Journal of Medical Systems (2021) 45: 35
https://doi.org/10.1007/s10916-021-01710-1

MOBILE & WIRELESS HEALTH

A Survey About Real-Time Location Systems in Healthcare Environments

Rodrigo Bazo[1] · **Cristiano André da Costa**[1] · **Lucas Adams Seewald**[1] · **Luiz Gonzaga da Silveira Jr.**[1] · **Rodolfo Stoffel Antunes**[1] · **Rodrigo da Rosa Righi**[1] · **Vinicius Facco Rodrigues**[1]

Received: 25 October 2018 / Accepted: 20 January 2021 / Published online: 9 February 2021

Abstract

Every year healthcare organizations suffer from several issues, such as unapropriated workflow, thousands of deaths caused by medical errors, counterfeit drugs, and increasing costs. To offer better patient care and increase profit, hospitals could adopt solutions that help remedy these problems. Real-Time Location Systems have the potential to deal with many of these issues, as well as offering means for developing new and intelligent solutions. This kind of system enables tracking assets and people, allowing several improvements. Even though the benefits of such solutions are well known and desired by healthcare providers, their large scale adoption is still distant. In this article, we surveyed Real-Time Location Systems usage in hospitals. While developing this survey, we observed a need for organizing important aspects of healthcare-oriented Real-Time Location Systems. Therefore, we analyzed challenges regarding this topic and a taxonomy proposed. This survey offers researchers and developers ways to comprehend the challenges surrounding this area while proposing a classification of aspects that a Real-Time Location System for healthcare environments must assess for it to be successful.

Keywords Real-time location systems · RTLS · Healthcare · Taxonomy

Introduction

Resulting in more deaths than AIDS or airplane crashes, medical errors are the cause of nearly 500.000 deaths yearly, according to the Food and Drug Administration (FDA) [55]. Additionally, the Institute of Medicine (IOM) estimates that, only in the U.S., 44.000 to 98.000 deaths are caused due to medical errors yearly [32]. The World Health Organization calculates that counterfeit drugs cause a deficit of over $40 billion for the pharmaceutical industry [49]. Theft of equipment and supplies cost up to $3.9 billion annually to healthcare providers in the U.S [55]. Furthermore, healthcare costs are expected to rise to $4.4 trillion in the United States this year [1].

By reducing these numbers, healthcare providers can decrease their waste, offer patients better services and safety as well as increase profit. One of the technologies that has the potential to deal with the aforementioned problems is Real-Time Location Systems (RTLS) [5, 37, 55]. RTLS are systems that enable identifying and tracking a given entity at near-real-time or real-time [4]. While working in a similar fashion to Global Positioning Systems (GPS), RTLS are usually local solutions. In healthcare environments, RTLS can be used in several ways, such as: tracking assets, personnel and patients; correlating location data with other data, such as Electronic Health Records (EHR) [24, 44]; enabling workflow improvement by mining data in unobtrusive means [2, 13].

These systems have long caught the attention of healthcare providers. Back in 2008, a research conducted with hospital administrators from the U.S. found that 15% of them already had some kind of tracking system implemented, and 43% were interested in implementing one in their respective hospitals [15]. Six years later, a research

This article is part of the Topical Collection: *Mobile & Wireless Health*

✉ Cristiano André da Costa
cac@unisinos.br

[1] Software Innovation Laboratory - SOFTWARELAB, Programa de Pós-Graduação em Computação Aplicada, Universidade do Vale do Rio dos Sinos, Av Unisinos, 950, São Leopoldo, RS, 93022-750, Brazil

conducted with 81 health directors from the largest public health system in Florida showed that healthcare entities are still enthusiastic towards RTLS [56].

Other academic surveys regarding RTLS in healthcare environments exist. In [37], a literature review regarding healthcare-oriented RTLS is conducted, however, the authors state that the study is not exhaustive literature research. In [15] a qualitative study with several hospitals is presented, pointing several issues that arise when using RTLS in healthcare environments, while in [4] a more technically driven survey regarding this topic is conducted. In the work of [22], recent patents for such systems are reviewed. Focused on Iran technologies, in [16] the authors reviewed specific works regarding RTLS in hospitals from 2006 to 2017.

Considering the scenario described above, this review aims to comprehend the current state-of-the-art regarding RTLS applied to healthcare, presenting a view of the challenges, technologies, and future research opportunities. By analyzing and understanding the challenges that arise in the development and deployment of such technologies, a taxonomy classifying important aspects of a RTLS for healthcare environments must assess is presented.

The remainder of this work is structured as follows: Section "Method" describes the methodology used on this survey, detailing the strategy used literature corpus and filtering results; Section "Literature analysis" presents the literature review; a discussion is conducted on Section "Discussion"; finally, Section "Conclusion" concludes the review.

Method

This review analyses the development and deployment of RTLS in healthcare, focusing on understanding the key factors holding back its adoption. In order to develop this review, the following steps were followed:

1. Definition of the research questions to be answered;
2. Obtaining literature corpus;
3. Filtering the acquired articles to review only relevant studies.

These steps will be detailed in the subsections next.

Research questions

Research questions are the most important part of a systematic review [26], therefore their definition is the first step of this study. One main question (MQ) and five specific questions (SQ) were used as guides. These questions are described in Table 1.

Table 1 Research questions

MQ: What are the challenges faced while developing and deploying Real-Time Location Systems for hospitals?
SQ1: Which sensors are used on this type of application?
SQ2: Which of the used sensors are interesting options for employing RTLS in healthcare environments?
SQ3: What are the main components and localization techniques of a Real-Time Location System?
SQ4: How can the aspects of a healthcare Real-Time Location System be classified?
SQ5: What are the future research opportunities on this area?

Search process

For the literature selection, a set of keywords were defined in order to create a search string that would allow the identification of relevant articles. With the chosen keywords, the following search string was created:

$$rtls \wedge (healthcare \vee hospital) \wedge (location \vee tracking \vee identification) \wedge (rfid \vee uwb \vee bluetooth \vee ble \vee wifi \vee zigbee \vee nfc \vee infrared \vee ultrasound)$$

This string was used in the following literature databases: ACM Digital Library, IEEE Xplore, Google Scholar, Science Direct, Springer and PubMed.

In Figure 1, the strategy used for obtaining the literature corpus for this review is detailed. First, relevant literature databases regarding the topic of this review were chosen. Afterwards, the literature corpus was extracted from the databases using the search string, resulting in a total amount of 1692 papers. Finally, five filters were used to select relevant studies, resulting in 47 papers. The filters are described next.

Filter 1 – date restriction

In order to guarantee that this analysis will review the most recent studies, as well as understand the most recent technologies and issues, the scope of this review is restricted to the last decade.

Filter 2 – duplicate removal

The duplicates of studies contained in the literature corpus are disconsidered.

Filter 3 – impurity removal

Results that are not full length research articles fall under our impurity criteria and are removed.

