Politecnico di Milano

Master Thesis

Human-walker interaction analysis and control strategy on slopes based on LRF and IMU sensors

Autore:
Luca Tausel

Relatore:
Dr. Hermes Giberti

Correlatori:
Dr. Anselmo Frizera Neto
Carlos A. Cifuentes García

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"Le doute est un état mental désagréable, mais la certitude est ridicule."

Voltaire

"Mathematics beats Malaria. Remember that it's all just a dance, Yahoo!"

Christian Lapotre

FIGURE 1: Legs during gait.

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Sommario

Human-walker interaction analysis and control strategy on slopes based on LRF and IMU sensors

by Luca Tausel

Questo lavoro si basa sull' *UFES smart walker*, un deambulatore robotico progettato nel *Laboratório de automação inteligente* del Dipartimento di Ingegneria Elettrica dell' Universidade Federal do Espirito Santo (UFES). Lo scopo di questo dispositivo è assisteree la locomozione di persone con problemi di mobilità, dal momento che può essere utilizzato sia per riabilitazione che per compensazione funzionale.

Uno studio è stato effettuato sui dispositivi di riabilitazione per la mobilità umana, soprattutto riguardo gli *smart walkers*, categoria di dispositivi definita come una tipologia di deambulatori in cui é integrata robotica avanzata e tecnologia elettronica e meccanica. Questi dispositivi sono tema di interesse in gruppi di ricerca di tutto il mondo e sono potenzialmente molto efficaci per il supporto alla deambulazione, in quanto riescono a sfruttare le capacità di locomozione residue dell'utente.

E' stato sviluppato un dispositivo di assistenza attivo, flessibile, sicuro e facile da usare, di grande aiuto per l'assistenza di un ampio segmento di popolazione più o meno limitata nella mobilità autonoma, che altrimenti sarebbe segregata all'uso di sedie a rotelle, considerando tutte le conseguenze fisiologiche che ciò implica.

L'UFES smart walker é un deambulatore attivo con tre ruote, equipaggiato con motori con meccanismo autobloccante sulle ruote posteriori e una ruota libera nella parte frontale. I parametri di interazione considerati da questa configurazione dell' UFES smart walker sono ottenuti da un Laser Range Finder (LRF), utilizzato per rilevare il movimento degli arti inferiori e due Inertial Measuring Unit (IMU) posizionati sul bacino dell'utente e sul deambulatore, che rilevano i rispettivi orientamenti 3D. La strategia per l'estrazione dei parametri utili dal LRF é stata sviluppata in un lavoro precedente svolto al *Laboratório de automação inteligente*. Tale metodo consiste nell'individuare le due gambe ad ogni scansione del sensore laser e considerarle come puntuali, definite quindi da un valore di distanza dal punto di lettura e un valore angolare di apertura rispetto all'asse longitudinale del deambulatore. Il metodo di estrazione dell'orientamento utilizzato per i sensori inerziali IMU é anch'esso stato sviluppato in lavori precedenti dal

medesimo dipartimento. Questo metodo si basa sull'integrazione con Matrici dei Coseni Direttori dei dati provenienti dai giroscopi, accelerometri e magnetometri presenti nel sensore inerziale. I dati ottenuti sono i tre angoli di Eulero che definiscono l'orientamento del corpo in misura.

La strategia di controllo utilizzata dal deambulatore su terreno orizzontale, che ha base in progetti anteriori del Dipartimento di Ingegneria Elettrica dell' *Universidade Federal do Espirito Santo (UFES)*, ha l'obiettivo di mantenere il deambulatore in una certa posizione desiderata relativamente all'utente, senza che l'utente lo debba controllare manualmente. Rispetto alle precedenti versioni della strategia di controllo il contributo più significativo della versione riportata in questa tesi è l'algoritmo di stima utilizzato per estrarre la velocità lineare dell'utente. Tale metodo di stima é efficace in determinare la velocità lineare moltiplicando la cadenza di passo per l'ampiezza di passo. Entrambi i parametri di passo sono determinati attraverso dei filtri adattativi WFLC (Weighted Frequency Fourier Linear Combiner) e FLC(Fourier Linear Combiner) che partono dal filtraggio del segnale di distanza delle gambe ottenuto dal LRF. L'autore di questa tesi ha avuto un ruolo nello sviluppo e principalmente nello svolgimento delle prove sperimentali di questa verione della strategia di controllo.

In questa tesi, partendo da una scrupolosa analisi dello stato dell'arte, è stata sviluppata una strategia innovativa in grado di gestire inclinazioni del suolo incontrate dagli *smart walkers*. Questa strategia é stata costruita sulla base della strategia di controllo utilizzata dal deambulatore su terreno orizzontale, introdotta nel precedente paragrafo. La necessità di questa ricerca è apparsa perché gli *smart walkers* dovrebbero essere in grado di affrontare in modo sicuro le inclinazioni al fine di essere un dispositivo utile ed efficace nella vita quotidiana della popolazione anziana o per qualche motivo limitata nella sua mobilità. In ambienti urbani gli utenti dei deambulatori hanno spesso a che fare con rampe e marciapiedi e *UFES smart walker* prima del progetto sviluppato in questa tesi non era preparato ad affrontarli in modo sicuro.

Questa tesi presenta l'ideazione, lo sviluppo e la validazione, con un soggetto sano, di un nuovo modello di interazione uomo-macchina su inclinazioni. Questo modello è chiamato "Pivot Model" e si basa sull'analisi cinematica della postura umana durante la locomozione assistita da deambulatore su inclinazioni. La struttura del metodo nasce da analisi video della camminata su rampa tramite le quali si é modellizzata l'interazione tra deambulatore e utente. Il Modello introdotto é composto da due sotto-modelli relativi alle inclinazioni longitudinali e trasversali che sono chiamati rispettivamente "Pitch Model" e "Roll Model".

Questo modello è integrato nell'anello di controllo chiuso come un blocco supervisore che modifica, sulla base delle inclinazioni, i setpoint di controllo. Tali modifiche permettono di rendere la posizione desiderata del deambulatore un parametro variabile con l'inclinazione, il che risulta più coerente con il naturale comportamento che si ha affrontando una rampa con deambulatore. Tale modifica dei setpoint di controllo induce un miglioramento del comfort e della sicurezza nell'utilizzo del deambulatore.

Le prove sperimentali effettuate su due percorsi differenti mostrano che i parametri estratti dal comportamento naturale dell'utente su piani inclinati e i setpoint stimati con il modello proposto sono altamente correlati, presentando un andamento simile. Questa correlazione permette, utilizzando i nuovi setpoint ottenuti con il "Pivot Model", di eseguire un controllo più naturale.

Uno dei vantaggi del metodo proposto è l'elevata efficienza computazionale, ciò é dovuto alla limitata complicatezza dell'algoritmo introdotto. I parametri stimati non introducono un notevole aumento del tempo di esecuzione e per questo motivo il "Pivot Model" è adatto per applicazioni in tempo reale.

In letteratura non è stato identificato alcun lavoro in cui la modellazione cinematica dell'atteggiamento naturale umano sulle inclinazioni sia stata considerata nella definizione della strategia di controllo di uno smart walker. Per questo motivo il metodo proposto è considerato un'innovazione.

Inoltre, i sensori presi in considerazione in questa configurazione del sistema sono facilmente interpretabili. I dati ottenuti dall'LRF sono la distanza e l'orientamento degli arti inferiori e dalla IMU l'orientamento del deambulatore e del bacino dell'uomo. Questo fatto è degno di nota perché altri sensori sono di interpretazione più difficile, come ad esempio i sensori di forza usati per misurare la forza impressa dagli arti superiori. I sensori di forza possono ricevere in ingresso uno stessso segnale che in diverse situazioni avrebbe un significato diverso, per esempio, se l'utente facesse più forza in direzione verticale verso il suolo potrebbe significare che ha bisogno di maggiore sostegno, quindi ha bisogno che il deambulatore rallenti, o che sta cercando di accelerare il deambulatore. Queste condizioni ovviamente genererebbero comandi diversi attraverso una strategia di controllo e potrebbero essere facilmente confusi tra di loro. Nella configurazione utilizzata in questa tesi il problema di malinterpretazione del segnale é meno critico.

Per ragioni di comfort e sicurezza é stato definito uno spazio camminabile all'interno del quale deve essere individuato l'usuario affinché i motori non si arrestino immediatamente. Lo spazio é limitato su tre lati dalla struttura del deambulatore e sul lato aperto il limite é fissato a $1m$ di distanza, distanza controllata con il LRF.

A causa della chiara interpretazione dei segnali dei sensori, delle limitazioni utilizzate nel definire lo spazio camminabile e del fatto che i motori autobloccanti in situazioni di mancanza di alimentazione si arrestano, la strategia di controllo è considerata sicura.

Una grande qualità del controllo proposto è il fatto che nessuna formazione dell'usuario è necessaria per utilizzare l'*UFES smart walker*. Gli input richiesti dal controllore vengono estratti dall'atteggiamento naturale che una persona ha sulle inclinazioni.

Come lavori futuri, si prevede di integrare i sensori di forza, applicati ai supporti per gli avambracci e dei sensori indossabili in altre parti del corpo dell'utente nel "Pivot Model" al fine di rafforzare l'interpretazione del comportamento umano durante la camminata assistita da deambulatore su inclinazioni.

Inoltre, si prevede di integrare il modello in tutte le strategie di controllo sviluppate per il *UFES smart walker* al fine di assistire attivamente la camminata umana, intendendo con motori collegati all'asse di trazione e il deambulatore controllato con l'uso del blocco supervisore "Pivot Model". Questa serie di esperimenti sarebbe utile per apprezzare il corretto funzionamento del modello, sia per il rollio che per il beccheggio. Per questi test potrebbe essere utilizzato un percorso a U o in diagonale.

Inoltre, una validazione clinica del modello proposto con soggetti con patologie legate alla locomozione è un obiettivo futuro, al fine di comprendere meglio il valore riabilitativo del metodo proposto.

Organizzazione della Tesi

I capitoli della tesi sono organizzati come segue.

Nel capitolo 1 viene presentato il mercato dei robot di assistenza e viene sottolineato che é in costante crescita. Inoltre viene introdotto il problema della crescità della parte di popolazione di maggiore età e dei problemi che ciò comporta in termini di necessità di dispositivi per il supporto alla locomozione.

Nel capitolo 2 é presentata un'introduzione alla deambulazione umana e delle patologie e condizioni che possono limitarla. Inoltre é presentata una revisione dello stato dell'arte sui dispositivi di supporto alla mobilità umana, con particolare attenzione ai deambulatori. In questo gruppo di dispositivi son inclusi gli *smart walkers*, argomento fulcro di questa tesi.

Nel capitolo 3 è mostrata una revisione dello stato dell'arte sui dispositivi di supporto alla mobilità umana su inclinazioni, in particolare concentrandosi su *smart walkers*. E' presentata un'analisi critica circa le soluzioni adattate dai dispositivi esistenti. Le debolezze di tali metodi sono state sottolineate individuando ampio margine di miglioramento riguardo la modellizzazione dell'interazione utente-deambulatore sulle inclinazioni e lo sviluppo di una strategia di controllo.

