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REVIEWS **Open Access**

Motorized hospital bed for mobility of patients: a review on wheel type design

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Abstract

Mobile bed to move patients in hospitals is a critical aspect in a healthcare system. Typical hospital beds often require significant manpower and impose physical stresses on caregivers. This paper explores potential solutions to improve hospital bed mobility, focusing on the integration of robotic technologies. Existing literatures on the subject are reviewed, including studies on hospital bed design structures, ergonomic considerations, and implementations of robotics. Different types of wheels suitable for robot movements are discussed, covering conventional wheels, omniwheels, mecanum wheels, swerve drives, and powered fifth wheels. Each wheel type is described and its advantages and disadvantages are highlighted. The comparison of these wheel types helps identify the most suitable option for modifying hospital beds while maintaining their maneuverability. Furthermore, the paper draws inspiration from many applications of mobile robots in other industries, such as automated guided vehicles (AGVs) and autonomous mobile robots (AMRs), to explore potential innovations for the healthcare. By leveraging robotic technologies, hospitals can enhance efficiency and alleviate the burden on healthcare workers.

Keywords: Hospital bed, Automation, Wheel, Robotics, Mobile robotics

Introduction

Hospital beds have always played a critical role in the healthcare system, serving as devices for patient treatment and transportation [1]. Unfortunately, this task can be inefficient, time-consuming, and require a significant amount of manpower to complete. The main reason for this is the heavy weight and large dimensions of the hospital bed, in addition to the weight of the patient and other attached equipment [2]. Typically, it takes between two to four operators to safely move a hospital bed [3].

Moreover, studies have shown that manual patient handling tasks, particularly during patient transfers, impose significant physical stress on caregivers [4], and are strongly linked to low back disorders and pain [5–8]. Recognizing these risks, it is crucial for hospitals to invest in technologies and procedures to reduce the burden on healthcare workers and enhance patient treatments.

The idea of reducing the effort required to operate hospital beds has been a subject of interest for some time. It is important to note that research efforts to enhance the features of hospital beds have been ongoing since the 1990s [9]. However, most of these efforts have primarily focused on design structures and ergonomic aspects aimed at improving user comfort for both patients and caregivers.

Kerstin Petzall et al. [10] conducted an experiment to investigate how different wheel arrangements on hospital beds impacted user effort. By testing four types of arrangements in two tasks—propelling in a straight corridor and maneuvering in a small space—they found that no single wheel arrangement met the requirements for both conditions. This suggests that simply improving the structure of the bed is insufficient to reduce effort. A more logical approach would involve adding a new assisting mechanism or introducing robotics to eliminate the need for operators. While there have been numerous studies on improving hospital bed mobility, robotics approaches have shown promise. A study by Zhao Guo et al. [11] demonstrated that implementing robotics in hospital beds could decrease the muscle load on operators. Currently, there are commercial products in development in this area, such as the addition of a motorized fifth wheel to the typical four-wheel hospital bed by Electrodrive [12] and Hospimek [13] and motorized bed movers created by various companies, which will be discussed further in the following section of this paper [14–17].

The objective of this paper is to review potential solutions for addressing hospital bed mobility issues. The focus is on examining and analyzing previous studies and existing solutions in this area. Various modifications are explored to identify the most suitable wheel type system that can be integrated into hospital bed design. The methodology of this paper involves surveying existing types of robotic wheels and their current applications in healthcare and other fields.

Mobile robot principal for hospital bed

Mobile robots are autonomous or semi-autonomous robots that are designed to move through various environments. These robots can be used for a wide range of applications, from household chores to industrial tasks. The working principle of mobile robots involves the use of sensors, control systems, and actuators to navigate and interact with their environment. These robots typically use a combination of sensors such as light radar (LIDAR), cameras, and ultrasonic sensors to perceive their surroundings [18]. The information gathered from these sensors is then processed by the robot's control system to make decisions about how to move and interact with the environment. Movement systems such as wheels, tracks, or legs are used to propel the robot and manipulate objects in its environment [19]. The control system coordinates the movements of these actuators based on the information gathered from the sensors, allowing the robot to move autonomously. In the context of hospital bed motorization, mobile robots can be utilized to assist in moving patients from one location to another within the hospital. These robots can be designed through complex hospital corridors, avoiding obstacles and ensuring the secure and efficient transportation of patients to their intended destinations.

Types of wheels

This section provides an overview of the different types of wheels commonly used for robot movement based on their characteristics and applications. The selection of the wheel type is crucial as it directly affects the mobile robot's ability to navigate and maneuver in its environment. This section aims to help readers understand the benefits and limitations of each wheel type, and make informed decisions when selecting the appropriate wheel type for a hospital bed mobility system.

Typical hospital beds use caster wheels, so the wheel types discussed here must have similar characteristics to caster wheels. Two factors are emphasized: first, the hospital bed wheel must prioritize patient comfort by imitating the smooth-rolling circular wheels, and second, the wheel must maintain the ability to move in all directions like caster wheels. The wheel types considered in this paper are conventional wheels, omni-wheels, and Mecanum wheels. Non-wheeled movement systems, such as tracked wheels and walker mechanisms, are not included because they may not necessarily be beneficial for hospital bed applications.

Conventional wheel

Conventional wheels are commonly used in driving systems, whether in mobile robots or other types of vehicles. They can be arranged in configurations of two to four wheels, as depicted in Fig. 1 below. In a four-wheel configuration, the wheels are positioned in a square or rectangular arrangement. The wheels are fixed, meaning they can only rotate around their main shaft axes. Steering is achieved by rotating the wheels on opposite sides at different angular speeds or in opposite directions, while on the same side they are driven in synchronization [20]. This type of steering also allows for zero turning radius, enabling on-the-spot turning at the center of the vehicle body [21].

