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Recent developments in the applications of two-wheeled robots: a review

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Abstract

Robotic systems are being developed to carry out complex activities that demand accuracy and are usually difficult for humans to operate and monitor. Two-wheeled robots use the inverted pendulum principle and are prime example of such systems with a wide range of applications in various industries, including surveillance, home security, medical, and health-care. The present paper highlights applications of these robots and the relevance of the control logic employed in developing these robots, which plays a critical role in ensuring stability and efficient operation. As technology advances, the cost-effectiveness, accessibility, and usability of these robots improve simultaneously, resulting in increased demand and market growth. The paper further highlights the prospects for two-wheeled robots, such as potential to incorporate machine learning and artificial intelligence algorithms to enhance their decision-making capabilities and expand their applications. Two-wheeled robots are a promising technology with significant potential for improving human life quality, and their development and applications will continue to grow in the coming years.

Keywords: Mobile robots, Robotic platforms, Self-balancing robots, Self-balancing systems, Two wheeled robots

1. Introduction

Robot autonomy has much potential to revolutionize surveillance technology, credits to recent advances in computer vision research. Robot mobility has advanced to the point where robots can now navigate complex environments and patrol like humans [1]. They can function as mobile surveillance nodes equipped with cameras and other sensors. Over the last decade, robots with the ability to move have made their way out of the military and into civilian spaces like hospitals, schools, and ordinary homes.

The two-wheeled robot combines capabilities of wheeled mobile robots and the inverted pendulum system [1, 2]. These robots have many applications in various fields. For instance, in crises, these bots can be used to provide medicine. In recent years, there has been an increased interest in the use of robots for surveillance and investigation purposes. Two-wheeled robots have gained more popularity due to their ability to traverse difficult terrain and navigate narrow spaces. [3] As a Spy Bot, it has a successful application [4]. By utilizing bots in hazardous terrains, such as mountains, during disasters, the danger to human life can be lessened. This can be achieved by utilizing bots to provide necessary services and to carry out rescue missions during times of crisis. In pandemic situations, self-balancing bots can be used to provide medicine. Medical assistance in mountain areas where humans find it difficult to access is highly beneficial.

Studies and trials have been conducted on two-wheeled robots, shifting the focus from self-balancing and obstacle avoidance to tasks such as transportation and surveillance. Advancements in control methods and AI have facilitated the maintenance of balance control. The use of linear controls, nonlinear controllers, and self-adapting controllers has enabled the system's successful operation. The Segway, Hover board, and Ball Bot are some of the most well-known examples of this type of robotic platform [5]. Since the introduction of Joe, two-wheeled-robot prototypes developed at the Swiss Federal Institutes of Technology (SFIT), Switzerland, two-wheeled robots have attracted much attention as an excellent test case for applications of control design and distributed controls system during implementation.

The main advantage of two-wheeled robots over other wheeled robots is their small structure and zero turning radius. They are less complex (in terms of driving mechanism) than other mobile robots, more regulated, and move much faster. A two-wheeled bot is challenging to balance since the wheels must continue to maneuver in direction of the bot's fall to maintain the balance. Two-wheeled bot systems come in two varieties: those with their Centre of Gravity (CG) above the wheel axis and those below the wheel axis. Those with CG above the wheel axis produce a volatile mechanism that requires a control system to keep them upright and balanced. The system is statically stable below the wheel axis, although oscillations occur in dynamic situations [6]. Adding an idler wheel to these systems is usual to improve their stability and control.

Two-wheeled mobile robots combine driving and steering wheels and differential drive wheels. Differential-drive wheels are the most widely used method due to ease of installation. It consists of two independently driven wheels with no steering wheel to direct the body. Hence steering is accomplished by the difference in velocities between these two wheels. If the wheels go at the same speed and in the same direction, they move forward or backwards. When one wheel is faster, the body moves in an arc, with the faster wheel on the outer side and the slower wheel on the inner side.

The development of two-wheeled robots has been a topic of interest for researchers and industries for many years. The control logic of these robots is critical for their stability and proper operation. Many different control strategies are developed to improve the performance of two-wheeled robots. For instance, sliding mode control (SMC) has been widely used to improve the tracking performance of these robots. SMC controls the balance and movement of a two-wheeled robot. A linear quadratic regulator (LQR) has also been used as a control system to balance two-wheeled robots. LQR was used to develop a robust controller for a two-wheeled robot. Studies showed that the combination of different control strategies enhances the performance of two-wheeled robots [7,8]. For example, a hybrid control strategy was proposed that combines SMC and LQR to improve the stability and tracking performance of these robots.