Nel capitolo 4 é presentato il *UFES smart walker* e ne viene spiegata nel dettaglio la struttura meccanica ed elettronica. I sottosistemi che compongono il robot sono trattati singolarmente, citando i lavori che li riguardano sviluppati in passato nel Dipartimento di Ingegneria Elettrica dell' *Universidade Federal do Espirito Santo (UFES)*. Inoltre, in questo capitolo viene presentata la strategia di controllo utilizzata in questa configurazione del deambulatore. Degno di nota è l'algoritmo di stima adattativa utilizzato per stimare la velocità lineare dell'utente, nel cui sviluppo l'autore della tesi ha avuto un ruolo.

Il Capitolo 5 presenta il modello sviluppato interamente in questa tesi di interazione utente-deambulatore su inclinazioni incentrato sull'analisi cinematica della postura umana durante la camminata assistita da deambulatore. Il modello é chiamato "Pivot Model" e i due sotto-modelli relativi alle inclinazioni longitudinali e trasversali sono chiamati rispettivamente "Pitch Model" e "Roll Model".

Il capitolo 6 mostra i setup sperimentali e i risultati ottenuti con la validazione sperimentale del "Pivot Model". Sono stati effettuati due esperimenti, uno su un percorso rettilineo e uno su un percorso a U, entrambi con un soggetto sano.

Infine, il capitolo 7 è il capitolo conclusivo.

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Abstract

Human-walker interaction analysis and control strategy on slopes based on LRF and IMU sensors

by Luca Tausel

This work is based on the *UFES smart walker* designed in the Postgraduate Program in Electrical Engineering of the Federal University of Espirito Santo (UFES). The goal of this device is to help the locomotion of people with mobility impairment, since it can be used for both rehabilitation support and functional compensation.

Research has been done about rehabilitative devices for human mobility, mostly regarding smart walkers, defined as a category of walkers that integrate advanced robotics, electronic and mechanic technology. These devices are theme of interest in actual research groups from all over the world and are devices potentially very effective in the rehabilitation world, because they manage to exploit the remaining walking abilities of the user.

It has been achieved an active, adaptive, secure and easy-to-use assistive device of great help in the assistance of a broad segment of population more or less limited in its autonomous mobility, that otherwise would be segregated to the use of wheelchairs, considering all the physiological consequences that it concerns.

The *UFES smart walker* is an active type walker with three wheels, equipped with self-blocking motors on the rear wheels and a caster wheel in the front. The interaction parameters necessary for the control strategy are obtained from a Laser Range Finder (LRF) detecting lower limb movement and two Inertial Measurement Unit (IMU) positioned on the user's pelvis and on the smart walker, detecting their 3D orientation.

The control strategy described in this thesis relative to the control on horizontal ground has the objective of keeping the walker in a desired position with respect to the user, without the need of the user to manually control it. Compared to previous versions of the control strategy the most significant contribution of this version is the adaptive estimation algorithm used to extract the linear velocity of the user. The author of the thesis had a role in the development and in the experimental validation of the estimation method.

In this thesis, starting from a scrupulous analysis of the state of the art, it has been developed an innovative strategy able to deal with ground inclination encountered by smart walkers. This strategy has its base on the control strategy used on horizontal ground introduced above.

The need of this research has appeared because smart walkers should be able to safely deal with inclinations in order to become a device effectively useful in the daily life of the elderly population or anybody that suffer of limited mobility. In urban environments smart walkers very commonly have to deal with ramps and curbsides and the UFES smart walker was not prepared to safely face them.

This thesis presents the conception, development and validation, with a sane subject, of a novel model of human-walker interaction on slopes. This model is called "Pivot Model" and is based on the kinematic analysis of human posture during walker assisted-gait on slopes. The structure of the proposed method has its roots in the analysis of videos of human gait on slopes and of recorded data from IMUs and LRF, through which the human-walker interaction has been modeled.

This model is integrated into the conventional closed control loop, as a supervisor block. This block modifies, based on inclinations, the control set points. These modifications define the human-walker desired relative position as a parameter that depends on inclinations and it results more coherent with the natural behavior that users have while walking on slope. This modification to the control setpoints induces an improvement in comfort and safety in the use of the walker and, moreover, enhances user's confidence in the walker.

The practical evaluation shows that the parameters extracted from the natural behavior of the user and the estimated set points determined with the model proposed are highly correlated, presenting a similar trend. This correlation allows performing a more natural control.

One of the advantages of the proposed method is the high computational efficiency, due to the light weight of the introduced algorithm. The estimated parameters don't present a considerable increase in the execution time and for this reason the "Pivot Model" is suitable for real time applications.

In literature no work has been identified in which the kinematic modeling of the human natural attitude on slope was considered in the definition of the control strategy of a smart walker. For this reason the proposed method is considered an innovation.

Moreover, the sensors taken into account in this configuration of the system are easily interpreted. The LRF data shows the actual distance and orientation of the lower limbs and the IMUs data show the orientation of the human pelvis and of the walker. This fact is noteworthy because other sensors are of more difficult interpretation, such as force sensors to measure upper limbs. The force sensors can receive as input a certain signal that in different situations would have a different meaning, for example if the user would impart more strength in vertical direction could mean that he needs more support, which means slow down the walker or that he is trying to accelerate the walker. These conditions would obviously generate different commands to the walker through a control strategy and can be easily confused. In the configuration used in this thesis this problem is not relevant.

For reasons of comfort and safety it has been defined a walkable space inside of which the user has to be encountered in order keep the motors turned on. This square space is limited by the mechanical structure in three sides and on the open side it is fixed at $1m$ the maximum distance that the LRF can detect.

Due to the clear interpretation of the sensor's signals, the limitations used in defining the walkable space and the self-blocking gear of the motors that block in emergency situations the control strategy is considered safe.

Finally, a great quality of the proposed control is the fact that no training is required in order to use the UFES smart walker. The input required by the controller are extracted from the natural attitude that a person has on slope.

As future works, it is intended to integrate force sensors, applied to the forearm supports, and other wearable sensors in the "Pivot Model" in order to strengthen the interpretation of human behavior during walker-assisted gait on slopes. Additionally, the aim is to integrate the model into all the control strategies developed for the UFES Smart Walker in order to actively assist human gait. Meaning with the motors connected to the axis of traction and the walker controlled with the use of the supervisor block "Pivot Model". This set of experiments would be useful to appreciate the correct functioning of the control strategy, both for pitch and roll. For these tests it could be used a U-turn path or a diagonal path.

Furthermore, a clinical validation of the proposed model with locomotion-related pathological subjects is intended to be done in order to better understand the rehabilitative value of the proposed method.

Thesis organization

The chapters of the thesis are organized as follows.

In Chapter 1 is presented the market of assistive robots and it is emphasized that it is constantly growing. It is also introduced the problem of the fast growth of the elderly population and the problems that this entails in terms of the need for locomotion assistance devices.

In chapter 2 a revision of the State of Art about human mobility support devices is shown, with special focus on walkers. In this group, there are smart walkers, which are a category of walkers that integrate advanced robotics, electronic and mechanic technology. Moreover, an introduction to human gait and its pathologies is proposed.

In chapter 3 a revision of the State of Art about human mobility support devices on slopes is shown, especially focusing on smart walkers. A critical analysis about the existing solutions adapted by these devices in order to face slopes is presented and the existing weaknesses have been pointed out.

In chapter 4 presents the *UFES Smart Walker* and explains in detail its structure and equipment. The subsystems that comprise the robot are deeply treated. Moreover, in this chapter is presented the control strategy used in this configuration of the walker. Noteworthy is the adaptive estimation algorithm used to estimate the human linear velocity.

Chapter 5 presents a novel model of human-walker interaction on slopes, focused on a kinematic analysis of human posture during walker assisted-gait.

Chapter 6 shows the experimental validation setups and results of the Pivot model. Two set of experiments have been used: on a straight path and on a U-turn path, both with a sane subject.

Finally chapter 7 is the conclusive chapter.

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A la buena onda!

Chapter 1

Introduction

Service robots still do not have an internationally recognized definition. The classification of a robot into service or industrial robot is done based on its intended application. The International Federation of Robotics (IFR) has proposed a tentative definition, "A service robot is a robot which operates semi- or fully autonomously to perform services useful to the well-being of humans and equipment, excluding manufacturing operations."[1]. Service robots can be also classified into personal or professional service robots. A service robot for personal use is a service robot used for a non-commercial task. Examples are entertainment robot, personal mobility assistive robot and generic domestic robot. Instead, a service robot for professional use is used for a commercial task, commonly operated by a trained operator. Examples are cleaning robot for public places, general delivery robot, search and rescue robots and rehabilitation robot[2].

The sales of robots, all categories included, in 2012 slightly decreased by 4% with respect to 2011. In the same year, about 3 million service robots for personal use were sold, 20% more than in 2011. The value of sales increased to US$1.2 billion[3]. It results that intelligent devices which are part of the service robot category are becoming very popular, and cover a wide range of scenarios present in the world population daily life. In the executive summary of World Robotics for 2013 it is reported that the sales of service robots for elderly and handicap assistance will be about 6,400 units in the period of 2013-2016 and that this market will increase substantially within the next 20 years[3]. Specifically the market of robots for personal transportation and handicap assistance will gain importance in the future and a lot of national research projects in many countries concentrate on this huge future market[3].

The Right to Health and Rehabilitation Working Group of the United Nations declared that the "States Parties recognize that all persons with disabilities have the right to the enjoyment of the highest attainable standard of health without discrimination on the basis of disability. States Parties shall strive to ensure no person with a disability is deprived of that right, and shall take all appropriate measures to ensure access for persons with disabilities to health and rehabilitation services."[4]. This statement puts pressure on the State Parties in providing access to the highest attainable standard of health, making the mobility research field a focus.

All the systems created in order to enhance lives of persons with disabilities are called assistive devices. Even if some of the technologies gathered under this name seem to have nothing in common with the others, all of them have a focus on satisfying the needs of disabled users.

Mobility is one of the most important human faculties as it affects not only the capacity of locomotion of an individual and the ability of carrying personal tasks, but is also related to personal and physiological issues determining the behavior of a person. There are many pathology such as poliomyelitis, spinal cord injury, multiple sclerosis or other injuries that affect mobility of an individual. Furthermore, it is known that the mobility of a person gradually decreases with age mainly due to neurological, muscular and osteoarticular deterioration. Because of this, many people need assistance devices to replace, maintain, restore or enhance their mobility[5].

The share of older persons is rapidly growing. Figure. 1.1 shows the percentage of population over 60 and 80 years old as a total and divided by sex in a time range of 70 years, from 1980 to 2050. The percentage of persons over 60 years old in the world increased of 3.17% in the last three decades and, for 2050, it is estimated to reach 21.2%, incrementing of 9.5%.

