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Enhancing Surgical Efficiency and Equipment Management Through Real-Time Location Systems (RTLS): A Comprehensive Literature Review

Shiva Kumar Madishetty
Advanced Embedded Software Engineer
Mentor, OH, USA
Email: shiva.madishetty1@gmail.com

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ABSTRACT

Real-Time Location Systems (RTLS) have gained higher importance in the contemporary health- care settings, offering more sophisticated asset, people, and workflow tracking frameworks. This review discusses RTLS implementation in the surgical environment with emphasis being placed on surgical equipment management, workflow optimization, and patient safety. This paper has been able to analyze more than twenty years of research and case studies to determine advantages, constraints, emerging technologies, and future prospects of RTLS in operating rooms. It will inform the hospital administrators, clinicians, and technology developers about the strategic importance of RTLS in operational excellence and clinical outcomes.

Keywords: RTLS, operational, clinical

Introduction

Surgical operations demand a high-level coordinated ecosystem in which time, accuracy, and equipment availability are of critical importance. Any interruption in the operations process, including missing equipment or misplaced tools, can have an impact on patient outcomes and resource use. RTLS can be seen as a promising solution, as it allows tracking the location of surgical tools, mobile devices, and staff in real-time. The paper provides an in-depth literature review on the application of RTLS in operating rooms, which outlines trends, challenges, and best practices.

I. Need For Location Tracking Of Equipment In Healthcare Environments

In modern healthcare settings, the timely and accurate tracking of medical equipment is a crit-ical operational requirement. Mobile medical equipment used with high value and frequency, including infusion pumps, defibrillators, ventilators, and surgical equipment, are typically shared between many departments and can be regularly lost or under-used or out of stock during emergencies. Research has shown that hospitals can use up to 20 percent of the equipment budget on equipment replacement or searching lost devices [14].

A. Operational Impact

Poor tracking of assets is another factor that leads to workflow bottlenecks, long patient waiting periods, and staff workload. Nurses and clinicians are actually reported to spend 30-60 minutes each shift searching equipment, decreasing time spent with direct patients [15][1]. The excess buying of unnecessary equipment in case of perceived shortage creates higher capital expenditure and maintenance overheads.

B. Patient Safety and Clinical Risk

The non-availability of equipment when required or delays in important processes can greatly affect patient safety. As an example, the lack of or sterility of surgical instruments can delay surgeries and increase the chances of surgical site infections (SSIs). Research has demonstrated that these delays occur commonly enough to affect clinical work- flows, and RTLS trials in hospitals have decreased the equip ment retrieval time by 90%, therefore enhancing operation effectiveness and patient outcomes (Hassan et al., 2020; Al-Turjman et

al., 2024). RTLS improves sterilized equipment traceability and allows alarms to inform when equipment was used outside the sterilization windows that have been val- idated to prevent SSIs. This is automated warning messages created by RTLS-based systems when surgical tools or trays have been used beyond their certified sterilization duration, or prior to appropriate sterilization being affirmed. These alerts contribute to discouragement of using contaminated or non-compliant equipment which minimizes the chances of getting infected with SSI. The latter kind of alerts can be combined with infection con- trol measures focusing on timely sterilization to avoid transfer of such pathogens as HBV, *Pseudomonas aeruginosa*, and *Acinetobacter* spp. [25], [27].

Surgical site infections (SSIs) are a common and expensive complication, with the prevalence in high-income settings ranging between 2 and 5% and reaching up to a third in low- and middle-income ones [56],[57]. Although RTLS has been reported to decrease equipment retrieval times by up to 90 percent, and thus improve surgical preparedness and compliance to sterilization guidelines, empir- ical data directly connecting RTLS use to a decrease in the occurrence of SSI is in its early stages.[25], [26]. Existing evidence indicates that there is a solid theoretical ground and indirect utility, and additional controlled research is required to prove causality.

C. Compliance and Accreditation

The healthcare regulations are starting to focus more on the traceability, documentation, and responsibility of asset management. The Joint Commission along with the Centers of Medicare and Medicaid Services (CMS) make hospitals demonstrate effective equipment management processes. RTLS allows real-time logging of data, automated audit trails and utilization reporting that facilitate compliance and simplify the process of inspections.

D. Technology Integration and Digital Transfor- mation

As smart hospitals emerge, RTLS has increasingly been integrated with other hospital information systems, including Electronic Medical Records (EMRs)[1], Computerised Maintenance Management Systems (CMMS) and surgical scheduling systems, to ensure seamless interoperability and automation. The integrations will facilitate predictive maintenance, demand forecasting, and smart scheduling, which will form the basis of AI in healthcare logistics.

The RTLS systems are commonly connected to the hospital IT infrastructure via middleware platforms and RESTful APIs. The middleware is an interface between RTLS sources of data and enterprise systems, it carries out data normalization, routing, security. The APIs (particularly the ones that comply with HL7 FHIR standards) enable real-time data sharing between RTLS systems and EMRs, CMMS, and other clinical systems.

