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Autonomous mobile robots in hospital logistics

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Abstract. The recent advances in technology have increased flexibility in indoor mobility and human-robot collaboration, opening up new opportunities to perform material handling tasks, especially in narrow, dynamic environments, such as hospitals. Sensing devices, powerful on-board computers, artificial intelligence, and collaborative equipment allow autonomous mobile robots (AMRs) to drive and fulfill material handling activities autonomously. In hospitals, material handling activities are widely performed manually. This study investigates five innovative applications of AMRs, highlighting their benefits compared with other material handling systems applied in hospitals, and presenting research needs. The study concludes that AMRs can support and collaborate closely with hospital personnel to increase value-added time for patient care.

Keywords: Autonomous Mobile Robots, Material Handling, Hospital, Logistics

1 Introduction

Automating material handling activities can significantly improve efficiency and productivity in the healthcare sector, since hospitals, compared to other industries, still, often perform these activities manually. A large survey conducted in the US, Canada, and Germany exposed that nursing's none–value-adding and non-nursing activities (e.g., delivery and retrieval of food trays, ancillary, or housekeeping services) consume around 40% of nurses' time [1]. Many of these activities could have been accomplished by other hospital personnel or advanced material handling systems [2-4]. However, finding the appropriate material handling system and level of automation for addressing hospitals' and patients' requirements is quite challenging [5]. The common material handling systems applied in hospitals allow low flexibility in mobility. Automated guided vehicles (AGV) cannot bypass obstacles and enter wards or departments due to safety and space concerns. Automated vacuum collection systems, pneumatic tube systems, and overhead transportation systems often have only fixed pick and/or delivery stations in departments. The low flexibility in mobility makes it difficult to automate material handling in the so-called last 50 meters, referring to the distance in the department to the patient, as well as in other departments.

The need for more flexibility has pushed the development of autonomous mobile robots (AMRs). Thanks to ubiquitous sensors, powerful on-board computers, artificial intelligence (AI), and simultaneous location and mapping (SLAM) technology, AMRs can understand their operating environments and navigate in facilities without the need to define and implement reference points in advance. AMRs are often small and agile, and they show their strength in high-traffic environments and low-volume transportation. Due to AMRs' characteristics, they can access narrower areas, interact with healthcare personnel and patients, and provide more services, such as assistive activities. AMRs have shown great potential in automotive, warehousing and process industry, in which they have supported increased production flexibility and productivity [6]. The potential of AMRs' high accessibility and flexibility in providing services has not been exploited and investigated in hospital environments.

Therefore, the aim of this paper is (I) to describe innovative material handling services and applications of AMRs in hospitals, (II) to compare them with other material handling systems in hospitals, and (III) to highlight future research needs for AMRs in hospital logistics. Two case studies have been conducted and three examples from the literature are presented to achieve these objectives.

The rest of the paper is organized as follows. The next section provides background information on traditional material handling systems in hospitals. Section three introduces and explains the cases and examples in which AMR has been applied in hospitals. The fourth section compares AMRs with other material handling systems in hospitals. The study ends with recommendations for future research areas for hospital logistics and AMRs.

2 Theoretical background

2.1 Material handling systems in hospitals

Logistics and material handling are crucial parts of the healthcare industry. Depending on the characteristics of the goods and the delivery requirements, a material handling system can be assigned to these tasks. Small objects, e.g., samples being delivered to laboratories, are mainly sent via pneumatic tube systems in hospitals due to time constraints. While automated vacuum collection systems are only used for return transportation of waste or linen, overhead transportation systems are used for both incoming and return transportation of loads of up to 15 kg to different departments. For transportation of heavier and bigger goods, AGVs have demonstrated good results in distributing high-volume goods to many pick-and-place positions and traveling long distances within hospitals without disturbing the hospital traffic [7]. The current material handling systems in hospitals are still largely dependent on human interaction for preparing, loading/unloading, and sending the items.

In contrast, AMRs have been recently introduced to hospitals, and their applicability in hospital logistics has not been exploited. AMRs possess a wide array of small and power-efficient sensing technologies, such as integrated laser scanners, 3D cameras, accelerometers, gyroscopes, etc., which allow them to digitalize an environment. Processing the sensing data with simultaneous location and mapping technology enables an AMR to create a map of its environment and calculate its position [8]. Unlike AGV systems, in which the central unit makes all routing and thus navigation decisions for all AGVs, AMRs can plan collision-free paths, make real-time decisions to avoid collisions, and so navigate in dynamic and unpredictable environments. AI techniques such as vision systems and machine learning enable the identification and classification of obstacles. These learning techniques enable AMRs to solve complex control problems in unfamiliar, real-world environments.

