimating method.

The advantage of RSS localization, as used in [50], is that it is nearly implemented in all Zigbee receivers, so it does not require dedicated hardware. Despite its low accuracy, as it can suffer from multipath interferences and noise, it still had a fair accuracy of 10m for a 100m range because it was deployed outdoors with no strong multipath interference.

b) Ultra-Wide Band

UWB is a radio technology for high-bandwidth, short-range communication holding the properties of strong multipath resistance and, to some extent, penetrability for building material which can be favorable for indoor distance estimation, localization, and tracking. UWB is expensive to scale because of the need to deploy more UWB sensors in a wide coverage area to improve performance UWB localization technology was used in only one study [65]. In this study, UWB was combined with GNSS to cover the demanding task of indoor localization. The distance between a node (called tag) and at least three reference anchors was estimated using the ToF technique.

Subsequently, the multilateration technique was adopted for actual position estimation. The results demonstrated positioning errors on the order of a few centimeters in a typical indoor scenario (area of 16m2).

c) Bluetooth

Bluetooth, like ZigBee, is a wireless standard for WPANs. In contrast to ZigBee, the Bluetooth standard is a proprietary format managed by the Bluetooth Special Interest Group. The new Bluetooth version, termed Bluetooth Low Energy (BLE), can cover a range of 70-100m and provides 24Mbps with higher power efficiency. BLE-based localization is utilized in smartphones [30]. The advantage of using Bluetooth in positioning systems lies in its high security, low-cost, low power, and small size [35], [74].

BLE technology [46], [47], [49], [68] was used in 12% of the reviewed studies. BLE was also used in combination with other technologies such as LoRaWAN in [46], and GNSS and IMU (accelerometer) in [68], mainly to cover the indoor environment and also to minimize power consumption.

The authors in [46] used a smartphone to sense the beacon from the wearable device of the missing persons and used the received signal strength indicator (RSS) measurements to find the missing person's location. Contrary, the authors in [47] used the tag ID (cellID) to locate the patients. Both studies do not report the position accuracy achieved and the range.

The authors in [68] used RSS to locate the tag based on trilateration positioning algorithms. The position accuracy of less than 4m was achieved for a range of up to 200m.

4) LPWAN TECHNOLOGIES

A low-power wide-area network (LPWAN) is a type of wireless telecommunication wide-area network designed to allow long-range communications at a low bit rate among connected objects (devices), such as sensors operated on a battery.

LPWAN provides low-power, low-cost, and long-range communication, and its signals can be used for communication and localization simultaneously. The LPWAN technologies have star topology. Typically, IoT nodes send uplink transmissions to LPWAN gateways as end nodes. The LPWAN gateway sends collected data from end nodes to the LPWAN network server throw UDP/IP protocol [21]. LPWAN localization methods, like other RF-based methods, often leverage wireless network infrastructure that is initially deployed for communication purposes. This means no additional hardware cost or energy is consumed for localization purposes. This is a significant benefit for many energy-constrained applications or resource-constrained environments.

Different technologies have been considered to be LPWAN, which include LTE-M, NB-IoT, Sigfox, and LoRaWAN. In this review, studies in [38], [39], [40], [41], [42], [43], [44], [45], [46], [69], [70], and [71] used LPWAN technologies for outdoor localization which represents 38% of all the reviewed papers, and of the LPWAN technologies, LoRaWAN [38], [39], [40], [41], [42], [43], [44], [46], [69], [70], [71] was used most.

Different LPWAN localization methods were used, and these include time-based positioning methods, such as TDoA, and RSS signal-based positioning methods, such as fingerprinting, and signal strength ranging methods (trilateration, multilateration) by different authors. For example, the authors in [38] and [43] used a trilateration algorithm based on RSS techniques and achieved accuracies of 40m-60m and 9m-22m, respectively. The experiments were performed outdoors in a range of 100m-200m and 200m x120m open areas, respectively. The authors in [43] using LoRaWAN saved the power by 33% compared to GPS.