The HL7 FHIR RTLS Implementation Guide characterizes standardized procedures of trading location information and associating/disassociating information, co-location warnings, and auxiliary features such as battery status or button presses. These workflows facilitate real-time communication between RTLS systems and healthcare applications, which allow patient tracking to be automated, as well as asset management and staff coordination [28].

Otherwise, the Standard of Biometric Open Protocol, IEEE 2410-2019, is an interoperability structure in healthcare settings, particularly where RTLS is incorporated with biometric or identity-based systems [29].

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The practical implementation on RTLS-based predictive analytics has proved to be valuable. As an example, a Swiss hospital deployed a FHIR-based intermediary engine to convert the HL7v2 messages to FHIR resources to provide the ability to integrate RTLS data with the EMRs and maintenance systems in real-time. The result was the quantifiable increase in equipment uptime and decreased surgical prep work- flow delays [30]. Likewise, Epic Systems and CenTrak have incorporated RTLS with predictive maintenance algorithm to predict service requirements based on the usage pattern to minimize downtime and enhance asset utilization[31].

Strategic Value: In addition to the efficiency of operations, RTLS provides strategic data regarding the utiliza- tion trend, idle time, and equipment lifecycle costs. Capital plan- ning, vendor negotiations, and clinical engineering practices will be able to utilize this data.With the current trends of staffing shortages, organizational financial burdens and mounting demands on high-quality care delivery, RTLS-powered equipment tracking is emerging as a necessary factor of operational resilience and patient outcomes.

Methodology

Systematic literature search was performed by using databases including PubMed, IEEE Xplore, ScienceDirect and Google Scholar. The keywords were RTLS in healthcare, RTLS in surgery, surgical equipment tracking, and operating room workflow. Articles dating between 2000-2024 were accepted with the emphasis on peer-reviewed articles, hospital case studies, and technology reviews. Quantitative and qualitative data were extracted, as well as new innovations and clinical impact measurement.

E. RTLS Technology Overview

RTLS is a type of technology based on hardware and software that identifies the position of tagged items or staff in real time. Examples of common technologies include RFID, Infrared, ULtrasound, Wi-Fi/BLE and UWB. The various technologies have varying degrees of accuracy, latency and cost-effectiveness to the surgical setting.

Table I gives a comparative analysis of RTLS technologies such as RFID, Infrared, Ultrasound, Wi-Fi/BLE, and UWB. UWB has been shown to have better accuracy (up to 10-30 cm) and lower latency which is why it is best suited to high-precision tasks like surgical tool tracking and staff movement analysis. RFID is affordable and applicable in in- ventory management but is not real-time precise. IR and Ultrasound have high accuracy but are affected by the line-of-sight and environmental interference. The use of Wi-Fi/BLE is also popular because of the available infrastructure but offers average accuracy (1-5 meters) and is therefore more applicable in general assets tracking than in emergency surgical tasks. High sensitivity in the case of IR and Ultrasound can also imply high sensitivity to environmental interference.

RTLS Applications in Surgical Settings

Table II provides an overview of the reported RTLS deployments in the surgical setting. These data are based on a compilation of peer-reviewed articles and vendor-provided case studies. Although certain metrics, e.g., equipment search time and OR turnover are backed by empirical research, others can be context specific and differ according to hos- pital size, maturity of workflow, and level of integration. An example is a decrease of equipment search time up to 60% in a private hospital pi-lot during six months[37]. In a multi-site study, OR turnover improvement in 3 hospitals showed 25-35% improvements [38]. Adherence to sterilization practices increased by 40 percent in an academic hospital within a period of one year[39]. Nevertheless, the stated decrease in cross-contamination (30-50 percent) is vendor based at one site and is not necessarily broadly applicable [40].

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Potential confounders are current process improvements, personnel training and integration of EMR, which would contribute to the observed gains independently of RTLS. Also, the differences in RTLS technology (e.g., RFID vs BLE), scale of the deployment and user adoption may play a role.

Regarding financial implications, work- flow optimization enabled by RTLS has been linked to savings of between $500, 000 and 1.2 million a year per hospital based on the size of asset base and the area of deployment [46]. The realization of ROI would usually occur in 18-24 months, particularly when RTLS is in combination with EMRs and scheduling systems to make delays shorter and coordination better.

RTLS Technology Comparison Analysis

Presented below is a detailed examination of the RTLS technology comparison table on five major dimensions.