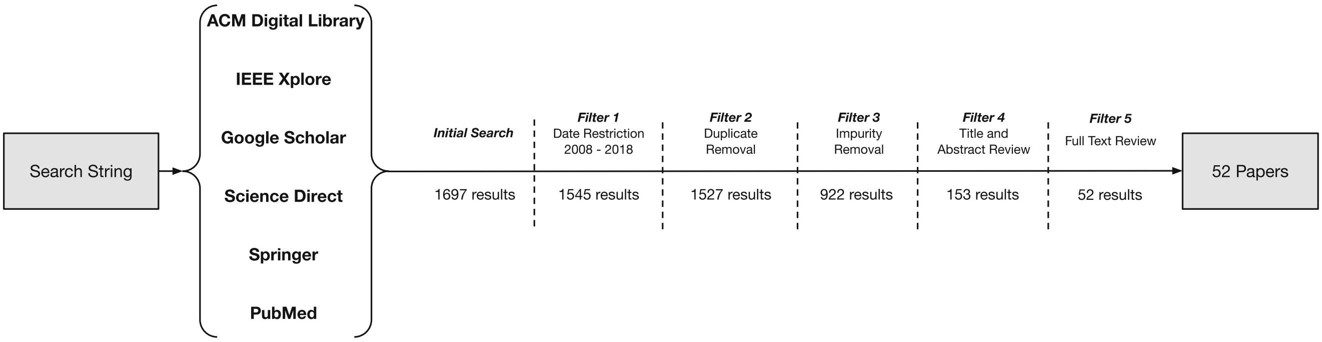

Fig. 1 Literature corpus extraction process

Filter 4 – title and abstract review

If the title and the abstract of the work do not reflect the goals of this review, the entry is removed.

Filter 5 – full text review

As the last filter, a full text review of the remaining studies is conducted in order to select only relevant studies.

Literature analysis

The analysis of the literature collected using the methods described in Section "Method" is presented in this section. The obtained literature corpus is presented in Table 2 together with the study description, respective used technology and RTLS accuracy level, if stated by the study. Regarding accuracy level, three accuracy levels are considered: Zone level (tracking if an entity is in a given large area), Room level (tracking in which room is a given entity) and Subroom level (tracking where in a given room an entity is). In order to perform the literature analysis, each research question is answered in its respective subsection.

Main question – what are the challenges faced while developing and deploying real-time location systems for hospitals?

The main question of this systematic analysis addresses the challenges that still hinder the development and deployment of RTLS in healthcare environments. Several studies focus on this topic aiming at proposing possible solutions. Most of them are academic works that propose methods and conduct pilot experiments. They detail the challenges faced during development and present solutions and novel strategies. Some offer insight on the difficulties found while deploying RTLS in healthcare environments, such as hospitals. However, most of these studies are proofs of concept and are not deployable in real healthcare environments [37]. And, considering that business cases of RTLS are rare [4], only a small amount of studies describing real use cases of RTLS on healthcare are expected to be found.

According to Okoniewska et al. [34], back in 2009, AeroScout (Stanley Healthcare) arose as the leading solution for RTLS in healthcare, holding 45% of the market and having being implemented in more than 500 organizations. Together with IBM and AeroScout itself, the authors of the study evaluate the solution. It was found out that the nurses that used the system grew discouraged of using it due to its lack of accuracy, while asking colleagues was a faster and more viable option.

In Fisher and Monahan [15], the authors conducted a 3-year study with 23 U.S. hospitals that implemented RTLS solutions. It was noticed that, overall, the systems would constantly fail to provide the promised precision and the majority of them have medium to low levels of accuracy and functionality. Also, the study states that a collective discontentment with the hospitals' experience with RTLS exists. It is important to note that some of the systems observed were old and the study does not detail the systems used by the hospitals, whether they were industrial solutions or not.

A study aiming at understanding the staff and patient adoption and acceptance of RTLS in two healthcare sites was conducted by Bowen et al [5]. The study describes four lessons learned while deploying and using the system: (a) additional time and effort should always be expected in the deployment of the application; (b) there will be staff and patient mistrust towards the technology; (c) difficulty in perceiving benefits, even though management staff may understand the benefits of the service, nurses and other staff members may be suspicious towards the solution, rising up the need for team maintenance with staff training; (d) many unexpected site-specific issues may affect the deployment of the solutions, so the RTLS provider should be aware and ready to adapt to changes that may be required.

Analyzing the three studies described earlier, some noteworthy points are already raised and described next.

Table 2 Literature corpus studies description

Study	Description	Year	Technologies						Accuracy
			RFID	BLE	WiFi	Zigbee	UWB	Infrared	
[20]	A case study of RTLS contact tracing of potentially infected individuals.	2017	✓						–
[54]	An analysis on the integration of blood supply chain and RFID.	2013	✓						–
[46]	Comparison of a commercial and custom-made tracking systems for patient tracking in an ambulatory clinic.	2015	✓					✓	Room
[28]	Proposal of an agent based model of a hospital emergency department for RTLS.	2010	✓						Room
[48]	Analysis of the performance of three different tracking systems in a healthcare site.	2016		✓	✓	✓			Room
[24]	Description of operational methods for combining RTLS and EHR data for workflow improvement.	2014	–	–	–	–	–	–	–
[33]	Implementation of two prototypes: (a) asset tracking; (b) patient control.	2011	✓						–
[23]	Conduction of a pilot study that presents effectiveness of RTLS for time use estimation by nursing personnel.	2014	✓						Room
[36]	Methodology proposal for optimizing asset tracking in a system with limited number of RFID readers.	2010	✓						–
[10]	Proposal of an approach for improving patient flow using RTLS.	2017	–	–	–	–	–	–	–
[39]	Presentation of the design, implementation and testing of a RTLS based on RFID.	2012	✓						Room
[45]	Analysis of the impact of a WLAN-based RTLS on patient satisfaction in a Level I trauma-center.	2014	–	–	–	–	–	–	–
[42]	Framework proposal for dealing with major privacy issues regarding RFID healthcare systems.	2017	✓						–
[9]	Design of a real time risk alert and location system for increasing patient safety and reducing medication administration errors.	2017	✓						Room
[57]	Description and result analysis of a centimeter precise 3D tracking system.	2010					✓		Subroom
[19]	Development of a proximity based tracking system for use in the operating room.	2015		✓					Room
[3]	Development of a solution for tracking and monitoring patients on psychiatric wards.	2015	✓						Room
[27]	Proposal of a thermal based tracking system.	2008						✓	Subroom
[41]	Study regarding the challenges and design of gamma-resistant RFID tags.	2010	✓						
[32]	Implementation of an asset tracking and managing system in a 120-bed hospital.	2007	✓						Room
[18]	Analysis of a Participatory Design for support design and implementation of a RTLS in an OR.	2015	✓						Room
[30]	Implementation of a secure real time tracking application.	2016		✓					Zone
[31]	Implementation of a health center personnel and asset tracking using an IoT environment.	2017			✓				Zone