Contrary, the authors in [40], [41], [70], and [71] used the RSS-based fingerprint algorithms. The authors achieved an accuracy range between 28.8m in a 0.34km2 area, and 398.40m in an area around 52.97km2, and Choi et al. [40] proposed using the interpolation technique to complete zones of the service areas that were not covered in the offline phase which is a very big issue in dynamic environments. This is still not realistic in long-range outdoor areas.

The authors in [39] and [42] used a multilateration algorithm, and the main feature of computing the location is the TDoA. The authors achieved accuracies of 40m-60m and 100m, respectively. The study in [39] was conducted in a range of 100-200m, and the study in [42] was in a range of 5km, and the device being located in [42] was in a static position.

5) INERTIAL SENSORS

Research studies in [62], [64], [65], [66], [67], [68], and [70] used inertial sensors for localization, representing 18% of the studies in the review. The accelerometer, gyroscope, magnetometers, and compass were the most used sensors. In all the studies, inertial sensors are mainly used in hybrid systems and only as a complementary technology.

Dead Reckoning refers to the estimation of the current position of a target based on a previously known position (a fix) of it and measurements of quantities that are used to describe its movement, e.g., heading and speed [19]. Dead Reckoning can be implemented with inertial sensors. Inertial data is most useful when combined with another technique(s) capable of absolute rather than relative positioning, and this is because the inaccuracy of the process is cumulative. Based on this background, we only considered work that used inertial sensors with other technologies in our review. For pedestrian navigation applications, MEMS-IMU data are used in two different ways to compute the navigation solution: INS and pedestrian dead reckoning (PDR) [80].

INS

The INS mechanization calculates the user's relative position, velocity, and attitude by integrating raw data from accelerometers and gyroscopes.

PDR

To improve the MEMS navigation performance for pedestrians, PDR is proposed to reduce the accumulated navigation errors. PDR has four critical procedures: step detection, step length estimation, heading estimation, and position calculation. These parameters are then used to set up a PDR mechanization equation in which the user's horizontal position will be estimated.

The advantage of INS is the ability to provide 3D position, velocity, and attitude. However, it suffers the demerit that navigation solution errors grow up with time rapidly. On the other hand, when using PDR, navigation solution errors are proportional to the distance traveled and not to the time [75]. Also, PDR provides a more accurate position solution than INS, without other aiding sources, because it uses fewer integration calculations. The authors in [62], [64], and [67] used PDR techniques to estimate the person's walking path.

PDR solutions have become practical in people's daily use [75] because many handheld devices are equipped with inertial sensors. PDR works have also used units that assemble inertial sensors, which are called Inertial Measurement Units (IMUs). IMUs are mounted mainly on feet and legs [64]. The shoe-mounted setting has been the most popular, given that the mechanics involving the walking process and the foot allow re-calibrations at every step by applying the Zero-velocity UPdate (ZUPT) method.

For Example, INS constituted by accelerometers, gyroscopes, and other types of sensors based on MEMS were used in [64]. This system was based on the DR technique. A Kalman filter-based algorithm was used to filter and fuse data from the sensors(accelerometer, gyroscope), and probabilistic methods were used to learn a person's gait behavior to correct, in real-time, the drift errors given by the sensors. An accuracy of 4.5m in a range of 50m was achieved using the Kalman filter in conjunction with a ZUPT module working only with the gyroscope and accelerometer data.

6) HYBRID LOCALIZATION SYSTEMS

The systems that rely on technology fusion are called ''hybrid''. While in surveys like [76], the term ''hybrid'' refers to the combination of different techniques like AoA, TDoA, and so forth, in the context of the current survey, ''hybrid'' refers to the combination of different technologies, such as GNSS and Wi-Fi technologies. Research studies in [41], [46], [62], [63], [64], [65], [66], [67], [68], [69], and [70] used hybrid systems for localization which represents 33% of the studies in the review.

