





Fundamentals for the Design of Smart Walkers 4

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4.1 Introduction

Advances in technology, especially in mobile robotics, have grown exponentially in recent years. One of these advances relates to mobile robots for gait rehabilitation and assistance, leading to the emergence of intelligent walkers or robotic walkers. These devices contain electronic components, control systems, and sensory architectures built into their conventional mechanical structure (see Chap. 2) [1]. These improvements have provided a better driving experience for users when controlling the devices, regarding their integrated sensory feedback, physical support, and cognitive support. Another advantage is minimizing the risk for falling and the possibility that users can experience a smoother and more natural gait (see Chap. 1) [2].

Several communication channels took place in walker-assisted gait. As described by *Sierra et al.*, the robotic walkers equip sensors and actuators that allow them to interact with the users and acquire information from them [1]. This concept refers to Human–Robot Interaction (HRI), which comprises strategies that provide cognitive and physical communication between the device and the user [2]. Similarly, the robotic walkers frequently move within complex and dynamic environments, such as clinical and rehabilitation settings. In this sense, the walkers employ sensory architectures and actuation interfaces to acquire information about the environment [2]. This concept refers to Robot–Environment Interaction (REI), which comprises

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control strategies that provide guidance, autonomous navigation, and safe movement within a particular environment [1].

In addition, recent studies in robotic walkers have coined the term Human–Robot–Environment Interaction (HREI) [1–3]. This concept refers to the communication loop that involves the user, the device, the environment, and the healthcare professional. In this way, the HREI strategies provide natural and compliant user interaction, and effective environment sensing while maintaining safety requirements [1]. As an illustration, Fig. 4.1 shows the communication loops that took place during walker-assisted gait.

The design process of an intelligent walker involves several considerations and parameters. It focuses on the user requirements and analyzes their locomotion impairments and their cognitive and sensory affectations. Moreover, the design process requires the continuous assessment of the user perception to guarantee daily living acceptance [4].

This chapter covers some of the main developments related to intelligent walkers, focusing on: (1) the assistance functionalities, (2) the employed control strategies, and (3) the mechanical structure. This chapter also details fundamental notions for the design of robotic walkers based on a literature review.

4.2 State of the Art About Smart Walkers

There is a wide variety of robotic walkers reported in the literature, which offer multiple functionalities for gait assistance and rehabilitation. On the one hand, these devices provide natural gait patterns, lateral stability, and weight support. On the other hand, they offer fall prevention, obstacle avoidance, intuitive control

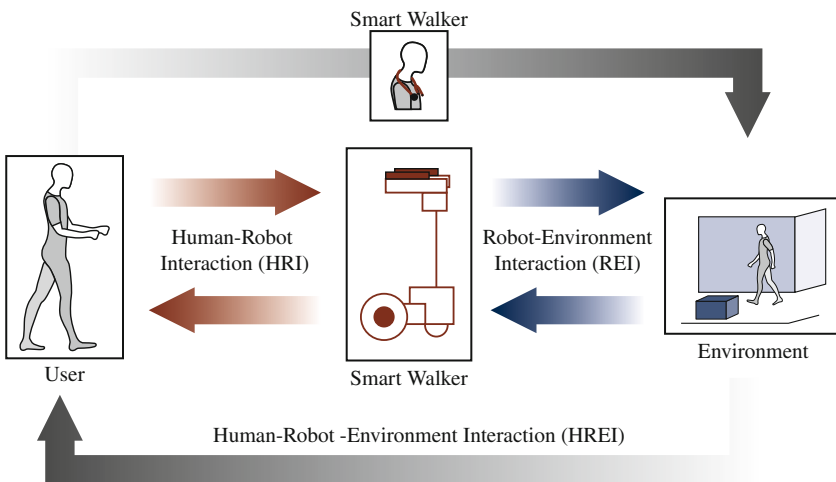


Fig. 4.1 Communication channels during a walker-assisted application

strategies, and comfortable interaction. This section describes the conduction of a literature review to categorize and analyze the most relevant functionalities and control strategies of the robotic walkers.

This literature review followed the PICO search strategy to obtain an evidence-based classification. PICO is an acronym for Patient, Intervention, Comparison, and Outcome. It aims at formulating an appropriate research question to find the most relevant information, using previous experience and reported outcomes [5]. In this chapter, the following constructs yielded the PICO strategy:

- **(P):** Patients with motor limitation and healthcare professionals who use smart walkers in rehabilitation processes.
- **(I):** Interventions and validations of a specific control strategy and assistance functionalities, conducted in laboratories or clinical settings.
- **(C):** Studies comparing the performance of the walker-assisted trials with unassisted gait or passive device such as conventional rollators.
- **(O):** Research outputs about the operation and performance of the control strategies in smart walkers.