The main characteristics of the aforementioned material handling systems are shown in Table 1. A recent literature review in material logistics pointed out that standards and best practices for how to transport goods in hospitals barely exist [9]. To the best of the authors' knowledge, the applicability and research needs of AMRs in hospital logistics have not been addressed.

Table 1. Characteristics of automated material handling systems in hospitals

	Automated guided vehicle	**Autonomous mobile robot**	**Automated vacuum collection system**	**Overhead transportation system**	**Pneumatic tube system**
Capacity load	1–500kg	1–100kg	1–50kg	1–15kg	up to 2kg
Transportation speed	1–2 km/h	3–4km/h	20–70km/h	2–3km/h	10–25km/h
Services provided	Transportation	Transportation, collaboration, assistance, etc.	Only return transportation	Transportation	Transportation
Service points	Fixed pick and delivery points	Flexible pick and delivery points	Fixed pick and delivery points	Fixed pick and delivery points	Fixed pick and delivery points
Navigation	Fixed guided path	Autonomous in predefined zones	Fixed tube path	Fixed guided path	Fixed tube path

3 Cases and examples

3.1 Case 1: Sterile instrument transportation

Sterile instruments are transported in wagons from and to departments in a closed-loop logistics system by an AMR. The sterile processing department is responsible for picking and sending the sterile instruments required for medical treatment from the storage area to the departments. After usage at the department level (e.g., operating room), the goods are sent back to the central sterile processing department for cleaning, inspection, and sterilization. Hospital personnel can request, send, and track transportation via a tablet. Due to the logistics setup and the reliable transportation offered by the AMR, sterile goods can be sent Just-in-Time and demand-based on demand.

There are 10 pick and delivery stations located among five different levels in the case hospital. The AMR can open doors, use elevators, enter departments, bypass obstacles, handle dynamic environments, and reach the destination pickup-and-delivery station to deliver the sterile instruments. The AMR delivers approximately 60 wagons daily and substitutes one full-time employee.

Fig. 1. AMR in sterile instrument logistics [10]

3.2 Case 2: Personalized cancer medicine transportation

In chemotherapy treatments, patients receive personalized cancer medicine that has a short lifetime and can cost several thousand euros. The medicine is produced in the pharmaceutical department in the basement of the case hospital, while the actual treatment takes place several floors above it. Therefore, high-precision delivery, reliability, safety, and security are required for the transportation of medicine between the two departments.

The case hospital uses an AMR to transport the medicine in a locked drawer from the basement through the hospital to the final destination in the department [10]. After delivery, the AMR returns to the pharmaceutical department and waits to receive the next order. The AMR reduces the healthcare personnel's responsibility and the amount of time involved in the transportation of medicine. This helps healthcare personnel increase patient care and value-added time and thus has enabled the return of the initial investment within one year.

Fig. 2. Sending and delivery of cancer medicine with secured transportation [10]

3.3 Example 1: AMR providing telemedicine

AMRs with teleoperating and medical equipment can be controlled by a human from a long distance and perform tasks in dynamic environments [11]. Tele-operation enables a new method of using this valuable resource and eases the high risk of infectious disease transfer. Physicians and specialists can communicate with patients and perform some of their duties at a safe distance from infected patients. A telemedicine robot with autonomous navigation technology has been introduced in hospitals in the US [12]. While the AMR moves from room to room, the physician can easily connect for patient consults and access clinical documentation, patient data, and medical imaging. Digitizing and robotizing the material handling activities will provide data for and insights into new options for process improvement.

Fig. 3. AMR providing telemedicine [12]

3.4 Example 2: Assistive, collaborative AMR in the hospital laboratory

AMRs with manipulators can assist workers by interacting with humans as robotic coworkers. In other industries, AMRs are used as assistive systems and can mount several heavy parts of a car body together at different stages along the car assembly line [13], thus increasing both productivity and quality while simultaneously reducing fatigue levels among workers. A dual-arm mobile robot has been introduced to a US hospital laboratory [14]. The AMR was designed to work alongside medical staff and help complete lab workers' repetitive tasks (Fig. 4).