F. Accuracy

The UWB has a very high accuracy (typ- ically 10-30 cm), which makes it suitable in surgical settings where precision is very important. Ultra- sound and IR are also highly accurate but sensitive to environmental conditions. RFID and

TABLE I. COMPARISON OF RTLS TECHNOLOGIES IN SURGICAL SETTINGS

Technology	Accuracy	Latency	Interference	Sensitivity	Cost
RFID	Medium	Low	Moderate	Low	Low
IR	High	Medium	High	Medium	Medium
Ultrasound	High	Low	Low	High	High
Wi-Fi/BLE	Medium	Medium	Moderate	Low	Low
UWB	Very High	Very Low	Low	High	High

TABLE II. TABLE II: QUANTIFIED BENEFITS OF RTLS IN SURGICAL SETTINGS

Metric	Improvement (%)	Setting / Sample Size	Reference
Equipment search time	60%	Private hospital, 6-month pilot	Abdelsamad et al., 2019 [37]
OR turnover time	25–35%	Multi-hospital study, 3 sites	Kim et al., 2018 [38]
Compliance with sterilization	40%	Academic hospital, 1-year study	Hassan et al., 2020 [39]
Equipment utilization	15–20%	Same as above	Kim et al., 2018 [38]
Cross-contamination reduction	30–50%	Vendor-reported, single site	Wang et al., 2022 [40]

Wi-Fi / BLE provide medium accuracy (1 to 5 meters), sufficient for general asset tracking but not for high-precision tasks.

G. Latency

UWB is once again the most successful with exceptionally low latency that allows real-time monitoring of rapid assets or personnel. The ultrasound and RFID also work effectively in the low-latency situations. IR and Wi-Fi/BLE are medium in terms of the latency and can cause delays in applications that require time.

H. Interference

UWB and ultrasound are least susceptible to interference and therefore are consistent in complex environments like operating rooms. IR is highly susceptible to interference from ambient light and obstructions. RFID and Wi-Fi/BLE face moderate interference, especially in environments with metal or electromagnetic noise.

I. Sensitivity

UWB and ultrasound are highly sensitive and capable of detecting subtle movements or changes in position. IR has medium sensitivity but requires line-of-sight. RFID and Wi-Fi/BLE are less sensi- tive, which limits their use in fine-grained tracking.

J. Cost

RFID and Wi-Fi/BLE are cost-effective, using existing infrastructure and inexpensive tags[2]. IR is moderately priced but requires dedicated emitters and receivers. Ultrasound and UWB are more expensive due to specialized hardware and installation requirements, butr superior performance.

Strategic Insights

UWB is the best choice for high-precision, low- latency applications such as surgical tool tracking, robotic surgery coordination, and staff move- ment analysis. RFID and Wi-Fi/BLE are ideal for large-scale, budget-conscious deployments where precision is less critical (e.g., inventory tracking). Ultrasound is suitable for high-accuracy needs in environments where line of sight can be maintained. IR is effective in controlled environments, but less reliable in dynamic or cluttered spaces.

Here is a heatmap-style visual chart comparing RTLS technologies across five key dimensions: accuracy, latency, interference, sensitivity, and cost.

Green implies improved performance (i.e. more accurate, less latent), whereas red implies less desirable properties.

K. Interpretation Highlights:

Ultra-Wideband (UWB) technology has been shown to perform better in most important measures of accuracy, latency and interference resistance making it the best solution in precision-sensitive applications. By contrast, RFID and Wi-Fi/BLE are cost-effective but have a wider scaling range but less positional accuracy and sensitivity- ity. Ultrasound is highly localized, and its interference is minimal, at the disadvantage of higher implementation cost. IR systems are reliable and are accurate under perfect conditions but are constrained by high levels of sensitivity to interference and moderate levels of latency, which can affect reliability in dynamic situations.

Emerging Methods and Techniques

The convergence of machine learning, sensor fusion and robotic integration is developing the latest developments in Real-Time Location Systems (RTLS), which are making surgical operations more precise, efficient, and yield better patient outcomes.

L. Machine Learning and Predictive Analytics

Machine learning models are becoming more frequently utilized on RTLS data to predict equipment demand, maintenance optimization and detecting work-flow inefficiencies. These anticipatory models allow making proactive decisions, which minimize downtimes and enhance resource distribution. As an

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illustration, AI-based analytics have been proven to cut the intraoperative complications by 30% and the operating time by 25% with robotic systems [20].

M. Sensor Fusion for Enhanced Accuracy

The integration of several sensing modalities, i.e. Ultra-Wideband (UWB), Bluetooth Low Energy (BLE), and infrared, increases the localization accuracy and resilience. Sensor fusion overcomes the weaknesses of each technology, including the vulnerability of BLE to interference or the line-of- sight of IR. The hybrid technique is highly successful in complicated operating rooms where precision counts [21].

N. Integration with Robotic Surgical Systems

Robotic surgical platforms are also being integrated with RTLS in order to allow dynamic positioning of equipment, real time tracking of tools and semi-autonomous pro-cadence adjustments. The systems make use of AI to improve targeting accuracy by up to 40%, surgeon workload, and cut patient recovery times by 15% [22]. The digital twin simulator and intraoperative feedback loops are some of the innovations that continue to advance the limits of surgical automation [3].