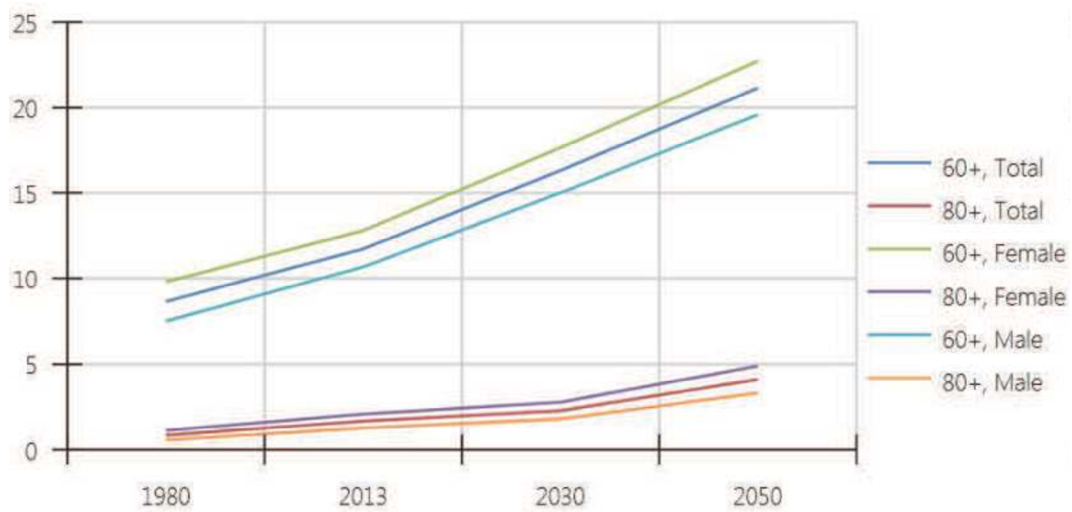


Figure 1.1: Evolution of the percentage of persons over 60 and 80 years old in the world population in between 1980 and 2050. Data are divided by age and sex[6].

Moreover, the share of persons over 80 years old is also growing, in 1980 it was just 0.9% of the population, while the expected percentage for 2050 is 4.1%. The estimation represents a strong positive trend for both sexes and both range of ages[6]. With the increasing number of older people, the problems that age brings, and the need for people to take care of them, it is a priority to develop devices that support the elderly in daily activities[7].

For these reasons it is extremely important to research about assistive devices, service robots that ameliorate people's life.

Chapter 2

State of the art: from crutches to Smart Walker

2.1 Introduction to human locomotion

Based on the top-bottom approach used in [8] are here introduced some concepts about human locomotion. The human gait process starts as a nerve impulse in the central nervous system and ends with the generation of reaction forces with the ground. The gait cycle is defined as the time interval between two successive occurrences of one of the repetitive events of walking. Figure. 2.1 represents the gait cycle divided into two phases, stance and swing. Stance is the entire period where the foot is in contact with the ground. This phase is subdivided into three intervals such as: two double supports and one single support. Both the start and the end of stance involve a period of bilateral foot contact with the floor (double support). Single support begins when a foot is lifted for swing (Leg Swing Phase). During the swing phase the foot in the air (Leg Swing Phase) and the leg is swinging in preparation for the next foot strike while the other foot is still in contact with the ground[8].

While walking the body functionally divides itself into passenger and motor units. The head, neck, trunk and arms are grouped as a passenger unit and the two lower limbs and pelvis are the motor system. The hip is the junction between the passenger and the motor units. The walking direction is expressed with the rotation of the body. First rotates the head and trunk, then the pelvis area and finally the lower limbs. During each stride in the pelvis occurs motion in all three directions. All motions follow small arcs, representing a continuum of postural change. The transverse plane of pelvic rotation is also shown in Figure. 2.1.

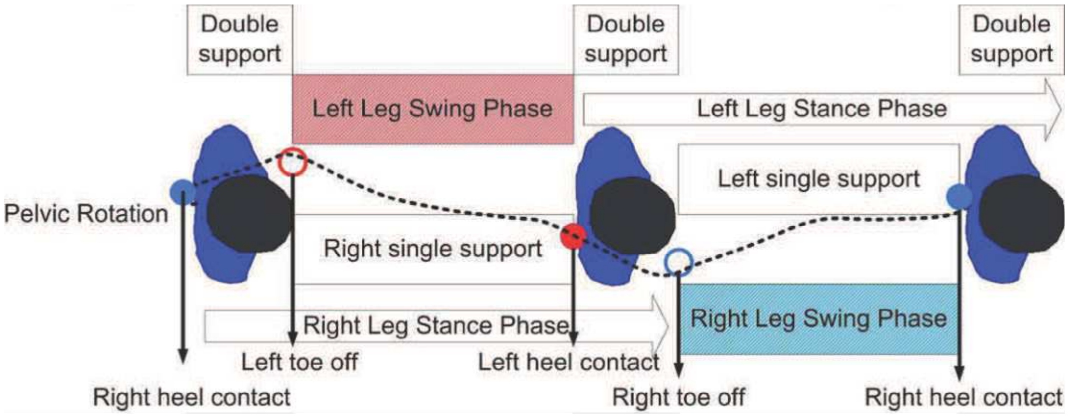


Figure 2.1: Phases of the human gait and transversal plane pelvic rotation in black dashed line.

Being human locomotion a complex task that relates the nervous, sensory and physical systems, the capacity for locomotion can be compromised in whole or in part by dysfunction in any of these systems.

Gait disorder is one of the most common problems for the elderly, it affects mobility skills and consequently reduce independence. This fact makes this category susceptible to falls and prone to suffer of diseases associated with a sedentary lifestyle, such as problems at the heart, kidney and bones. With the lack of walking elderly subjects begin to show a decrease in muscle tone and hence the force, which can cause diseases such as osteoporosis or arthritis[9].

2.2 Mobility Assistive Devices

For several years researchers have addressed the needs of people with mobility disabilities using assistive technologies. The developed devices are used for a diverse population with different degrees of pathology [10]. Once known the motivations that can lead to limited mobility it is now presented an overview over the existing devices that enhance human capacity to move.

2.2.1 Alternative Devices

The alternative devices come in help for mobility problem of people with complete or almost complete mobility loss. In this category are found wheelchairs, automatic wheelchairs and autonomous vehicles, such as scooters. Wheelchairs are the most used mobility assistant tool in the world[11].

Manual wheelchairs have the merit to be of small size, of light weight and do not consume energy. However, it is often found that they induce pain in the upper body, due to the continuous and unnatural effort of the user. Even more when moving on slopes, in uphill situation in which the effort required to the user is large and in downhill situations, in which it is needed a safe control of the wheelchair to avoid accidents[12]. Moreover the lack of physical activity of the lower body can cause a degeneration of the remained mobility of the user[5]. Manual wheelchairs have a low propulsion efficiency in between 5 and 18%[13]. Injuries to wrist, shoulder, elbow and spine is common among wheelchair users and the incidence of injuries is reported to be higher than 25 percent. This incidence increases with extended use of wheelchairs[12].

In order to increment usability and reduce injury rates, electric alternative propulsion has been introduced, the big challenge for alternative solutions is to keep the tool of small size and price and having a friendly and safe control strategy[11].

The power-assisted wheelchairs assist locomotion reducing drastically the required effort of the user, owing to the motorized wheels, solving partially the pain problem encountered with manual wheelchairs. The presence of motors, batteries and electronic components increase the total weight and size, making harder fine motion control and transportation in general. Additionally, power-assistance increments problems related to inactivity of the user. However, in some cases it is possible to regulate the rate of assistance, so to adapt the device to the specific needs of the user[11].

2.2.2 Augmentative Devices

The augmentative devices are the ideal solution for users who own residual capabilities of locomotion or for patients in rehabilitation. Previous researches prove that there are many benefits associated with maintaining the standing and walking position. In [14] few aspect are explained:

- The decrease of secondary problems such as the formation of skin wounds, the contraction of the lower extremities and osteoporosis;
- the reduction of the dependency on the caregiver;
- the improvement of cardio-respiratory functions;
- the improvement in psychological aspects in the rehabilitation process such as self-esteem and social life.

Such devices are presented in the following paragraphs.

Self-ported: Orthoses and prostheses

Self-ported devices are carried by the user either to improve function of movable parts of the body (orthoses) or to substitute a lost member (prostheses). Between these two, orthoses are the ones that present an intense physical and cognitive interaction with the user, and are intended to offset the loss of mechanical function and work together with the movements of the patient. Orthoses can be active or passive. Active orthoses bring the necessary energy to enable the movement by applying actuators or motors.. Passive orthoses do not provide energy, which is provided by the user[15][16].

External

Augmentative external devices usedto improve human mobility are very common and are mainly represented by canes, crutches and walkers. These devices are indicated to help the user with balance or stability problems and for partial weight discharge.

Canes and Crutches are devices used in order to provide a wider base to the user and a better balance during gait. Based on the pathology of the patient there exist a large variety of augmentative external supports, on one hand normal canes and offset canes (with single or multiple legs) mostly in use for elderly; on the other hand crutches and canadian crutches more specific for rehabilititive purposes.

Walkers have an important place among the external augmentative devices, given the number of users, its simplicity and potential for rehabilitation. These devices serve both to support the user while standing and to benefit of the residual mobility skills of the individual in locomotion. Thus, avoiding the early use of wheelchairs and the deterioration of health[17].

Three kind of walkers are here introduced.

- **With legs** as shown in Figure.2.2a is a kind of walker indicated for users without much strength in the lower limbs and a slow and controlled gait, because provides a wide and stable base. On the contrary, they should be avoided by individuals with cognitive problems due to the necessary attention they require and because they have to be lifted at every gait cycle.
- **Hybrids, with legs and wheels** as shown in Figure.2.2b are suitable for users with faster gait speed or for users unable to lift the device. These devices provide a wide base of support to the user and require easy movements in order to be moved.

- **Rollator, with three or four wheels** as shown in Figure.2.2c are a kind of walker used for users in need of little support, able to walk at high speed and not in need of much weight discharge. The rollators present a great maneuverability.

In between the alternative devices, walkers are the ones that provide a very complete support for everyday tasks for a wide group of users. Researchers like Lacey G. and F. van Hook presented in [17] and [18] a classification of the various types of walkers and of the pathologies for which they are prescribed.

FIGURE 2.2: Different kind of walkers: (a) walker with legs, (b) hybrid walker, (c) rollator walker

2.3 Smart Devices

In the field of mobility assistance there are many studies regarding advances version of the introduced augmentative external devices, also referred to as smart devices because of their incremented funcionalities obtained with the integration of robotic features. Smart devices offer features typically found in robotic systems, such as power-assisted locomotion, electronic instrumentation and control algorithms, based on the detection of motion and user intentions, in order to provide better support for the gait. The additional features are especially important during navigation, for safety reasons and for the discharge of body weight.

2.3.1 Smart canes

Smart canes are robotic devices mostly used for guiding assistance; these devices are less profitable in improving stability and weight discharge. An example focused on helping the user in navigation is the SmartCane[16], a device developed by the Massachusetts Institute of Technology that through force and torque sensors measures the forces applied by the user on the cane type device mounted on a mobile robot. These input signals are used to determine speed and direction of the robot, through the impedance model control strategy[16]. Moreover, the cane helps navigation in case of dangerous situation.

Another cane type robotic device is the Guidecane[19], which is exclusively oriented to guidance assistance and helping people with visual disabilities avoid obstacles.

2.3.2 Smart walkers

Conventional walkers have some limitations in providing the support, stabilization, propulsion, breaking power or restraining forces necessary for a safe and comfortable mobility. However, with the incorporation of robotic components, such as motors, sensors and a human-machine interface, it's provided a better human-walker mobility. These devices are called smart walkers and provide assistance to the user at different levels, depending on the different functions in the specific application and on the conditions of the user[20]. Is here listed a classification of the functions realized by this kind of devices[7].

Physical support

Most of the smart walker provide a physical support to gain stability during assisted gait. Two types of physical assistance can be provided: passive and active.