The hybrid method takes advantage of the strengths of one system and combines it with another system that has strengths where the first system exhibits inhibitions to compensate for the limitations of single model positioning technologies [35]. In these systems, one of the technologies is commonly considered more relevant for estimating the user's location, and the rest are complementary. They are used to improve the system, such as energy consumption, robustness, accuracy, and coverage area [18].

a: ENERGY CONSUMPTION

Energy Consumption is one of the most important issues in systems operating in a resource-constrained environment and IoT systems. These systems are embedded in different environments for an important purpose. Therefore, long battery life and low energy consumption are fundamental points for these systems.

The authors in [62], [63], [64], [65], [66], [67], [68], and [69] combined GNSS technology with technologies such as INS [62], [64], [66], [67], [68], Wi-Fi [62], [63], [66], UWB [65], and BLE [68] to minimize the power consumption of the technology. For example, the authors in [62] leverage WiFi signals and built-in smartphone sensors to achieve high localization precision and low power consumption. Their results from the hybrid system(GNSS+Wi-Fi+INS) enhanced the battery life by 50% compared to GNSS alone, achieving energy-saving purposes.

b: COVERAGE

Coverage describes the spatial extension where system performance must be guaranteed by a positioning system. GNSS technology was combined with inertial sensors in [64] and [66], [UWB] in [65], Wi-Fi in [63] and [66], and BLE in [68] in order to suppress the limitations of GNSS and to provide location everywhere. For example, the authors in [65] combined UWB and GNSS to cover indoor environments where GNSS technology has poor or no coverage. Accuracy. The term accuracy has been defined as the closeness of agreement between a measured quantity value and a true quantity value of a measured [74]. The authors in [62], [63], [64], [65], [66], [67], [68], [69], and [70] designed hybrid systems to improve the accuracy and precision of the measurements. For example, the authors in [63] combined GNSS with Wi-Fi technology to provide auxiliary anchors of opportunity to enhance indoor/outdoor positioning capabilities. Hybridization was also done to improve localization accuracy and precision. GPS alone achieved a median error of 40m; after hybridization, the horizontal errors went down to roughly 25m. Similarly, the authors in [62] achieved an accuracy of 7.57m from the hybrid of GPS +Wi-Fi and 10.3m for GPS only.

Some of the hybrid systems were designed to cover more than one criterion. For example, the authors in [68] combined GNSS with BLE and INS to minimize power consumption and also to cover indoor environments without GNSS coverage. BLE covered the indoor environment, and an accelerometer was used to indicate motion and count steps. No motion detected over a period indicates the pedestrian may be stationary, and the GNSS module can then be shut down to preserve power unless movements wake it up.

Similarly, the authors in [66] combined GNSS, INS, and Wi-Fi to improve the energy efficiency of traditional location tracking service (GNSS) as well as to expand its coverage areas (indoor). Utilizing the information from acceleration and orientation sensors, the system was able to select the location sensing methods between WiFi and GPS smartly and reduce the sampling rate. The results show that time of the GPS sensor being active is decreased by nearly 90%.

Also, the authors in [70] combined LoRaWAN technology and a compass sensor to increase the accuracy. For driving, cycling, and walking trajectories, they obtained minimal improvements of 65, 76, and 82% on the median errors, which were reduced from 206 to 68 m, 197 to 47 m, and 175 to 31 m, respectively. Their approach was 14 times more energy efficient than a GPS-over-LoRaWAN solution.

Furthermore, Extended Kalman Filter (EKF) and Particle filters were the most widely used algorithm, more so for the fusion of dead reckoning positions. For example, the studies by Minetto et al. [63] and Anacleto et al. [64], among others, use the Kalman filter. Particle Filter (PF) was used in the study of Dai and Podd [68]. The Kalman filter performs the statistical combination of INS information with other methods in hybrid to track drifting parameters of the sensors in the INS, while the KF provides a way for map information to be fused with pedestrian position information.