Table 2 (continued)

Study	Description	Year	Technologies						Accuracy
			RFID	BLE	WiFi	Zigbee	UWB	Infrared	
[43]	Proposal of a highly secure RTLS model for tracking patients and personnel.	2012	✓						-
[38]	Proposal of an optimization framework for planning the position of a sensor network in healthcare environments.	2013	–	–	–	–	–	–	–
[13]	Presentation of a tool and mining-based methodology for process tracking using RTLS.	2015	–	–	–	–	–	–	–
[34]	Evaluation of a commercial RTLS deployed in a clinical setting.	2012			✓				Room
[35]	Description of a participatory design of RTLS, conducted on two nursing home organizations.	2017	–	–	–	–	–	–	–
[6]	Study that analyzes the impact of the adoption of RFID asset tracking system in a general care hospital.	2010	✓						Room
[50]	Conduction of a review of papers from 1997 to 2011 regarding RFID healthcare applications.	2012	✓						-
[59]	Survey on IoT applications for healthcare environments.	2016	–	–	–	–	–	–	–
[8]	Comparison between different indoor localization systems.	2012	–	–	–	–	–	–	–
[12]	Review of recent wireless indoor localization techniques and systems.	2013	–	–	–	–	–	–	–
[51]	Comparison of RFID and Wifi technologies for use in healthcare RTLS applications.	2013	✓		✓				–
[29]	Analysis of the advancements on UWB positioning systems.	2009					✓		Subroom
[47]	Assessment and classification of electromagnetic interference of RFID with care equipments.	2008	✓						-
[25]	Analysis of electric magnetic interference with RFID in healthcare settings.	2011	✓						–
[21]	Study on understanding the deployment of RFID on healthcare settings.	2015	✓						–
[55]	Literature review on the use of RFID by hospitals and healthcare settings.	2012	✓						–
[49]	Presentation of barriers and success factors for understanding RFID adoption on southeast asian healthcare.	2008	✓						–
[1]	Study conducted on understanding RFID adoption on United Arab Emirates.	2017	✓						–
[37]	Literature review aiming to identify common features for successful healthcare RTLS features in common RTLS technologies.		–	–	–	–	–	–	
[5]	Description of staff and patient adoption of RTLS in two healthcare sites.	2013					✓		Room
[44]	Development, proposal and testing of a tracking system using RFID in a hospital.	2012	✓						Room
[14]	Evaluation of RTLS implementations in 23 U.S. hospitals.	2008	–	–	–	–	–	–	–
[56]	Survey on understanding hospital perspectives of real time information technologies.	2014	–	–	–	–	–	–	–
[4]	Survey on RTLS technologies, applications and benefits in healthcare environments.	2012	–	–	–	–	–	–	–

Table 2 (continued)

Study	Description	Year	Technologies						Accuracy
			RFID	BLE	WiFi	Zigbee	UWB	Infrared	
[17]	Overview of the UWB technology for healthcare systems.	2016					✓		Subroom
[53]	Survey comparing the deployment of RTLS on nursing homes against other healthcare sites.	2018	–	–	–	–	–	–	–
[16]	Work reviewing RTLS literature and proposing a model for Iranian hospitals.	2019	–	–	–	–	–	–	–
[58]	Study analyzing the deployment of a BLE-based asset tracking system on a tertiary care hospital.	2018		✓	✓				Room
[22]	Survey of recent patents on technologies enabling IoT solutions for healthcare.	2016	–	–	–	–	–	–	–

Human factors can be considered one of the major challenges in deploying such technologies since people are reluctant to accept them due reasons: (a) privacy concerns; (b) unfamiliarity with new technology; (c) usability, engaged users feedback indicate that they are sensible to system complexity; (d) difficulty in perceiving benefits, even though the advantages of this solution seem to be clear, many participants still cannot perceive benefits regarding its use and adoption. It is also noticeable that, overall, the RTLS solutions failed to effectively perform their most basic and desired functionality, which is providing the correct location of a given entity when needed, showing that the solutions lack satisfactory precision. In the second study [14], administrators, clinicians and non-clinical staff of the majority of the 23 hospitals surveyed, pressed the authors on giving details on how other hospitals were leveraging their RTLS applications, showing general discontentment with the solutions. This may be one of the most critical challenges faced, considering that low level of reliability may repel user acceptance [35]. Also, challenges regarding infrastructural needs also appear. Hospitals usually work non-stop, therefore they are unlikely to block access to its facilities in order to handle maintenance or install RTLS components.

On the other hand, successful business cases of RTLS on hospitals also exist. In Christe et al [6], the authors surveyed the impact of using a RFID asset tracking system on Southeastern Regional Medical Center (SRMC), a 337 bed hospital in North Carolina, U.S. The study indicates that the system had a strong acceptance within the nursing and clinical engineering staff. Surveys conducted with both teams indicate that the system improved the workflow and all staff members agree that it made looking for equipments easier. Also, the study shows that there is a huge financial impact on implementing this technology. Most of the cost savings comes from nurses spending less time looking for equipment. However, this study did not analyze the deployment process of the system, which was meant only to track assets and not humans, thus offering little insight into challenges that arise from tracking persons.

From what was learned while analyzing the literature corpus of this review, nearly all aspects that compose the development and deployment of an RTLS for Healthcare environments have challenges that still lack definitive answers or solutions. The academic works revealed several development and even some deployment barriers, while business cases studies described many other issues related to organizational factors of the hospitals. Some of the observed challenges are simply technical and eventually will be overcome, such as data management and security aspects (interference, privacy). However other aspects include human factors, which may not find optimal solutions, considering that this kind of issue may raise ethical discussions. In Table 3, the challenges found while analyzing the literature corpus are presented.

Specific question 1 – which sensors are used on this type of application?

Several sensors are currently used and studied for implementing RTLS solutions. Since GPS fails to reproduce its success in indoor environments [4], several sensors are studied as alternatives for indoor tracking. In this study, focus is kept in sensors used in RTLS for healthcare environments. Figure 2 presents the identified sensing technologies and the number of times they appeared in surveyed studies.