According to the above, the following equation based on Boolean logic was used:

(“Smart Walker*” OR “Robotic Walker*”) AND
 (“Gait Assistance” OR “Assistive Gait” OR
 “Walker-assisted Gait” OR “Gait Rehabilitation” OR
 “Walker functionalities” OR “Walking Assistance”) AND
 (“Control systems”)

The inclusion criteria were as follows: (1) articles that described the walker functionality and internal systems, (2) articles reporting smart walkers targeted at individuals with gait impairments, (3) articles in English. The exclusion criteria were as follows: (1) articles reporting rehabilitation robots for different conditions, (2) non-intelligent assistive devices, (3) publications before 1998. The search strategy was implemented in the following databases: *IEEE Xplore*, *PUBMED*, and *Google Scholar*.

The PICO search methodology resulted in 407 articles found at Google Scholar, 48 at IEEE Xplore, and one at PUBMED. A total of 65 articles were selected based on the inclusion and exclusion criteria. Table 4.1 describes a summary of the robotic walkers found from the literature review. From these walkers, the following sections explain an analysis of their main characteristics.

Table 4.1 Summary of smart walkers with their purpose and configuration

Year	Name	Main purpose	Configuration
2000	PAMM [6]	Biomechanical monitoring	Active + Caster/Orientable wheels
2003	VA-PAMAID [7]	Safety provision	Active + Caster/Orientable wheels
2003	NOMAD [8]	Guidance and navigation	Active + Fixed/Swedish wheels
2005	MONIMAD [9]	Safety provision	Active + Fixed/Orientable wheels
2008	GUIDO [10]	Safety provision	Active + Caster/Orientable wheels
2008	I-WALKER [11]	Safety provision	Active + Orientable wheels
2010	JARoW [12]	Biomechanical monitoring	Active + Omni-d. wheels
2011	I-GO [13]	Estimation of movement's intention	Active + Fixed/Omni-d. wheels
2011	SIMBIOSIS [14]	Estimation of Movement's Intention	Active + Caster/orientable wheels
2011	ODW [15]	Guidance and navigation	Active + Omni-d. wheels
2012	UFES [16]	Biomechanical monitoring	Active + Fixed/Caster wheels
2012	WCIWAR [17]	Estimation of movement's intention	Active + Omni-d. wheels
2012	CAIROW [18]	Remote control	Active + Fixed/Caster wheels
2013	ASBGo [19]	Guidance and navigation	Active + Fixed/ASOC wheels
2015	EYE WALK [20]	Guidance and navigation	Passive + Orientable/Fixed wheels
2017	MOBOT [21]	Estimation of movement's intention	Active + Fixed/Caster wheels
2017	WACHAJA [22]	Guidance and navigation	Passive + Caster/Orientable wheels
2019	AGoRA [1]	Guidance and navigation	Active + Fixed/Caster wheels

4.3 Physical Structures

This section will provide insights into the structural differences in the construction of robotic walkers and their advantages and disadvantages. Moreover, this section will describe several safety structures that aim at providing additional physical support and balance to the users.

4.3.1 Definition of Physical Structure

At first glance, several factors influence the mechanical structure of a robotic walker. For instance, it involves factors such as the shape, the number and configuration of the wheels, the type of grip, and the locomotion type. The most common structures in robotic walkers involve three or four-wheeled devices. Similarly, depending on the locomotion type, the walkers can be passive, active, or hybrid. More specifically, the active and hybrid configurations employ electric motors such as DC motors, brushless hubs (i.e., motors embedded in wheels), servomotors, and steppers (see Chap. 2).

The physical structure of a robotic walker influences the ability to provide assistance, rehabilitation, stability, and balance during mobility [23, 24]. On the one hand, passive structures introduce mechanical enhancements to improving gait stability without employing traction actuators. Some of these improvements include

increasing the base size or distributing weightier elements in the lower part of the structure. Similarly, passive approaches have also reported replacing of conventional handlebars with forearm support platforms [2].

On the other hand, the walkers offer active physical structures by installing traction or steering motors in the wheels and employing electrical braking systems. These actuators aim at compensating the user locomotion requirements, the device kinematics, and the environmental demands (e.g., slopes). The actuators also provide the necessary energy to move the device [2].

4.3.2 Examples of Physical Structures

According to the findings of the search strategy, these are some of the physical structures:

- **Circular shape:** The *JARoW* smart walker (School of Information Science, Japan Advanced Institute of Science and Technology, Japan) is an active device with three structural parts, the base frame, the upper frame, and the connecting rods. This smart walker provides forearm support and offers help during gait by reducing the weight load on the joints of the lower extremities [12]. The *JARoW* has two semi-circular frames that engage with vertical poles, three omnidirectional wheels, and the frame allows forearm support and joint grip [12]. Overall, the *JARoW* smart walker has a circular shape, reducing collisions with obstacles [24].
- **U-Shape and square shape:** The *i-go* smart walker (Chyao Shiunn Electronic Industrial Ltd., Shanghai, China) comprises an *U-shaped* frame and a regulating rod to adjust the height of the handles [24]. Similarly, the *AGoRA* (Department of Biomedical Engineering, Colombian School of Engineering Julio Garavito, Colombia) is an active device with a small square shape, six wheels, and long handles [1]. The *CAIROW* robotic walker (Department of Electrical Engineering, National Taiwan University, Taiwan) is an active device with a medium-sized cubic frame, motorized and steerable wheels, and u-shaped handles that provide support and firmness [18].
- **Adjustable shape:** The *WCIWAR* smart walker (Centre of Neural Interface & Rehabilitation Technology, Huazhong University of Science and Technology, China) is a Width Changeable Intelligent Walking Aid Robot. It integrates a support frame, a mobile base with three servo-driven castor wheels, and two wheels in the middle for weight support. This walker has an array of sensors placed in the armrest to measure the interaction forces, a signal processing system, a rechargeable battery, and a control system for the servo motors to move the base in all directions. The *WCIWAR* also has an electric cylinder aimed at stretching the rods positioned at both sides of the walker. With this system, the walker can vary its width to confer the ability to pass through narrow corridors or give more stability in spacious environments [17].

