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INTEGRATION OF AUTONOMOUS MOBILE ROBOTS (AMRs) WITH LiDAR AND 5G CONNECTIVITY: A STUDY ON APPLICATIONS IN HOSPITAL ENVIRONMENTS

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ABSTRACT

The integration of Autonomous Mobile Robots (AMRs) with LiDAR technology and 5G connectivity presents transformative potential for hospital environments. This study evaluates the performance of these technologies in critical metrics such as latency, throughput, reliability, and reaction time, with an emphasis on their application in the automation of logistics tasks, such as the transportation of medical materials. The results indicate that 5G networks outperform WiFi in terms of low latency, high throughput, and performance consistency, making them ideal for real-time applications. In addition, LiDAR technology enhances the navigation of AMRs by providing accurate three-dimensional mapping in dynamic environments. Despite promising technical advances, challenges remain, including infrastructure costs, interoperability, and cybersecurity concerns. The findings highlight the need for multidisciplinary approaches to overcome these barriers and pave the way for innovative solutions in healthcare. This research contributes to the growing knowledge about the applications of Industry 4.0 in the healthcare sector, aiming to improve the efficiency, safety, and quality of patient care.

Keywords: Autonomous Mobile Robots (AMRs), LiDAR Technology, 5G Connectivity, Hospital Automation, Industry 4.0.

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INTRODUCTION

The technological evolution associated with the Fourth Industrial Revolution has the potential to radically transform the work patterns of the most diverse sectors of human activity. In the healthcare sector, where the demand for professionals grows continuously with aging populations, the integration of these advanced technologies, such as Autonomous Mobile Robots (AMRs), LiDAR, and 5G connectivity, can be one of the key components to balance the outpatient and hospital operation, in terms of efficiency and effectiveness demands (SAHU et al., 2024) and (GUSTAVSSON, 2021). In complex environments such as hospitals, where accuracy, safety, and efficiency are critical, these technologies can offer significant support for routine tasks while relieving healthcare teams of repetitive and potentially risky activities such as transporting medications and laboratory samples. Automation at this level not only promises efficiency gains, but can also promote safer environments for professionals and patients, (WEI, 2023) and (GIUFFRIDA & MARTINA, 2023)

AMRs, equipped with LiDAR sensors, can navigate autonomously and adaptively in any dynamic flow environment and complex geometry, adjusting to changes in the environment, such as hospitals and outpatient clinics, in real time. This capability is crucial, because dynamic environments require precise navigation to avoid accidents and ensure the fulfillment of tasks in effective times. LiDAR Sensors bring the ability to create three-dimensional maps that facilitate safe and efficient navigation, anticipating and avoiding obstacles safely.

Compared to other sensing technologies such as cameras, LiDAR sensors perform better in low-light conditions and can map 360-degree objects around them. This set, in this way, makes autonomous operation possible because it reduces the need to exchange extensive data packets related to image interpretation, because it helps to reduce response times, data packet losses and above all the cost of network infrastructure and computing. This favors the progression of the development and implementation of this technology in situations of budget constraints.

In this context, 5G Indoor connectivity is essential to make the operation of AMRs more efficient in dynamic environments, such as hospitals, because it enables low-latency communication in the networks where they are inserted and the ability to securely transact large data packets. These attributes are prerequisites for ensuring that interactions between

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devices and control systems are fast and reliable (SIDDIQI & JOUNG, 2019) and (SEFATI & SIMONA).

In indoor environments where there is 5G infrastructure, data is transmitted practically in real time, this brings the ability to AMRs to respond almost immediately to commands and avoid dynamic obstacles: flow of people and objects, reconfigurations of environments, changes in routes, etc. This agility is essential for the operation of outpatient clinics and hospitals, because serious events can arise due to communication delays, or accidents on the way, which delay the delivery, for example, the delivery of a medicine.

It is important to remember that the operation at this level of AMRs in hospital environments is far from being possible, but we are here taking the structural learning steps so that this will be a possible alternative, soon, as an alternative to reduce the cost of their operations with the automation of the repetitive work of health professionals (AKBARZADEH & HANI, 2022) and (KHAN & MIR, 2023).

RESEARCH PROBLEM AND OBJECTIVE

Despite the high technological and implementation potential, the integration of AMRs, LiDAR, and 5G Indoor into an effective solution for ambulatory and hospital environments still has to face significant challenges: interoperability between systems, implementation costs, and cybersecurity concerns (NOKIA, 2024) and (HERMANT et al., 2021).