O. Patient-Centric RTLS Platforms

In addition to equipment and staff tracking, RTLS is currently applied to track the movement of patients during the surgical process- pre-op to post-op. These systems enhance the experience of patients because they help decrease wait times, boost communication, and provide individual care pathways. They also facilitate adherence to the safety measures and optimize the discharge planning.

P. Comparative Technology Analysis

A comparative analysis of five RTLS technologies RFID, Infrared (IR), Ultrasound, Wi-Fi / BLE, and Ultra-Wideband (UWB) on five performance dimensions accuracy, latency, interference, sensitivity, and cost, is provided in Figure 1.

Benefits of RTLS in Surgical Contexts

Real-Time Location System (RTLS) is increasingly being considered to be a disruptive technology in the operating room. RTLS allows real-time insight into the position and condition of assets, personnel and patients, which improves operational efficiency, patient safety and resource utilization. The benefits of RTLS in surgical contexts can be categorized into the following key domains:

Q. Equipment Visibility and Utilization

RTLS allows the constant monitoring of surgical equipment, mobile medical equipment, and con-consumables. This real-time visibility will save time actually finding equipment by up to 60% and make sure that important equipment is easily accessible on demand. Enhanced utilization rates, frequently extended by 1520, can enable healthcare amenities to cut back on redundant inventory, optimize capital expenditure, and enhance preparation readiness to surgical procedures [19].

R. Workflow Optimization and Turnaround Time

RTLS makes the coordination of surgical teams possible by interconnection with scheduling systems, as well as automated time-motion studies. Operating Room (OR) turnover time is decreased 25-35% and more procedures can be done each day, increasing the total patient throughput. This

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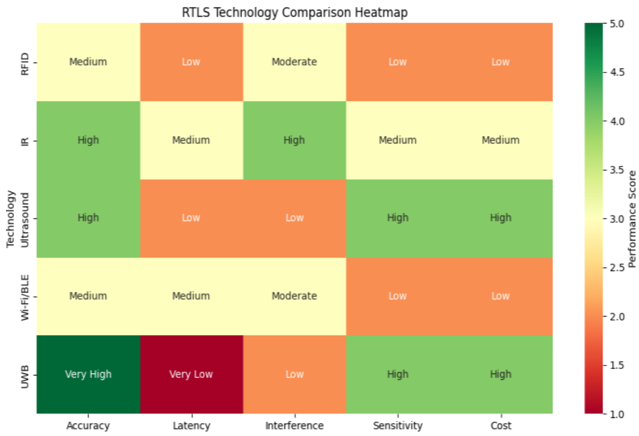

Fig. 1. Heatmap comparing RTLS technologies across key performance dimensions. Green indicates better performance; Red indicates less favorable characteristics.

is particularly valuable in high-volume surgical cen- ters where even minor delays can cascade into sig- nificant scheduling disruptions. The study by Berg et al. [17] used a retrospective observational design based on RTLS data files of an academic outpatient clinic. The researchers used the data on the histori- cal utilization and scheduling to determine the likelihood of RTLS insights to enhance the operational efficiency, which can be extended to surgical systems where coordination issues are also present.

S. Compliance and Infection Control

RTLS helps to monitor sterilization processes and adherence to hand hygiene automatically. Research has proven a 40 percent sterilization compliance, and a decrease in cross-contamination risks by 30-50 percent. These enhancements will directly relate to reduced cases of surgical site infections (SSIs), which will improve patient safety and out- comes and aid regulatory compliance [19].

T. Staff Efficiency and Safety

The ability to track movement and location of staff improves safety measures especially in emergency scenarios. RTLS equally lowers the burden of staff cognition since it automates common documentation and produces real-time alerts. These functions lead to high job satisfaction levels, low burnout rates, and better team on-task coordination in high-stress surgical settings [18].

Quantitative and qualitative analyses have proved that RTLS is an effective approach to enhancing operational performance and employee safety in healthcare settings.

Time-motion analyses show that only 30% of time on shift is devoted by nurses to direct patient care, and up to 12% of the time is wasted in finding equipment [45]. This in-efficiency can translate to 2147 minutes per nurse per shift, or roughly 200 hours per year in certain U.S. hospitals. This amounts to more than 14 billion dollars of lost productivity in the U.S. healthcare system at an average RN wage of 40/hour [46].

These findings are supported with qualitative evidence of staff surveys. In a 2010 survey conducted by the Healthcare Management Council, equipment location was found to be the second biggest time-waster to nurses [47]. Implementations of RTLS have been linked to a higher level of job satisfaction, less stress, and the visibility of workflows. Also, RTLS tools, including panic buttons and infection tracking, have helped improve the safety of the staff and their responsiveness to an emergency [48].

A systematic review of 42 peer-reviewed articles supported finding that RTLS is effective in workflow analysis, asset tracking, and infection control, but integration challenges and user adoption are also important factors to consider [49].