Another device with an adjustable shape is the *ASBGo* robotic walker (Center for MicroElectroMechanical Systems, University of Minho, Guimarães, Portugal). This device equips electric lifting columns to adjust the device height. Moreover, this walker can also perform lateral adjustments of the handles to meet the patient shoulder width. In addition to this, the *ASBGo* walker includes a handle to assist sit-to-stand transfers [24].

As reported by the *ASBGo* walker, another essential physical feature of the robotic walkers is their ability to assist in sit-to-stand and stand-to-sit transfers. This feature reduces the patient effort and decreases the workload of the healthcare professional [25]. The *MONIMAD* walker (Institut des Systemes Intelligents et de Robotique, Université Pierre et Marie Curie, France) also offers this feature. It is an assistive device that combines sit-to-stand transfers with walking assistance for older adults and people with locomotion impairments. In this way, the *MONIMAD* walker allows rehabilitation and mobility assistance and postural stabilization [9]. Particularly, postural stabilization has become a significant characteristic in walkers, as it is an essential step in the rehabilitation process of neurological patients and older adults [13].

4.4 Safety Provisions

Safety is one of the main features of assistive devices such as robotic walkers. In general, walkers can provide safety strategies with physical equipment or through software and sensing architectures. The following sections describe these two approaches.

4.4.1 Safety Physical Provisions

In gait rehabilitation and assistance, the patients commonly exhibit stability and balance impairments. In this sense, walkers often equip safety equipment such as belts and suspension systems. This type of equipment is mainly required at the early stages of rehabilitation or in neurological patients. It provides partial body weight support and increased stability [25]. For instance, the *CPWalker* is a combined platform (i.e., exoskeleton and walker) that provides gait rehabilitation to children with cerebral palsy. This device equips a suspension system that lifts the patients during training sessions [26].

Some solutions help the users during sit-to-stand and stand-to-sit transfers. They include special handlebars attached to the walker structural frame. For instance, the *MOBOT* platform and the walker proposed by *Chugo et al.* are active walkers with this functionality [27, 28]. These implementations are of great relevance, as they reduce the risk for falls during these transfers.

Other safety approaches employ braking and emergency stop systems. These systems aim at stopping the device when the user needs it [2]. For instance,

some walkers like the *Wachaja et al.* walker (University of Freiburg, Freiburg, Germany), and the *I-walker* (Technical University of Catalonia, Spain), equip braking systems on the handles [11, 22]. The *I-walker* also uses a vibration alarm system interconnected to the brakes. This system warns the users about nearby obstacles. Thus, they can activate the brakes, avoiding possible falls and injuries [11].

4.4.2 Sensory Provisions for Safety

In addition to the physical approaches, some solutions employ the walker sensory interface. For instance, walkers provide using fall prevention systems and speed limiters. Likewise, other devices also equip modules for detecting obstacles, slopes, and stairs [2, 4]. To this end, the walkers exploit the information retrieved from laser rangefinders, ultrasonic sensors, proximity sensors, force and pressure sensors, infrared sensors, inertial sensors, among others [2, 25].

4.4.2.1 Fall Prevention

Fall prevention systems are essential modules that detect hazardous conditions that could lead to falls. In most cases, these systems employ vision systems and inertial sensors to monitor the users [29].

For instance, the *ASBGo* walker includes a safety strategy that continuously monitors the user center of mass and performs a trajectory and orientation change when an abnormality is detected [30]. Likewise, this walker detects dangerous situations such as excessive separation between the user and the device, abnormal gait patterns, and asymmetrical supporting forces on the handles [30]. These situations are detected to reduce the risk for falls.

Another concept to prevent falls is the Zero Moment Point (ZMP) recognition. This concept is essential for bipedal modeling and consists of detecting the vertical projection of the user center of gravity [31]. A polygon within the walker is defined, and the user center of gravity must lie inside it [31]. Exceeding the limits could mean an imminent fall, and the position of the center of gravity determines the type of fall (e.g., backward, lateral, or frontal) [31]. This strategy combines the information from force sensors and a laser rangefinder. The *SIMBIOSIS* walker (Bioengineering Group, CSIC, Spain) has reported implementation of this strategy [14].