However, the major challenge with this model(hybridization) is the increase in infrastructure usage due to the combination of technologies and time consumption. This, in turn, increases complexity and, in other cases, increases cost [35].

V. DISCUSSION AND RECOMMENDATIONS

In this section, we will discuss the problems and limitations of current localization systems and look at alternative techniques and technologies not being considered in the literature that might impact the resource-constrained systems.

A. SUITABILITY OF CURRENT MONITORING TOOLS FOR RESOURCE-CONSTRAINED ENVIRONMENTS

The current localization and positioning systems as they are or as they were conceived are not suitable for a resource-constrained environment because of the following reasons:

1) HIGH POWER CONSUMPTION OF THE MAIN LOCALIZATION TECHNOLOGY: GNSS

Location estimation has been successfully implemented in outdoor environments using GNSS technology. This is clearly manifested in this review, as more than 50% of the reviewed work used GNSS for localization. It may not be the best solution as per the use case in this review for the following reasons.

a) The relatively high energy consumption of the technology aligns poorly with the stringent constraints of battery-powered devices. Different power optimization strategies employed by different authors are presented in section IV-A to mitigate some of the related power challenges. For example, the authors in [54], [57], [61], and [63] perform the location estimation from the cloud instead of the device. This solution greatly reduces energy consumption but requires stable and reliable communication networks and the Internet for exchanging data, resources very scarce in constrained environments.

b) The time to first fix (which is a measure of time required to obtain satellite signals and produce a valid coordinate within a specific performance [90]) of a GNSS receiver plays an essential role in the magnitude of this additional energy consumption and must therefore be considered when designing a GNSS- based low power localization system [85]. So as the authors implemented duty cycling, update rate, and sampling rate solutions, a good trade-off was supposed to be done to minimize the overall power consumption, something not discussed in any of the works.

Multiple new techniques exist to overcome this challenge, such as extended and autonomous ephemeris prediction and assisted GPS (AGPS), which dramatically improve the TTFF [82]. Still, most require Internet or GSM connectivity and a communication channel such as LTE and NB-IoT with sufficient capacity, and data rate not available in resource-constrained environments.

AGPS systems do not work in remote areas where mobile networks do not provide coverage [90].

Using multi-constellation can increase the number of satellites in the view and greatly affect the TTFF duration. Also, if a receiver can track and use multiple signals (multi-frequency), the convergence time to get positioning and heading (dual-antenna receivers) is decreased to several seconds [89]. We propose that further research be done to assess the effect of using multi-constellation and multi-frequency receivers to reduce the TTFF versus the overall energy consumption.

2) REQUIRED HIGH-CAPACITY COMMUNICATION NETWORKS

This review is biased toward remote monitoring and localization tools and systems, so there will always be a need to connect with a server (cloud). This explains the need for a communication network with low power, long-range, and stable connections. Some authors used communication networks such as cellular networks [47], [53], [57], [60], [62], [63] and Wi-Fi [46], [63], [66], which have high power consumption and also do not exist in the environments discussed in this review. The authors also used short-range communication networks such as Bluetooth [49], and UWB [50], [64] for data exchange. However, depending on the application requirements, these technologies may not be suited for outdoor localization systems or those covering large areas.