The implementation of 5G Indoor networks is complex, especially in terms of infrastructure and network management. In addition, it is necessary to ensure that sensitive data is rigorously protected, as 5G connectivity exposes this data to new security risks. In this context, this study aims to evaluate the feasibility and effectiveness of integrating AMRs, LiDAR sensors and 5G Indoor connectivity to optimize efficiency and safety in hospital environments, through the understanding of how the construction of these applications should be planned, structured and implemented from the understanding of their key performance indicators.

SIGNIFICANCE OF THE STUDY

The application of AMRs with LiDAR sensors and 5G connectivity has the potential to redefine the way routine tasks are performed in hospitals, allowing healthcare professionals to focus on activities that require clinical skills. Automating routine and repetitive tasks can not only improve operational efficiency, but also minimize risks inherent in human traffic in biologically contaminated areas: cross-contamination. Enabling truly autonomous AMRs effectively is essential to this. In addition, previous studies clearly point out that the use of AMRs in hospital environments can increase productivity by reducing the response time for the transport of materials, (SAHU et al., 2024).

The relevance of LiDAR lies in its ability to provide accurate data for real-time navigation and object detection. According to Berman (2018), LiDAR excels in environments where it is necessary to map with high resolution, offering an advantage over cameras and ultrasound sensors in terms of accuracy and speed. In hospitals, this precision is essential to avoid collisions and ensure that the robot follows safe trajectories. In addition, LiDAR's ability to identify different surfaces and materials in low-light conditions is a significant differentiator, GUSTAVSSON ET AL., 2021)

CHALLENGES AND PROSPECTS

Integrating these technologies into a specific application has a specific set of challenges to overcome.

The implementation of 5G Indoor also requires a robust infrastructure and efficient network management, especially with regard to low latency and high reliability in the transmission of data packets, for the control of AMRs in real time. SHAFI et al. (2017) highlight that the maximum potential for the application of 5G Indoor in dynamic environments, such as hospitals, requires investment in infrastructure and security solutions to protect users' sensitive data. To do this, it is necessary to accurately determine the demands of each application area. This need, along with the interoperability issues of control systems, AMRs and LiDAR sensors require full mastery of their control and performance variables, which is the objective of the present work, so that rigorous, synchronous coordination and data protection is possible, (SAHFI et al., 2017).

This work aims to help guide the application of Industry 4.0 enabling technologies in dynamic environments, especially outpatient and hospital environments that urgently need solutions to optimize the work of health professionals, through the evaluation of the technical feasibility of the integration of AMRs, LiDAR sensors and 5G connectivity.

THEORETICAL FRAMEWORK

The integration of Autonomous Mobile Robots (AMRs) with LiDAR sensors and 5G connectivity in dynamic environments, such as outpatient and hospital environments, represents a convergence of emerging technologies in applications that have the potential to profoundly modify routines and work processes in logistics. Including in this scope the health care environments and their internal logistics. To fully understand the challenges and current solution paths of this integration, it is essential to review the advances and solutions associated with each of its components and their joint application.

AUTONOMOUS MOBILE ROBOTS (AMRs)

The use of AMRs as logistical and maintenance aids in complex and dynamic environments has received more and more attention from the world's large automation companies, due to their inherent ability to perform repetitive, physical tasks without concern for ergonomics and, thus, physically spare human workers. In health care environments, these applications have clear adherence to tasks such as transporting medicines, laboratory samples, and medical equipment, in addition to many other possible tasks that can be imagined, (VAJJHALA & EAPPEN, 2023).

For this to become a reality, challenges such as navigating in dynamic environments and safe interaction with humans must be worked on and solved, before we can talk about commercial applications, (CABANILLAS et al., 2023).

LiDAR TECHNOLOGY FOR AUTONOMOUS NAVIGATION

LiDAR (Light Detection and Ranging) technology fundamentally uses laser pulses to map the environment in three dimensions and has been very well known for almost 50 years. This mapping capability allows AMRs to develop accurate navigation strategies, avoiding obstacles and making decisions in unexpected situations. In addition, as stated (CHOE & CHUNG, 2024), LiDAR has advantages over cameras and ultrasound sensors, especially in low-light conditions, and provides more accurate and accurate data for autonomous navigation.

However, it is necessary to work on the lower-cost alternatives of LiDAR sensing, since its cutting-edge alternatives can bring with them high complexity, need for specific knowledge and high costs, (FAWOLE & RAWAT, 2024).