There are several sensors useful to detect and prevent falls. For instance, Fig. 4.2 illustrates a particular sensory architecture for this purpose. Implementations in the literature also report alarm systems to advise when the user is about to fall [32].

4.4.2.2 Obstacle Detection and Avoidance

Detecting surrounding obstacles in robotic walkers is essential to guarantee security in patients with visual, balance, and coordination impairments [2]. These systems help users to avoid obstacles through sound or vibration alerts. Several walkers offer this sensory system employing multiple sensory interfaces as shown in Fig. 4.3 [4, 33].

Fig. 4.2 Fall detection systems employ several sensor modalities. Force and pressure sensors measure physical interaction applied to the forearm supports by the user. Laser rangefinders estimate the position of the user's legs. Tilt sensors and IMUs acquire the orientation or inclination of the user. CCD cameras measure the user's head position

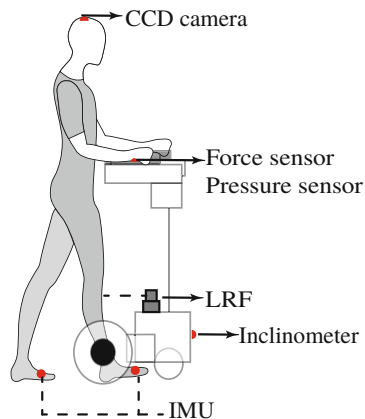
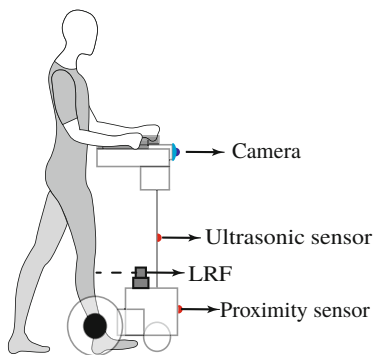


Fig. 4.3 Obstacle detection requires laser rangefinders, cameras, and ultrasonic sensors to measure the distance to obstacles



The *PAMM* (Department of Mechanical Engineering Massachusetts Institute of Technology Cambridge, USA) and *CAIROW* walker provide support on unstable terrains because it has a camera and laser to detect obstacles [18, 34]. This walker uses a camera and a sonar to detect possible obstacles [6]. Similarly, the *AGoRA* walker, the *CAIROW*, the *i-Walker* and the *Width Changeable Intelligent Walking Aid Robot (WCIWAR)* are designed for obstacle detection [17]. These robots slow down when the sensors detect an obstacle, ignoring the impulse force of the user. Finally, the platform stops at a short distance no matter how large the force is the force that the user exerts [11].

These systems employ ranging sensors (e.g., laser rangefinders and ultrasonic sensors) to detect the obstacles around the walker [1, 2]. A particular shortcoming of these strategies refers to the inability to sense low-rise obstacles. Likewise, light-based sensors exhibit problems detecting reflecting objects and glass-like surfaces.

Other platforms with obstacle detection systems are the *NOMAD XR4000* walker (School of Computer Science Carnegie Mellon University Pittsburgh, USA) and the *GUIDO* (University of Pittsburgh, USA) walker. Given that visually impaired populations are the target population of these walkers, they employ laser scanners, ultrasonic sensors, and infrared sensors to detect obstacles [8]. Also, the *WACHAJA*

walker equips an obstacle detection system with a haptic alarm system. It has a vibration belt and two vibration motors on the handles. These motors send haptic warnings when an obstacle is nearby [22].

4.4.2.3 Stairs and Slopes Detection

The detection of slopes and stairs differs from the detection of obstacles because horizontally placed sensors cannot detect changes in the ground slope [35]. The presence of stairs also requires a different approach based on specific programming, sensors, and functions. Figure 4.4 illustrates a sensory architecture for stairs and slope detection.

As shown in Fig. 4.4, inclination sensors allow sensing significant changes in the ground slope. Cameras can feed video processing algorithms to estimate the presence of stairs. Ranging sensors detect changes in surfaces and detect stairs by sensing distances in the environment [14].

4.4.2.4 Speed Detection

Speed detection systems seek to implement safety measures when the walker moves at high speed. If the users exceed the speed limits, the robot takes action and slows down. Moreover, speed detection systems also aim at adjusting the walker's speed to meet the user walking pattern. To this end, the walker requires odometry sensors to estimate its velocity. Likewise, the speed calculation also requires ranging sensors to locate the lower limbs of the user [12, 15].

For instance, the *JARoW* walker can autonomously adjust the direction and speed of its movement according to the walking behavior of the user. To this end, it equips a rotating infrared system to estimate the current location of the lower limbs of the user. A control algorithm is in charge of sending actuation commands to the motors and matches the user speed [12].

Similarly, the *PAMM* walker automatically adjusts its motion to the user behavior. It monitors the walking direction, gait speed, and grip strength of the walker. This robotic walker has an adaptive shared control system that allows the patient to modulate the speed and direction of movement. If a hazardous condition occurs, the platform takes control of the speed [34]. Figure 4.5 shows sensors related to speed detection on robotic walkers.