Conventional wheels offer several advantages. They provide simplicity in design and control, as there is no need for a separate steering mechanism. The robot can achieve a small turning radius, making it suitable for maneuvering in tight spaces. Additionally, the system offers good traction and stability, allowing the robot to effectively handle uneven terrain or obstacles. However, one limitation of the four-wheel skid-steering system is that it can cause excessive wear on the wheels and may not be suitable for delicate surfaces [24]. The wheels can experience scrubbing and skidding friction forces when the robot changes direction, potentially leading to faster wear and reduced lifespan of the wheels. Therefore, two-wheel drive robots are more commonly used with this type of wheels. A variety of applications can be easily found in robotics competitions, education, research, and industrial automation. Some examples of two-wheel drive robots include line-following robots, warehouse carriers, and vacuum cleaners [25].

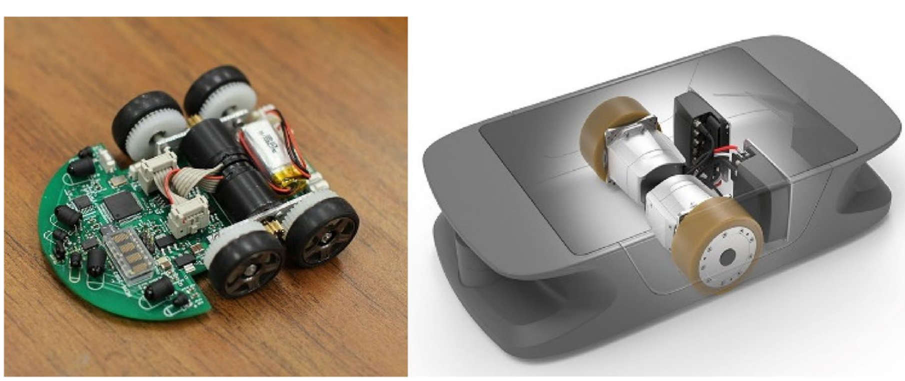

Fig. 1 Four and two wheel robots [22, 23]

Mecanum wheel

The Mecanum wheel is a type of omni-directional wheel that was first developed by Bengt Erland Ilon in 1972 [26]. The wheel consists of a base connected to the driving motor and a set of rollers, as shown in Fig. 2. The rollers are attached at a specific angle (typically a 45° angle). The Mecanum wheel has three degree of freedom, including steering drive, roller motion, and vertical axis turning slip at the point of interaction. Unlike other omnidirectional wheel, the Mecanum wheel is more efficient in driving forward and backward because the wheel is positioned at a straight angle, acting like a normal wheel [27].

The Mecanum wheel has been utilized in a variety of industries, such as education, military, industry, and aeronautics. It is known for its ability to provide omnidirectional movement in different applications. However, its effectiveness may be hindered by the type of surface it is used on. The wheel performs best on flat surfaces, but may struggle to maintain traction and mobility on uneven surfaces. In such cases, the rollers may lose grip, leading to a reduction in the wheel's tractive effort [29, 30].

Omniwheel

The omniwheel, also known as a universal wheel, is a type of wheel that allows a vehicle to move in any direction. Similar to the Mecanum wheel, the omniwheel consists of a main frame and a set of rollers placed perpendicular to the frame, as shown in Fig. 3. Omniwheels are typically used in three- to four-wheel configurations where the wheels are positioned at an angle or perpendicular to the side of the robot body. The direction of the wheel is determined by the rotational speed and the combined vector of each omniwheel [31]. Omniwheels come in various designs, using either short cylindrical rollers or long curved rollers similar to the Mecanum wheel, and often consist of two or more layers of sets of rollers. These layers compensate for the empty

Fig. 2 Mecanum wheel [28]

Fig. 3 Omniwheel [33]

contact surface area left uncovered by a single layer of rollers. Since the roller axes are perpendicular to the wheel axis, omniwheels on a vehicle are typically arranged at an angle to each other in order to function properly [32].

Comparison of wheel types

This section compares different types of wheels discussed in the previous section, along with their respective advantages and disadvantages. The goal is to determine the most appropriate wheel type for the hospital bed that needs modification. Specifically, the modified wheel type should retain the previously mentioned mobility, focusing on agility in the confined spaces of healthcare facilities. Furthermore, the introduction of a powered wheel type is anticipated to decrease the effort needed to move the hospital bed, while also ensuring easy maneuverability to adapt to the dynamic and constantly changing healthcare setting. Table 1 provides a summary of the advantages and disadvantages of each wheel type.

Table 3 provides technical details regarding various types of wheels that can be valuable for designing a mobile robot model [27, 36]. Each wheel type is characterized by a minimum diameter and maximum load capacity. This parameters are the most common parameter of wheel available in the market, but it may vary among different manufacturer and various applications [37].

Based on the Tables 1 and 2, each wheel type possesses its own set of advantages and disadvantages. Conventional wheels are highly reliable and durable but lack the ability to move freely in all directions, while omniwheels and Mecanum wheel are an excellent choice for enhancing a robot's maneuverability. The overall performance of the movement system of a mobile robot is influenced not only by the type of wheel chosen, but also by the configuration of the wheel.