INDOOR 5G CONNECTIVITY

Indoor 5G connectivity provides data communication solutions with high bandwidth and low latency, requirements for communication processes that demand high accuracy, quality, and low response time, such as the application of AMRs in complex and dynamic environments (YAO et al., 2024). SAHU et al. (2024) indicate that Indoor 5G, due to its performance in these requirements, can support even advanced medical services, including telemedicine and remote patient monitoring. This characteristic can support the search for specific solutions in health care.

However, the implementation of 5G Indoor in ambulatory and hospital settings faces challenges related to infrastructure, data security, and interoperability with existing systems, which must be explored to the limit of their key performance definitions.

INTEGRATION OF AMRs, LiDAR, AND 5G: OPPORTUNITIES AND CHALLENGES

The integration of Autonomous Mobile Robots (AMRs) equipped with LiDAR sensors and 5G connectivity in hospital environments represents a technological convergence with the potential to revolutionize healthcare operations. This synergy enables the automation of logistical tasks, such as the transport of medicines and laboratory samples, in addition to allowing quick responses to emergency situations, (GEOURGIUS & SATAVA, 2021).

LiDAR sensors provide AMRs with the ability to map environments in three dimensions with high accuracy, facilitating autonomous navigation and real-time obstacle detection. This technology is especially effective in low-light conditions, where other sensors, such as cameras, may have limitations. 5G Inddor connectivity, meanwhile, offers high bandwidth and low latency, allowing AMRs to instantly communicate with core systems and other connected devices. This real-time communication is crucial for the efficient coordination of hospital operations and for immediate response to critical events.

The synergy between AMRs, LiDAR, and 5G results in safer and more efficient systems. The AMRs' precise navigation reduces the risk of collisions and accidents, while real-time communication ensures that robots can react quickly to changes in the environment, such as the presence of patients or healthcare professionals in the corridors. In addition, the automation of repetitive tasks frees professionals to focus on activities that require clinical expertise, improving the quality of patient care.

However, the integration of these technologies presents significant challenges. Deploying 5G networks in hospital environments requires substantial investments in infrastructure and ensuring reliable coverage in all critical areas. In addition, interoperability between existing AMRs, LiDAR sensors, and hospital systems must be carefully planned to avoid incompatibilities and ensure smooth operation.

Cybersecurity is another central concern. The transmission of sensitive data, such as patient information and operational details, over 5G networks increases the attack surface for cybercriminals. Therefore, it is imperative to implement robust security measures, including advanced encryption, multi-factor authentication, and continuous monitoring of networks, to protect against unauthorized access and ensure data integrity, (GEORGIU & SATAVA, 2021).

Cases of application of this integration are already being explored in several hospitals around the world. For example, the Hospital das Clínicas of the Faculty of Medicine of USP launched the OpenCare 5G project, which uses a private 5G network to test advanced connectivity in healthcare, including the operation of AMRs for transporting medical materials, DELLOITE (2021) and another example is in China, where robots are employed for disinfection of environments and delivery of supplies, minimizing the exposure of health workers to contaminated areas (ZHAO et al., 2022).

APPLICATIONS OF AMRs IN OTHER INDUSTRIES

In addition to the healthcare sector, AMRs have been applied in industries such as manufacturing and construction. DELGADO et al. (2019) analyze the use of AMRs in flexible manufacturing systems, highlighting improvements in production efficiency and flexibility. GHAFARIANHOSEINI et al. (2016) explore the application of autonomous robotic systems in the construction industry, emphasizing benefits such as increased accuracy and safety. These applications demonstrate the versatility of AMRs and provide valuable insights for their implementation in hospital settings.

SECURITY AND PRIVACY CHALLENGES

The integration of AMRs, LiDAR, and 5G in hospital environments raises significant security and privacy concerns. LOU et al. (2023) discuss the vulnerabilities introduced by the adoption of emerging technologies, such as IoT and 5G, in healthcare settings, including potential threats such as denial-of-service attacks and interception of sensitive data. The authors propose mitigation strategies, such as advanced encryption, multi-factor authentication, and continuous network monitoring, to ensure the security of smart healthcare systems.

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FUTURE PROSPECTS

The continued evolution of AMRs, LiDAR, and 5G technologies points to a future where automation and advanced connectivity will play crucial roles in hospital environments. FANG et al. (2017) emphasize that while reducing latency in 5G networks presents significant technical challenges, it offers substantial opportunities for the development of innovative real-time applications. In addition, the integration of artificial intelligence and real-time data analytics can further enhance the performance of AMRs, making them more adaptable and efficient in dynamic environments, (PARVEZ et al., 2018).