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U. Predictive Maintenance and Asset Management

More complex RTLS solutions, particularly those based on an Ultra-Wideband (UWB) or RFID technology, can identify patterns of equipment usage to determine required maintenance. This is proactive and reduces equipment downtime, increases life of high valuable surgical equipment, and has critical equipment always in the best working condition [19].

V. Financial and Strategic Impact

The overall outcome of RTLS implementation is the reduction of enormous costs and enhancing return on investment (ROI). Hospitals implementing RTLS have cited a decrease in OR delay, increased patient satisfaction in scores and increased preparedness in accreditation audit since more data is documented and complies are tracked [17].

Uwb Techniques

UWB-based RTLS systems primarily use two localization techniques: Two-Way Ranging (TWR) and Time Difference of Arrival (TDoA).

TWR entails the initiation of a signal to an anchor by a tag, that reacts. Distance is computed by using the round-trip time. TWR is applicable in situations where there are fewer anchors and a bidirectional communication is possible. It is very strong in dynamic conditions and is also very accurate with minimal infrastructure [4]. The TWR is however, slower in a relative sense because it has a model of sequential communication. Depending on optimized environment, in practice, TWR systems may reach a rate up to 100-250 Hz per tag with 6-8 anchors[42], [43]. This renders TWR to be applicable in surgical tracking applications that require high precision but a limited number of tracked objects.

TDoA, in its turn, needs several synchronized anchors. The tag sends a signal that is received by several anchors, the difference in time is used to triangulate the position. TDoA is also favorable in large scale applications because of scalability and reduced tag power consumption. Theoretical Scheduled TDoA systems are capable of supporting up to 8000 Hz of the total number of tags in a cell, or about 80 Hz per tag in a 100-tag system [44]. This renders TDoA a perfect fit as a surgical asset tracking tool in real time where multiple instruments and trays need to be tracked simultaneously with very low latency.

The selection between the TWR and TDoA is determined by implementation: TWR is better performance in anchor- sparse and ad-hoc deployment, whereas TDoA is optimal in the high- density, low-power, and large-scale implementation. Both methods can be improved by cooperative positioning and Kalman filtering in order to increase accuracy under non-line-of-sight (NLOS) circumstances [43].

Use Cases: - TWR: Best on surgical equipment tracking, mobile equipment localization in limited ORs. TDoA: Applicable to hospital wide employee monitoring, patient flow, and emergency response coordination.

Recent RTLS-based Wi-Fi Protocols and SOM Vendors Newer developments in the Wi-Fi protocols include Wi-Fi RTT (802.11mc) protocols that can provide sub-meter indoor positioning with existing Wi-Fi infrastructure. This lowers the cost of deployment, and takes advantage of everywhere connectivity.

Vendors offering RTLS-capable System-on- Modules (SOMs) include NXP Semiconductors: i.MX RT series with UWB and BLE integration.

Decawave (Qorvo) DW3000 UWB transceivers with SOM kits. Silicon Labs: Wi-Fi 6 and BLE SoCs with RTLS SDKs. Nordic Semiconductor: nRF5340 with BLE AoA/AoD support for RTLS.

These SOMs allow hybrid RTLS solutions with UWB, BLE and Wi-Fi to support flexible deployments with respect to healthcare setups.

RTLS offers better equipment visibility, faster turnaround times, automatic compliance monitoring, better asset utilization, increased staff efficiency, and improved patient care outcomes.

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Two-Way Ranging vs Time Difference of Arrival

Ultra-Wideband (UWB) technology provides very precise positioning abilities and is a very vital en- abler in real-time location systems (RTLS). There are Two-Way Ranging (TWR) and Time Differ- ence of Arrival (TDoA) as two main localization methods employed in UWB. The methods differ in the operational principles, infrastructure needs, and the suitability of the use.

W. Two-Way Ranging (TWR)

TWR is point-to-point distance estimation technology. In this method, the tag sends out a signal to the anchor which replies. The tag measures the round-trip time of the signal exchange and calculates distance using the speed of light:

$$\text{Distance} = \frac{(\text{Round-trip Time} - \text{Processing Delay})}{2} \times c \quad (1)$$

where c is the speed of light.

Advantages

- Does not require clock synchronisation between tag and anchor.
- High accuracy in small, high-interference en- environments.
- Robust to multipath and dynamic obstacles.

Limitations

- Requires bidirectional communication — each tag must wait for replies.
- Not scalable for environments with hundreds of tags.
- Increased latency due to sequential commune- cation.

TWR is best suited for surgical suites, robotic tool tracking, or scenarios requiring high-precision, low-latency performance.

X. Time Difference of Arrival (TDoA)

TDoA, in contrast, is a one-way transmission method. The tag transmits a single signal, which is received by multiple time-synchronised anchors. The system measures the differences in arrival time at each anchor and uses multiliterate to estimate the tag's position.