Table 1 Comparison of wheel types

Wheel types	Description	Advantage	Disadvantage	Ref
Four independent conventional wheel	Each wheel is directly connected to a motor, can be moved independently	Simple design and easy to use, especially on small vehicles like toy cars or mini robots	Less flexible and challenging to maneuver in diverse environments, high wear	[24, 32, 34]
Two independent conventional wheel	Each wheel is directly connected to a motor, can be moved independently, usually located in the front or rear of the vehicle	Easy to control, excellent acceleration, and reasonably stable on flat terrains	Less stable on rough or bumpy terrains and requires good traction to operate effectively	[25, 32, 34]
Omniwheel	A wheel with rollers mounted perpendicularly to the rotating wheel axis, enabling free movement in all directions	Highly flexible and maneuverable on flat surface terrains, easy to control, and provides good acceleration	Requires more complex control and is not suitable for high-speed or heavy-duty operations	[31, 32, 34]
Mecanum wheel	Wheel mounted with rollers set at a 45° angle to the rotating wheel axis, enabling movement in all directions	Highly flexible and maneuverable on flat surface terrains, including at high speeds, easy to control, and stable	Requires more complex control and is more expensive compared to conventional wheel	[29, 32, 34, 35]

Table 2 Technical parameter of wheel types

Wheel types	Minimum diameter	Maximum load
Conventional wheel	50.8 mm	Up to 40–60 kg
Omniwheel	101.6 mm	2–30 kg
Mecanum wheel	101.6 mm	7–15 kg

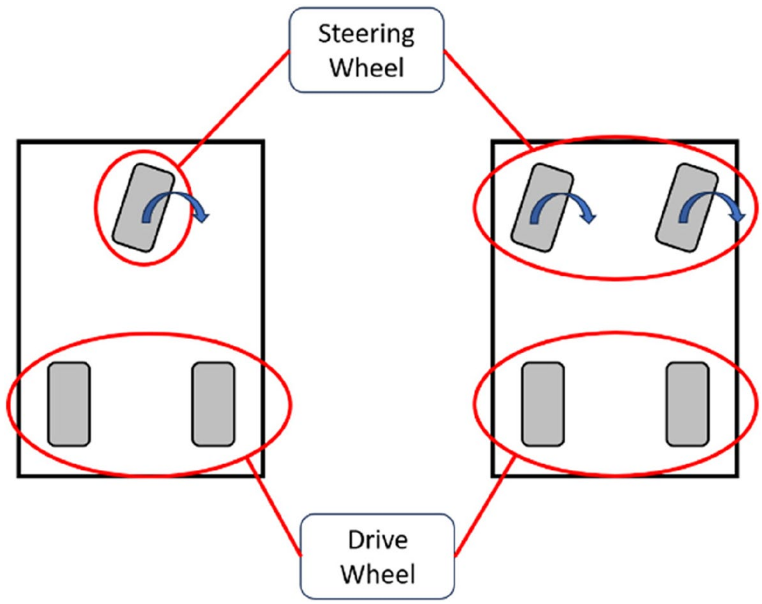

Fig. 4 Conventional steering [42]

Types of drivetrains

This section provides an overview of the different types of drivetrains commonly used for mobile robots and is related to the various wheel types. In robotics, a drivetrain refers to all the components and mechanisms configured in a way that enables a robot to move. The simplest type of drivetrain is a wheel directly powered by a motor. The types of drivetrains include car drive, skid-steer, holonomic drive, Mecanum drive, H-drive, and swerve drive.

Car drive

In the field of robotics and autonomous systems, the concept of car drive refers to a method of locomotion that emulates the movement principles of conventional automobiles. This drive mechanism is popular due to its simplicity and versatility. It uses conventional wheels, typically powered by motors, to generate motion in a manner like a car runs on the roads. The key characteristic of the car drive is that the wheels are aligned parallel to each other, resulting in forward or backward movement [38, 39]. Steering is achieved by turning a wheel or a set of wheels, placed in the front or back of the robot as illustrated in Fig. 4. This type of drive system is highly effective for applications that require reliable, stable movement over various surfaces [40].

It is commonly utilized in situations where precise turns and controlled straight-line motion are essential, such as warehouse logistics, material handlings, and even basic robotic platforms. The simplicity of the car drive system makes it a popular choice from beginner-level robotics projects to sophisticated industrial applications [41].

Skid-steer

The skid-steer drive mechanism is a distinctive approach to robotic locomotion that capitalizes on differential motion and wheel slippage to achieve precise movement. It is characterized by the use of wheels on either side of the vehicle that are independently driven at the same speed, allowing forward or backward straight motion, or at different speeds, allowing radius turning as well as turning (rotating) on the spot, as demonstrated in Fig. 5. One key characteristic of the wheel system in the skid-steer drive is that the wheels do not have a steering mechanism like traditional steering wheels found in common cars. Instead, they rely on differential speeds to change the direction of the robot. When one side vehicle wheels are driven faster than the others, the robot undergoes a controlled skidding motion, resulting in a change of direction [43]. By driving the wheels on one side at a different speed or in the opposite direction compared to the other side, the robot can turn or pivot effectively. To turn the robot while moving forward, the wheels on one side are driven faster than the wheels on the other side, causing a difference in rotational speed and resulting in a turning motion. By adjusting the speed and direction of each wheel independently, the robot can execute complex maneuvers, such as rotating in place or following curved paths. Figure 5 below shows the movement mechanism of skid-steer drive.

Skid-steer is particularly advantageous in situations where tight maneuverability is required, such as in construction equipment, agricultural machinery, and various types of robotic exploration vehicles. The ability to pivot on the spot makes it ideal for navigating through constrained spaces and executing intricate maneuvers. However, it does require careful control and coordination of the wheel speeds to prevent excessive wear and tear on the wheels and drivetrain components [44].