Fig. 4.4 Stairs and slope detection systems require several sensory interfaces. They include cameras to detecting slopes and stairs from images. Laser rangefinders allow to detect stairs. Inclinometers measure displacements in the ground and inclinations of the walkers

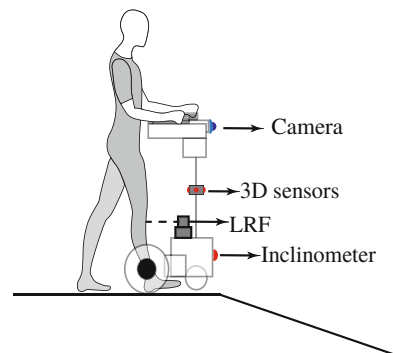
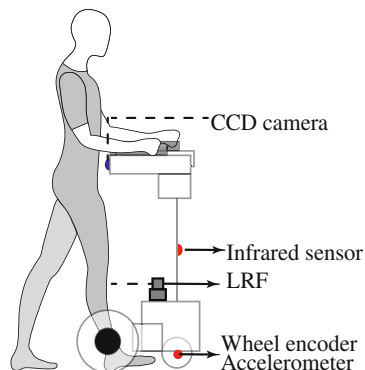


Fig. 4.5 Speed detection require several sensors such as cameras, infrared sensors, laser rangefinders, encoders, and accelerometers. They allow to measuring the speed of the user and the smart walker



4.5 Human–Robot Interaction Strategies

There is evidence in several fields of society about the need for human–robot interaction to reduce human workload, increase productivity, reduce costs, and reduce fatigue-associated factors [36]. In walker-assisted gait also occurs a human–robot interaction loop between the user and the device (see Fig. 4.1). This interaction can be whether cognitive or physical, and the device sensors, actuators, and physical structure facilitate it [23]. Multiple robotic walkers employ human–robot interfaces to provide compliant, safe, and natural interaction [1]. The following sections will describe the main functionalities of such interfaces and the used sensors.

4.5.1 Estimation of Movement's Intention

Making the robot understand the motion intention of the user is a critical problem in human–robot interaction. It allows the robot to actuate compliantly. There are several ways to achieve this interaction. On the one hand, admittance controllers employ information about the force exerted by the user to generate linear and angular velocities from the interaction force and torque (see Chap. 9). These strategies should guarantee that the device is easy to maneuver and does not add additional load to the user. On the other hand, other approaches employ cognitive or non-physical interaction between the user and the robotic walker. These strategies commonly apply touch-less follow-in-front controllers that use the orientation and distance between the user and the device.

In general, the estimation of motion intention facilitates the control of the walker by the user. These controllers are present in multiple robotic walkers reported in the literature. For instance, the *UFES* walker (Electrical Engineering Department at the Universidade Federal do Espírito Santo, Brazil) employs a sensor fusion strategy to extract the force and torque signals. An adaptive admittance controller uses these signals to generate motion on the device, while a modulation strategy sets the gains

to make the user follow a specific path [23]. Other developments with the *UFES* walker have proposed follow-in-front controllers based on an inertial sensor and a laser rangefinder [23]. Likewise, the *ODW* (Department of Intelligent Mechanical Systems Engineering, Kochi University of Technology, Japan) robotic walker and the *AGoRA* walker also equip force and torque sensors that measure the intention and intensity of the user support [1, 3].

On the one hand, to identify the directional motion intention, the walkers use force sensors and pressure sensors [1, 2, 23]. On the other hand, cognitive strategies employ cameras and sensors to detect user intention [37]. In some cases, these sensors can be expensive. Therefore, recent studies proposed variants based on optical fiber, dynamometers, or instruments to transfer the force pattern [38].

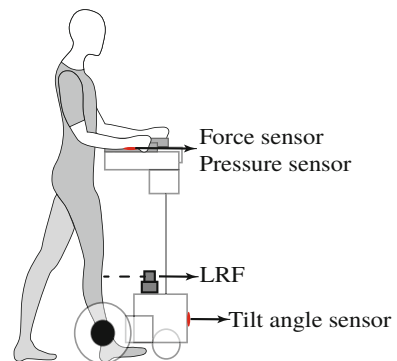
The estimation of motion intention ensures the safety of the walker and offers an intuitive walker-user interaction. This functionality requires several sensor modalities, as shown in Fig. 4.6.

4.5.2 Biomechanical and Health Monitoring

Biomechanical monitoring aims at obtaining physiological measurements of the user through multiple sensory modalities. For this, the robotic walkers employ heart rate sensors, inertial sensors, SpO₂ sensors, thermometers, laser rangefinders, infrared sensors, among others [2]. Non-wearable technologies such as motion analysis laboratories (e.g., VICON and BTS) are also helpful to extract kinematic information of the human-walker interaction [39].

On the one hand, these sensors monitor the users and make them feel more secure. Monitoring also has a direct impact on the walker acceptability and helps the users get used to it. On the other hand, these sensors provide the physiotherapists with data from the user gait pattern and rehabilitation progress [1, 25].