Fig. 4. Assistive, collaborative AMR in a hospital laboratory [14]

It can sense and navigate its way around its human coworkers autonomously and simultaneously learn to find optimized routes from one location to another. The vision for using AMRs in laboratories is that they will take over a wide range of repetitive and time-consuming activities, such as preparation of medicines, loading and unloading centrifuges, pipetting and handling liquids, and picking up and sorting test tubes.

3.5 Example 3: AMR disinfecting rooms

Hospitals must clean and disinfect rooms after usage to reduce the spread of hazardous bacteria. Hospitals are strategizing to reduce the risk of such spread and simultaneously increase awareness [15]. The development of UV-C light systems significantly supports the destruction of bacteria. UV-C light systems need 10 min of exposure time to kill 99.99% of bacteria [16]. While the equipment can often be found on wheels and is moved manually from room to room, AMRs provide a platform for autonomously transporting the equipment into and within rooms (Fig. 5a). Therefore, an AMR can cover more surfaces compared to a fixed UV-C system and reduce the exposure of hospital personnel to bacteria (Fig. 5b). Further, it can collect relevant data during the disinfection process and communicate when the room is ready for usage.

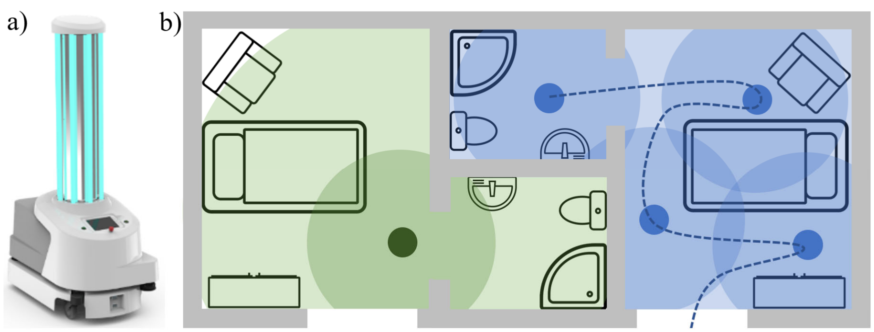

Fig. 5a: AMR with disinfection equipment[16]. **5b**: Left room disinfected with stationary equipment; right room disinfected by AMR (green/blue areas symbolizes disinfection range)

4 Discussion and conclusion

Unlike other material handling systems applied in hospitals, AMRs utilize AI for decision making, which significantly increases their flexibility in performing material handling activities in hospitals. AI especially supports AMRs' decision making in path and motion planning. While typically, an A* algorithm is applied in path planning to find the shortest path, AI allows analysis of the dynamic environment and reacts appropriately to congestions. Machine learning techniques can suggest optimized paths based on previous deliveries. These processes increase the reliability of precision delivery, which is crucial in hospitals since small delivery deviations can have large impacts on patient treatment. For instance, missing instruments or medicine will postpone treatments or negatively impact the health of the patient. Robust and reliable material handling systems like AMRs are crucial for transferring material flows that can highly impact patient health from manual to automated.

AI can further support interaction between humans and machines, enabling assistive or collaborative tasks. Vision-based sensing, manipulators for grabbing and handling probes, and the use of machine learning allow AMRs to learn to perform a wide variety of repetitive activities. AMRs can function as robotic coworkers in laboratories, autonomously improving both specific processes and overall performance. This allows for the reduction of workload for highly trained laboratory workers.

AMRs can deliver to the point-of-use, the patient, and so cover a wide service area. For many years, mobile robots were a virtually unimaginable and practically unacceptable solution in healthcare support. People could not associate hospitals with a production environment. The increased social acceptance of AMRs allows integration into departments and wards. AMRs can deliver to the point of use, the patient, and so cover a wide service area. The integration of AMRs as transporting, collaborating, or assisting robots allows a rethinking of logistics and material handling activities in hospitals. Therefore, future research should focus on:

- What manual material handling activities should AMRs assist with or take over, and when?
- How should AMRs interact with hospital personnel and patients to achieve high social acceptance and safety
- How should hospital goods be transported by AMRs to achieve high reliability, productivity, safety, and quality
- How should AMRs be integrated with AGVs and other stationary automated material handling systems?
- How should AMRs be designed and planned at the strategic level in hospitals?
- How can the optimal number of AMRs be determined in hospital logistics?
- How should path planning and motion planning be adapted for hospital environments?

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