RFID [52] is the technology present in most of the studies. The RFID global market is expected to grow up to $2.03 billion this year [1], therefore a huge market interest exists behind it. Several other technologies are also present in the obtained literature corpus and appear as interesting choices. Bluetooth Low-Energy (BLE) offers low energy consumption and small tag size [12]. WiFi [7] is a

Table 3 Observed challenges regarding RTLS in healthcare

Pointed Challenges	Study
Development	
Implementation	
Complexity	[8, 12, 16, 48]
Data management and integrity	[38, 50]
Interference	[16, 25, 47]
Scalability	[37, 42, 44]
Security	[16, 37, 42, 43, 50, 53, 59]
Standardization	[16, 59]
RTLS Manufacturers Organizational Factors	
Cost	Several
Financial Stability	[4]
Deployment	
Application Reliability	
Functionality	[12, 35, 44]
Precision	[12, 35, 37, 51]
Healthcare Providers Organizational Factors	
Bureaucracy	[13, 35]
Comfort	[5, 37, 58]
Cost	Several
Difficulty in Perceiving Benefits	[5, 15]
Privacy Concerns	[5, 15, 16, 42, 53, 59]
Shallow Tech Knowledge	[5, 15, 58]
Staff and Patient Reluctancy	[5, 15, 53]
Usability	[5, 15, 51, 53, 58]
Infrastructure	
Constant Maintenance	[4, 16, 37, 44, 51, 58]
Installation Complexity	[4, 12, 16, 37, 38, 44, 48, 51, 53]

technology that is present in nearly all organizations, and is a particularly interesting choice regarding RTLS because the applications can take advantage of the existing WiFi infrastructure already installed in the organization [37, 45]. ZigBee [12], similarly to BLE, is also a wireless communication technology that is an interesting choice for applications that require low energy consumption [11].

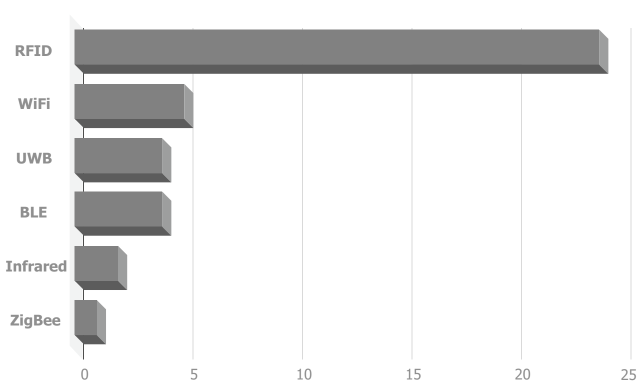

Fig. 2 Technology usage in literature corpus

Other used technologies are: the Ultrawide Band [17, 40] (UWB), Infrared and Ultrasound. Even though Infrared is precise, it is limitated by Line of Sight (LoS). Ultrasound has low cost and is energy efficient, but offers poor scalability. UWB is one of the most promising choices of sensors, offering high precision level, strong resistance to multipath propagation, low energy consumption, small tag size and working on high frequencies [29, 51, 57]. However, it is still restricted due to its high cost.

Specific question 2 – which of the used sensors are interesting options for employing rtls in healthcare environments?

As observed in Section "Specific question 1 – which sensors are used on this type of application?", several sensors are used and studied for developing RTLS for healthcare environments, RFID being the most used. How ever some of these sensors have downsides that discourage and limit their use. For instance, RFID has interference problems with several medical equipments [47]. Many of the interferences observed while using RFID are hazardous. Also, RFID based systems show privacy and security concerns [42]. Despite known issues, RFID is an interesting option for deploying RTLS in healthcare sites with reduced scope and in applications that require Zone or Room level accuracy.

We observed that most of the business cases of healthcare RTLS used WiFi. Considering that infrastructural issues are one of the hugest challenges in deploying such applications, WiFi is an exciting option considering that many hospitals already have WiFi installed. This enables applications to benefit from the existing infrastructure and extend it for obtaining the desired accuracy. Using this strategy, it is possible to overcome some of the infrastructural issues faced while deploying RTLS. ZigBee and BLE offer similar functionality and results, with low energy consumption and cost but are less precise [48]. BLE has shown decent results on real scenario case studies. Reports from users of such technology for asset tracking classify it as being useful and would be eager to further use it [58].

UWB appears to be one of the most prominent choices among the used sensors. Offering high precision, low energy consumption, small tag size and working on frequencies from 3.1 GHz to 10.6 GHz, this technology stands as an interesting choice that could be safe regarding interference and offers high precision tracking, down to 20 centimeters [12]. However, its widespread usage still depends on higher market availability and lower cost.

Other technologies such as Infrared and Ultrasound also appear as options for implementing RTLS in healthcare. Infrared offers high precision, however has privacy and security issues [12], LoS restrictions and high cost [27]. Despite having lower cost, Ultrasound is the technology with least use, considering that it is not suitable for tracking several moving objects at the same moment, it also lacks satisfactory scalability [21].

Specific question 3 – what are the main components and localization techniques of a real-time location system?

In order to provide a broader view of RTLS, the main components and used localization techniques will be detailed. Similarly to satellite navigation systems, RTLS consist of: a set of anchors, which work similarly to satellites on GPS; a set of tags attached to entities to be tracked; and a location engine, which estimates the tag position based on the data collected from them by the anchors, the estimates are made by applying a localization technique.

In Figure 3, the basic components and the data flow of a basic distance-based RTLS is presented [48]. The tag constantly emits it's signal, which is captured by the anchors. The RTLS Server contains a localization engine that estimates the position of the tags by consuming the data collected by the anchors. The collected data is used as parameter for the localization techniques implemented in the RTLS Server localization engine.

In Haute et al [48], the authors organize the techniques into three different categories: Proximity, Range Based and Scene Analysis. The idea behind Proximity localization strategies is to locate an entity using the highest intenstiy signal obtained on a single anchor. This approach is easy to implement and is cheap, however has low accuracy. Usually the main technique used on this strategy is the Received Signal Strength Indicator (RSSI). Second, the Range Based strategies, use the distance of the tag to the anchors in order to estimate it's position. This approach can be divided into two categories, Direction Based and Distance Based. Under the Direction Based category, there is the Angle of Arrival (AoA), and on the Distance Based techniques there are the Time of Arrival (ToA), Time Difference of Arrival (TDoA) and RSSI Multilaterion. Generally speaking, these techniques convert some kind of data (time, angle) into distance and then apply Multilateration in order to transform this data into coordinates. All of these Range Based strategies usually yield high accuracy and precision, at the cost of expensive hardware, therefore a trade-off between cost and precision is observed. The last category is the Scene Analysis, which consists of mapping the real world into a database and, afterwards, the obtained read wireless data is compared with the mapped data from the database. While highly accuracte, these kind of methods are impracticable for healthcare environments, due to the known chaotic nature of them and this kind of technique requiring that each change on the real world to be manually recorded into the database. The most typical example of Scene Analysis technique is Fingerprinting.

Specific question 4 – how can the aspects of a healthcare real-time location system be classified?

After reading through the corpus and evaluating the challenges and requirements of such applications, it was noticed a huge need for organizing and formalizing important aspects of a healthcare RTLS. In Figure 4, a taxonomy is proposed specifying the key aspects that must be assessed for a successful deployment of RTLS in a hospital. The taxonomy was developed after analyzing both barriers and success factors of RTLS in healthcare environments. Basic features of the system, such as accuracy levels, tracked entities and used sensors were identified and added to the taxonomy. Further, several requirements identified while developing and deploying such systems were organized into Hardware, Application and Maintenance requirements.