Fig. 4.6 The estimation of motion intention employs force sensors, pressure sensors, laser rangefinders, and tilt sensors to detect the user's motivational demands



4.5.2.1 Gait Parameters Monitoring

Gait monitoring system detects and records the movements, characteristics, and events of human walking. These parameters are of great importance to recognize pathological gait patterns in patients with neuromusculoskeletal diseases [4, 40]. These elements provide safety and assistance to the user because it allows the assessment of alignment and plantar support imbalances that can trigger the appearance of overloads and possible injuries [41, 42].

As previously explained in Chap. 5, these systems detect gait phases such as heel strike, toe-off, heel-rise, and toe contact events [4]. To this end, the walkers require several sensors, as shown in Fig. 4.7. For instance, the *PAMM* walker and the *AGoRA* walker can track the user speed, calculate the step-by-step variability, the gait symmetry, the step length, and estimate the user's frequency stride [6, 34].

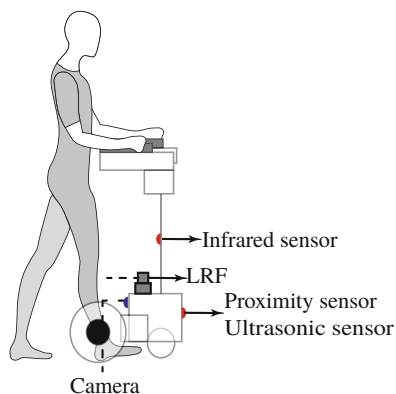
To this end, these systems require the implementation of ultrasonic sensors, laser rangefinders, inertial sensors, force sensors, among others [34]. In some cases, the detection of human gait requires additional devices worn on the human body, e.g., belts and inertial sensors. However, this can cause difficulties in outdoor environments.

For instance, the *JARoW* walker uses rotating infrared sensors to detect the user's lower limbs [12]. The *SIMBIOSIS* walker includes a monitoring system that tracks the gait trajectory [43]. The *CAIROW* walker utilizes a laser to monitor the gait pattern, especially for the Parkinsonian gait [18]. The device employs an advanced gait analysis system, two integrated lasers, and an arrangement of sensors on the handles.

4.5.2.2 Health Monitoring

This concept refers to the detection and analysis of physiological parameters related to the user-health. Similarly, health monitoring also seeks to support the therapist in monitoring the user's motor skills and supervising daily exercises [4]. The user-related information is often processed and analyzed by medical partners for rehabilitation purposes [11].

Fig. 4.7 Gait monitoring requires laser rangefinders, cameras, ultrasonic sensors, proximity sensors, inertial sensors, and infrared sensors to measure the lower-limb's kinematics



Continuous monitoring of patients is a challenging task in physical rehabilitation. Moreover, patient self-assessments are often unreliable, either because of poor memory or to avoid therapeutic interventions. Therefore, the walkers can help therapists obtain a complete and valid assessment of the user-health condition. To do this, the walker must have the ability to collect and recognize the user activity [2, 25]. These types of systems include several sensors as shown in Fig. 4.8.

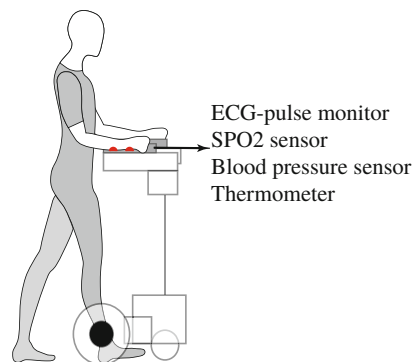
For instance, the *VA-PAMAID* walker (Human Engineering Research Laboratories, University of Pittsburgh, USA) includes an application that collects relevant data taken through physiological sensors. It employs a heart rate sensor, a SpO₂ sensor, a blood pressure sensor, and thermometers that display vital signs. The system is also externally supervised via Wi-Fi, allowing therapists to obtain real-time information on the user-health [7]. In addition, research with the *UFES* walker shows that this technology can store emergency reports and patient medical history [7]. In the case of the *PAMM* walker, it incorporates an ECG-based monitor intended to detect short-term changes and long-term health trends [34].

4.5.3 Guidance and Navigation

Guidance and navigation require odometry sensors and ranging sensors. For instance, encoders, GPS, compasses, and inertial sensors provide the position and orientation information of the walker. Similarly, laser rangefinders, cameras, and ultrasonic sensors provide environmental data. These navigation systems use software that allows a shared control between the user and the walker. Studies with the *AGoRA* walker report that when walkers provide this type of control, users feel more comfortable and natural when interacting with the environment [1]. This shared control is helpful in crowded navigation environments because the device has a general map of the environment, while the user controls the decisions on the local navigation [22].

The navigation system commonly requires path monitoring modules that handle discrete and continuous planning, providing unobstructed routes. This feature also

Fig. 4.8 User-health monitoring require sensors such as heart rate sensors, SpO₂ sensors to measure the oxygen saturation, blood pressure sensor, and thermometers



allows the dynamic detection of obstacles and the safe locomotion of the robot while guiding the human. These systems help users walking more naturally as they reduce their cognitive load [1, 44]. It requires several sensors, as shown in Fig. 4.9.