2. Working principle of two-wheeled robots

The inverted pendulum hypothesis underpins self-balancing bots. A Self-Balanced Robot can stand upright only by using the two wheels that minimize the bot's height. The functioning of these robots is primarily based on the inverted pendulum principle and balanced control, which is achieved through the use of advanced controllers and PID algorithms. It is a dynamically unstable and nonlinear open-loop system with a Single-Input, Multi-Output system (SIMO) setting in which the location of the centre of mass is above the pivot point. The wheeled inverted pendulum is not self-balancing and requires dynamic balance to remain upright. It detects the inclination of the vertical axis using gyroscopes and accelerometers and then generates torque signals to each motor to overcome the inclination and keep the system away from falling. In a two-wheeled robot, the linear speed parameter controls how fast the robot moves forward or backwards. In contrast, the angular velocity parameter controls how fast the robot rotates around its centre of mass [9].

The principle of balancing a vertically standing robot with two parallel wheels is illustrated in Figure 1. One upward-standing homogeneous pendulum is connected to the wheels on an axis to represent the system. First, the force of gravity causes a tilt from its proper equilibrium, which is detected. The motor system must generate a counter-torque in the opposite direction more remarkable than the torque caused by the gravitational force. This torque will accelerate in the same direction as the tilt or system. An acceleration in the same direction as the tilt will result from this created torque [10,11].

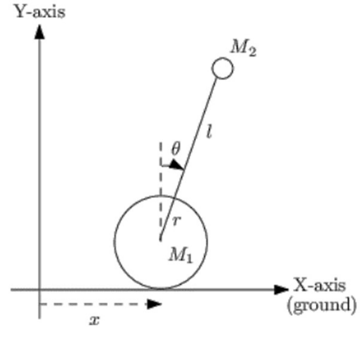

Figure 1 Wheeled Inverted Pendulum Schematic [9].

A typical design of this robot has the mass of the vehicle situated on top of the centre of configuration. Several researchers are working on the control algorithms required to keep a robot balanced while travelling. Making sure that the self-balancing bot is upright is an highly tedious task. This is because keeping the robot erect is dependent on both, the efficiency of the control system and the response time. Furthermore, if the robot falls, it does not stand up independently. As a result, self-balancing is not considered a reliable method of conducting autonomous exploration in amorphous or unstructured environments [12].

The relationship between wheel diameter and terrain traversability is important for two-wheeled robots. A larger wheel diameter increases ground clearance, which allows the robot to surmount obstacles and uneven terrain. However, a large wheel also increases the moment of inertia of the robot, which can negatively affect its agility and responsiveness. In contrast, smaller wheels provide better maneuverability and agility but may struggle to traverse obstacles or rough terrain. Therefore, the choice of wheel diameter for a two-wheeled robot involves a trade-off between these factors and depends on the requirements/applications. For example, a robot designed for rough terrain may benefit from larger wheels, while a robot designed for agility and precise control may prefer smaller wheels.

The mechanics and dynamics of two-wheeled robots are crucial for their performances in various applications. Recent studies have investigated the impact of wheel diameter on the stability, maneuverability, and energy efficiency of such robots. One such study analyzed the dynamic modelling and control of a two-wheeled robot with different wheel diameters and found that larger wheels led to better stability and energy efficiency. Similarly, it investigated the effect of wheel diameter on the performance of a self-balancing two-wheeled robot and concluded that larger wheels improved stability and reduced power consumption [13]. These findings highlight the importance of selecting an appropriate wheel diameter for two-wheeled robots, taking into account various factors such as terrain type, payload, and performance requirements.

The equations of motion for a two-wheeled robot can be derived based on its kinematic and dynamic properties. One commonly used model is the non-holonomic constraint model, which assumes that the robot can only move in a plane and cannot move sideways [14]. The equation of motion for this model is:

$$M(q)\, q'' + C(q, q')\, q' + G(q) = u \tag{1}$$

where M(q) is the mass matrix, q is the state vector consisting of the robot's position and orientation, q' and q" are the first and the second derivatives of q with respect to time, C (q, q') is the Coriolis and centrifugal matrix, G(q) is the gravitational and other external force vector, and u is the control input vector. While the equation for the kinematic model of a two-wheeled robot can be expressed as:

$$v = (r/2) \times (wR + wL) \tag{2}$$

where v is the linear velocity of the robot's centre of mass, r is the radius of the wheels, wR and wL are the angular velocities of the right and left wheels, respectively.