The literature review shows that the integration of AMRs with LiDAR technology and 5G connectivity in hospital environments offers significant opportunities to improve operational efficiency and safety. However, challenges related to infrastructure, data security, and interoperability need to be addressed for a successful implementation. Future research should focus on the development of integrated solutions that consider the specificities of hospital environments and ensure the reliability and safety of the implemented systems.

METHODOLOGICAL PROPOSAL

The methodology developed for this study aims to evaluate the effectiveness of the integration of Autonomous Mobile Robots (AMRs) with LiDAR technology and 5G connectivity in hospital environments, using rigorous metrics that reflect the specific demands of this context. The methodological steps are designed to address technical and operational challenges, ensuring that the results contribute to the practical implementation of AMRs in these critical environments.

EVALUATION PARAMETERS

The parameters chosen include latency, response speed, reliability, execution time, and throughput. These metrics were selected because of their relevance to the performance of AMRs in hospital tasks. Each of these metrics reflects distinct aspects of the operation of robots in 5G networks, aligning with the requirements of real-time communication and efficient automation.

Latency: This refers to the total time it takes for a data packet to travel from source to destination within the network. In hospital applications, where AMRs perform time-sensitive tasks such as drug delivery and material transportation, high latencies can

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compromise the effectiveness of the operation. To measure latency, the Iperf tool was used, which simulates network loads and evaluates the impact in real time. The 5G network is evaluated by its ability to maintain latencies below 1 millisecond, which is essential for efficient navigation and autonomous decision-making.

Response Speed: This metric measures the time it takes for the AMR to process and execute a command received from the cloud. In hospital settings, where quick decisions can directly impact patient care, speed of response is crucial. Using the Wireshark tool, traffic data was captured to measure the efficiency of communication between AMRs and core systems, validating the impact of 5G on reducing delays.

Reliability: Evaluating the ability of AMRs to operate continuously and predictably in different network conditions and workload is critical for the hospital environment. To this end, continuous monitoring systems were implemented with the Prometheus tool. This approach allowed the identification of bottlenecks and the analysis of performance patterns, ensuring the stable operation of the robots even in adverse situations.

Execution Time: Represents the time it takes for the AMR to complete a task, from initial command to completion. This metric is essential to ensure that robots not only operate quickly but also consistently. The AMR's operating system has been configured to automatically record the runtime, allowing for real-time adjustments to optimize its efficiency.

Throughput: This refers to the amount of data that can be transmitted between the AMR and the cloud in a time interval. This metric is critical for applications that require the transmission of large volumes of data, such as navigation sensors and real-time monitoring. Again, Iperf was used to test the capacity of the 5G network, ensuring reliable and high-speed communication.

IMPLEMENTATION OF THE METHODOLOGY

The tests were conducted in a simulated environment that reflects the conditions of a modern hospital, including network interference, multiple connected devices, and workload variations. For each metric, specific scenarios were defined that simulate real challenges faced by AMRs.

1. **Latency and Throughput:** Test scenarios included different distances between the AMR and the 5G access point, as well as simulations with high data traffic. These

tests helped validate 5G's promise of delivering high bandwidth and low latency under load conditions.

2. **Response Speed:** Critical commands, such as route changes and response to unforeseen obstacles, were simulated. Wireshark recorded communication times, allowing adjustments to improve efficiency.
3. **Reliability:** The performance of the AMRs was continuously monitored with Prometheus, allowing for the identification of communication failures or performance drops before they became critical.
4. **Execution Time:** AMRs' tasks have been timed to ensure consistency in operating times, evaluating the impact of internal processing and network conditions.

TOOLS USED

The choice of tools was strategic to ensure the accuracy and robustness of the tests. **Iperf** was essential to measure latency and throughput, offering a detailed view of network performance. **Wireshark**, with its real-time packet analysis capability, allowed it to evaluate the response speed of AMRs. **Prometheus** was used to continuously monitor the robots, identifying anomalies and adjusting parameters to improve reliability.

In addition, the operating system of AMRs has played a crucial role, automatically recording execution times and providing detailed reports for analysis. Integration with visualization platforms, such as Grafana, has made it easier to interpret the data and make metrics-based decisions.

CONNECTION TO THE 5G NETWORK

The 5G network was the central element of this methodology, offering the necessary infrastructure to ensure low latency, high communication speed, and support for multiple connected devices. Tests have demonstrated that 5G is capable of meeting the demands of AMRs in hospital environments, allowing for efficient automation and improving the quality of care.