For instance, the *GUIDO* robotic walker is a healthcare robot that serves as a support and navigation aid for the fragile and visually impaired population. Many technologies are implemented in *GUIDO* to let it achieve its tasks: simultaneous localization and map building, pose tracking, path planning, and human–robot interaction [10].

Likewise, the *Nomad XR4000* walker is for people with cognitive impairments. This walker provides navigation and global orientation through robot localization and navigation software combined with a shared control interface [45]. This robot has an omnidirectional drive. It provides physical support to users and is ideal for navigating in corridors, similar to the *WCIWAR* walker. It uses a motion model of the user, combining force data with navigation. The force sensor records the reading and logs it to the trajectory commands [17].

4.5.3.1 Autopilot System

Autopilot systems intend to allow a robot that navigates by itself following the desired route while avoiding obstacles. They also comprise systems like GPS, infrared sensors, cameras, magnetometer, and onboard microcontrollers to help route following processes [46].

The *C-walker* walker developed by Siemens has this system, and the target population is people with cognitive impairments. The walker equips a Kinect sensor (see Fig. 4.10) that enables the system to monitor its spatial surroundings in real-time [47].

Fig. 4.9 Path monitoring requires sensors such as digital compasses, cameras, laser rangefinders, inclinometers, and inertial sensors (IMU)

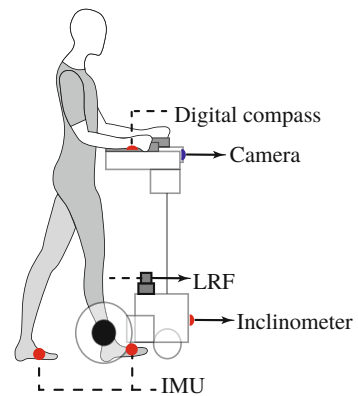
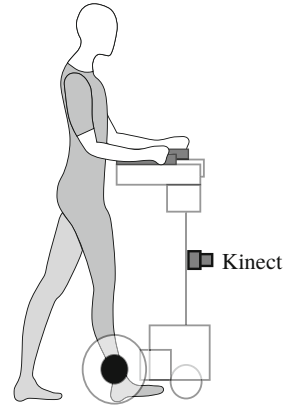


Fig. 4.10 For the autopilot system the smart walker comprises a Kinect sensor that enables the device to determine obstacles, the direction in which people are moving and warning signals on buildings [47]



4.6 Control Strategies

A control strategy is in charge of executing the corresponding actuation commands to achieve a desired functionality or objective. The robotic walkers employ different control strategies for multiple purposes. This chapter describes several controllers such as (1) fuzzy logic controllers, (2) kinematic controllers, (3) admittance controllers, (4) follow-in-front controllers, among others. These control strategies aim at providing motion intention detection, safe and natural interaction, obstacle detection, and gait monitoring.

4.6.1 Fuzzy Logic Controller

Fuzzy logic is a concept that uses expressions that are neither true nor false. It applies to statements that can take any value within a set of values that oscillate between absolute truth and total falsehood. This term allows treating imprecise information in terms of fuzzy sets to define actions [48].

Many walkers use fuzzy logic controllers since they can infer environmental data even under motion uncertainties. These receive as inputs distances obtained from sensors, and their output is differential velocities for the walker [14]. The idea of these drivers is that they employ information obtained from experimental situations (see Fig. 4.11). New ways of developing fuzzy controlled systems include neuro-fuzzy systems that allow the programmer to obtain more data from prediction [49].

The *ODW* and the *SIMBIOSIS* walkers employ fuzzy logic to develop their control system. These devices establish relationships between forearm pressure and directional intention extracted from fuzzy logic [15]. The measurements used to carry out fuzzy reasoning were forearm pressure while turning right/left while moving forward/backward and going right/left from the start. Finally, the knowledge from fuzzy reasoning has its basis on the compatibility grade between the *fact* and

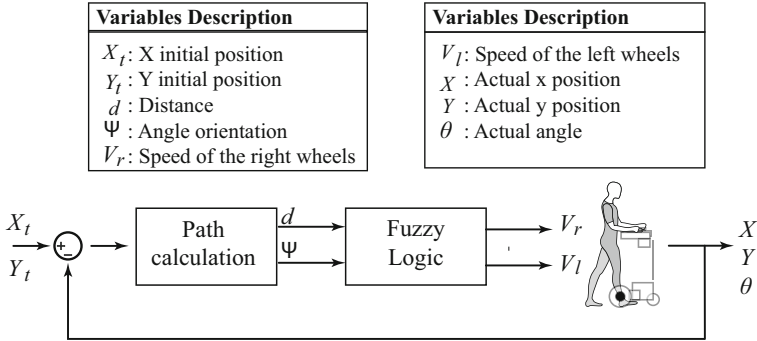


Fig. 4.11 Block diagram of an application from a fuzzy controller in a smart walker

the antecedent [50]. In this case, the fact is the force exerted by users with walking impairments on the sensors. The antecedent is the force exerted by healthy users on the sensors [15].