Many times, solutions would end having poor design and integration, and would not accommodate specific client requirements [35]. With this taxonomy is expected to

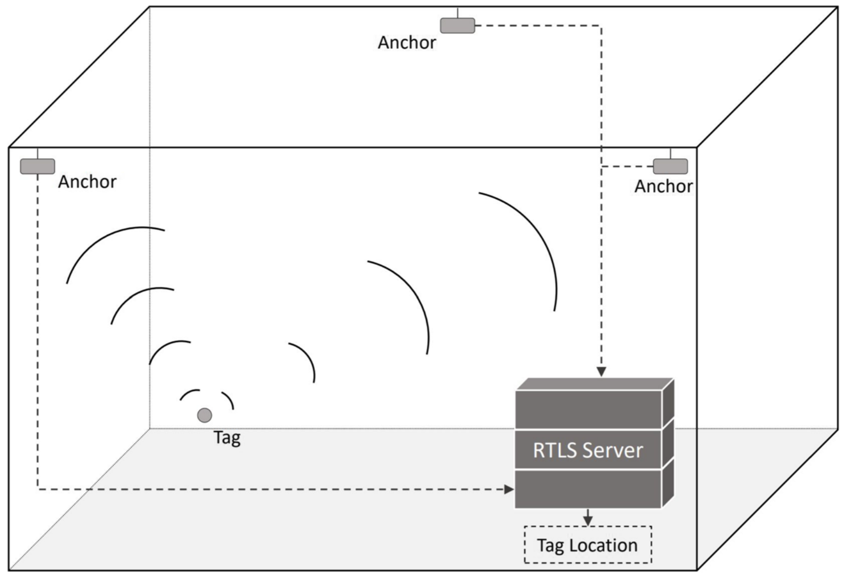

Fig. 3 Real-Time Location System basic components and dataflow. The Anchors collect the Tag signal, the location engine inside the RTLS Server consumes the Anchors data and estimates the tag position using a given localization technique

offer easier ways for developers to understand what the application must assess, while also offering means for healthcare providers to understand what features can be offered by the solution.

Specific question 5 – what are the future research opportunities on this area?

Several points still need to be addressed when talking about this kind of application. Even though RTLS for healthcare environments have been long desired, after analyzing the current state-of-the-art, it is noticeable that it is still facing its early days, and its adoption must be taken slowly by hospitals. Further studies analyzing business cases of RTLS employed in healthcare sites need to be developed in order to understand issues that may still not be clear to the current date. Considering that cost appears to be one of the main barriers holding back the large adoption of such systems, studies that understand how much installation and maintenance cost

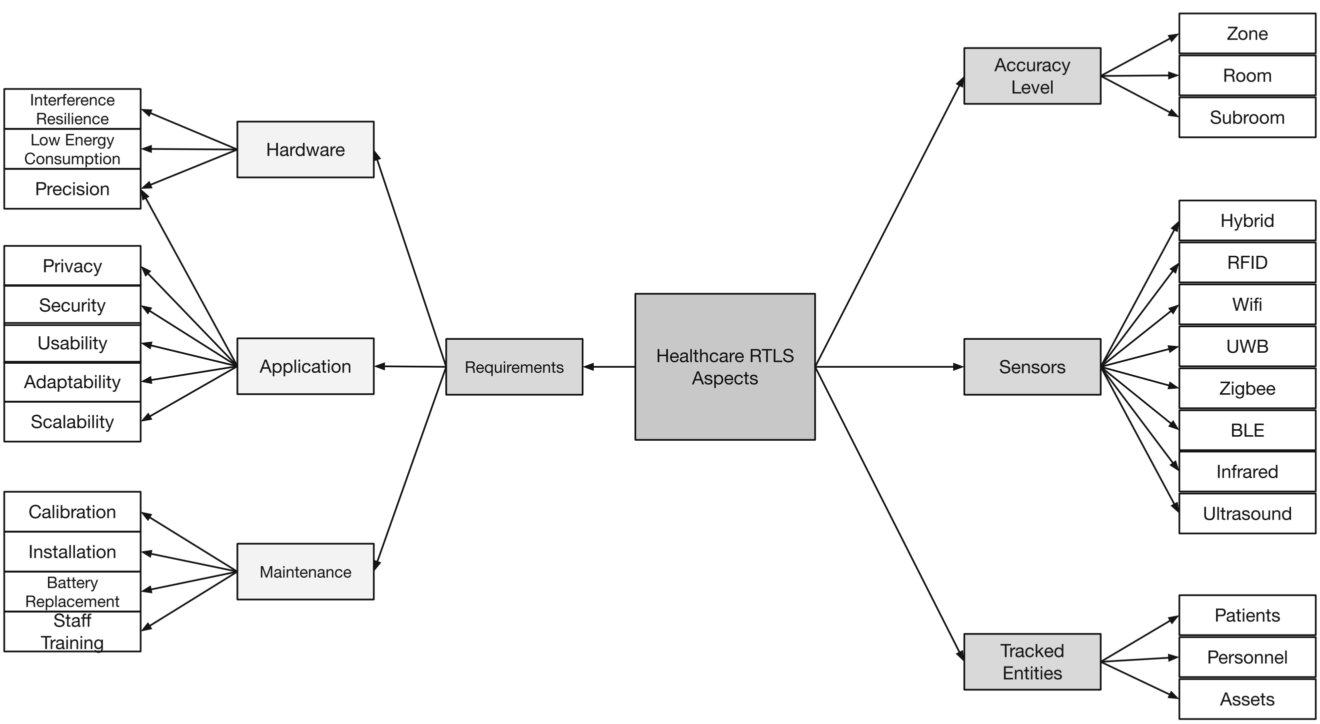

Fig. 4 Taxonomy of important aspects of a healthcare RTLS

to the hospitals may offer interesting success factors for RTLS.

Regarding sensors, more studies are required with technologies besides RFID as observed in Section "Specific question 2 – which of the used sensors are interesting options for employing rtls in healthcare environments?". It is a technology that is trending for more than 10 years, having lots of studies exploring its potential. Aside from academic studies, RFID is a widely used technology in the market. Other technologies are interesting choices for Real-Time Location Systems, such as the UWB and WiFi, which started receiving more attention in the later years due to specific factors such as increased accuracy [17, 58].

Understanding that infrastructural issues are huge challenges, studies similar to Pietrabissa et al [38] are particularly interesting. Enabling applications to blend in with the existing infrastructure or planning optimal position for the sensor network seems to be an interesting approach for arranging large scale deployment of RTLS, thus reducing effort and cost of installation and maintenance.

Discussion

This section discusses some noteworthy topics raised while answering the research questions of this systematic analysis.

Healthcare organizations and RTLS

Healthcare entities are complex and each healthcare provider has different organizational structure [15]. These differences demand customizable RTLS that fit each hospital particular needs. Developing customizable and functional RTLS that assesses each customers need is a real challenge. Realistically, a hospital that is willing to adopt such solution should precisely identify their needs and demand an application that fits their own necessity. The adoption of such system should be taken slowly and thoroughly planned together with the RTLS vendor, possibly working directly with a member of the vendors team. The development and deployment of this application is time consuming and the staff should be trained. This is important because human factors are one of the toughest barriers to overcome, as previously stated. While looking for a vendor, hospitals should be aware that many RTLS providers may facing financial instability and may be desperate for revenue [4]. Sometimes the marketing strategies of some providers may not reflect what the solution actually offers. Finally, it is of vital importance for the application to be reliable since, as already mentioned, it is one of the key factors for the its acceptance.