In the passive case, the objective is to introduce mechanical or structural enhancements to the device. The most common improvements consist in the enlargement of the support base and the placement of heavy components in the lower planes of the walker to increase stability. Another common passive change is the introduction of wider supports for the upper limbs instead of the common hand grips to increment the weight discharge.

In the active case, a common improvement is the installation of motors on the wheels that are able to control the brakes and provide the pushing energy necessary to move the device. Conventional walkers are usually equipped with bicycle-type brakes to limit free motion. In smart walkers the control over the breaking system is found very effective because manual breaking requires muscular strength, motor coordination and a good reaction time. If any of these human faculties fail, the user risks an excessive acceleration and a possible fall. The motors are usually controlled by a human-machine interface that interprets user's commands and determines the control input for the motors to provide a safer and more comfortable performance of the walker.

Sensorial support

Smart walkers can also provide sensorial assistance, detecting the surrounding environment and guaranteeing safety. Usually infrared, ultrasound and laser sensor are mounted on the structure of the walker to detect static and dynamic obstacles. In some cases walkers have acustic or vibrating alarms that advise the user of the presence of an obstacle, in other cases they deviate the trajectory to avoid it. This functional improvement is fundamental in the case of guidance of users with vision deficit.

Additionally, sensorial support is provided also in monitoring the user. The correct position of the user on the walker in controlled to improve safety and comfort.

Cognitive support

In this group are found the supports for navigation and localization in structured and unstructured environments. Usually this feature is useful for users that suffer from loss of memory or have to be directed in structured places, such as hospitals. Some walkers with this kind of support are able to navigate in *a priori* known maps or create maps avoiding disorientation of the user. Moreover, these devices can be equipped with bidirectional communication supports, as voice commands or touchscreens.

Health monitoring

Another support consists in monitoring the health conditions of the user while using the walker. These walkers are equipped with sensors capable of measuring physiological signals, such as temperature, heart beat, arterial pressure, generate alarms and report to a health center or caregiver in the event of an emergency.

2.3.3 Smart walkers in Literature

Commonly people who use a smart walker, especially the elderly, can suffer from a great variety of health issues and often multiple issues at the same time, needing a walker that includes many of the functions before mentioned. For this reason the smart walker found in literature are of many different shapes and accomplish different tasks. In this paragraph few of the most popular and referenced smart walkers are presented.

PAM-AID (Personal Adaptative Mobility) The PAM-AID is a smart walker oriented to provide independency to users with a visual deficit and in need of mobility assistance. This walker is powered with a motor just in the front wheel that can orient itself depending on the desired direction. Moreover, this walker monitors the environment with ultrasound sensors. The PAM-AID can be used in manual mode, in which the user is in control or in assisted mode, in which the walker tries to avoid obstacles and communicates with the user through voice commands[21].

GUIDO The Guido commercial smart walker is guided by the user through a support equipped with force sensors. The force signals are used to detect user intentions, as direction and walking speed and consequently move the walker. Moreover, the walker is equipped with a breaking system, a navigation and mapping system and some security precautions[22].

SIMBIOSIS This smart walker is a modification of a conventional walker and provides a multisensor biomecanic platform for the human-machine cooperation. This walker is equipped with ultrasound sensors used to detect the lower limbs and force sensors for the upper limb[7]. These information are used in order to detect user's gestures and intentions and control the walker.

2.3.4 Actual limits and future directions

In this chapter have been introduced assistive devices from the simplest up to the advanced robotic versions of walkers. Many aspects of the actual smart walkers present in literature still can be modified and innovated. On one hand, a mechanical ad-hoc structure helps in the performance of the walker, but, on the other hand, adapt a conventional structure to a robotic version is much cheaper. In the two directions the mechanical structure and its adjustments can be improved[23].

Another important aspect is the signal treatment, which are provided by the sensors and have to be used for the control. It is important to develop algorithms to detect, attenuate and estimate component of the signal in order to provide cleaner signals to the control strategy, with low computational cost, possible to implement in real time[63].

Moreover, developing control algorithms based on the human-walker interaction has brought good results, as the strategy adopted in the Simbiosis [7], in which the analysis done without control, "with free wheels", only with the acquisition of sensors, revealed the true intentions of the user in a certain condition. Thus, this algorithm created a natural interface that does not require a learning phase or special skills of the user to conduct the walker.

Finally, most works done with smart walkers have been done in hospital environments with users without any kind of disability, which doesn't evaluate the true capacity of rehabilitation of walkers[24]. Clinical validation with disabled patients and/or in unstructured "out of lab" situations is a future direction.

Chapter 3

State of the art: robots on slopes

Smart walkers encounter terrains that are not flat and horizontal. In real applications they have to deal with soil irregularities such as bumps or small obstacles and soil inclinations, both longitudinal and transversal. This leads to the problem of how to detect inclinations and how to control the walker on them.

3.1 Conventional angles on slope

In order to face the chapter it is compulsory to define the used conventions regarding angles. Euler angles describe the orientation of an object, in three-dimensional Euclidean space, using 3 parameters: pitch, roll and yaw. These parameters are elemental rotations around the 3 axes of the object local coordinate system.

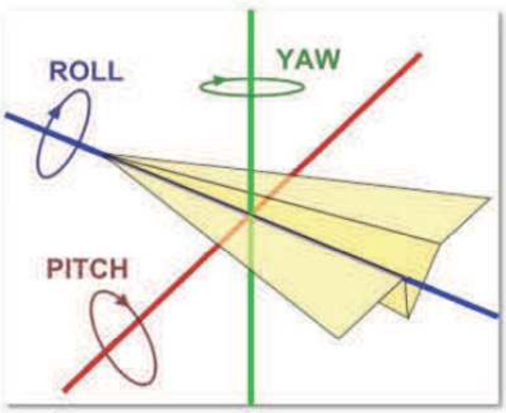


Figure 3.1: Conventions in Euler angles: Pitch, Roll and Yaw

In Figure. 3.1 are visible the 3 possible rotations of the moving object:

- around the longitudinal axis (blue), so called Roll angle,
- around the vertical axis (green), so called Yaw angle,
- around the lateral axis (red), so called Pitch angle.

3.2 Robots on slopes

In the literature, there are several studies that approach navigation and control in 3D environments considering inclinations. Some of this ”out of lab” situations are the following:

- Generic indoor and outdoor autonomous mobile robot used in rescue, exploration, surveillance, military and transportation field etc.,
- Rehabilitation robotics, such as canes, walkers, wheelchairs and scooters.

From a general point of view, many mobile robot applications in real life have to deal with slopes, but often it is much easier to limit their operating area to flat horizontal surfaces in order to simplify the control scheme [25]. Detecting presence of slopes and determining a correspondent control strategy has been proposed in the world of autonomous mobile robots. The variety of environments and conditions in which a robot has to work lead to choose different solutions of hardware and control strategy from case to case.

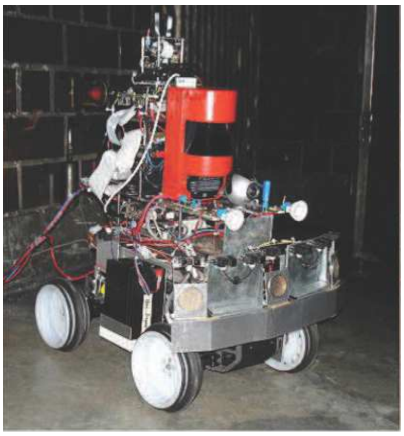


FIGURE 3.2: The fire fighter mobile robot PeLoTe is a member of a search and rescue team and explores the dangerous indicated area preserving the integrity of the human team.

Mobile robots are developed for varieties of tasks: tourist guiding, entertainment, rehabilitation tasks, space missions, rescue and surveillance in between others. Each of these situations brings the project to a very specific choice of components and required performances of the robot. Among them, some are developed to operate in extreme environments, as a matter of terrain conditions (slopes or soil material), or environmental conditions (presence of fire, radiation or out of atmosphere situations). These robots are the ones that most have to deal with the presence of slope and, in literature, many works treat the topic.

In the search and rescue area of research, mobile robots have been introduced and constantly improve they performance in order to assist the rescue team during missions in dangerous and hazardous situations. In the specific case of the PeLoTe project[26], shown in Figure. 3.2, the robot is equipped with encoders, inertial navigation system (INS) with magnetometers and gyroscopes and environment recognition system based on ultrasonic and infrared sensors (IR). This robot is able to detect inclinations thanks to the environment sensors and to regulate its speed in order to accomplish its tasks.

Moreover, mobile robots have succeeded as exploration vehicles for space tasks, such as moon and Martian surfaces. Harsh conditions can be found in these environments, mostly steep slopes and loose soil conditions. In [27] some wheeled robots have been developed such as El Dorado-II and Big Wheel Rover, climbing up to 40 degrees slippery slopes. Figure. 3.3 shows the two mobile spatial robots tested in outdoor and indoor extreme environments.

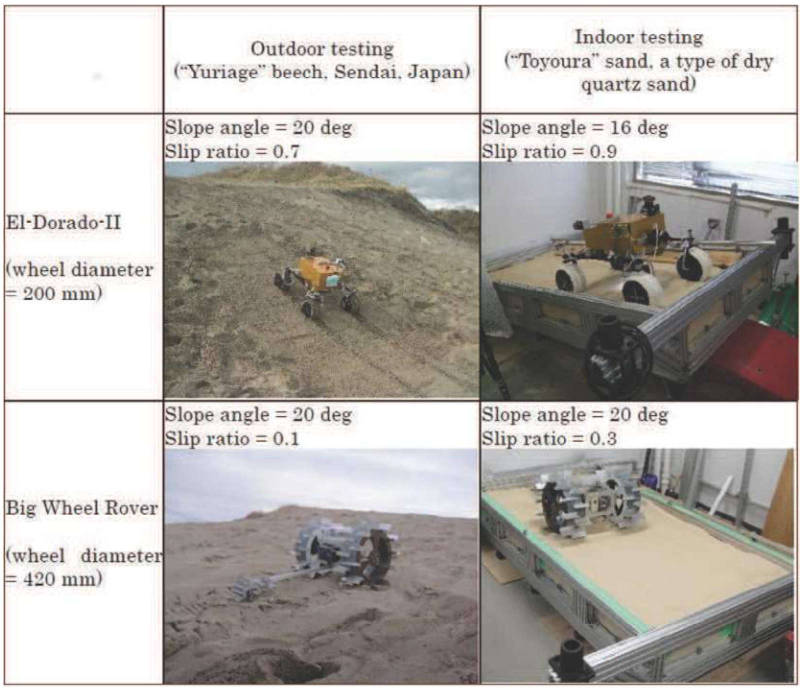


Figure 3.3: Outdoor and Indoor testing of the spatial robots El Dorado-II and Big Wheel Rover with indication of slope angle and slip ratio for each test.

Other solutions have been proposed for extreme inclinations and very irregular soil conditions such as the Coal mine detect and rescue robot presented in [28], which has developed a complex arms-wheels mobile solution that permits it to climb very irregular and steep slopes.

Also the autonomous mobile robot developed in [29], equipped with global positioning system (GPS), an INS, IR, an ultrasonic sensor and a mobile arm mounted on top is able to deal with steep slopes and complicated tasks. The robot is able to work indoor and outdoor with precise navigation skills and slope detection thanks to the computation of data received from the IR and ultrasonic sensors. Moreover, the swing arm positioned on top of the robot is controlled to improve stability on slopes.