Holonomic drive

The concept of a holonomic drive introduces a paradigm shift in robotic locomotion by enabling a robot to achieve omnidirectional movement without the need for

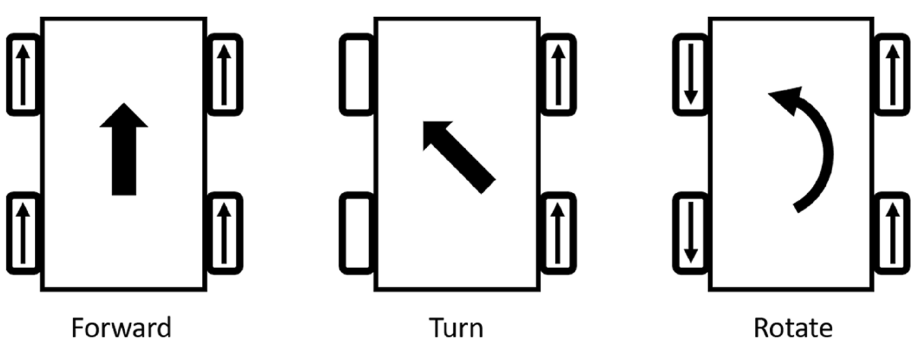

Fig. 5 Skid-steer drive

complex steering mechanisms. In a holonomic drive, omniwheels are used and positioned in a specific configuration, often in a triangular or square arrangement, such as shown in Fig. 6. In a three omniwheel configuration, each wheel is typically positioned at 120° angles with respect to the others, evenly spaced around the center of the robot's chassis. In a four omniwheel configuration, each wheel is typically positioned at 90° angles, also evenly spaced around the center [45]. Each wheel is independently powered and can move in any direction, including forward, backward, and sideways, without the needs to alter the wheel's orientation [46].

This unique ability to move instantaneously in any direction is achieved through a combination of the precise motor control and the strategic arrangement of the wheels. Holonomic drive system is invaluable in many applications that demand high degrees of agilities, such as indoor navigations, mobile robotics, and even advanced automation processes. By allowing robots to move effortlessly in any direction, holonomic drives enhance efficiency and versatility in various tasks, reducing the need for constantly repositioning and turning the vehicle [47–49]. Figure 6 also illustrates the rotations of vehicle wheels and the resulting direction in four- and three-wheel configurations.

Mecanum drive

A Mecanum drive is a drivetrain that employs a set of uniquely designed wheels, ordinarily using four Mecanum wheels. These wheels feature rollers positioned at an angle to the wheel's rotation axis, enabling them to generate both forward and lateral forces [50]. By carefully controlling the rotation of each individual motorized wheel, a Mecanum drive-equipped robot can achieve complex movements, including translations and rotations in any direction [51]. This drive system's distinct capability to move diagonally and pivot smoothly makes it highly suitable for applications where precise maneuvering and positioning are crucial, such as robotic arms, automated guided vehicles (AGVs), and even entertainment robots [52]. However, the complexity of the wheel design and the intricacies of the control algorithms required for accurate motion make the Mecanum drive systems more challenging to implement compared to the traditional drive mechanisms. The movement diagram of the Mecanum drive is shown in Fig. 7 below.