3) THE LOCALIZATION ACCURACY OF LPWAN IS NOT GOOD ENOUGH FOR PEDESTRIAN MONITORING

LPWAN technologies were used for localization in 38% of all the reviewed works. LPWANs offer the best power consumption and long-range coverage solutions, but the accuracy achieved is not suitable for pedestrian monitoring, more so elderly with dementia. For example, authors in [41] suggest that GNSS receivers be only omitted in favor of LPWANs when an error of more than 100m is acceptable, and the energy budget is extremely constrained. The suggestion is supported by the experiment they conducted, which achieved an accuracy of 214.58m for the rural Sigfox and 398.40m for the urban LoRaWAN dataset in an area of around 52.97 km2. We acknowledge that authors in [38] and [43] achieved low accuracies ranging below 50m using LPWANs. But for all the cases, small open ranges of 200m and less were considered for the experiments, which are not typical of rural areas where elderly people move freely. Therefore, we argue that the LoRaWAN localization in real-life conditions is ineffective, as the estimation of the distance between the node and the gateway changes heavily depending on the location of the node and radio channel attenuation. When little is known about the node placement, as in most cases, and the signal is subject to interferences due to the use of unlicensed bands, the LoRaWAN positioning provides very low precision in hundreds of meters.

4) LOW-COST BUT NOT AFFORDABLE

Localization sensors and systems are now readily available for personalized use and have been trending for quite some time in developed countries. The rate at which such platforms have been adopted is lower in low-developed countries and rural areas. Affordability (cost) is one of the factors that contribute to these low adoption rates. From the review, we found that most designed user devices or systems (custom and commercial) are estimated to cost 100-500 less the infrastructure cost. As explained in section II-A, users can not buy these existing localization systems with poverty levels in their areas. This explains why such systems have thus far had minimal influence and adaption in rural environments such as the one described in this review.

5) MANY PROPOSED SYSTEMS HAVE NOT BEEN VALIDATED IN THE WILD

Evaluation is done over simulations in some of the reviewed works [49], [53], [54] because it does not require deploying expensive hardware and manual labor. Although some simulated environments are able to mimic the real world, a comprehensive empirical evaluation is needed to demonstrate the feasibility of the proposed solution in realistic conditions. We further note that even for those not simulated, they were designed and tested in labs, and there is no proof that real users were involved in developing and validating these systems. It is very important to make your users feel like they are involved and valued in the system's initiatives through co-creation and co-design. This greatly impacts user experience, trust, awareness, and acceptance.

6) REPLICABILITY

It is very important that research can be replicated. This means that other researchers can test the findings of the research and make recommendations. Replicability keeps researchers honest and can give readers confidence in research. Many authors in this review do not provide enough details about the methods used, making reproducibility of suitable devices and systems for the right environment challenging.

7) SECURITY AND PRIVACY

Security and privacy are open issues that need to be considered more so for localization systems with remote access in a resource-constrained environment. Most authors used LPWAN technologies for communication, and these contain important security and safety vulnerabilities [86], [87]. These vulnerabilities can be exploited by malicious entities and lead to great damage. Security and privacy become more important as the data being exchanged contains location data for vulnerable elderly people. Therefore, providing a reliable security mechanism based on their limitations is a challenging and open issue task.

8) DEVICES NOT DESIGNED FOR USERS WITH NO DIGITAL LITERACY

In this review, commercial devices, such as smartphones, were used for positioning and monitoring pedestrians, including elderly and dementia patients with little or no digital literacy. Digital literacy is one of the key barriers to adopting the technologies but was not considered in all the works. Because of that, existing initiatives still need to provide adequate monitoring and localization to rural areas with low-literate users since current designs expect literate users.

B. RECOMMENDATIONS AND RESEARCH OPPORTUNITIES

1) TTFF TECHNIQUES ADAPTED TO LPWAN

To improve the TTFF, extended and autonomous ephemeris prediction, and AGPS can be done differently. LPWANs can be used to download assisted data packages necessary for faster position fixes and therefore reduced energy consumption. To decrease energy consumption and increase autonomy, the provision of assistance data with a validity of up to multiple weeks, as already offered by several companies, should be exploited. This will minimize the download frequency of data and thus allow LPWANs operating in the unlicensed ISM bands to comply with radio regulations. This solution significantly affects accuracy, so a good trade-off needs to be made.