In order to get closer to the problem of mobility assistive robots on inclinations, are here introduced the most significant inclinations presents in the environments in which these robots are meant to function.

3.3 Architectural barriers: ramps and curbsides

When projecting smart walkers the presence of architectural barriers has to be taken into account. An architectural barrier is a structure or a design feature of a home or a public building that limits the access and mobility of disabled persons.

All over the world norms regulate size and constructive features of architectural elements built to overcome architectural barriers. Ramps and curbsides can be considered as the focus of the research presented in this work. On one hand, ramps are constructed to be an accessible alternative to stairs. On the other, curbsides are placed on the sides of streets in order to let pedestrians transit. It is important to notice that the lateral leaning for curbside is present because of the need to drain rain and waste water in the street and keep the curbside available.

Regarding curbsides, it's possible to define as the most important parameters to measure the lateral and longitudinal leanings. For ramps are the longitudinal leaning and the maximum continuous length.

In order to keep the same conventions throughout this thesis it is defined the longitudinal leaning as a variation of the pitch angle and a lateral leaning as a variation in the roll angle. Italian and Brazilian norms are presented in next paragraphs.

3.3.1 Italian regulation

Curbside

- *Lateral leaning*: maximum of 2 % [30],
- *Longitudinal leaning*: maximum of 5 %, where not possible it can be higher but providing horizontal shelves every 10-15 meters in relation to the necessary slope respectively higher or lower of 8 %[30].

Ramp

- *Longitudinal leaning*: 8 % is usually the limit, if is not possible to use this limit, the maximum accepted is 15 % (its strongly suggested to always stay under 8 %)[31],
- *Maximum continuous length*: every 10 meters and at every interruption (e.g. door openings) horizontal shelves have to be provided[31].

3.3.2 Brazilian regulation

Curbside

- *Lateral leaning*: maximum of 3 % [32],
- *Longitudinal leaning*: maximum of 8,33 % (1:12)[32].

Ramp

- *longitudinal leaning*: it is calculated with respect to equation 3.1

  $$i = \frac{h * 100}{c} \tag{3.1}$$

  in which c is the horizontal projection of ramp's length, h is the ramp's height and i is the inclination in percentage. The limits for i depend on h: $i < 5\ if\ h < 1.5m$, $5 < i < 6.25\ if\ h < 1m\ and\ 6.25 < i < 8.33\ if\ h < 0.8m$ [32].

The ramp used in the tests proposed in Chapter 6 respect both of the norms.

3.4 Mobility assistive devices on slopes

Few research papers have been written regarding human-robot interaction on slopes in the world of assistive robots. The vast majority of these papers found in literature about assistive robots on slope are associable to the research area of medical and rehabilitative robotics. Other robots that could somehow benefit of a control strategy for slopes, haven't still been researched. The supermarket Walker [33] [34] could be helpful to the user also in presence of the ramps placed to reach the car in a shopping mall. The Adept SPH-2200 [35] could take adventage to move the transported material in an outdoor warehouse passing through a ramp. The versatile mobile robot PeopleBot [36] would expand its operation areas if it could run on slopes, while helping a blind to navigate, guiding a person inside a museum or supporting it's gait in a rehabilitation task.

In the research field of human mobility assistance it's possible to simplify the problem of navigation on inclination compared to other field, for example regarding not considering dynamics effects. The simplification is possible because of the limited speed, the reasonably safe and controlled environment and the not too pushed performance required to the robot[64].

Issues treated up to now, such as steep slopes and rough soil conditions, are not a focus in this thesis, but the nature of the problem and, indeed the solution, keeps being the same. Slopes are a big obstacle for people in need of assistance in their mobility. Urban environments are not always in flat areas and present a great quantity of ramps and inclined surfaces, making the development of slope assistance a priority. It has to be said that, in many cases, slope standard regulations are not respected, creating critical conditions or actual barriers that complicate mobility for the impaired, even when supported with highly efficient smart devices.

Few devices that deal with slopes are now presented.

The mobility assistant device Intelligent City Walker (ICW) [37] is a commercial scooter used for elderly mobility, fully equipped with GPS, INS and environment sensors such as IR and LRF and fully motorized locomotion. The presence of slope is detected to have an accurate odometry but is ignored in the control strategy. To explain the fact that a gravity compensation was not considered necessary in this situation it is introduced an example. In an up-hill inclined surface it will be natural for the user sitting on the Scooter to accelerate, if in need to maintain a constant speed. So a compensation was deemed unnecessary.

Another group of devices that deal with slopes are wheelchairs and, in many cases, in their design a dedicated control strategy is developed.

Manual wheelchairs allow mobility to users with complete loss of autonomous locomotion in the lower body. As explained in Chapter 2, it is often found that they induce pain and permanent problems to upper and lower limbs. When wheelchairs run on slope the situation is even worse, e.g. in downhill situations, where the need of a safe control is high, the effort required to the user to secure the device is significant. In order to increment usability and reduce injury rates, alternative propulsion has been introduced and many active wheelchairs have developed a friendly and safe control strategy for slopes. Active wheelchairs usually include a control strategy specifically planned for the presence of slopes.

In a simple case, the wheelchair implemented by Hwang et al. in [38] detects the rider's

Figure 3.4: The CGPAW wheelchair while testing the control on slope. The User is able to check his mobile phone while the wheelchair by itself remains still on slope.

propelling intentional force, therefore activates the power assistance which reduces the effort required to the user to move. When riding on a slope, the gravitation-compensating power-assisted wheelchair (GCPAW) introduces a torque to the wheels equivalent in module, but in the opposite direction, to the one that makes the wheelchair roll downhill because of the gravity acceleration, as shown in Figure.3.4 the wheelchair remains balanced. This compensation makes the wheelchair able to move on the slope as if it was on flatland. The limit of this model is that helps in solving the control problem on slope just when the wheelchair moves on a straight line in the longitudinal direction and not diagonally. Moreover, it is necessary to know the exact weight of the rider in order to compensate correctly, which can be impractical in real applications.

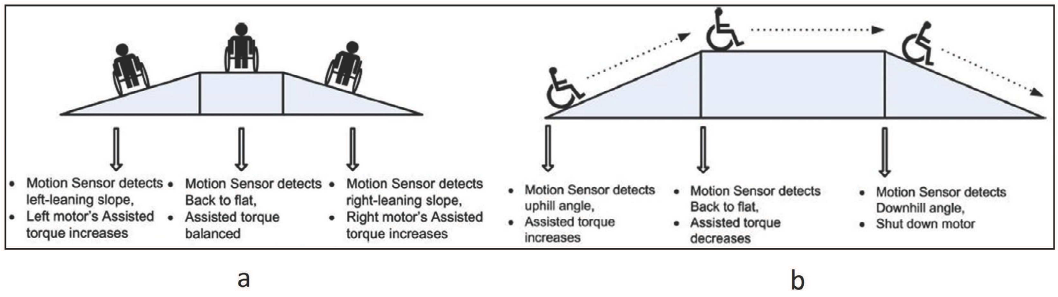


FIGURE 3.5: Scheme of how a wheelchair behaves on slope. (a) is the scheme on lateral leaning path and (b) is the longitudinal one.

Hou et al. in [39] proposed a power-assisted wheelchair equipped with infrared sensors to detect the presence of hands giving propulsion, two DC motors and a motion sensor, which detects inclinations; the power assistance is triggered by the presence of hands on the wheelchair's rims. The control strategy determines the appropriate torque to be applied to each wheel in order to keep a comfortable velocity, with respect to user intentions. The assisted torque is generated proportional to the torque produced by the user, to reduce the required effort.

In [39] it has been observed that when a wheeled robot travels up/down hill and also when across a left/right leaning path, it requires the application of an additional force/torque to achieve moving forward.

On one hand, when on longitudinal slopes the robot makes effort to keep a constant velocity, as shown in Figure.3.5b without control it would decelerate when uphill and accelerate when downhill. On the other hand, when on right/left leaning ground the robot has to make an effort in order to keep a constant forward direction of motion: the robot would autonomously tend to turn in direction of the descending leaning slope and loose it's desired direction, as shown in Figure.3.5a.

The control strategy proposed in [39] regulates the torque depending on inclination. Torque is incremented when the wheelchair moves longitudinally uphill, the motors are shut down and the breaking system is activated in downhill situations. Moreover, torque is added just to the wheel in the leaning side when the ground is laterally inclined. However, the gravity compensation strategy of this support is not shown at work when a ramp is climbed diagonally, requiring at the same time lateral and longitudinal compensations.

The presented work introduced the problem of lateral inclination, that in real life is commonly encountered by human mobility devices in any environment.

In [25] is criticized the solution proposed for conventional power-assisted wheelchairs, as the strategy proposed in [39], because simply multiplying the user's generated torque to produce the assisted torque could cause dangerous situations in matter of exaggerated speed, loss of maneuverability and risk to flip over. In [25] a control strategy that modifies the dynamics of the wheelchair while running has been developed. The power-assistance amplifies the manual force inputs applied to the rims with a transfer function with first order delay and changes the inertia value of the wheelchair in the transfer function to produce different behaviors.

The tendency is to have, on one side, a small inertia value to generate a fast response of the controller when the push begins, and produce assisted torque right when force is impressed. On the other side, a higher inertia generating a slower response when the push is ending, in order to make the speed decrees slowly and don't be null when the user is between two pushing cycles. Additionally, it is proposed a different approach to slope control based on the variability of the center of mass of the wheelchair on inclined surfaces. When in uphill/downhill situation the center of mass moves backwards/forwards and makes it easier for the wheelchair to flip over. Moreover, when high acceleration is provided by the control the instability of the device con be increased. For this reason, the control takes care of avoiding dangerous situations, setting a variable maximum acceleration depending on pitch angle.

The rehabilitative device Omnidirectional Cane Robot[40] has been developed to accomplish 3 main tasks: fall prevention, rehabilitation training improvement and guiding. The device is equipped with a 6-axis torque/force sensor on the handlebar and two LRF sensors to monitor the distance between the cane and user's knees and waist respectively. Through force and LRF signals it is estimated the user's attitude and intentions, in order to define the desired speed and direction of the cane. Through an admittance model the cane modifies the dynamic parameters of its transfer function to facilitate the maneuverability in the desired direction and impede motions in the others. Making the push in a certain direction easier or harder results in a influence of the cane in the choice of preferred direction of the user.

Additionally, a tilt angle is used to detect inclinations of pitch and roll and consequently the control compensates gravity effects when the cane is static. In Figure.3.6 it is shown a model of the cane and its local and global reference frames.