3. Control architecture

To maintain stability, a balancing robot necessitates a dynamic controller as the statically unstable structure compels its use. The ultimate purpose of control is to maintain the virtual link's centre of gravity, whose position and angle change in response to commands from the manipulator. A strong control system is required to quell the undesirable effects of different parameters such as disturbances and perturbations to the control task. After all, linear and nonlinear controls are the only two types of controls that can be used to govern a system. One of the most popular controls used by numerous researchers is PID [15]. To build the required framework, a number of variables have to be taken into consideration. As a result, the system is complicated [15,16]. Nonetheless, only a few requirements for modelling the system are on a smaller scale. As a result, most researchers prefer it as it is more straightforward and effective in some situations.

The control of two-wheeled robots is a complex and challenging task that requires the use of advanced control techniques to achieve stability and performance. While PID control is a widespread technique, recent research has shown that other techniques, such as model predictive control (MPC) and adaptive control provide better performance in many scenarios. MPC is a powerful technique that uses a mathematical model of the system to predict its future behavior and optimizes the control inputs accordingly [17]. Adaptive control, on the other hand, adjusts the control parameters in real-time based on the system's behaviour and changes in the environment.

Two control schemes, PDFLC and SNNPID, were proposed for a two-wheeled non-holonomic robot navigating a hostile environment [18]. These controllers allowed the robot to make independent decisions, avoid obstacles, and defend itself from load torques, resulting in precise and reliable navigation. The PDFLC controller had superior trajectory tracking and faster response time in comparison with SNNPIDC, and both controllers outperformed the PID controller. This study demonstrated the potential of these controllers in improving the performance of two-wheeled robots in hazardous environments.

In recent research, a PD-PI navigational control was proposed for a two-wheeled self-balancing robot (TWSBR) in a sensed environment, using a Kalman filter algorithm. The study showed that the PD-PI control technique was effective in maintaining self-balance with two wheels, using a combination of upright control (PD control), speed control (PI control), and turn control (P control) [3]. The Kalman filter algorithm was used to eliminate drift in MPU6050's gyro, providing an accurate estimate of the tilt angle. The robot's obstacle detection and avoidance mechanism relied on ultrasonic waves. The simulation results demonstrated that the TWSBR could maintain equilibrium and stability with minimal overshoot and zero steady-state error. These results suggest that the proposed control method can be a useful tool for improving the performance of two-wheeled self-balancing robots in sensed environments.

Several control methods have been proposed in recent studies, including Linear Quadratic Regulator (LQR), Sliding Mode Control (SMC), and Fuzzy Logic Control (FLC) [6]. The LQR method uses a state-feedback controller to minimize a quadratic cost function, ensuring optimal control performance. A recent study proposed an LQR controller for a two-wheeled robot, showing improved stability and trajectory tracking in comparison with a traditional proportional-integral-derivative (PID) controller. SMC is another control method that provides robustness against parameter variations and disturbances. It enhanced performance in tracking and robustness in presence of external disturbances. Fuzzy Logic Control (FLC) is widely used in mobile robot control due to its ability to handle nonlinearities and uncertainties. The control architecture for these methods typically involves sensor fusion, state estimation, and feedback control.

4. Applications of two wheeled robots

Two-wheeled robots have a variety of applications. These topics are explored further in the subsequent sub-sections.

4.1 Surveillance robots

4.1.1 Spy robots

Spy robots are a type of robot used for surveillance purposes [19]. They are useful in remote places with limited human interference. Intelligent spybots have the capability of decision-making. They are deployed in the military for surveillance and relief operations. Besides collision avoidance, they can judge their surroundings with the help of sensors and cameras and act accordingly [20,21]. The use of radiofrequency for wireless access to intelligent spybots has been the subject of research. [22]. A two-wheeled robot was designed for outdoor surveillance and security purposes. The robot was equipped with a thermal camera and a microphone to detect abnormal sounds. These studies highlight the potential of two-wheeled robots for various applications in surveillance and investigation, particularly in challenging environments [23]. Another two-wheeled robot was designed for military surveillance purposes. The robot was equipped with a laser scanner and a camera for data collection and mapping. Spy bots, developed by researchers at the University of Tokyo, are an example of such robots that can be used to investigate abnormal circumstances in disturbed areas. These robots are equipped with a camera and a microphone and can move quietly and quickly, making them suitable for stealth operations. With the rapid advancements in robotics technology, it is expected that two-wheeled robots will continue to play a vital role in various surveillance and investigation scenarios in the near future.