Positioning principle: If three anchors receive a signal at slightly different times, the tag must lie on a hyperbola defined by the time differences. In 3D space, this generalizes to a hyperboloid. Adding more anchors allows multiliterate in 2D or 3D space.

Mathematical model: Let anchors be located at positions A1(x1, y1) and A2(x2, y2), and let the signal from the tag arrive at times t1 and t2 respectively. The difference in arrival time Δt = t2 – t1 corresponds to a difference in distance:

$$|r_2 - r_1| = c \cdot \Delta t$$

where ri is the distance from the tag to anchorAi, and c is the signal propagation speed. This defines a hyperbola in Equation 2.

In 3D, with anchors at A1(x1, y1, z1) and A2(x2, y2, z2), the tag lies on a hyperboloid in Equation 3::

These equations form the basis for multiliterate algorithms used in RTLS systems.

Advantages:

- Highly scalable: ideal for tracking many tags simultaneously.

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- Low power consumption on the tag side: Nsuitable for wearable RTLS.
- Permits real time positioning within expansive regions.

Limitations:

- Needs the accuracy of synchronization across an- chors (nanosecond-level).
- Time jitter sensitive, anchor sensitive and clock drift sensitive.
- Lower per-device accuracy in dense, cluttered environments.

Environmental confounding factors:

- Electromagnetic (EM) interference: Can distort signal timing and reduce accuracy.
- Metallic surfaces: Cause multipath reflec- tions, leading to erroneous time measure- ments.
- RF shadowing: Physical obstructions block or attenuate signals, degrading per- formance.

$$\sqrt{(x-x_2)^2+(y-y_2)^2}-\sqrt{(x-x_1)^2+(y-y_1)^2}=c\cdot\Delta t$$

Fig. 2: 2D hyperbola equation for TDoA positioning.

$$\sqrt{(x-x_2)^2+(y-y_2)^2+(z-z_2)^2}-\sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2}=c\cdot\Delta t$$

Mitigation strategies:

- Calibration routines: Periodic recalibration of anchor clocks and signal paths.
- Hybrid systems: Combine TDoA with RSSI, AoA, or inertial sensors for robust- ness.
- Anchor diversity: Strategic placement of additional anchors to reduce blind spots.
- Signal filtering: Use of statistical or ma- chine learning filters to reject outliers.

TDoA is widely used for hospital-wide staff track- ing, patient monitoring, and logistics optimization.

Y. Visual Comparison

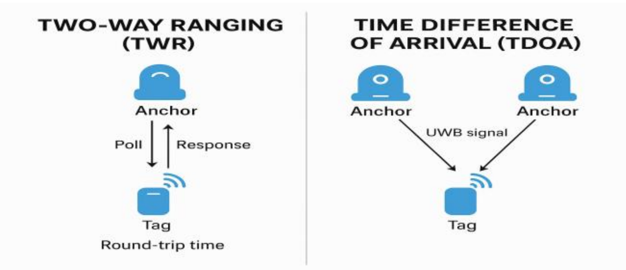

Fig. 2. Visual comparison of TWR and TDoA signal flow in UWB systems. TWR relies on bidirectional exchange with a single anchor, while TDoA passively observes signal arrival at synchronized anchors.

A visual comparison of TWR and TDoA signal flow in UWB systems is shown in Figure 2

Challenges and Limitations

Challenges include high initial costs, system in- titration complexity, signal interference, data overload, and privacy/security concerns.

Despite the transformative potential of Real Time Location Systems (RTLS) in surgical environments, several challenges and limitations must be addressed to ensure successful deployment and sustained performance.

Environmental factors impacting RTLS per- performance:

- Electromagnetic interference (EMI): Common in surgical environments due to high-powered equipment, EMI can distort RF signals and reduce location accuracy.

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- Metallic surfaces and equipment stacks: These cause multipath propagation and signal attenuation, leading to errors in position estimation. Studies have shown that metal-rich environments can reduce signal strength and increase location error by several meters depending on anchor placement and signal type [?].
- RF shadowing due to walls and obstructions: Thick walls and dense equipment layouts can block or reflect signals, degrading system performance. Experiments in hospital settings have demonstrated reduced accuracy in rooms with concrete walls and cluttered layouts [?].

Z. High Initial Costs and ROI Uncertainty RTLS implementation often requires substantial

upfront investment in hardware (tags, anchors, sen- sors), software platforms, and integration services. Technologies like UWB, while offering superior accuracy, are particularly cost-intensive due to spe-cialized infrastructure and calibration requirements. In smaller healthcare facilities, the payback period (ROI) might take a long time or be challenging to estimate due to insufficient performance measures and strategic planning

AA. Integration Complexity

RTLS systems have to connect to available hos- pital information systems (HIS), electronic medical records (EMRs), scheduling solutions, and asset management databases. The interoperability between these systems is not easily achieved technically and might need custom middleware, API development, and continuous maintenance. The absence of uniform vendors protocols also worsens integration work.