The methodological proposal presented in this study provides a robust approach to evaluate the integration of AMRs with LiDAR and 5G technology. The practical application of the tests in a simulated environment reflects real challenges, ensuring that the results are directly applicable to the implementation in hospitals. The use of specific metrics and advanced tools allows for a detailed analysis of the performance of AMRs, contributing to

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their optimization and expansion on a large scale. This methodology lays a solid foundation for future research and the advancement of hospital automation.

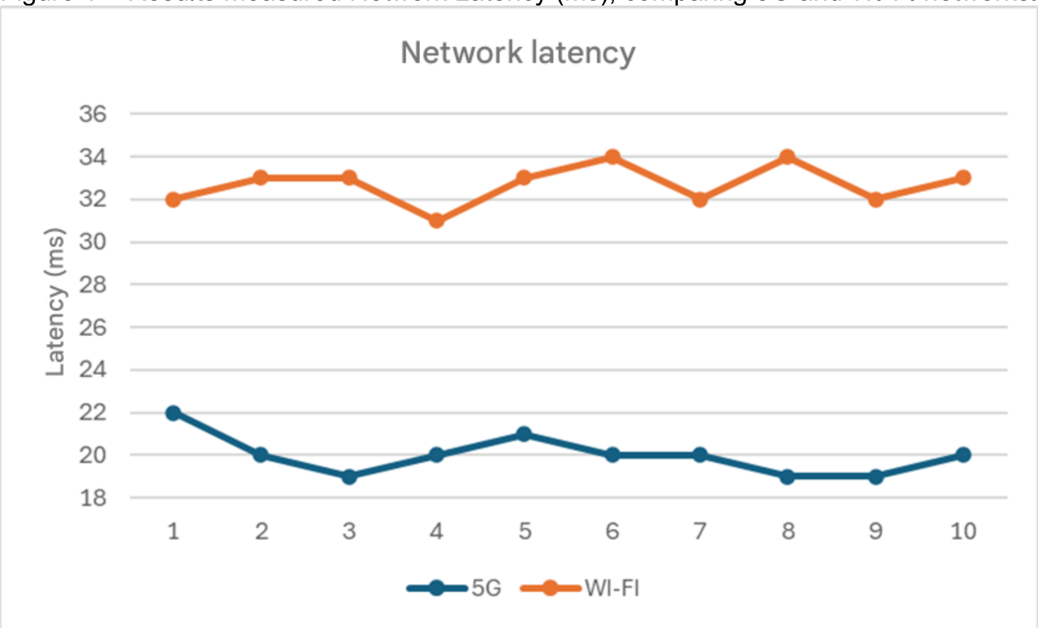
EXPERIMENTAL RESULTS AND ANALYSIS

The experiments carried out in this research were developed to evaluate the performance of Autonomous Mobile Robots (AMRs) integrated with 5G and WiFi networks in hospital environments, considering the defined methodological parameters. The analysis focused on latency, throughput, reaction time and reliability of communication systems, using specific tools for data collection and processing.

NETWORK LATENCY

Latency, defined as the time it takes for a data packet to travel between the server and the AMR, was measured based on the Round-Trip Time (RTT) formula. 10 consecutive tests were conducted, each sending 1000 packets of 128 bytes with an interval of 250 ms. The test environment included the AMR's edge server and on-board computer, both operating with 5G and WiFi networks. The graph in Figure 1 shows these results.

Figure 1 – Results measured Network Latency (ms), comparing 5G and WI-FI networks.



Results for 5G Network:

- **Average:** 19.92 ms
- **Mediana:** 19,91 ms

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- **Standard Deviation:** 0.176 ms

Results for WiFi Network:

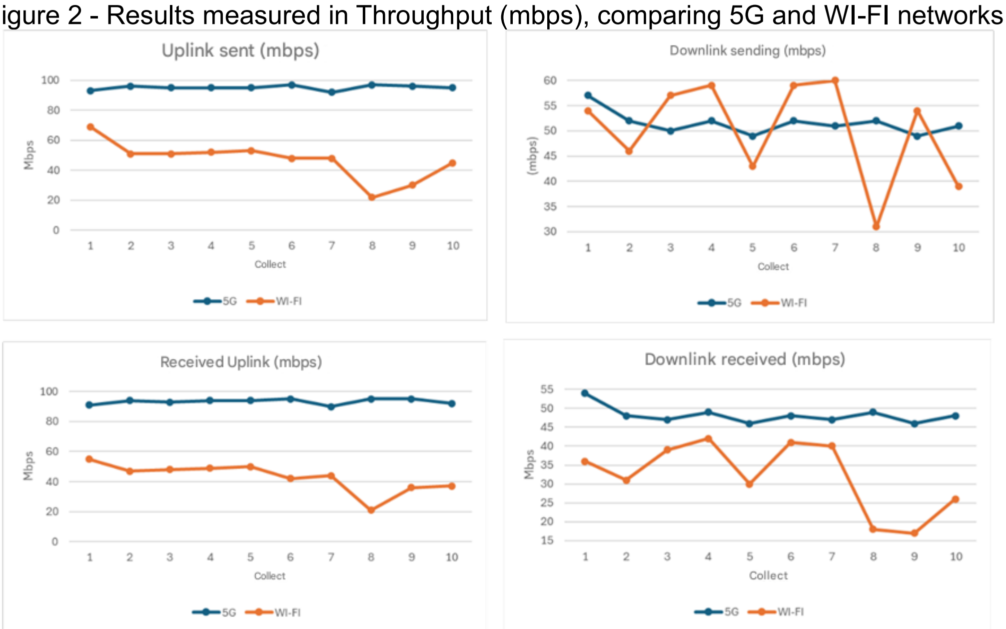
- **Average:** 32.65 ms
- **Mediana:** 32,64 ms
- **Standard Deviation:** 0.89 ms

The analysis revealed that the 5G network offers significantly lower and more consistent latency compared to the WiFi network, with a 3 times lower coefficient of variation, highlighting its superiority for real-time applications such as navigation and mapping with the SLAM algorithm.

TRANSFER RATE

The throughput, representing the amount of data exchanged between the server and the AMR per unit of time, was evaluated with the Iperf 3 tool. The experiment simulated high-demand scenarios, with 10 simultaneous streams and bandwidth limited to 100 Mbps. Figure 2 shows the results of the Throughput evaluation.

Figure 2 - Results measured in Throughput (mbps), comparing 5G and WI-FI networks.



Results for Uplink (Submitted) on 5G Network:

- **Average:** 95.12 Mbps

- **Standard Deviation:** 1.39 Mbps

Results for Uplink on WiFi Network:

- **Average:** 46.58 Mbps
- **Standard Deviation:** 12.63 Mbps

Results for Downlink (Received) on 5G Network:

- **Average:** 92.00 Mbps
- **Standard Deviation:** 1.04 Mbps

Results for Downlink on WiFi Network:

- **Average:** 41.72 Mbps
- **Standard Deviation:** 10.97 Mbps

The 5G network showed significantly higher transfer rates, with less variability, demonstrating greater stability and efficiency in supporting critical tasks, such as transmission of maps generated by SLAM.

REACTION TIME

The reaction time of the system was measured considering the interval between the receipt of an external stimulus, generated by a LIDAR sensor, and the sending of the first speed command by the AMR system. The analysis compared 5G and WiFi networks. Figure 3 shows the Reaction Time (ms) results, comparing %G and WI-FI networks.

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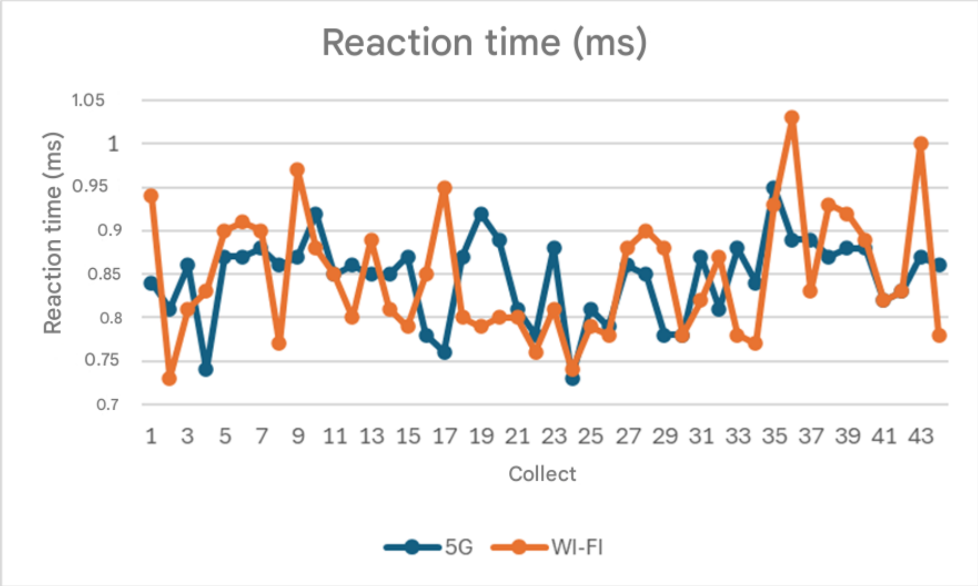
Figure 3 - Results measured Reaction Time (ms), comparing 5G and WI-FI networks.