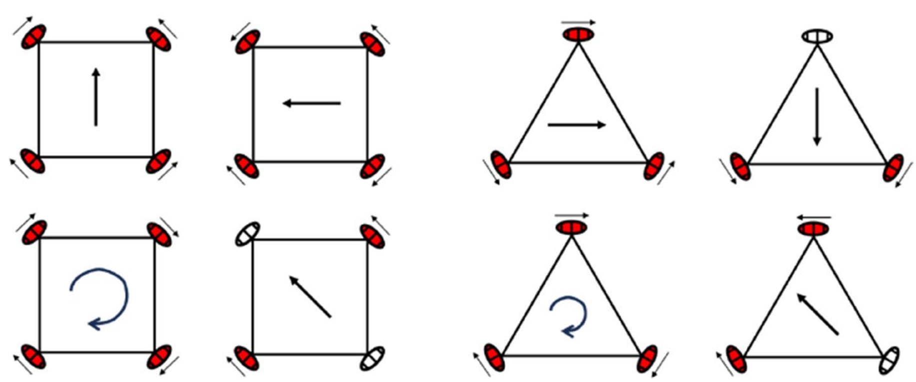

Fig. 6 Omniwheel type and movement schematic

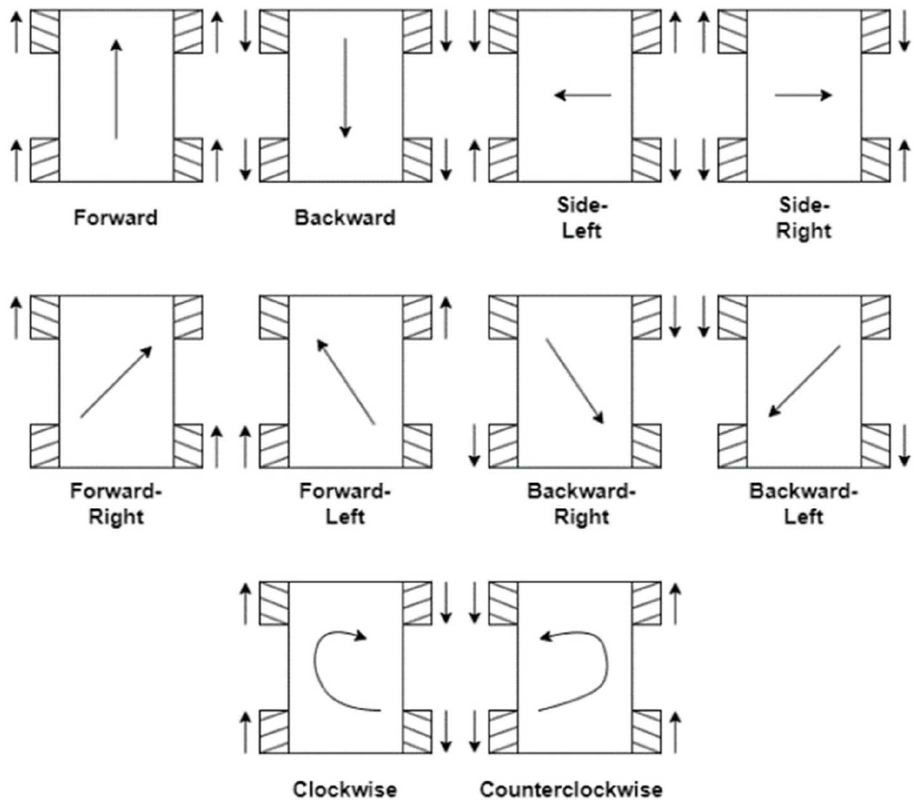

Fig. 7 Movement schematic of the Mecanum wheel

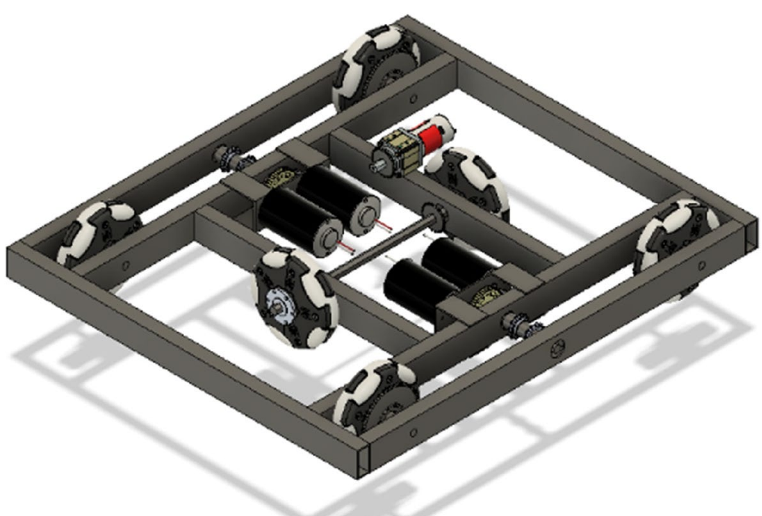

Fig. 8 H-drive configuration using omniwheel [55]

H-drive

The H-drive is a hybrid drivetrain that merges the principles of both omnidirectional and skid-steer mechanisms. The configuration consists of central, powered wheels perpendicular to the direction of the main drive wheels, forming an "H" shape. An example of the H-drive is shown in Fig. 8, with two wheels located at the middle and the four main drive wheels are placed at the corners of the H shape. They can be independently controlled for forward, backward, and sideways movements. The central wheels can be lowered or raised, enabling the robot to pivot for on-the-spot turning [53]. This unique design allows the H-drive to combine the advantages of skid-steer maneuverability with the benefits of omnidirectional movement. H-drive systems are especially useful in scenarios where the robot needs to navigate through confined spaces while maintaining stable and controlled motion. However, since more moving parts are needed, this makes the build more complicated. Furthermore, the H-drive requires precise coordination of the central and peripheral wheels, making the advanced control algorithms of the wheels becomes a critical aspect for the mobility. This drivetrain finds applications in fields such as warehouse automations, robotics competitions, and even assistive devices for individuals with mobility challenges [54].

Swerve drive

Swerve drive is a unique type of drivetrain that enables individual wheels to be both driven and steered independently of each other. This configuration requires two motors—one to rotate the wheel and the other to rotate the steering system. Since each wheel can be powered and controlled independently, hence vehicle which use swerve drive could be driven in omnidirectional, the swerve drive also classified into the holonomic drive system, providing a level of precision and maneuverability that is difficult to achieve with other drive systems. By enabling each wheel to move in any direction and rotate on its own axis, swerve drive systems are particularly well-suited for tasks that require omnidirectional movement, such as robotics competitions, industrial automations, and mobile robotics [56]. Figure 9 below is an example of swerve drive module used for robotics applications.

Comparison of the drivetrain

Table 3 below provides a comprehensive comparison of different drivetrain types, highlighting their respective advantages and disadvantages.

Inspiration from different applications

This section presents the ways in which mobile robots are being used in various fields, and how these applications could inspire innovation in the healthcare industry. While mobile robots have already proven to be effective in fields such as logistics, manufacturing, and agriculture, their potential to revolutionize healthcare is just beginning to be realized. By examining the successes and challenges of using mobile robots in other industries, we can identify potential areas for improvement and innovation in healthcare, especially in improving the capability of the hospital bed.

Automated guided vehicle

In automation industries, many types of robots had been adopted. One of the types of the robot is automated guided vehicle (AGV). AGV is a type of material handling robot or load carrier that operates without the need for an onboard human operator or driver. The robot is mainly designed to travel automatically with guidance positioned along the

Fig. 9 Swerve drive module [57]

path throughout warehouses, distribution centers, or manufacturing facility/assembly lines, performing tasks such as transporting goods and materials from one location to another. It effectively performs tasks that would typically be handled by forklifts, conveyor systems or manual carts, moving large volumes of material in repetitive manners [59].