4.1.2 Miniature robots

Civilian organizations rely heavily on reconnaissance and surveillance. Certain operations, such as hostage and survivor rescue, toxic waste contamination, and critical detections necessitate secret surveillance in constrained spaces. These unique tasks require the use of a robot to relay information in potentially dangerous environments. Miniature robots are frequently utilized in these scenarios because they can more easily infiltrate spatially restricted areas and evade detection compared to larger robots [24]. It can provide short-range surveillance in such cases. They can be easily transported and deployed due to their small size and lightweight and also allow for flexible deployment. However, the compact size of miniature robots presents substantial difficulties. The challenge of incorporating motion, detection and perception, computation, and power systems into a limited space due to the limited volume of miniature robots is a crucial concern [25]. Additionally, a two-wheeled robot has its own inadequacies as its two-wheeled configuration makes it difficult to balance the chassis' unwanted motion with the wheels' desired motion. In a two-wheeled robot, the application of torque to the wheels by the motors necessitates the creation of a balancing moment at the point of connection between the wheels and the chassis to prevent the wheels from spinning and causing rotation of the chassis around the drive shaft.

Nonetheless, if the mass centre of the chassis is situated below the drive shaft, the gravitational forces acting on the rotating chassis produce a counteracting moment, leading to the stabilization of the chassis and the redistribution of torque to the wheels.

4.1.3 Throwable Robots

They are ideal for rescue operations and other emergencies due to their lightweight, low cost, small size, and ease of deployment. The most crucial factor in developing a throwable miniature reconnaissance robot is its ability to withstand the force of impact from a specified height. Additionally, it must be able to adapt to both indoor and outdoor environments [26]. The two-wheel throwable reconnaissance robots have been recognized as the most viable option for short-range reconnaissance due to their favorable weight-to-flexibility ratio. They can be rapidly deployed through manual or mechanical means. As a result, they are ideal for dangerous missions in multifaceted and intricate environments. It has a significant impact on increasing success rates and decreasing casualties. The suspended two-wheeled robot, developed by D. O'Halloran and colleagues, is designed to withstand a fall of 4 meters onto the grassy ground and consists of key components such as a spring suspension and shock-absorbing belt transmission. The Defense Advanced Research Projects Agency (DARPA) in the United States has conducted a research study on Recon Scout robots and made them available to law enforcement agencies. Raff Czupryniak and Maciej Trojnacki created the Throwable Tactical Robot (TTR), a throwable reconnaissance robot, which withstands a 7-meter drop. The Beijing Institute of Technology has developed a series of two-wheeled throwable reconnaissance robots, the latest iteration capable of surviving a fall from a height of 7 meters. They have also created the BHTBOT-3, a two-wheeled throwable reconnaissance robot that is characterized by its co-centric shaft design and flexible spokes. The Control System of BHBOT-3 is shown in Figure 2. The co-centric shaft design addresses the limited shaft diameter issue in throwable robots. Tests have confirmed that the robot is capable of surviving an impact from a height of 10 meters [27].

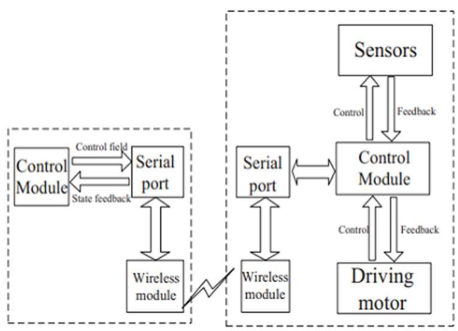

Figure 2 Control system of BHBOT-3 [27].

4.1.4 Rescue robots

Any robot operating remotely to take images/video for specified objectives is considered a remote-controlled surveillance robot. A rescue robot is a specialized surveillance device intended to assist in saving individuals during both civilian emergencies, such as accidents in mines or explosions, as well as specific military missions, such as hostage rescues. For specific purposes, such as rescuing disaster victims in Indonesia, a vision-based rescue robot is used to run surveillance and capture images from its dynamic environment. Military robots can be self-contained or remotely controlled devices. When building mobile robotic systems for military use, the centre of gravity, mountaineering torque requirements, and payloads form the primary considerations [28]. Several militaries are currently researching such systems. The U.S. Mechatronics has developed an automated sentry gun that can be operated remotely for commercial and military use. Building a robot that can easily climb and descend barriers in unstructured situations is a design problem that requires more power. The system must be able to negotiate regularly shaped barriers such as stairs and irregularly shaped obstacles such as rocks, fallen trees, and various other objects.