In order to better understand the aspects that surround the development of a healthcare RTLS and classify desired characteristics, a taxonomy is proposed in Section "Specific question 3 – what are the main components and localization techniques of a real-time location system?". With it, it expected to offer means for clients to choose the solution that better fits their demand and for vendors to understand important requirements of the RTLS, which is one the key success factors in its deployment in healthcare environments [4].

Sensor choice

As discussed in Section "Literature analysis", several sensors are used for implementing RTLS in healthcare environments. By analyzing the many studies that conduct experiments with different types of sensors, it is clear that the sensor choice for each application is related to the scope that the client wants the application to work. If the hospital wants to track inventory, a RTLS using RFID is the optimal choice for it, on the other hand, if the client wants to precisely monitor the workflow of doctors in an operating room, UWB seems like a most interesting option. Meanwhile, WiFi offers good cost-benefit regarding tracking in huge zones in applications that require medium precision levels.

Infrastructural issues are major in the deployment of healthcare RTLS. Therefore, a solution that uses the existing hospital infrastructure without the need of major modifications is likely a good approach. As observed in the literature review in Section "Literature analysis", many of the analyzed business cases of healthcare RTLS use technologies that take advantage of the existing WiFi infrastructure, thus reducing cost. If there is a demand for an RTLS that covers huge areas with different levels of precision, even though it is risky, a hybrid sensor approach is most likely to succeed.

While analyzing the literature corpus of this review, it was noticed that the desired precision of the RTLS appears to be related to the system cost. For instance, UWB offers a tracking precision in the magnitude of centimeters at a high cost [29, 57]. RFID, on the other hand, offers smaller precision but at lower costs. However, the literature indicates that it is possible to obtain higher precision level with less precise sensors, in exchange of cost (increased amount of sensors and readers) and system complexity (tracking complexity and computational cost). In Figure 5, a draft comparing RFID, WiFi, BLE and UWB cost and precision is presented in the same fashion as presented in [29], with the addition of a Cost axis. Noteworthy to mention, the cost axis does not contain any values, all the growth in the technologies cost are meant to demonstrate the expected cost growth associated with the precision.

With UWB, one can obtain precisions on the house of centimeters [29] a high cost. WiFi does not offer good precision levels but has a coverage of up to 100m [11], how-

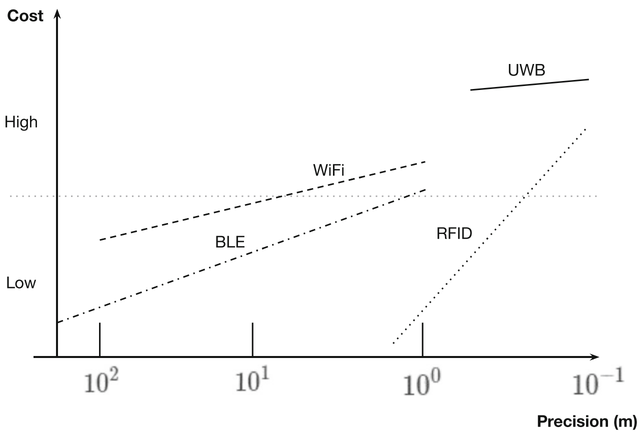

Fig. 5 Draft relating RFID, WiFi, BLE and UWB cost and precision

ever as aforementioned, in exchange of cost and complexity it is possible to obtain precision up to a meter [48]. Similarly to WiFi, BLE also does not offer high precision levels, but covers areas up to 200m [2], and it is possible to obtain precisions of a meter with it [48]. RFID has the lowest cost among all the sensors on this analysis, yet it is possible to develop a system with RFID with centimeter-wise precision [44]. However, a large scale deployment of such RFID system in healthcare environments is unfeasible due to known interference [25] and costs that would revolve around the amount of tags and readers.

Conclusion

This article presents a systematic review about the use of RTLS on healthcare environments. The interest for RTLS applications in healthcare is not new. The potential benefits of such a technology are known and grow more desirable each year, due to the increase of issues and expenses in hospitals, as explained in Section "Introduction". However, RTLS are still far from being vastly used by hospitals, and the causes behind the shallow adoption of this technology are explained throughout this survey.

The development of RTLS is still a challenge to the present date, especially for use in critical environments such as hospitals. Its development is expensive, demands time and must be customizable, for each hospital has different organizational structure. The sensor choice is a key point in the development of such solutions, considering that is still no optimal sensor, but several that enable different tracking methods.

Many difficulties also appear during the deployment in hospitals. Lack of proper infrastructure, reluctant and mistrustful staff, and patient rejection are some problems faced while implementing and using some of the business cases of healthcare RTLS. Another noteworthy point is that, even considering the known benefits of this technology, some healthcare providers still cannot perceive advantages that could be attained with its use [15]. Cost is a persistent issue that is most likely to continue being a huge problem, considering that not only the development and the application costs are a problem, but many other aspects also aggravate it, such as: hardware used by the solution, need of infrastructure remodel, installation, maintenance and staff training. While having huge financial and organizational benefits, barriers may persist regarding patient and staff tracking due to known low usability that such systems have and known human factors, such as privacy concerns, this should always be taken into account when adopting such system.

Concluding the review, RTLS applied to healthcare environments are still in their early days [45] and its adoption should be taken slowly. This technology has already been implemented in several hospitals, but successful cases are the ones where the application works with reduced scope and its adoption was thoroughly planned. Sensor technologies are widely recognized as one of the most impacting and promising technologies in several sectors of the industry. And, as seen in this review, it's adoption on RTLS brings concrete benefits to healthcare providers in sites such as hospitals and nursing homes. Every year sensing technologies become more accessible and effective, and several studies show that it's adoption brings a plethora of benefits. This way adoption in healthcare environments is expected to rise in the coming years.

Declarations

Ethics approval and consent to participate This article does not contain any studies with human participants or animals performed by any of the authors.

Conflict of Interests The authors declare that they have no conflict of interest.

Informed Consent This article does not contain any studies with human participants.

References

1. Abugabah, A., Rfid adoption in healthcare organizations in uae, 2017.
2. Antunes, R. S., Seewald, L. A., Rodrigues, V. F., Da Costa, C. A., Gonzaga, L. Jr, Righi, R. R., Maier, A., Eskofier, B., Ollenschlaeger, M., Naderi, F. et al., A survey of sensors in healthcare workflow monitoring. *ACM Computing Surveys (CSUR)* 51(2):1–37, 2018.
3. Ariffin, F. N. H., Wan, A. T., and Suhaili, W. S. H., Psychiatric patients monitoring using rfid: an affordable approach. In: *2015 IEEE International Conference on Computer and Communications (ICCC)*, pp. 181–185: IEEE, 2015.