BB. Signal Interference and Environmental Con- straints

Environ- related factors that degrade the RTLS performance include metallic surfaces, dense equipment layouts and electromagnetic interfer- ence. Such technologies as IR and Ultrasound are especially vulnerable to the line of sight obstructions and noises. Even UWB which is reputed to be robust can have attenuation of the signal in a cluttered or shielded environment and needs cautious location planning and calibration.

Data Overload and Analytics Bottlenecks Location data are large and are produced by high-resolution RTLS systems and should be analyzed, stored, and processed in real time. In the absence of sophisticated analytics systems and machine learning models, this information might flood IT infrastructure and not provide actionable information. Scalable data pipelines and visualization tools have to be invested in by hospitals to gain value on RTLS deployments.

1) Privacy and Security Concerns

Supervision of patients and personnel also creates ethical and legal issues, including privacy, consent, and data protection. The RTLS systems are required to be in accordance with the laws and policies like the Health Insurance Portability and Accountability Act (HIPAA) in the U.S. and the General Data Protection Regulation (GDPR) in the EU.

Regulatory requirements

- HIPAA requires protection of electronic protected health information (ePHI) such as access control, audit controls, integrity and transmission security.
- GDPR mandates minimum data collection, limitation of purpose and express permission of tracking, and the notification of breach within 72 hours.

Cybersecurity risks

- RTLS systems commonly use the W Fi networks in hospitals and can potentially connect to electronic health records (EHRs), which can become an entry point of attackers.
- A 2022 study by Cognos pointed out that numerous RTLS systems do not have network segmentation, making it easier to allow the mobility of attackers once they have access to the system [50].

- The 2024 ransomware attack on Change Healthcare affected more than 100 mil- lion Americans and is one of the many examples of interconnected systems (including RTLS) making breaches more potent [51].
- Ascension Health also experienced a massive cy- cyberattack in 2024, disabling access to EHR and affecting clinical operations in 11 states [52].

Best-practice mitigation strategies

- Network segmentation: Isolate RTLS traffic from critical systems like EHRs.
- End-to-end encryption: Protect location data in transit and at rest.
- Zero Trust Architecture (ZTA): Enforce least-privilege access and continuous verification.
- Regular audits and penetration testing: Identify vulnerabilities before they are exploited.

Privacy Impact Assessments (PIAs): Evaluate and mitigate risks during system design and deployment.

The inability to enact effective security systems may cause breaches of data, fines, and even loss of confidence by the stakeholders.

2) Scalability and Maintenance

The expansion of RTLS to various departments or fa- cilities adds logistical issues in the management of tags, the sitting of anchors and calibration of the system. Hardware maintenance, updating of firmware and troubleshooting need specific tech- nical support, which may not be easily present in every healthcare environment. III shows the comparison of RTLS technologies in terms of scalability and latency.

Deployment Limitations:

- Anchor calibration: UWB and BLE AoA systems require precise anchor placement and calibration.
- Environmental interference: Metal surfaces, walls, and medical equipment can degrade signal quality.
- Maintenance overhead: Active systems require battery replacement and firmware updates.
- Integration complexity: Hybrid systems offer flexibility but increase deployment and main- tenance complexity.

Best Practice: Select technology depending on application- BLE- scalable, cost-effective tracking; UWB-high precision of zones; RFID- inventory; Wi-Fi- leveraging available infrastructure.

Vendor Lock-In and Standardization Gaps RTLS itself is a proprietary technology, as are several vendors, and this means that it is a lock-in, resulting in a lack of flexibility to upgrade or switch. Lack of universal standards on RTLS data formats, communication protocols and performance benchmarks discourages interoperability and cross-platform integration.

Future Directions

The trends of the future involve AI and predictive mod- eling, blockchain, augmented reality interfaces, standardization and interoperability, and sustainability.

With the ongoing adoption of digital transformation in healthcare systems, Real-Time Location Systems (RTLS) are on the verge of transforming passive tracking systems into intelligent predictive and interoperable platforms. Several key trends and innovations are shaping the future of RTLS in surgical contexts:

CC. AI-Driven Predictive Analytics

By combining RTLS data with artificial intelligence (AI) and machine learning (ML), it becomes possible to predict surgical workflow, equipment demand, and patient movement, which is beneficial. These models are able to predict bottlenecks, optimize OR scheduling and assist in the dynamic allocation of resources. As an example, AI could predict the moment a surgical tray is required, according to the historical usage trend, which reduces idle time and enhances throughput.

DD. Digital Twins and Simulation

Digital twin technology enables hospitals to build virtual copies of surgeries inside the hospitals using RTLS data. These simulations are applicable in training, optimization of workflow, and planning. As modelling the influence of layout modifications or staffing solutions, the healthcare administrators can make evidence-based decisions that do not interfere with the real-life activities.