4.1.5 Amphibious robots

The robot can accommodate itself on rough terrain and climb stairs by balancing its centre of gravity due to its innovative structure and the material of the wheels. The wheels also absorb any impact caused by the robot falling from a great height, making it a robust system. The wheel design allows the robot to travel on sand, snow, and mud. It comprises four Brushless DC motors (BLDC) that work together to provide planetary gearhead reduction [16,19]. This robot has a couple of sensors that locate the presence of the enemy, seize it in a digicam and supply the stay video and audio to the legal person. Detect smoke, footsteps, and improvised explosive device (IEDs) and transmit their vicinity to the management centre. Many sensors can be used to control the robot's dynamics. There are many algorithms available, including the PID, LQR, and MPC controllers and many more. Its amphibious nature permits it to traverse terrains with sand, mud, snow, and water simply without hindering its functionality. It is a multifunctional robotic primarily based totally on IoT aspects. This UGV can help a soldier at a border vicinity or various centres lessening their burden and supplying tight protection even domestically. This device does not replace human resources but facilitates their operation, increasing efficiency and reducing their burden. The said robot integrates with existing, making it very cost-effective. The bot's mobility is feasible for a large number of traversing regions.

4.2 Indoor robots

Jumping Bipedal Robots: Robots equipped with rotating elements like wheels may experience difficulty in navigating rough terrain, particularly when obstacles are larger than the diameter of the wheels. Indoor environments with limited space can further restrict the mobility of these robots. To overcome this, a leg-equipped indoor robot can be utilized to traverse rough and compact areas by enabling it to jump over obstacles for improved efficiency [29]. One such prototype is the two-wheeled bot Ascento, [30] which combines two main abilities: rapid and smooth flat-ground maneuvering and dynamic obstacle conquering. The model's leg geometry has been optimized for fall recovery. A Linear Quadratic Regulator controller is employed for stability and movement control, while a sequential feed-forward controller with feedback tracking is used for executing jumping and recovery from falls. The concept has been successfully validated through demonstration. Each leg is attached to the "hip" and can be independently extended and retracted. A three-bar linkage is used to achieve this approximating linear motion. The leg components were engineered using topology optimization techniques to minimize mass and maximize the strength of the system, using inspired geometries [31]. A home security and surveillance robot, modeled after the hopping abilities of frogs, locusts, and kangaroos, has been created. It features two wheels and a hopping leg, powered by DC motors, as its mechanical components. The robot relies on its two wheels to move around and maneuver in different directions. The hopping leg of the robot is a six-bar linkage equipped with two extension springs attached at its centre. The hopping motion is achieved by winding the leg to stretch the springs, followed by a sudden release [32]. Thus, the robot leaps around obstacles in the absence of any other method to avoid them. The ability to hop allows a two-wheeled robot to clear barriers four times its size. The elastic components in a six-bar linkage leg system enables hopping locomotion. It is capable of changing directions and rolling smoothly on flat surfaces thanks to its two-wheel differential drive system. It can be added as a mobile video sensor node to a ZigBee-based home control network as it employs the ZigBee protocol for wireless communication. Research is underway on the hopping robot to be more stable while landing. Several technical challenges, such as smooth landings, must be addressed to make the robot more serviceable [33].

4.3 Disaster management robots

Disasters, regardless of whether they are natural or artificial, are largely unpredictable. They are often difficult to contain and require swift action. A timely and precise situation diagnosis is required to assess the resources and action required accurately. Response teams require environmental statistics, and the data was provided before entering the endangered zone as the analysis would alert them to any impending dangers or problems they might encounter when entering the zone. They can also be prepared to know what caused the disaster, how many people are at risk, and what kind of equipment they need to deal with the problem, among other things. The DRASB – Disaster Response and Surveillance Bot is one such robot that fulfils the aforementioned requirements [34]. The DRASB was designed and developed with all relevant factors in mind. The implications for various fields are numerous. The DRASB can be extremely valuable owing to its high resistance to fire and other poisonous or flammable gases. The DRASB's heart is the Robot End, each of which serves a specific purpose and performs a specific function in the DRASB. Its Robot Control Architecture is shown in Figure 3. Additionally, the robot is simple to control and very user-friendly and can be customized to meet specific requirements.

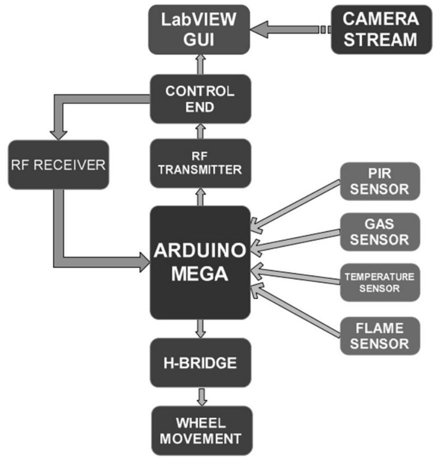

Figure 3 DRASB robot control architecture [34].