4. Boulos, M. N. K., and Berry, G., Real-time locating systems (rtls) in healthcare: a condensed primer. *International Journal of Health Geographics* 11(1):1–8, 2012.
5. Bowen, M. E., Wingrave, C. A., Klanchar, A., and Craighead, J., Tracking technology: lessons learned in two health care sites. *Technol. Health Care* 21(3):191–197, 2013.
6. Christe, B., Rogers, R., and Cooney, E., Analysis of the impact of a radiofrequency identification asset-tracking system in the healthcare setting. *J. Clin. Eng.* 35(1):49–55, 2010.
7. I. E. E. E. Computer Society LAN/MAN Standards Committee, et al., Ieee standard for information technology-telecommunications and information exchange between systems-local and metropolitan area networks-specific requirements part 11: wireless lan medium access control (mac) and physical layer (phy) specifications IEEE Std 802.11^, 2007.
8. Deak, G., Curran, K., and Condell, J., A survey of active and passive indoor localisation systems. *Comput. Commun.* 35(16): 1939–1954, 2012.
9. Decia, I., Farías, A., Szerman, D., Grundel, L., Briatore, D., Piñeyrúa, M., Villar, A., and Simini, F., Camacua: low cost real time risk alert and location system for healthcare environments. In: *VII Latin American Congress on Biomedical Engineering CLAIB 2016, Bucaramanga, Santander, Colombia, October 26th-28th, 2016*, pp. 90–93: Springer, 2017.
10. Ewing, A., Rogus, J., Chintagunta, P., Kraus, L., Sabol, M., and Kang, H., A systems approach to improving patient flow at uva cancer center using real-time locating system. In: *2017 Systems and Information Engineering Design Symposium (SIEDS)*, pp. 259–264: IEEE, 2017.
11. Farahani, S., *ZigBee wireless networks and transceivers*. Newnes, 2011.
12. Farid, Z., Nordin, R., and Ismail, M., Recent advances in wireless indoor localization techniques and system. *Journal of Computer Networks and Communications*, 2013, 2013.
13. Fernandez-Llatas, C., Lizondo, A., Monton, E., Benedi, J.-M., and Traver, V., Process mining methodology for health process tracking using real-time indoor location systems. *Sensors* 15(12):29821–29840, 2015.
14. Fisher, J. A., and Monahan, T., Tracking the social dimensions of rfid systems in hospitals. *International Journal of Medical Informatics* 77(3):176–183, 2008.
15. Fisher, J. A., and Monahan, T., Evaluation of real-time location systems in their hospital contexts. *International Journal of Medical Informatics* 81(10):705–712, 2012.
16. Gholamhosseini, L., Sadoughi, F., and Safaei, A., Hospital real-time location system (a practical approach in healthcare): a narrative review article. *Iranian Journal of Public Health* 48(4):593, 2019.
17. Ghosh, D., and Sahu, P. K., Uwb in healthcare. In: *International Conference on Electromagnetics in Advanced Applications (ICEAA)*, p. 2016: IEEE, 2016.
18. Guédon, A. C. P, Wauben, L. S. G. L., De Korne, D. F., Overvelde, M., Dankelman, J., and van Den Dobbelsteen, J. J., A rfid specific participatory design approach to support design and implementation of real-time location systems in the operating room. *Journal of Medical Systems* 39(1):168, 2015.
19. Han, G., Klinker, G. J., Ostler, D., and Schneider, A., Testing a proximity-based location tracking system with bluetooth low energy tags for future use in the or. In: *2015 17th International Conference on E-health Networking, Application & Services (HealthCom)*, pp. 17–21: IEEE, 2015.
20. Hellmich, T. R., Clements, C. M., El-Sherif, N., Pasupathy, K. S., Nestler, D. M., Boggust, A., Ernste, V. K., Marisamy, G., Koenig, K. R., and Hallbeck, M. S., Contact tracing with a real-time location system A case study of increasing relative effectiveness in an emergency department. *Am. J. Infect. Control* 45(12):1308–1311, 2017.
21. Hu, L., Ong, D. M., Zhu, X., Liu, Q., and Song, E., Enabling rfid technology for healthcare: application, architecture, and challenges. *Telecommun. Syst.* 58(3):259–271, 2015.
22. Brumlik, C. J., Choudury, A., Vaidya, M., and Nimbolkar, R., Real-time location, position and motion data for healthcare information systems-a patent review. *Recent Advances in Communications and Networking Technology (Formerly Recent Patents on Telecommunication)* 5(2):66–72, 2016.
23. Jones, T. L., and Schlegel, C., Can real time location system technology (rtls) provide useful estimates of time use by nursing personnel? *Research in Nursing & Health* 37(1):75–84, 2014.
24. Kang, H., Hostetler, S., Devapriya, P., Banciu, M., and Andrews, Z., Rtls and ehr enabled workflow modeling in the emergency department. In: *IIE Annual Conference. Proceedings, page 3112. Institute of Industrial and Systems Engineers (IISE)*, 2014.
25. Kapa, S., Pierce, T., Hayes, D. L., Holmes, D. R. Jr, and Asirvatham, S. J., Electromagnetic interference of magnetic field based auto identification technologies in healthcare settings. *International Journal of Medical Informatics* 80(4):239–250, 2011.
26. Keele, S., et al., Guidelines for performing systematic literature reviews in software engineering. Technical report, Technical report, Ver. 2.3 EBSE Technical Report. EBSE, 2007.
27. Kemper, J., and Linde, H., Challenges of passive infrared indoor localization. In: *2008 5th Workshop on Positioning, Navigation and Communication*, pp. 63–70: IEEE, 2008.
28. Laskowski, M., Demianyk, B., Friesen, M. R., and McLeod, R. D., Uncertainties inherent in rfid tracking systems in an emergency department. In: *IEEE workshop on health care management (WHCM)*, p. 2010: IEEE, 2010.
29. Mahfouz, M. R., Fathy, A. E., Kuhn, M. J., and Wang, Y., Recent trends and advances in uwb positioning. In: *2009 IEEE MTT-S International Microwave Workshop on Wireless Sensing, Local Positioning, and RFID*, pp. 1–4: IEEE, 2009.
30. Martin, P. D., Rushanan, M., Tantillo, T., Lehmann, C. U., and Rubin, A. D., Applications of secure location sensing in healthcare. In: *Proceedings of the 7th ACM International Conference on Bioinformatics, Computational Biology, and Health Informatics*, pp. 58–67, 2016.
31. McAllister, T. D., El-Tawab, S., and Heydari, M. H., 2017 Systems and Information Engineering Design Symposium (SIEDS), pp. 132–137: IEEE, 2017.
32. Mun, I. K., Kantrowitz, A. B., Carmel, P. W., Mason, K. P., and Engels, D. W., Active rfid system augmented with 2d barcode for asset management in a hospital setting. In: *IEEE International Conference on RFID*, p. 2007: IEEE, 2007.
33. Najera, P., Lopez, J., and Roman, R., Real-time location and inpatient care systems based on passive rfid. *J. Netw. Comput. Appl.* 34(3):980–989, 2011.
34. Okoniewska, B., Graham, A., Gavrilova, M., Wah, D., Gilgen, J., Coke, J., Burden, J., Nayyar, S., Kaunda, J., Yergens, D. et al., Multidimensional evaluation of a radio frequency identification wi-fi location tracking system in an acute-care hospital setting. *J. Am. Med. Inform. Assoc.* 19(4):674–679, 2012.
35. Weernink, C. E. O., Sweegers, L., Relou, L., Van der Zijpp, T. J., and Van Hoof, J., Lost and misplaced items and assistive devices in nursing homes: Identifying problems and technological opportunities through participatory design research. *Technology and Disability* 29(3):129–140, 2017.
36. Oztekin, A., Pajouh, F. M., Delen, D., and Swim, L. K., An rfid network design methodology for asset tracking in healthcare. *Decis. Support. Syst.* 49(1):100–109, 2010.
37. Pancham, J., Millham, R., and Fong, S. J., Evaluation of real time location system technologies in the health care sector. In: *2017*