4.6.2 Admittance Controller

The admittance control transforms the forces and torques to the desired velocities for the walker. When the admittance control is in the task space needs the Jacobian matrix, while the joint space requires inverse kinematics [51]. In robotic walkers, these controllers generate reference speeds from movement intention [1, 3].

The admittance controller allows driving the walker from the forces and torsions exerted on the handles. The controller gains can be constant or periodically re-configured to give users the feeling of ease and naturalness during physical interaction with the walker [1]. Admittance controllers model robotic walkers as first-order mass damping systems. The inputs are force (F) and torque (t) applied to the device by the user, and the outputs of these controllers are linear (v) and angular (w) velocities [1, 3].

Robotic walkers such as the *UFES* walker, *AGoRA* walker, and the *PAMM* walker extract force and torque signals and feed admittance controllers for motion control [1, 3, 34]. Figure 4.12 shows the block diagram of an admittance controller.

4.6.3 Kinematic Controller

The kinematic models of a mobile robot are used within the design of controllers when the robot performs tasks or missions at low speed and with little load about its structure. Path tracking is possible to achieve using a control law, in which the mobile robot reaches and follows with zero error desired states that vary with time. This trajectory control uses two subsystems in cascade: (1) kinematic control is in

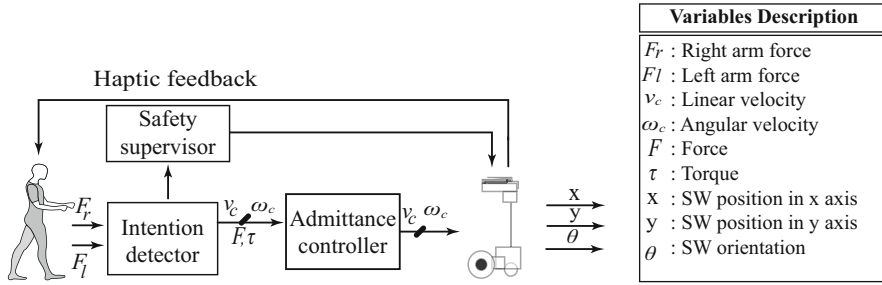


Fig. 4.12 Block diagram of an application from an admittance controller in a smart walker

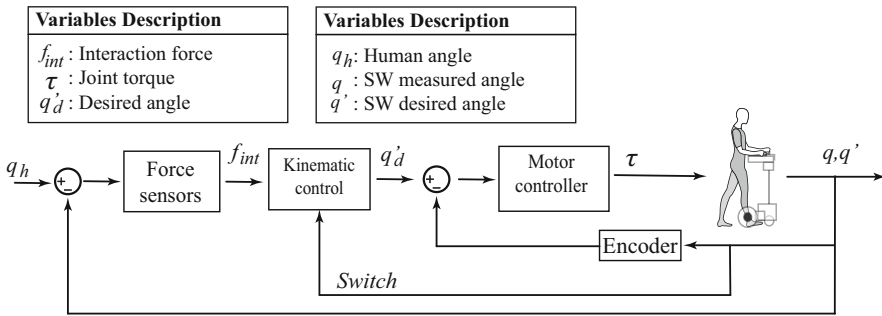


Fig. 4.13 Block diagram of an application from a Kinematic controller in a smart walker

charge of fulfilling the objective of the task; (2) dynamic compensation control is the one in charge of compensating the robot dynamics [52].

The diagram shown in Fig. 4.13 shows the general scheme of a kinematic controller used in an intelligent walker application. The system broadly indicates the interaction between the sensors and the movement angles of the user’s knees. In this interaction, the controller ensures correct and harmonic movement [53].

A device developed from the frontal tracking of the user is the *Rollator*, which proposes a virtual push approach through a kinematic controller. An equilibrium distance is defined when the system is at rest. If the user passes the balance point and approaches the robot, the robot starts moving depending on the human–robot distance [54].

The *iReGo* walker is a rehabilitation platform designed to facilitate lower extremity rehabilitation training based on movement intention recognition. The walker first identifies the user’s intention to move from the interaction forces on the left and right sides of the pelvis. Then it uses the kinematic model to generate the appropriate riding speeds to support the weight of the body and improve mobility. For this device, the workspace, dexterity, and force field are analyzed based on a Jacobian system [55].

4.7 Conclusions

This chapter analyzed a total of 18 relevant robotic walkers from the literature. At first, it described several physical structures according to some of the found walkers. Then, it presented an overall description of the sensors, functionalities, and interfaces of these walkers. Similarly, this chapter described some of the most common interaction strategies for robotic walkers. The information described in this chapter provides fundamental concepts in the design process of new smart walkers. Chapter 9 delves into the mathematical formulation and implementation of multiple control strategies for human–robot interaction, robot–environment interaction, and human–robot–environment interaction.

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