Once defined a Rotation Matrix, that can transfer a vector from global to local frame of reference (r is the local frame of reference and 0 is the global one in Figure.3.6), the gravity force vector in the global frame of reference $G_0 = [0 \;\; 0 \;\; m * g]^t$of dimensions $3x1$ and just one non-null component in the z-direction, is multiplied to it generating the G_r vector. m is the mass of the cane. G_r is the gravity force vector in the local

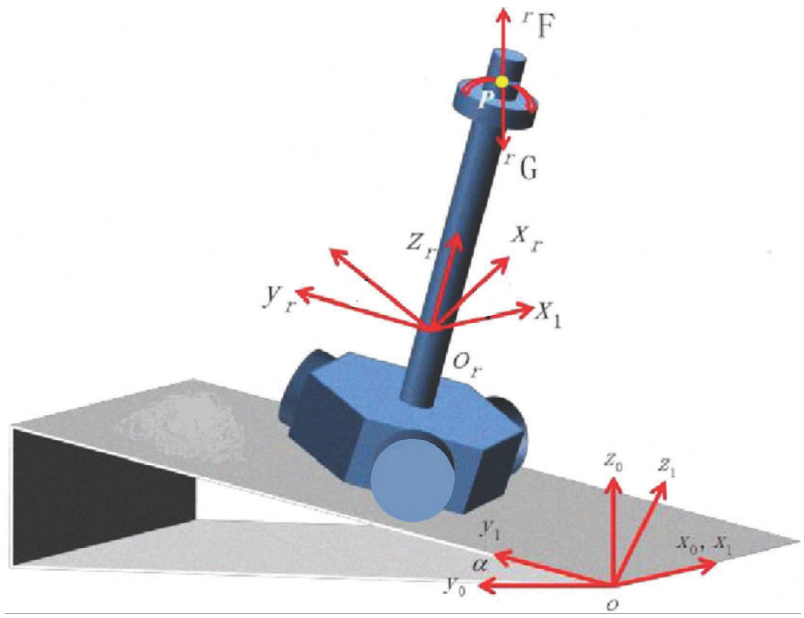


FIGURE 3.6: Scheme of the Omnidirectional Cane Robot on slope. In red are represented the global (0) and local(r) reference frame. Point P is the contact point between User and cane. The two force vector F_r and G_r are respectively the vector introduced for compensation and the gravity force vector.

frame of reference. In order to have a compensation of gravity effect on slope the control makes the force sensor subject to a force vector F_r that balances the gravity vector G_r. F_r generates a command to the motors which impedes the device to move downhill for the gravity acceleration, but indeed stays in equilibrium.

3.5 Smart walkers on slopes

Smart walkers are developed with the purpose to be used in urban environments and, in some cases, as an alternative for wheelchairs. For this reason, they have to be projected to be able to face any condition which is normal to a wheelchair. Taken into account the Brazilian and the Italian regulations regarding architectural barriers, any smart walker should be able to deal with inclined environments, such as ramps and curbsides.

Few smart walkers that deal with slope control are introduced in this paragraph.

The passive type smart walker called RT Walker exposed in [23] is equipped with two passive casters, two wheels with powered servo brakes, a LRF in front and two tilt sensors. This passive walker has some innovative features because by changing the braking torque of the rear wheels appropriately, the motion of RT Walker is controlled on user intentions and/or environmental information. The device is programmed to compensate gravity using braking torque, it doesn't move autonomously on slope: it remains stopped when not moved by the user and applies a breaking torque when pushed by the user to secure the push that the device receives from gravity acceleration. Additionally, the walker, is programmed for obstacle avoidance while navigating and for individuation of stairs, achieved with the use of the LRF.

Roll and pitch angles are calculated with respect to horizontal ground using the tilt sensors. To determine the control strategy for gravity compensation, the force and torque applied to the center of mass due to the gravity component are extracted. Then, it is determined the necessary breaking intensity to be applied to each wheel. This method generates a very secure device that doesn't move if not pushed by the user, which increments security when descending slopes, but doesn't provide assistance in ascending a slope due to its passive nature.

The Walking Support System is an active type smart walker developed by Nemoto et al. in [41]. The device is designed to provide weight support to the user during navigation tasks and the control of the walker is based on the force sensor mounted on the handlebar at waist height. A gravity compensation technique is applied to the walker with the goal of making the user feel no additional load due to inclination when running on slopes. The research bases the control on the concept that a component of user weight can result as an undesired input to the force sensor when on slope. As shown in Figure. 3.7 W_s is

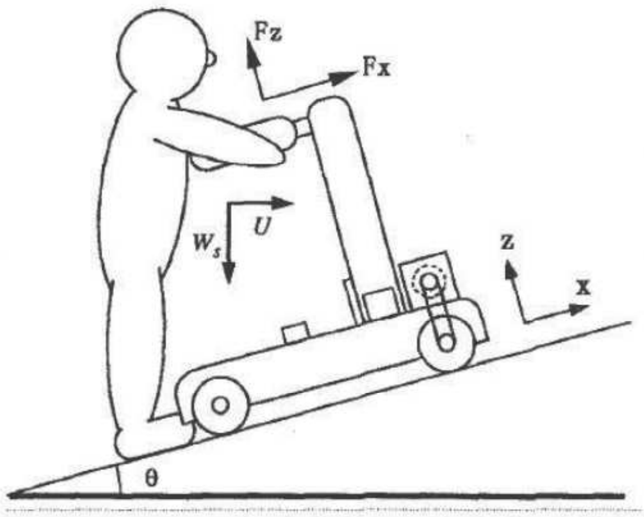


FIGURE 3.7: Scheme of the Walking Support System on slope.

the user's partial weight force vector due to gravity acceleration that is descharged on the walker and U is the input force in the horizontal direction exerted by the user. The force sensor reads F_x and F_z, the horizontal and vertical applied forces and attributes them, respectively, to the weight discharge W_s and the horizontal input given by the user U, but when on slopes these forces don't correspond, as explained in Equation. 3.2 and 3.3.

$$F_x = U * cos(\theta) - W_s * sin(\theta) \tag{3.2}$$

$$F_z = -U * sin(\theta) - W_s * cos(\theta) \tag{3.3}$$

It is observable that if the user increments his partial weight with which leans on the system W_s, the F_x forward input force decreases, slowing down the walker and making the user impress more force in the U direction to keep a constant speed. This means that the user perceives the walker as heavier, therefore it is not achieved the objective to make the user running on slope feel as if he was on flat ground. In order to improve mobility and make more comfortable the control of the walker is it introduced a gravity compensation method in the project. Once detected the inclination angle θ, a new force component is introduced: F'_x, described in Equation. 3.4

$$F'_x = F_x - (F_x * sin(\theta) + F_z * cos(\theta)) * sin(\theta) \tag{3.4}$$

Where F_z is the detected force input in the z direction, calculated in Equation. 3.3.

Substituting 3.2 and 3.3 in 3.4 it results in a operational force that compensates the inclination of the system; being U and W_s known, we calculate the effective horizontal force, shown in Equation. 3.5

$$F'_x = -U * cos(\theta) \tag{3.5}$$

F'_x is used in the control strategy as the intentional horizontal impressed force, resulting in a compensation of the presence of slope.

Another trend of researchers have approached the control on slope from a different point of view, they have developed robots that can modify their physical features to incline themselves and keep the support area globally horizontal.
Yuk et al. in [42] have developed the Smart Mobile Walker, which is a smart walker with four actuated legs that can independently regulate their length, as shown in Figure. 3.8. Indeed, the walker is able to remain with the top plate always horizontal and the four wheels in contact with the ground. Referring to the scheme presented in Figure. 3.7, this control eliminates the problem of non parallelism between the intended front direction push and the weight discharged on the walker with the x and z force read by the walker. The direction of the forces read by the sensor and the forces impressed by the user is the same, because the forearm support, placed on the top plate, is horizontal. This independent solution of the four legs allows compensating an inclination both in the pitch and the roll plane. In Figure.3.8a and 3.8b the CAD representation of the Smart

Mobile Walker is illustrated. In Figure. 3.8c user and walker are walking uphill in a

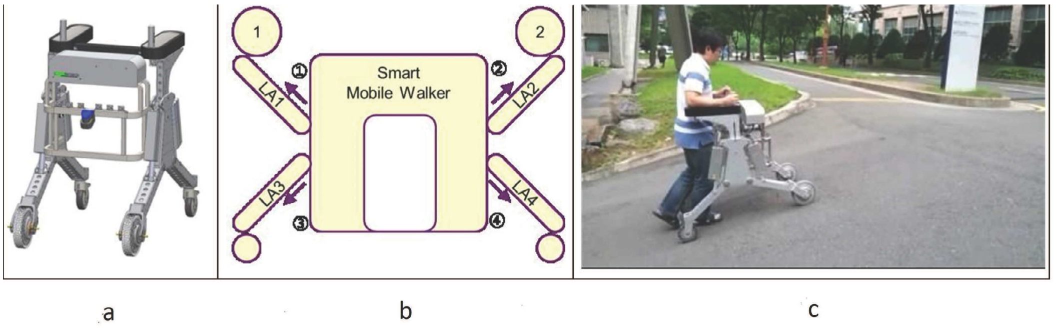


FIGURE 3.8: The Smart Mobile Walker is represented in its CAD model in (a), its upper view with its linear actuators(LA) in (b) and operating on slope in (c).

street and it's visible that the top plate on which the user finds support is horizontal, even if the street is inclined.

Very similar solution has been encountered in [43]. Four legs are linked to the body by linear actuators, controlled in order to orientate the top plate and two extra linear actuators are used to create up and down motion of the top plate. Finally obtaining an always plane support for the user at the desired height.

Noteworthy is that a wheelchair pushed by a caregiver is a configuration very similar to a smart walker. Wheelchairs can be used in two different operation modes: user-propelled and assistant-propelled. User-propelled is the mode in which the patient sitting on the wheelchair is the only person that pushes and controls the device as in Figure.3.9a. Assistant-propelled is intended the condition in which a caregiver pushes and controls the wheelchair with the patient sitting on it, as in Figure.3.9b.

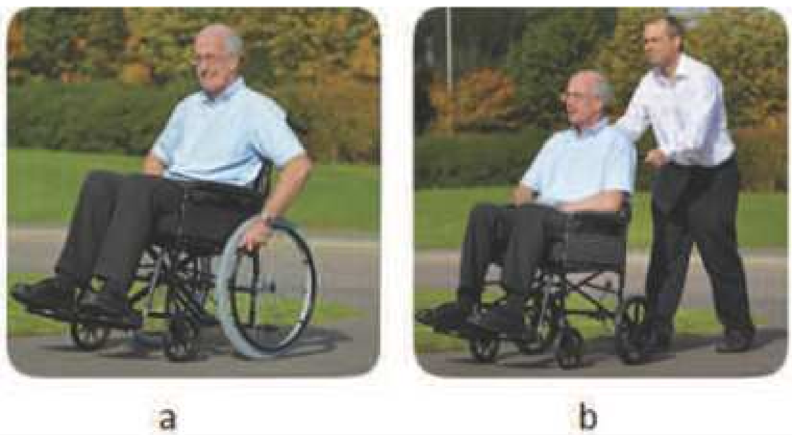


FIGURE 3.9: Pictures representing the possible configuration of wheelchair propulsion: User propelled in (a) and attendant propelled in (b)

A parallelism between assistant-propelled mode wheelchairs and smart walkers is clearly visible. On one hand, the attendant of the wheelchair finds its equivalent in the user of the walker. On the other hand, the wheelchair with the passive user sat on corresponds to the walker. For this reason, solutions for wheelchair in assistant-propelled mode can be considered in the development of control strategies for smart walkers.

In this thesis, it has been taken inspiration from works made on attendant-propelled wheelchairs in order to propose a control strategy. An innovative solution that deals with slopes is the control strategy of the omnidirectional hybrid walker and wheelchair developed by Suzuki et al. in [44] (Figure. 3.10). In this work two operation modes are treated the same way: the attendant-propelled wheelchair and the smart walker. Both modes are used in rehabilitation tasks and for elderly mobility. The person behind the walker/wheelchair will be called user, referring to the attendant, the disabled or the elderly. The device [**?**] is composed by two rear active wheels and two front free caster

FIGURE 3.10: The hybrid walker. The User can push the walker or sit on it as if it was a wheelchair.

wheels. A 6-axis force sensor is mounted on the shaft of the handlebar in order to detect forces and torques exerted by the user, from these signals velocity and direction of the user is detected. Moreover, a LRF sensor and a Radio Frequency Identification (RFID) system are used to detect obstacles in a structured environment and help the navigation.