4.4 Space exploration robots

A high-performance robot must have a reliable locomotion subsystem to move it across any terrain. Extraterrestrial terrain can be travelled on by a wheeled rover, a leg-powered walker, or a hybrid vehicle. Numerous planetary and terrestrial robotic vehicles use wheels as their primary propulsion system [35]. Wheels, along with other components of the locomotion subsystem such as chassis, sensors, actuators, controllers, and steering system are responsible for providing motion [36]. Robotic precursor missions to nearby astronomical bodies are being planned for future space missions [37,38].

Various science experiments involving autonomous robotic vehicles are planned to detect polar ice in lunar craters or investigate life on other planets. There have been many models proposed for various space exploration applications. A notable model is a prototype developed by UC Berkeley named PUFFER, an expendable rover. This prototype can climb up to 47 rock inclines and is also capable of flipping itself over with a minimal number of actuators. PUFFER gets its name from its capability to consolidate itself to fit into a smaller size. PUFFER is designed to have sprawl and its chassis is made up of a 3D linkage which allows it to vary the wheel's sprawl angle. It is also beneficial in lowering the centre of mass of PUFFER giving it better slope climbing abilities. The nitinol brushes outfitted on the wheel further improve its climbing abilities owing to better ground traction achieved by having several contact points with respect to the ground. These were chosen as the traction mechanism as they outperformed all the other evaluated configurations. Although the ability to sprawl is not a unique innovation in mobile robots, PUFFER is distinguished from all similar robots due to its use of special linkages made from plates and hinges instead of conventional gears. Linkages can be significantly more impact resistant if properly designed than gears [39].

4.5 Health care robots

The usage of artificial intelligence and robotics in healthcare is wide. AI and robotics are increasingly an aspect of our health-care environment, just as they are in our daily lives. One of the robot's tasks includes assisting patients in their everyday activities and reminding them of the assignments that must be accomplished during the day, such as drug consumption. The presence of a patient can be determined based on bidirectional signal transmission in real-time from equipment called I.D. Webcam is connected to the internet through optic fiber thanks to telemedicine (Telemedicine is a broad term that encompasses all the way you and your doctor can connect via technology without being in the same room). Video conferencing is one such example. A one-on-one discussion held nearby the platform is emphasized and improves the participant's capacity for interaction as a dialogist [12,15].

Since it serves as an individual communication interface between the doctor and the patient, the robot presented in this study has a special mechanism. The main objective is to have adequate room to hold all the necessary technology without sacrificing aesthetics. Second, it must be resilient enough to support the entire robot's weight without cracking or warping. Three parts make up the robot: a movable platform that includes the whole control system. The head module contains a screen for communication with the outside world, while all patient medications and medical supplies are kept in the robot body. The Tele-Medicine robot is built in four layers: application programming interfaces, hardware, software frameworks, and service applications [11].

4.6 Robots for disabled and elderly people

This article primarily concerns the progress of robots for individuals with disabilities. The goal was to create a mobile platform and its command system with unique restrictions. The planning-navigation-piloting approach is the foundation for the bulk of mobile robot motion controls. The most difficult task was presented by the mapping function, which must react quickly and with the shortest possible reaction time. Many factors, such as cost, force us to pick low-cost sensors regardless of their effectiveness. Human presence needs high security; use in diverse contexts imposes a portable set of algorithms on various systems. When it comes to the robot's functioning, effectively managing a mobile robot's movements in complicated situations requires a hierarchical technique [40,41].

A high level of path planning uses a globe map to approximate human behaviour. Data from numerous sensors covering the immediate radius of the vehicle serves as the main ground for the local level for robot movement. The laboratory design Robotics and Machine Intelligence (RMI) and the Micro Robot Khepra are two distinct robots with different architectures. Eight infrared light sources were used by the Khepra robot, and they were positioned around its body in a semicircular arrangement [42]. The hardware includes an on-board computer based on a Motorola 68331 microcontroller. RMI includes eight ultrasonic Polaroid sensors all around its body. The report also discusses the primary disadvantage of the blind zone caused by the transducer's dual role as transmitter and receiver. The hardware comprises a series of processor boards that make up the onboard computer. The serial R.S. 232C connection has forced a master-slave architecture on the Khepra (small bot) and RMI (large bot) communication.

The frequency of inaccurate measurements is high in the ultrasonic sensing system, caused by many echoes. Regardless, the robot completes its mission of going through a doorway despite impediments that the planner was unaware of. The navigator can be easily transferable to another platform and its high insensitivity to incorrect measurements. Only the sensor range has been used to standardise the measurements. The normalising of the fuzzy inputs does provide homothetic invariance. As a result, the robot's size does not affect the control. The robot that has been designed was intended to assist those who are disabled. Testing the method in a more complicated context, such as an apartment is still necessary [40].