17th International Conference on Computational Science and Its Applications (ICCSA), pp. 1–7: IEEE, 2017.
38. Pietrabissa, A., Poli, C., Ferriero, D. G., and Grigioni, M., Optimal planning of sensor networks for asset tracking in hospital environments. *Decis. Support. Syst.* 55(1):304–313, 2013.
39. Polycarpou, A. C., Dimitriou, A., Bletsas, A., Polycarpou, P. C., Papaloizou, L., Gregoriou, G., and Sahalos, J. N., On the design, installation, and evaluation of a radio-frequency identification system for healthcare applications [wireless corner]. *IEEE Antennas and Propagation Magazine* 54(4):255–271, 2012.
40. Porcino, D., and Hirt, W., Ultra-wideband radio technology: potential and challenges ahead. *IEEE Communications Magazine* 41(7):66–74, 2003.
41. Potyrailo, R. A., Surman, C., Morris, W. G., Ehring, H., Wortley, T., Pizzi, V., Carter, J., and Gach, G., Passive gamma-resistant rfid tags integrated into gamma-sterilizable pharmaceutical components. In: *2010 IEEE International Conference on RFID (IEEE RFID 2010)*, pp. 110–117: IEEE, 2010.
42. Rahman, F., Md, Z. A. B., and Ahamed, S. I., A privacy preserving framework for rfid based healthcare systems. *Future Generation Computer Systems* 72:339–352, 2017.
43. Rrub, J. A., Al-Jabi, J., and El-Khatib, K., Security model for real time tracking system (rtls) in the healthcare sector. In: *International Conference on Communications and Information Technology (ICCIT)*, p. 2012: IEEE, 2012.
44. Shirehjini, A. A. N., Yassine, A., and Shirmohammadi, S., Equipment location in hospitals using rfid-based positioning system. *IEEE Transactions on Information Technology in Biomedicine* 16(6):1058–1069, 2012.
45. Stübig, T., Zeckey, C., Min, W., Janzen, L., Citak, M., Krettek, C., Hüfner, T., and Gaulke, R., Effects of a wlan-based real time location system on outpatient contentment in a level i trauma center. *International Journal of Medical Informatics* 83(1):19–26, 2014.
46. Vakili, S., Pandit, R., Singman, E. L., Appelbaum, J., and Boland, M. V., A comparison of commercial and custom-made electronic tracking systems to measure patient flow through an ambulatory clinic. *International Journal of Health Geographics* 14(1):32, 2015.
47. Van Der Togt, R., van Lieshout, E. J., Hensbroek, R., Beinat, E., Binnekade, J. M., and Bakker, P. J. M., Electromagnetic interference from radio frequency identification inducing potentially hazardous incidents in critical care medical equipment. *Jama* 299(24):2884–2890, 2008.
48. Haute, T. V., Poorter, E. D., Crombez, P., Lemic, F., Handziski, V., Wirström, N., Wolisz, A., Voigt, T., and Moerman, I., Performance analysis of multiple indoor positioning systems in a healthcare environment. *International Journal of Health Geographics* 15(1):1–15, 2016.
49. Vanany, I., Shaharoun, A. B. M. et al., Barriers and critical success factors towards rfid technology adoption in south-east asian healthcare industry. In: *Proceedings of the 9th Asia Pacific Industrial Engineering & Management Systems Conference, Bali, Indonesia*, pp. 148–155, 2008.
50. Wamba, S. F., Rfid-enabled healthcare applications, issues and benefits: an archival analysis (1997–2011). *Journal of Medical Systems* 36(6):3393–3398, 2012.
51. Wang, B., Toobaei, M., Danskin, R., Ngarmnil, T., Pham, L., and Pham. H., Evaluation of rfid and wi-fi technologies for rtls applications in healthcare centers. In: *Proceedings of PICMET'13: Technology Management in the IT-Driven Services (PICMET)*, p. 2013: IEEE, 2013.
52. Want, R., An introduction to rfid technology ieee pervasive computing, 2006.
53. Oude Weernink, C. E., Felix, E., Verkuijlen, P. J. E. M., Dierick-van Daele, A. T. M., Kazak, J. K., and Van Hoof, J., Real-time location systems in nursing homes: state of the art and future applications. *Journal of Enabling Technologies*, 2018.
54. Xu, W., Lian, Z., and Yao, X., Integrating rfid with blood supply chain: a technical and business analysis. In: *2013 IEEE International Conference on Industrial Engineering and Engineering Management*, pp. 1087–1091: IEEE, 2013.
55. Yao, W., Chu, C.-H., and Li, Z., The adoption and implementation of rfid technologies in healthcare: a literature review. *Journal of Medical Systems* 36(6):3507–3525, 2012.
56. Yazici, H. J., An exploratory analysis of hospital perspectives on real time information requirements and perceived benefits of rfid technology for future adoption. *Int. J. Inf. Manag.* 34(5):603–621, 2014.
57. Ye, R., Redfield, S., and Liu, H., High-precision indoor uwb localization: technical challenges and method. In: *2010 IEEE International Conference on Ultra-Wideband*, Vol. 2, pp. 1–4: IEEE, 2010.
58. Yoo, S., Kim, S., Kim, E., Jung, E., Lee, K.-H., and Hwang, H., Real-time location system-based asset tracking in the healthcare field: lessons learned from a feasibility study. *BMC Medical Informatics and Decision Making* 18(1):80, 2018.
59. Yuehong, Y. I. N., Zeng, Y., Chen, X., and Fan, Y., The internet of things in healthcare: an overview. *Journal of Industrial Information Integration* 1:3–13, 2016.