2) TRANSMISSION OF PSEUDORANGES BASED ON SNAPSHOT DATA

A significant part of the energy consumption of a conventional GNSS receiver results from the long time required for decoding the navigation messages disseminated by the satellites. With the recent disclosure of GNSS raw measurements in the mass market GNSS receivers in Android devices [88], new trend techniques mainly oriented to IoT devices could be tested and adapted for pedestrian monitoring. We are suggesting that snapshot techniques could play an important role, as they make it possible to determine position by using only a minuscule interval of a GNSS signal. This highly flexible approach allows for multiple configurations, including outsourcing energy-intensive computations to cloud servers, resulting in cheaper, simpler, and more energy-efficient hardware. Although innovative snapshot techniques have multiple advantages, their real-world adoption is currently only starting but promising. Also, the transmission of raw snapshots is not possible for proprietary LPWANs such as Sigfox or LoRaWAN, communication networks we highly recommend for the environment being considered in this review [7]. Therefore an alternative configuration like the transmission of pseudoranges based on a snapshot of the signals is recommended instead.

3) LEO POSITIONING

Satellite technologies are moving towards offering a seamless localization solution. For example, Galileo promises better indoor performance than GPS, but we have yet to see any real-world tests. Currently, ephemeris downloads at a bit rate of 50 bits/sec, which is the main reason for the prolonged time to attain a fix in a weak signal environment. By increasing the bit rate of the ephemeris broadcast, we can alleviate this problem. Adopting low-earth orbit (LEO) positioning could enhance indoor performance by relaying data at higher data rates [110].

4) GALILEO SIGNAL COMPONENT

Recently, one Galileo satellite has been reconfigured to emit a new signal (G1 E5 Quasi Pilot) component optimized to serve low-end receiver devices and Internet of Things (IoT) applications. The initial receiver tests have demonstrated that the signal component has the potential to reduce the signal acquisition time by a factor of three compared to the current GPS L5. This is an exciting development for future researchers as this will significantly improve power efficiency [111].

5) NEW HYBRID LOCALIZATION TECHNIQUES USING LPWAN

Further research into new hybrid localization architectures that try to better adapt to the characteristics of pedestrian monitoring systems in resource-constrained environments would be advisable. For example, there are proposals that merge GNSS with INS, GNSS with PDR, or GNSS with LoRaWAN, but we did not find any proposal fusing GNSS+INS/PDR+LoRaWAN. The fusion of inertial navigation and GNSS allows for infrastructure-free positioning, and LPWANs such as LoRaWAN provides the possibility for long-range private network deployments by working in a license-free spectrum, its open access specifications. LoRaWAN also provides energy consumption management by different class type definitions and adaptive data rates.

Combining the three technologies can also help minimize power consumption by determining when there is a need for the modules to be off and on or their sampling/frequency rate.

VI. CONCLUSION

We have managed to provide an in-depth, state-of-the-art systematic review of remote pedestrian localization systems with the aim of identifying if they are suitable for resource-constrained environments. We used the PRISMA model as the basis of our literature review in order to provide a replicable work and report the studies' main findings. Although the search queries provided 932 works, only 37 fulfilled all the criteria established in this work and were analyzed, and the key information was extracted to answer the five defined research questions along with the article in various sections.

This systematic review has demonstrated that several general surveys and reviews exist related to localization systems, but none has been done considering a constrained environment, yet these environments exist. We demonstrated this by explaining what we mean by a resource-constrained environment and showing how current surveys do not consider the characteristics of resource-constrained environments, such as lack of digital literacy, poverty (affordability), limited or no access to electricity, Internet, and cellular network among others.

From the results of the systematic review, it can be concluded that many of the proposed systems are not suitable for resource-constrained environments, as they assume the availability of resources and infrastructures such as Wi-Fi networks, cellular networks, Internet, and power grid access.