For people to continue to be independent, engineering help is required. To help with the development of these critical technical solutions, Fraunhofer IPA, Stuttgart, created and built a prototype known as Care-0-bot TM. This is a mobile service robot, a bot that is capable of carrying, retrieving, and doing several other domestic activities. Communicational and social integration duties, such as video telephone, automated emergency calls, and interactive communication, are prioritised. For the next few decades, the core will be implementing the notion of 'home care is the best care', which is already established in existing care regulations. In the best-case scenario, the researchers believe that a mobile service robot would support functions such as communication and social integration, technical house management (infrastructure), personal supply, handling aid, mobility support, individual management, housekeeping tasks, and personal security [43]. The Care-O-bot TM may operate in a variety of ways depending on the needs of its users, including automated, manual, and reactive modes. For communication, the CAN protocol is employed. With the concept of an autonomous Care-O-bot developed, a novel strategy is now available that enables older citizens to live securely in their own homes and according to their preferences. Nonetheless, the Care-O-core bot's technology notion is not confined to healthcare applications [40,43].

4.7 Segways and bike-type two-wheeled robots

Segway-type two-wheels and bike-type two-wheels are popular and innovative transportation methods in two-wheeled robots. Segway-type two-wheels are characterized by their self-balancing mechanism and ease of use. These vehicles have high stability due to their advanced control systems, which keep them balanced every time. They are also highly energy efficient, making them an environmentally friendly transportation option [44]. However, Segway-type two-wheels have low maneuverability and speed, making them less suitable for activities such as sports or racing.

On the other hand, bike-type two-wheels are characterized by their traditional design and high maneuverability. These vehicles are popular in sports, recreation, and commuting due to their high speed and agility. However, they require more driving skills and are less stable than Segway-type two-wheels. Bike-type two-wheels are also less energy efficient, as they rely on human power or gasoline to operate [45]. However, they are typically more affordable than Segway-type two-wheels. Table 1 illustrates the comparison between them.

Table 1 Comparative analysis of segways and bike-type two-wheeled robots.

Parameter	Segway-type two-wheeled robot	Bike-type two-wheeled robot
Design	Self-balancing platform with handlebar	Self-balancing platform without handlebar
Top-Speed	20 km/h	10-20 km/h
Range	20-40 km	10-30 km
Payload capacity	100- 200 kg	60-80 kg
Energy consumption	150 Wh/km	55 Wh/km
Cost	Between 3000-10000 USD	Between 500-5000 USD

5. Market analysis of two wheeled robots

The increased interest from the government and consumers resulted in the development of existing technology. This increase has also been aided by an increase in recreational activities. Segway was invented as self-balancing battery-powered personal transporter. It can generally operate quietly and efficiently through a wide range of terrains with minimal negative environmental impact. The locomotion unit was made up of servos that were powered by rechargeable lithium-ion batteries. Two tilt sensors, five gyroscopes, and a pair of twin processors running proprietary software were used to keep it balanced. However, the market appears to be positive about Segway, whose demand was expected to grow at a comparable rate to that of electric automobiles. The global two-wheeled robot market was valued at around USD 250 million in 2021, and it is expected to reach a market value of around USD 1.5 billion by 2026. During the forthcoming years of 2021-2026, growth is expected to be approximately 30% CAGR.

In India, for example, the Mumbai Police Department has begun deploying Segways to patrol seashores and ensure tourist safety and security. The business area was reliant on the growing interest in Segway among security and law enforcement personnel. As a result, police deployment of Segway in several nations may aid the Segway industry's growth. Segway can be used for commercial purposes, personal mobility, or as a public gateway. Northern America is expected to make the most revenue over the forecasting period due to factors such as high pattern-setting progress and the presence of significant market participants, resulting in an adept market. The Asia Pacific (APAC) region is predicted to provide excellent entry points into the industry and to have the highest Compound Annual Growth Rate in the period (2018-2028) [46]. Despite this, the market may reach a saturation point due to a lack of mindfulness, a battery explosion, high costs, and general low well-being. The global Segway market was worth 750.2 million dollars in 2018 and is expected to be worth 100.6 million dollars in 2028. Figure 4 shows the anticipated market share in 2021-2031 of two-wheeled robots. Table 2 shows a comparison of robots based on wheeled mechanisms.

Table 2 Comparative analysis of robots.