Autonomous mobile robot

An autonomous mobile robot (AMR) is a type of robot that can navigate and perform tasks in a variety of environments without the need for human intervention. AMRs are equipped with various sensors, such as cameras, light detection and ranging (LiDAR), and ultrasonic sensors, which enable them to perceive their surroundings and avoid

Table 3 Comparison of the drivetrains

Types of drivetrains	Description	Advantages	Disadvantages	Ref
Car drive	Most commonly used type of drive-train, direct movement by turning pair of wheels, left or right	Simple and reliable movement, stable on various surfaces, easy to control and implement	Limited to forward or backward motion, less maneuverability not omni-directional	[35, 38, 39]
Skid-steer	Wheels directly connected to a motor, turning by differentiating wheels directions and speeds	Easy to control, excellent acceleration, and reasonably stable on flat terrains, less components	Less stable on rough or bumpy terrains and requires good traction to operate effectively	[38, 39]
Holonomic drive	Utilizes 3 to 4 set of omniwheels, direction controlled by speed and rotation of each wheel	Omnidirectional movement, sufficient indoor navigation and repositioning	Complex control algorithms required, complex structure	[28, 29, 40–43]
Mecanum drive	Utilizes Mecanum wheels to achieve omnidirectional movement, direction controlled by speed and rotation of each wheel	Omnidirectional movement, precise positioning and manipulation, easy to install	Complex wheel design and maintenance, sensitive to uneven surfaces and obstacles, requires advanced control algorithms	[28, 29, 44, 46, 47]
H-drive	Combines skid-steer and omni-directional principles with a central wheel for pivoting	Hybrid capabilities for tight spaces and omnidirectional movement, Effective in constrained environments, Precise turning around the central wheel	Requires coordinated control of multiple wheels, more complex design and control, limited load capacity	[48, 49]
Swerve drive	Wheel system that can rotate and steered independently, allowing free movement in all directions	Simple components, highly flexible and maneuverable on various terrains, including at high speeds, easy maintenance	Complex to control, more effort to synchronize between each wheel, has lot of components compared to other type of drivetrain	[32, 34, 58]

obstacles. AMRs are designed to operate in a range of settings, including warehouses, factories, hospitals, and even outdoor environments. They can perform a variety of tasks, such as transporting goods, picking and placing objects, and inspecting facilities [60].

One of the key features of AMRs is the ability to operate autonomously. This means that they can plan their own paths, make decisions, and adapt to changing conditions without human input [61]. They are also able to communicate with other robots and systems to coordinate their actions and share information.

AMRs are increasingly being used in industrial and commercial settings to improve efficiency, reduce costs, and enhance safety. By automating repetitive or dangerous tasks, they can free up human workers to focus on more complex and creative work. Additionally, they can work around the clock, without the need for breaks or rest periods, further increasing productivity. The difference between AMR and AGV is mainly in its automation system. For example, when there is an object blocks its guide path, AGV could detect the objects in front of it, then stop and wait until the obstacle removed from its path. AMR is able to not only detect the object but capable to plan and take alternative route to avoid the obstacle [62].

AMRs are being increasingly used in healthcare to improve patient care, increase efficiency, and reduce costs. The followings are some of the ways AMRs are being used in the healthcare [63]:

- Deliveries of medications and supplies: AMRs are used to deliver medications, medical supplies, and equipment throughout hospitals and clinics as shown in Fig. 10 [64]. This reduces the time and effort needed for manual delivery, freeing up healthcare workers to focus on patient care.

Fig. 10 AGV in healthcare [64]

- Sterilization: AMRs equipped with ultraviolet-C (UV-C) light technology are used to disinfect patient rooms, operating rooms, and other high-touch areas in the healthcare facilities. This reduces the spread of infections and enhances safety for patients and healthcare workers.
- Inventory management: AMRs are used to track inventory levels and automatically reorder supplies when needed. This reduces waste and ensures that healthcare facilities have the necessary supplies on hand to provide quality patient care.
- Waste management: AMRs are used to collect and transport medical waste, reducing the need for human involvement in this potentially hazardous task.

Motorized wheelchair

Swerve drive A motorized wheelchair, also known as an electric wheelchair, is a type of mobile device powered by an electric motor. It is designed to help people who have difficulties to walk or unable to walk due to disabilities, injury, or illness. Motorized wheelchairs have a seat, footrests, and a set of wheels. Typical motorized wheelchairs are controlled by a joystick or other type of control mechanism, as shown in Fig. 11a. Some models have rechargeable batteries that store the electric energy to power the motor, allowing the user to travel short distances on their own. Other types of wheelchairs must be plugged in to an electrical outlet for supplying the energy [65].

In addition to the traditional motorized wheelchairs, there are now also autonomous wheelchairs that are equipped with advanced technology to navigate and move independently without human intervention. These wheelchairs are designed for individuals with disabilities or limited mobility who desire greater independence and freedom of movement.

Compared to the traditional motorized wheelchairs, autonomous wheelchairs are more advanced in terms of their technologies and features. They are typically equipped

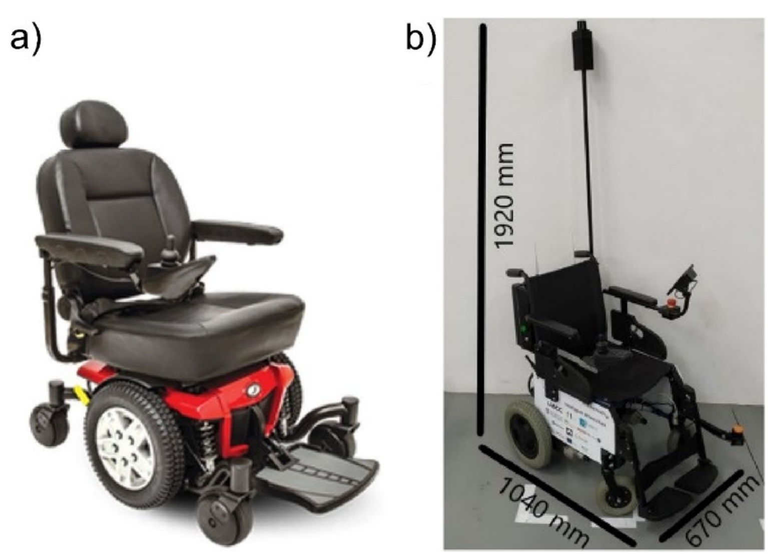

Fig. 11 **a** Typical motorized wheelchair [66], and **b** motorized wheelchair with LiDAR sensor for autonomous mobility [67]

with a range of sensors, including cameras, LiDARs, and ultrasonic sensors, that allow them to detect obstacles and other objects in the environment. Figure 11b shows an example of autonomous motorized wheelchair developed by Baltazar et al. [67] equipped with LiDAR sensor. This advanced sensing technologies enable the wheelchair to navigate complex indoor and outdoor environments with ease, providing the user with a greater degree of independence and mobility.