An admittance model emulates the dynamics of the system, defined as a transfer function $G(s)$ for three degrees of freedom, forward, lateral and rotational, and gives the user the "feeling" as if he/she is interacting with the system defined by the model. The transfer function in direction x, shown in Equation. 3.6 has user's forces applied on the handlebar, $F_x(s)$, as input and the desired velocity of the device, $V_x(s)$, as output.

$$G_x(s) = \frac{V_x(s)}{F_x(s)} = \frac{1}{M_x s + D_x} \tag{3.6}$$

Being M_x and D_x the virtual mass and damping in the x direction. By regulating the virtual mass, it's obtained the desired dynamic behavior of the walker, from extremely easy to move to a stiff walker, mostly at the starting and stopping of the motion. Usually, this parameter is regulated to limit the effort required to the user to maneuver the walker at the beginning of motion.

Changing the virtual damping coefficient has the effect of changing the burden felt by the user in steady-state condition. The regulation of this parameter is very helpful in situations in which the user is not able to produce much pushing force, providing a "light" walker. Alternatively, if needed for rehabilitative tasks, is required to the user an extra effort to move the walker, making a "heavy" walker.

Looking at the control block shown in Figure. 3.11, it is possible to observe that the force signal F is provided to the admittance model, which generates the desired velocity command V_d. Then, through the inverse kinematics, the desired speed of each wheel is determined (ω_d) which enters a control loop that outputs the robot velocity ω_r.

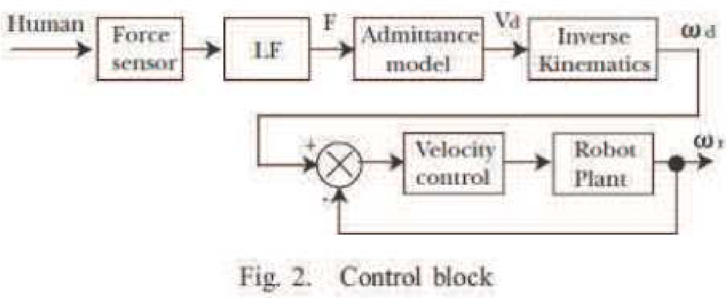


FIGURE 3.11: Scheme of the admittance model used in the control of the hybrid walker.

The research paper on this robot dedicated to slopes[44] analyzes the problem of inclinations and defines that if the control strategy is based on an admittance model and as long as the user and the walker have the same speed, a modification to the control due to the presence of gravity is unnecessary. This is because the velocity of the walker is determined only through the forces and torques applied by the user. On inclined ground, the gravity component of the wheelchair along the slope is countervailed by the extra output of the driving wheels, necessary to keep the desired velocity received as a command from the user, through the forces impressed. The load perceived by the user results almost the same as on horizontal flat ground. By the fact that in steady-state the velocities of the walker and of the user are equal, the power assistance is only determined by the product of the damping coefficient and the impressed forces/torques. It's more complicated when the walker and the user are not on the same plane (horizontal or inclined): the walker is beginning to ascend or descend a slope. The two velocities will be different and a pick of exerted force will be present while beginning and ending the slope, this will generate a sudden change in the felt load.

It's found that, when starting to ascend a slope, the walker is undergoing pure rotation around an instantaneous center of rotation. This fact results in an acceleration of the user with respect to the walker and it is resolved increasing the robot speed when beginning to ascend a slope. The found result can also be applied to the situation in which the robot is descending the slope and encounters an horizontal plane. Similarly, when passing from ascending slope to horizontal and from horizontal to descending slope, it is favorable to decrease robot velocity in order to keep a constant "load feeling". Experimental results prove that this method is reasonable, achieving smaller fluctuation of forces while passing through slope. The strategy proposed is very innovative and focuses the need of changes in the control just in the transitory conditions of passing from an inclination to another. The used control strategy on slopes is the same one used on horizontal surfaces, with just little modifications: the desired velocity is multiplied for a coefficient when walker and user are inclined differently.

Remarkable is that when descending a slope the user perceives the same load feeling, as in other conditions, generating an interesting effect: the walker needs to be pushed also when going downhill, which for sure results strange to the user. Moreover, in this research paper it has not been developed a control strategy to compensate a lateral inclination, a variation in the roll angle.

Another research group, in [45] has developed an active smart walker and a specific control strategy to deal with slopes. The walker, shown in Figure.3.12 carries the following equipment: two wheels driven by motors with encoders, two passive casters, a force sensor mounted on the handlebar and a slope sensor.

On one hand, this smart walker is thought to be as passive as possible, due to the intrinsic nature of the passive mode: dissipates energy giving security to the user. The brake system is used to modify the direction of the walker when needed. On the other hand, active control mode is planned for uphill situations, torque is added to the walker to compensate gravity, this results in a reduction of user's exerted force and is achieved a strategy that preserves a waste of energy of the user.

Figure 3.12: Picture of the active type SmartWalker developed by KO et al.

A dynamic model of the robot on a slope is defined, including the gravity component. In order to compensate the gravity effect, the control law is chosen to have a component in the two wheels control equations that depends on the inclination angle and counterbalances gravity. The results are obtained with the hypothesis of no slip condition, so to have just a one direction velocity. Differential flatness method is used to define control gain parameters and plan the trajectory, in order to obtain desired position and orientation.

Finally, an outdoor intelligent Walking Assistant Robot-WAR, shown in Figure.3.13, has been developed by Shim et al. in [46]. This device has four motorized wheels: the front ones are used for steering and the rear ones for driving. Moreover it is also equipped with a LRF and a CCD camera in order to detect obstacles, GPS for localization and an haptic handlebar that recognizes human intentions. The haptic handlebar determines walking intentions through pushing or pulling pressure. When on slopes a gravity compensation strategy is applied in order to eliminate the effect of human and robot weight, seen as force input.

3.6 Conclusions

As discussed in this chapter, in an urban setting a person with disabilities often has the need to move on inclined surfaces. Remarkable is that smart walkers are a category of supports that would widely benefit of solutions for slopes because of two main factors.

FIGURE 3.13: Pictures of the outdoor intelligent Walking Assistant Robot (WAR)

Firstly, because of batteries and equipment in general, their weight is significant, making a hard task for the user to push uphill and secure downhill the uncontrolled device.

Secondly, the Human-Robot interaction of these devices is very complex, because of the large freedom of movement that the person has and the very limited points of contact between the robot and the user; this makes very ineffective the solutions that treat the human-walker compound as a single entity, as if it was a vehicle. These strategies, indeed, work very well with wheelchairs.

Many strategies for slope climbing found in literature are not specifically designed for smart walkers and are characterized by the detection of the inclination angle, used to identify the orientation of the gravity vector and the compensation of the gravitational acceleration on the robot. The compensation happens with the introduction of a vector of acceleration of same magnitude and opposite direction of the component of the gravity acceleration vector parallel to the inclined surface. As an example, it's recalled a version of this solution in [41]. This is an extremely logic strategy and, in many cases, it works.

On one side, in passive smart walkers this strategy leads to a stable device, whose goal is to stay still and not autonomously move on inclined surfaces, without tough making easier the possibility to be pushed, under user's intentions. In this case, the walker is balanced in its position due to the gravity component and the counter-vector introduced.

On the other side, when this method is applied to an active smart walker it drastically reduces the required pushing effort of the user when going uphill, because of propulsion. The acceleration introduced with propulsion balances with the gravity component, that tends to drive the walker backwards, making the walker ready to respond to the normal control strategy. On downhill situations, just the breaking system is usually exploited, sufficient to stabilize the descent of the slope, but in some cases the walker has to be pushed also in downhill conditions, due to the control strategy.

Morevoer, other works have introduced a compensation strategy also for the roll angle, as [39]. In urban settings this compensation is useful, mostly because of the presence of curbsides, which, inclined laterally street-side make mobility more complicated. The general idea is that the walker will tend to turn while on transversely inclined paths without user's intention and go downhill. For this reason the propulsion of the lower wheel is incremented.

Few of the projects described in this chapter have implemented a very effective strategy of compensating inclinations, modifying their physical features to incline themselves and keep the support area globally horizontal. Unfortunately these strategies are very expensive in terms of robot construction and actuation costs.

Inspiring work has been the one developed by Suzuki et al. in [47], deeply treated in this chapter, in which a new point of view to the problem is introduced: not anymore thinking of inclinations as something to detect and compensate, but more as an index of variation of state that leads to a different control setting. The analysis presented about the transitory stages of approaching and leaving a slope has also inspired the proposed strategy of this thesis.

Most of the works found in literature have developed a control strategy for slopes based on the force upper limb interaction. Force interaction on slopes can be a very hard input to interpret, the challenge is to understand which action defines which intention and in many cases the same input can be considered as index of different intentions. For this reason control strategies that exploit other sensors alone or side-by-side with force sensors could genrate an interface of more certain interpretation providing a safer control.

Chapter 4

UFES Smart Walker

This chapter presents the project of the UFES smart walker, a robotic walker developed at the *Laboratório de automação inteligente*, which is an evolution of the Projeto SIMBIOSIS smart walker [7]. It is a roller type walker with three wheels and support for forearms. The device is equipped with a Laser Range Finder (LRF) sensor for legs detection and two Inertial Measurement Unit (IMU), which are used to detect inertial parameters of user and walker, one on human pelvic area and the other mounted on the walker. Motors are installed to allow traction and braking of the wheels by the control system. Encoders attached to the wheels are used to close the control loop.

4.1 Structure

Trend in the development of smart walkers is the adaptation of commercial walkers to the specific needs of the project [48] [23]. Accordingly, modifications are made on the mechanical structure to allow the installation of sensors, electronics, motors and all the necessary instrumentation. However, these changes may have some drawbacks, such as:

- Affect the stability and security of the original walker due to changes in the mass distribution of the structure;
- Affect the aesthetics of the device, making its appearance not encouraging confidence to the user;
- Require constant adjustments to troubleshoot mechanical clearances, since the original design of a walker is not designed to withstand changes in its structure.

To avoid possible problems arising from adjustments in the mechanical structures in a previous work developed in *Universidade Federal do Espirito Santo* [49] is presented the design and development of the mechanical structure suitable for the desired walker. The project has been studied with finite element methods in order to assure a robust structure and a correct weight distribution. In Figure.4.1 is possible to observe the structure conceived.

Figure 4.1: Structure of the UFES SmartWalker without instrumentation.

In order to improve the stability and security of the march, the UFES SmartWalker is equipped with two DC motors coupled to the rear wheels, which allow the motion control of the device.

The locomotion system is differential with a caster wheel in the front and two actuated wheels in the rear part. The use of three wheels supporting the machine was decided to allow permanently isostatic support on the ground [49]. Three wheels were chosen because in the case of four wheeled devices, without a sophisticated suspension system, it's not possible to assure a constant contact of all the wheels with the ground, resulting in an unpredictable and unstable device.

The use of forearm supports increments the partial discharge of user's weight on the structure of the walker. This reduces the load on the lower limbs and extends the use of the device to subjects with problems of muscle weakness, joint pain and injuries [50].