Results for 5G Network:

- **Average:** 0.847 ms
- **Standard Deviation:** 0.046 ms

Results for WiFi Network:

- **Average:** 0.841 ms
- **Standard Deviation:** 0.071 ms

Both networks had reaction times below 1 ms, but the 5G network showed greater consistency, reflected in the lowest standard deviation. This consistency is critical to avoid failures in navigation and collision avoidance tasks.

RELIABILITY AND CONSISTENCY

To assess reliability, Prometheus was used for continuous monitoring, focusing on the stability of AMR operations under different network conditions. The analysis indicated that the 5G network maintained a more predictable performance, even under high workloads.

DISCUSSION OF THE RESULTS

The experimental results presented in this study clearly demonstrate the benefits of integrating AMRs with 5G networks and LiDAR sensors in hospital environments. However,

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the challenges and implications of this integration need to be discussed in depth to provide a complete picture of the feasibility and future opportunities.

TECHNICAL SUPERIORITY OF THE 5G NETWORK

The tests confirmed the superiority of the 5G network in terms of latency, throughput, and performance consistency. 5G's ability to operate with latencies below 1 ms is a significant differentiator for applications that require real-time responses, such as autonomous navigation and collision avoidance. In addition, the high throughput allows for the efficient transmission of data generated by LiDAR sensors, such as three-dimensional maps and obstacle information. This efficiency is critical in hospital settings, where delays can compromise the safety and effectiveness of operations.

On the other hand, the stability offered by the 5G network is particularly relevant in high-demand scenarios, where multiple devices need to operate simultaneously. The results indicate that while WiFi has greater variability, especially under load, 5G maintains consistent performance. This characteristic makes 5G more suitable to support advanced automation in hospitals, especially in critical situations.

PRACTICAL LIMITATIONS OF IMPLEMENTATION

Despite the technical advantages, the implementation of 5G networks in hospital environments presents significant challenges. The infrastructure required to support 5G Indoor, such as dedicated PicoCell and Network Core antennas, requires substantial investments and rigorous planning. In addition, reliable coverage in critical areas of the hospital must be ensured to avoid communication failures.

Another challenge is interoperability. For AMRs to operate effectively, LiDAR sensors, central control systems, and network infrastructure need to be perfectly synchronized. This requires clear integration standards and exhaustive testing to identify and resolve potential incompatibilities.

DATA SECURITY AND PRIVACY

The adoption of 5G networks in hospital settings also raises cybersecurity concerns. The transmission of sensitive data, such as patient information and operational records, must be protected from unauthorized access. Strategies such as advanced encryption, multi-factor authentication, and continuous monitoring of networks are indispensable to ensure the integrity and confidentiality of data. Additionally, the creation of robust security policies and regular training for technical staff are essential to mitigate risks.

IMPACT ON HOSPITAL WORKFLOW

The introduction of AMRs integrated with 5G and LiDAR has the potential to profoundly transform workflow in hospitals. By automating routine tasks such as transporting medications and laboratory samples, these robots can free up healthcare providers to focus on activities that require clinical expertise. This redistribution of tasks can result in a more efficient and safe work environment, reducing the risk of cross-contamination and improving the quality of patient care.

However, this transformation requires organizational restructuring. Hospital managers need to carefully plan how AMRs will be integrated into existing processes, considering factors such as maintenance, training, and adaptation of professionals to new technologies. Future studies should explore strategies to facilitate this transition and maximize the benefits of automation.

SCALABILITY POTENTIAL AND GLOBAL ADOPTION

The results of this study suggest that the integration of AMRs with LiDAR and 5G technology can be scaled up to areas other than hospitals, such as pharmaceutical distribution centers and home healthcare settings. However, the scalability of this solution depends on advances in the affordability of the technologies involved. Lower-cost LiDAR sensors and more affordable 5G networks are crucial to expanding the use of these systems in different contexts.

FUTURE RECOMMENDATIONS

Based on the challenges identified, some recommendations can be made for future research and practical implementation:

1. **Explore Infrastructure Alternatives:** Investigate the use of hybrid networks, combining 5G with high-density WiFi, to reduce costs and improve coverage in hospital environments.
2. **Focus on Interoperability Protocols:** Develop universal standards for the integration of AMRs, sensors, and 5G networks, facilitating implementation in different contexts.