Autonomous wheelchairs also typically use mapping and localization algorithms to understand their environment and plan their movements accordingly. This allows the wheelchair to navigate around obstacles and find the most efficient path to a given destination. Additionally, some autonomous wheelchairs are also capable of avoiding collisions and adapting to changes in their environment in real-time.

Existing technologies of active mobile hospital bed

This section describes several solutions that have been implemented to improve the hospital bed mobilities.

Robotic hospital bed

Swerve drive Wang et al. [68] have designed and built a prototype of an automated hospital bed that has a focus on navigation, mapping, and obstacle avoidance. The wheel type system used in this prototype, however, is relatively basic, as it only has two differential wheels that restrict its maneuverability to a nonholonomic type. The hospital environment is typically a dynamic setting with many people and objects moving around, making it unrealistic to expect hospital beds to have the capability for omnidirectional mobility, which is a key feature of a holonomic wheel type. The current wheel type used in the prototype developed by Wang et al. [60] lacks the ability to perform 360° turns and may not be able to navigate around obstacles with ease. This highlights the need for further advancements in the wheel type technology used in automated hospital beds to improve their mobility and functionality in the hospital environment [69]. Figure 12a shows the prototype of the automated hospital bed.

In the pursuit of cost reduction in the development of motorized hospital beds, Dhelika et al. [9] undertook an innovative approach of constructing a prototype. Their methodology involved the adaptation of a conventional passive hospital bed wheel system,

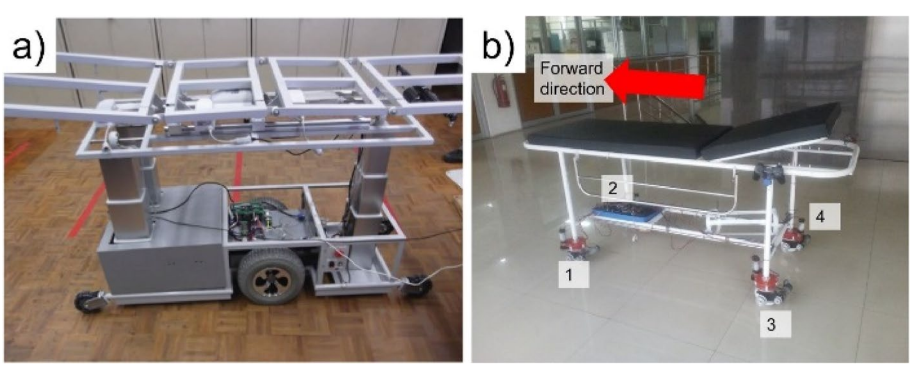

Fig. 12 **a** Automated hospital bed by Wang et al. [68], and **b** motorized hospital bed using the swerve drive by Dhelika et al. [9]

wherein they integrated a four-module active swerve drive system to enhance the bed mobility, as presented in Fig. 12b. The majorities of the components comprising each module were fabricated via 3D printing technology, utilizing polylactic acid (PLA) plastic as the primary material. The active power for these modules was harnessed from a pair of direct current (DC) motors, facilitating in both forward and lateral wheel movements. Furthermore, the system's maneuverability was conveniently orchestrated through the employment of a Wireless Joystick interface.

To improve the previous work, Girindra et al. [70] conducted an evaluation of assembly time of motorized wheel module for hospital bed using Boothroyd-Dewhurst method, enabling the identification of opportunities for optimization. In a strategic move to bolster the module's longevity, material substitutions were judiciously made. The team opted for aluminium and stainless steel as alternative materials for selected components, thereby elevating the overall structural robustness and resilience of the system.

Fifth wheel modification

As the name suggests, the fifth wheel is a wheel type system which adds an extra active powered wheel into a typical passive four-wheel system. Typically, an electric motor rotates the fifth wheel. The idea is basically to convert a manual bed into a motorized one, hence reduce the amount of work needed to push the bed. Because of its design, it does not have the ability to steer by itself; hence, the operator needs to steer manually. The advantages of using the fifth wheel include its feature to be attached to the bed frame avoiding major modification which reduces the required resources and time.

Shown in Fig. 13 is an example of the fifth wheel application to the hospital bed product developed by Hospimek [13]. The wheel is placed right in the center of the hospital bed and controlled using controller placed in the position where the handler could reach easily.

Fig. 13 Hospital bed equipped with the fifth wheel [13]

Bed mover

The bed mover is a device to move hospital beds. Rather than redesigning new hospital beds and discarding the old ones, the bed mover preserves the existing passive hospital beds and can be used to move many. The principle of the bed mover is similar to a towing tractor used in factories or warehouses. The bed mover has its own active power. Therefore, when it is attached to the hospital bed, the operator could move the bed easily. Current hospital bed movers come with various types and design, but most of it come with two powered wheel design such as shown in Fig. 14a.

The other variation of the bed mover, for example a concept developed by ZED [71], is displayed in Fig. 14b. Similar to the forklift principle where the bed mover lifts the bed and transports it. This mover is equipped with the swerve drive which can do omnidirectional movement. It also comes with a remote control for easy operation.