EE. Interoperability and Standardization

Historically, RTLS is not scaled because of the absence of standardized protocols. The next generation systems will progressively embrace the open standards like IEEE 802.15.4z to UWB and HL7 FHIR to exchange data. It will enable smooth integration with hospital information systems, decrease vendor lock-in, and support ecosystem-wide interoperability.

FF. Edge Computing and Real-Time Decision Making

To minimize latency and bandwidth, edge computing architectures are becoming used more and more in RTLS platforms. The edge processing location information, which handles it close to the source, can make decisions more quickly, e.g. alerting to unauthorized equipment movement or patient wandering, without a need to access central servers.

Edge (On-Premises Gateway) Functions:

- Real-time event detection: A response to preset stimuli (e.g. patient entering restricted area, equipment leaving a zone).
- Local filtering and reprocessing: Reduction in noise, signal smoothing, and the removal of outliers in data transferred to the cloud.
- Device health monitoring: Real time detection of an- chor/tag failures or battery status.
- Latency-sensitive control: Turning on alarms, shutting the doors, or informing the personnel in a milli-second.

Cloud-Based Functions:

- Historical analytics: Long-term trend analysis, heatmaps, and utilization reports

TABLE III. SCALABILITY AND LATENCY COMPARISON OF RTLS TECHNOLOGIES.

Technology	Max Tags	Latency	Limitations
BLE	Thousands (mesh)	1–3 s	RF interference, reduced accuracy in dense environments
UWB	Hundreds (per zone)	<1 ms	High cost, power usage, line-of-sight required [54]
RFID (Passive)	Thousands	Event-based	No real-time tracking, limited range [53]
RFID (Active)	Hundreds	1–5 s	Battery maintenance, infrastructure needs [53]

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Wi-Fi RTLS	Thousands	2–10 s	Lower accuracy, high power con- sumption [55]

- Machine learning model training: Predicting workflow constraints or making ag- aggregated data more location accurate.
- Cross-site coordination: Coordination of data between facilities or departments.
- Compliance and audit logging: Safe storage of access logs and history of movement to use them in the control.

This hybrid architecture will ensure that time sensitive decisions are made locally and the cloud performs system wide intel- ligence and compute intensive analytics.

GG. Augmented Reality (AR) Integration

AR RTLS applications are started to appear, especially in surgery navigation and coordination between staff. Smart glasses or AR headsets may superimpose real-time location information over the view of the user to improve situational awareness and decrease mental load during complicated processes.

HH. Energy Efficiency and Sustainability

Future RTLS tags and infrastructure will priori- tize low-power operation and recyclable materials. Energy harvesting technologies and ultra-low-power chipsets will extend battery life, reduce maintenance, and align with hospital sustainability goals.

II. Blockchain for Data Integrity

The concept of blockchain technology is being considered in order to guarantee the integrity and traceability of RTLS data. Unalterable records of the use of equipment, sterilization, and staff mobility could increase the level of au- auditability, regulatory compliance, especially in high-risk surgery units.

JJ. Hybrid RTLS Architectures

Hybrid RTLS systems, a combination of multiple technologies including UWB, BLE, and Wi-Fi RTT, will allow creating systems based on the needs of a particular clinical setting. These systems will automatically alternate between technologies depending on accuracy demands, power restrictions and environmental factors.

Conclusion

RTLS is an important element of contemporary surgical practice. Its capacity to simplify equip- ment management and increase workflow visibil- ity helps to increase patient care outcomes. RTLS is becoming an intelligent infrastructure with AI, sensor fusion, and system interoperability, which will support high-reliable surgical settings. The success relies on proper planning, strong integration, and constant assessment.

The use of Real-Time Location Systems (RTLS) has become a basic technology in contemporary surgery and provides unmatched visibility in equipment, staff, and workflow dynam- ics. Their capacity to optimize the asset management system, minimize delays in operations, and increase the compliance with safety measures directly leads to the better patient outcomes and hospital efficiency.

With the development of RTLS technologies, they are being integrated with artificial intelligence (AI), sensor fusion, and edge computing to become intelli- gent infrastructure with real-time decision-making and predictive analytics. Ultra-Wideband (UWB), specifically, is establishing new standards of precision and responsiveness, making it possible to use in robotic coordination, surgical navigation and optimization of patient flow.

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Nevertheless, the effectiveness of RTLS implementation is based on the strategic planning, the sound system integration, and the ongoing performance assessment. High initial cost, data governance, and interoperability challenges need to be overcome by using standardization and scalable architectures. The future trends are directed at hybrid RTLS, digital twins and augmented reality interfaces that will transform how the surgical environments are operated and experienced.

To sum it up, RTLS is not only a tracking solution but also the driver of operational excellence and clinical innovation. Its further development will be a key factor in development of high-reliability, data-driven surgical ecosystems.

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