Parameter	Single-wheeled robot	Two-wheeled robot	Four-wheeled robot
Stability	Extremely unstable and requires advanced engineering.	Comparatively stable than a single-wheeled robot but still more difficult to balance vertically.	Superior to the others in terms of balance.
Purpose	Used as balancing robots with limited mobility actions.	Due to their straightforward design and simple control algorithm, two-wheeled robots which use differential navigation are frequently adopted.	Most of the robots used on a daily basis are four wheeled, which proves their existence and function.
Direction	The single-wheeled robot typically moves in a single direction with zero radius turns.	Two-wheeled robots can move in both forward and reverse directions.	Four-wheeled robots can move in both forward as well as reverse directions.

Market analysis of two-wheeled robots can be divided into two segments: consumer and industrial. In the consumer segment, two-wheeled robots are primarily used for personal transportation. The market for electric two-wheeled robots is expected to grow at a CAGR of over 20% from 2021 to 2026. In the industrial segment, two-wheeled robots are used for various applications, including material handling, inspection, and surveillance. The market is driven by the increasing demand for automation and the need to improve efficiency and safety in industrial processes [47].

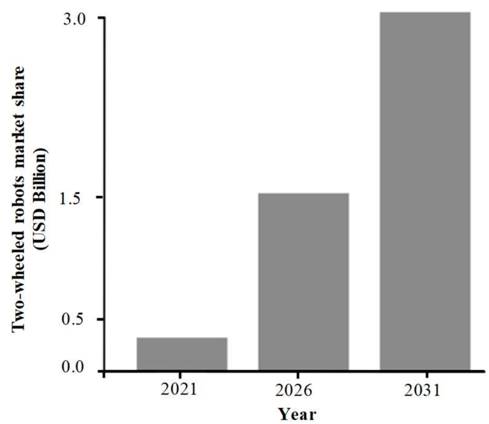

Figure 4 Expected market share of two-wheeled robots in 2021-2031.

6. Technological advancements

Two-wheeled robots have made significant progress in recent years. These robots can now perform tasks, including obstacle avoidance, navigation, and transportation, thanks to the development of stable balance and dynamic locomotion. The creation of control algorithms for balancing has been one field of research. The direction and motion of the robot are measured using algorithms based on gyroscopes and accelerometer, and then use this information to control the robot's movements and maintain balance. The development of energy-efficient actuators and drive systems has been another field of research, which allows robots to move more efficiently and for long periods. Recent advancements in deep learning and machine learning techniques have enabled more sophisticated control and decision-making in two-wheeled robots. This has led to the development of robots that can adapt to different environments and perform more complex tasks.

However, developing two-wheeled robots still poses challenges, such as high production costs. According to a study, the production cost of two-wheeled robots can be significantly reduced by adopting a modular design approach, which involves the use of standardized components that can be easily assembled. This approach can help reduce development time and production costs [48]. Challenges such as navigation through rough terrain remain [49]. Nonetheless, the increasing investment in this field is a positive sign for the future of two-wheeled robots, as they continue to prove their worth in various industries.

7. Future scope

The future scope of two-wheeled robots is wide-ranging and has the potential to impact many industries. They can be used as transportation devices, similar to Segways or electric scooters. They could be used for short-distance travel, especially in crowded urban areas, or for people with mobility issues. Delivering goods, packages, and food within a specific area or campus through these robots can reduce human labor and increase efficiency.

Two-wheeled robots can be equipped with cameras and other sensors for surveillance and monitoring, making them useful for security and safety purposes. Health-care facilities can use these as medication robots and personal assistants for patients. Warehouse automation sees a huge potential for using these robots. Overall, the future scope of two-wheeled robots is expected to grow as technology improves and costs decrease, making them more accessible and useful in a variety of applications. The Figure 5 below summarizes an overview of the two-wheeled robot subsystems, which are generally adapted in all situations.

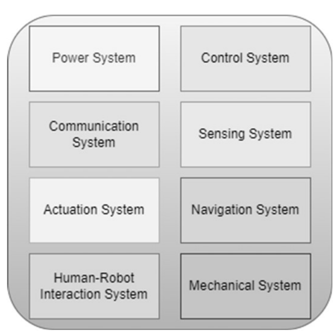

Figure 5 Overview of two-wheeled robot subsystems.

8. Summary

The industrial robot industry is expected to grow significantly to USD 3 U by 2031, with a focus on service robots in medicine, surveillance, warfare, and transportation. Miniaturization of electronics will create smaller, more portable two-wheeled robots for a broader range of environments. Advancements in AI will enable complex tasks like autonomous navigation and object recognition. Integration of sensors and IoT will improve performance and efficiency. Two-wheeled robots are ideal for health-care, entertainment, logistics, and industrial automation. The demand for two-wheeled robots is expected to grow with technological improvements.

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