Comparison of mobile hospital bed technologies

Table 4 below presents a comparison of the aforementioned technologies of mobile hospital bed. It provides a brief description of each technology along with their respective advantages and disadvantages.

Conclusions

Conclusion

The mobility of hospital beds is a critical aspect in healthcare systems, as it affects patient care and the well-being of healthcare workers. Manual handling of hospital beds can be inefficient, time-consuming, and physically demanding, leading to potential risks and injuries for caregivers. Therefore, it is essential to explore solutions that can improve the mobility of hospital beds and alleviate the burden on healthcare workers. While previous research has primarily focused on the design structure and ergonomic aspects of hospital beds, it is evident that improving the structure alone is not enough to reduce the effort required for their movement. The introduction of robotics and automated systems shows promises in addressing this challenge. Studies have demonstrated that implementing robotics in hospital beds can reduce the physical strain on operators.

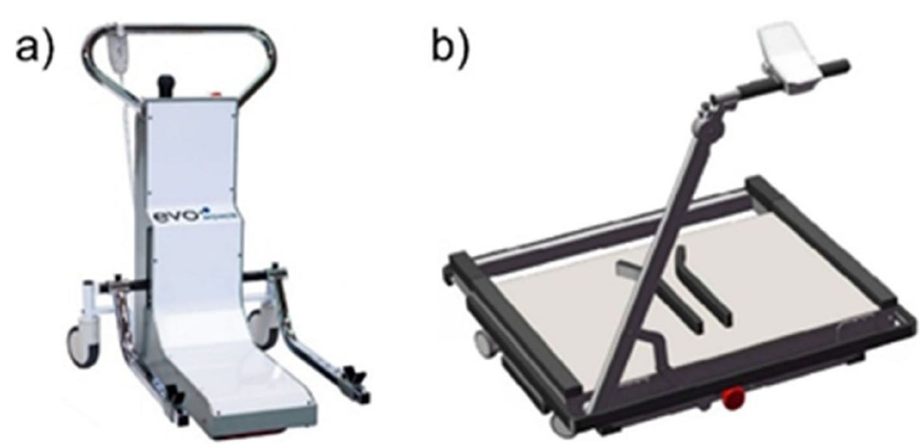

Fig. 14 **a** Typical bed mover [13] and **b** ZED Bed mover [71]

Table 4 Comparison of mobile hospital bed technologies

Types of technology	Description	Advantage	Disadvantage
Robotic hospital bed	A hospital bed specifically developed with an automatic mobility feature, allowing it to move and adjust positions without manual intervention	Can be built for specific functions, easy to implement automation	Need to build from scratch, more expensive, more complex
Fifth wheel	A motorized fifth wheel designed as an additional attachment for hospital beds, enabling easier mobility and transport	Easy installation, configuration, and use	Only provides locomotion, still need human power for steering
Bed mover	An additional equipment specifically built to tow hospital beds, facilitating their movement within healthcare facilities	No bed modification, easy to use, interchangeability	Still need human power for steering, requires separate maintenance and storage as it is additional equipment

One key focus area is the selection of the appropriate wheel type system for the hospital bed mobility. This review paper discussed various wheel types, including steering wheels, two-wheel drive systems, omniwheels, Mecanum wheels, and swerve drives. Each configuration has its own advantages and limitations, and their suitability for hospital bed mobility depends on factors such as maneuverability, traction, control complexity, and cost.

Drawing inspiration from other fields, such as the use of automated guided vehicles (AGVs) and autonomous mobile robots (AMRs) in logistics and healthcare, offers valuable insights. These applications have demonstrated the effectiveness of automation in improving efficiency, reducing costs, and enhancing safety. Implementing similar concepts in hospital bed mobility, such as automated deliveries of medications and supplies, sterilization capabilities, inventory management, and waste management, can greatly benefit the healthcare industry.

In summary, addressing the mobility challenges of the hospital beds requires a multidimensional approach. It involves considering not only the design structure and ergonomics but also exploring robotics and automation solutions. The selection of an appropriate wheel type system is crucial, considering the specific requirements of hospital bed mobility. By leveraging the successes and lessons learned from other industries, the healthcare sector can innovate and enhance patient care while alleviating the physical burden on healthcare workers.

Future development

The advancements in technology and infrastructure for hospital bed mobility are expected to bring significant improvements. These developments may include the use of advanced robotic systems with sensors, such as path follower, odometry, infrared, and LiDAR, could significantly improve mobility by providing more accurate environment perception for autonomous hospital bed or navigational aids for individuals with visual impairments.

Artificial intelligence and machine learning algorithms could be utilized to improve bed movement, ensure safety, and provide better and efficient path planning for patient mobility. This may involve refining the human–machine interface to allow for more intuitive control and feedback mechanisms. Additionally, integrating remote monitoring and reporting capabilities could enhance overall patient care.

Integration with hospital infrastructure, such as electronic health records and smart hospital systems, can optimize bed allocation and tracking. Additionally, Internet of Things connectivity will enable real-time monitoring of patient vital signs and bed status, facilitating remote monitoring and proactive care.

Future developments may also focus on human–robot collaboration by combining the strengths of robots with the judgment of healthcare workers. It is likely that safety features like intelligent braking systems and collision avoidance mechanisms will be prioritized in these advancements. Considerations for energy efficiency, sustainability, user feedback, iterative design processes will also contribute toward shaping future developments in hospital bed mobility.

Abbreviations

AGV	Automated guided vehicle
AMR	Autonomous mobile robot
LiDAR	Light radar
PLA	Polylactic acid
DC	Direct current

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Not applicable

Authors' contributions
ANR was mainly in charge of the analysis and writing of the manuscript. BH contributed to the analysis and writing the manuscript. RD contributed to analysis and writing the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare no competing interests.

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