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3. **Scalable Solution Development:** Design more affordable and compact LiDAR sensors, without compromising accuracy and reliability, to extend use in critical applications.
4. **Cost-Benefit Studies:** Conduct detailed economic analysis to assess the return on investment in AMRs integrated with 5G and LiDAR, considering different sizes and types of hospitals.

While this study demonstrated the technical feasibility of integrating AMRs, LiDAR, and 5G, the practical implementation of these technologies requires a multidisciplinary approach. From infrastructure issues to safety concerns and organizational adaptation, there is a way to go before these solutions become standard in hospital environments. Still, the results obtained here pave the way for future innovations, highlighting the transformative potential of these technologies in the healthcare sector.

CONCLUSION

This study explored the integration of Autonomous Mobile Robots (AMRs) with LiDAR sensors and 5G connectivity in hospital settings, analyzing their performance on critical metrics such as latency, throughput, reliability, and reaction time. The results obtained demonstrated the transformative potential of these technologies in the health sector, while highlighting significant challenges that need to be overcome for their practical implementation.

ADVANCES AND CONTRIBUTIONS

The experiments conducted confirmed that 5G connectivity, compared to the WiFi network, offers substantial advantages in terms of stability and performance. The significantly lower latency and consistency of reaction times make 5G an ideal choice for real-time applications such as autonomous navigation and the transportation of critical materials in hospitals. In addition, the high throughput seen in the 5G network allows AMRs to process and transmit complex data from LiDAR sensors efficiently, ensuring accurate mappings and quick responses to changes in the environment.

These advances not only strengthen the technical feasibility of this integration, but also point to opportunities for operational restructuring in hospital environments. Automating repetitive tasks with AMRs can free up human resources for activities that require clinical

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skills, improving overall efficiency and safety in patient care. Thus, the study directly contributes to the advancement of knowledge about the application of Industry 4.0 technologies in the health sector.

STUDY LIMITATIONS

Despite the promising results, this study has some limitations that need to be considered. First, the experiments were conducted in a simulated environment, which, while replicating real-world conditions, may not fully capture the complexities of hospitals. Factors such as signal interference, density of connected devices, and specific architectural configurations can impact the performance of AMRs and 5G networks in real-world scenarios.

In addition, interoperability and cybersecurity issues were mainly addressed in terms of technical feasibility, but no specific solutions were implemented in the scope of this study. Protecting sensitive data and integrating with existing hospital systems pose challenges that require more detailed investigations and multidisciplinary approaches.

IMPACT AND RELEVANCE TO THE HEALTHCARE INDUSTRY

The potential impact of this integration on the healthcare sector is significant. AMRs equipped with LiDAR sensors and 5G connectivity can revolutionize hospital logistics, providing greater agility and accuracy in the transport of medicines, laboratory samples, and medical equipment. This automation not only reduces the risk of errors and delays, but also contributes to the creation of a safer environment by minimizing healthcare workers' exposure to contaminated areas.

Additionally, the successful implementation of these technologies can serve as a model for other applications in healthcare, such as remote patient monitoring, telemedicine, and robotic assistance in clinical procedures. The development of integrated solutions that combine automation, advanced connectivity, and artificial intelligence can set a new standard for efficiency and innovation in the industry.

FUTURE RECOMMENDATIONS

To maximize the impact and applicability of this research, some recommendations can be made:

1. **Studies in Real Settings:** Conduct experiments in operational hospitals to validate the findings of this study in more complex and dynamic scenarios.
2. **Hybrid Network Exploration:** Investigate the integration of 5G networks with other communication technologies, such as high-density WiFi, to create more affordable and robust solutions.
3. **Deepening in Cybersecurity:** Developing and implementing specific security protocols to protect sensitive data in healthcare applications.
4. **Economic and Feasibility Studies:** Evaluate the cost-benefit of implementing AMRs integrated with LiDAR and 5G, considering different scales and hospital contexts.
5. **Organizational Adaptation:** Investigate strategies to facilitate the adaptation of health professionals to automation, including training and adjustments to workflows.

FINAL REFLECTION

The results obtained in this study demonstrate that the integration of AMRs, LiDAR sensors, and 5G connectivity is a technologically viable and highly promising solution for hospital automation. However, the full realization of this potential requires coordinated efforts to overcome technical, economic, and organizational challenges. Based on the findings presented, it is believed that this research contributes significantly to the advancement of knowledge in the field of automation in healthcare and lays a solid foundation for the development of future applications that positively transform the sector.

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