It has also been noted that the usual features of a remote monitoring system trying to take care of energy consumption usually include a GNSS receiver (mainly GPS) as the main source of location information, LPWAN technologies (mainly LoRaWAN) for data communication, use of inertial sensors mainly to try to reduce GNSS consumption, and custom-made user devices, which allows choosing components and technologies with lower power consumption compared to commercial devices.

However, as discussed in Section V, there are opportunities for further work in designing people monitoring systems that are better suited to these environments. For example, with location acquisition being one of the most important and, at the same time, most consuming components, it is noted that little research has been done on the fusion of GNSS, LoRaWAN, and inertial sensors. Although these technologies are used in many proposed systems, they are used in a loosely coupled manner, and more could be made of their complementarity in terms of consumption and location information.

In the future, we will investigate the proposed combination of GNSS, INS/PDR, and LoRaWAN, following the suggested co-design and co-creation good practices.

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ASIIMWE PADDY JUNIOR received the bachelor's degree in computer science and the master's degree in data communications and software engineering from Makerere University, Uganda, where he is currently pursuing the Ph.D. degree in engineering for the information society and sustainable development, under the supervision of Luis Enrique Díez Blanco and Dr. Odongo Steven Eyobu. He has been an Assistant Lecturer and a Researcher with the Department of Information Systems, College of Computing and Information Science, Makerere University, since 2012. He joined the 6i Dirs COFUND Project, in February 2021. He is also a Research Assistant with the DeustoTech, University of Deusto. His research interests include wireless sensor networks, mobile application development, localization, ambient assisted living, and artificial intelligence.

LUIS ENRIQUE DÍEZ received the degree in telecommunications engineering from the University of Deusto, in 2005, the master's degree in communications technologies and systems from the Telecommunications Engineering School, Polytechnic University of Madrid, in 2012, and the Ph.D. degree in engineering from the University of Deusto, in 2019. From 2005 to 2011, he was a Senior IT Consultant with Everis. From 2013 to 2014, he joined the SOFTLAB Research Group, Carlos III University of Madrid (UC3M), as a Research Support Technician. From 2014 to 2022, he was a Researcher with DeustoTech, Engineering Faculty, University of Deusto. He is currently an Assistant Professor with the Faculty of Engineering, University of Deusto, and a member of the Research Group "Deusto Smart Mobility." He has worked (leading some of them) on more than ten regional, national, and international research projects and contracts. He has coauthored 15 research manuscripts published in international journals and more than ten communications in international congresses. His research interests include signal processing and data fusion for the development of location-based services, ambient assisted living, and intelligent environments.

ALFONSO BAHILLO received the degree in telecommunications engineering and the Ph.D. degree from the University of Valladolid, Spain, in 2006 and 2010, respectively. From 2006 to 2010, he joined CEDETEL as a Research Engineer. From 2006 to 2011, he was an Assistant Professor with the University of Valladolid. From 2013 to 2017, he held a postdoctoral position with the DeustoTech-Fundacion Deusto, University of Deusto, Bilbao, where he was the Director, from 2017 to 2020. Currently, he is an Associate Professor with the University of Valladolid. He has worked (leading some of them) in more than 25 regional, national, and international research projects and contracts. He has coauthored more than 35 research papers, published in international journals, more than 40 communications in international conferences, and four national patents. His interests include local and global positioning techniques, ambient assisted living, biomedical and health informatics, and wireless networking. He received the PMP Certification from PMI, in 2014.

ODONGO STEVEN EYOBU received the B.Sc. degree in computer science from Islamic University, Uganda, in 2004, the M.Sc. degree in data communication and software engineering from Makerere University, Uganda, in 2007, and the Ph.D. degree in electronics engineering from Kyungpook National University, South Korea, in 2018. He is currently a Lecturer with the School of Computing and Informatics Technology, Makerere University. His research interests include deep learning systems, indoor localization, vehicular communications, intelligent transportation systems, and wireless sensors.

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