The support of the forearms developed is coupled to a column with height adjustment from 1100cm to 1200cm, which enables an adequate adaptation to the specific size of the user.

A walker must have an appropriate walkable space not to impose physical limitations, which hinder the movement of the user. Otherwise, instead of stimulating natural gait, the device eventually restricts the space for legs motion, resulting in a not appropriate march and causing discomfort to the user.
In [51] data were collected about length and width of human gait during natural and assisted gait. Thus, such information was used to estimate the minimum walking space required to prevent the impact of patient's foot in the structure of the walker [49].

Figure.4.2 shows the dimensions of the designed main structure.

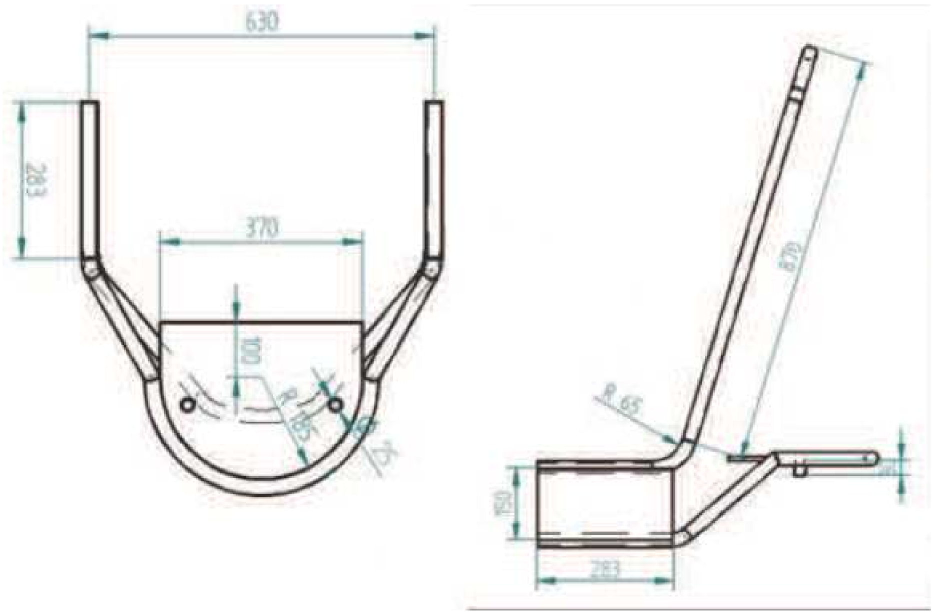


Figure 4.2: Details and dimensions in the upper and lateral views of the structure of the UFES SmartWalker.

In [52], it's reported a study about aesthetics in mobility assistive devices. Often impaired refuse the use of an assistive device due to its visual impact. Thus, when designing such a device, one must consider not only functional, but also, psychological aspects [53]. For this reason aesthetic factors also were a concern during the design of the UFES smart walker. For the structure was used the AISI 304 stainless steel, because of few features of this material:

- meets the desired mechanical resistance and stiffness;
- prevents corrosion;

- is aesthetically appropriate.

4.2 Modules and Subsystems

Figure. 4.3 provides an overview of the UFES smart walker in the used configuration, with a simplified representation.

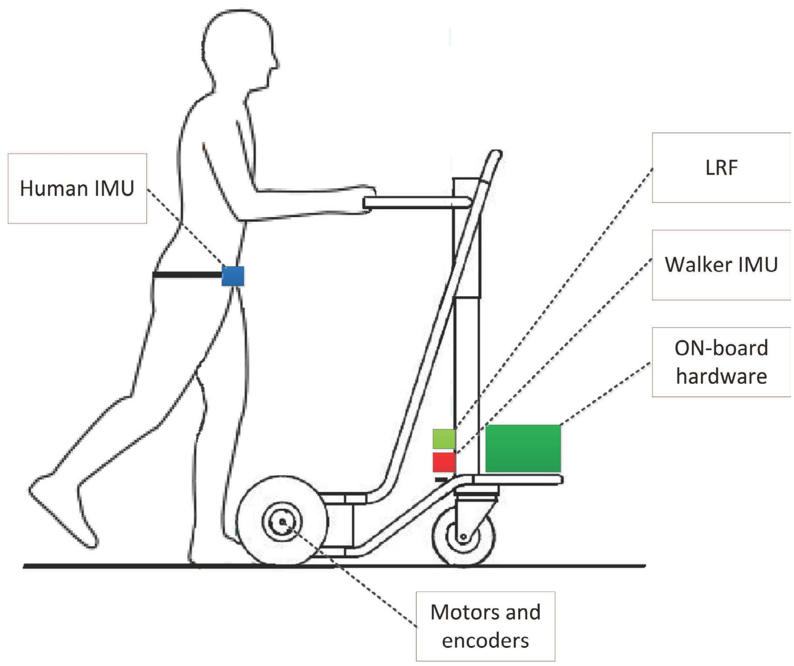


Figure 4.3: Scheme of the UFES smart walker with the desired equipment.

As shown in Figure. 4.4 The developed system architecture can be divided into three modules with distinct functions: the human-machine interface module, the processing and control module and the actuation module. The human-machine interface module is responsible for the acquisition and pre-processing of signals coming from the sensorial interfaces, this information is passed to the processing and control module, whose main objective is the implementation of algorithms to generate motion commands and low level control. Finally, the actuation module triggers engines according to the commands supplied by the control. Each of these modules is composed by subsystems which are schematized in Figure. 4.4.

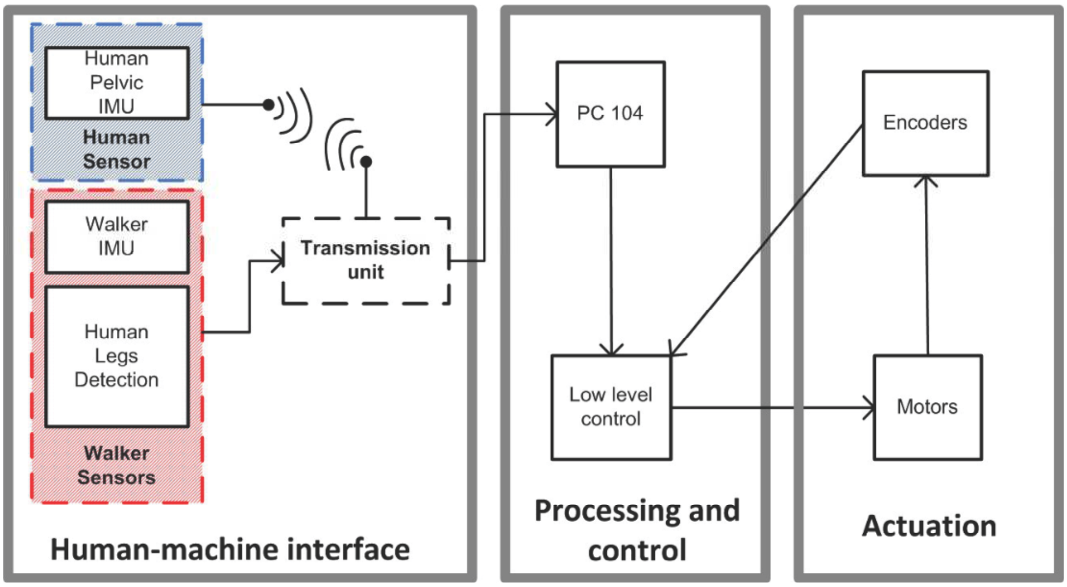


FIGURE 4.4: Scheme of the three modules: human-machine interface module, processing and control module and actuation module. Within each module are indicated the subsystems part of it.

The following paragraphs explain in detail the subsystems that compose the presented architecture.

4.2.1 LRF: Laser Range Finder

This subsystem is responsible of the acquisition of spatio-temporal parameters related to the evolution of lower limbs of the patient.

The sensor used in the project is a 04lx-URG Laser Range Finder produced by the manufacturer Hokuyo [54], shown in Figure. 4.5. It is a sensor that provides information about distances in a radial sweep at a sampling frequency of $10Hz$.

FIGURE 4.5: Laser Range Finder *URG-04LX*.

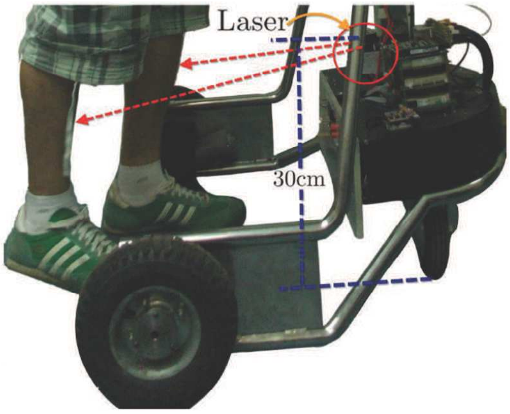
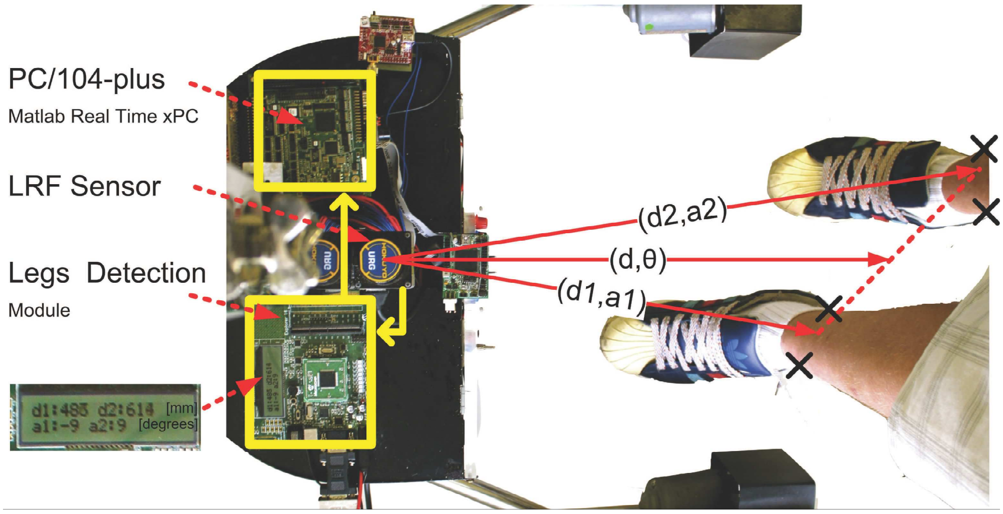


FIGURE 4.6: Positioning of the LRF sensor.

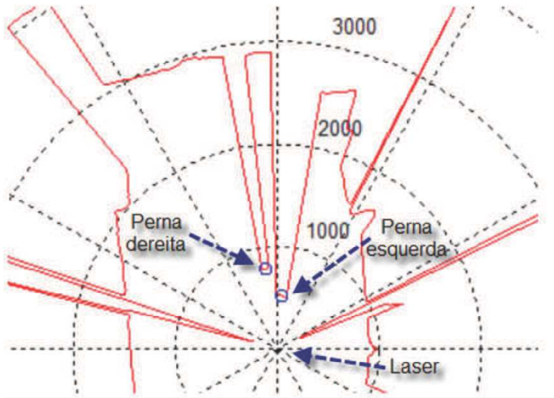
The sensor is positioned in the center of the rear part of the walker, at a height of 30 cm from the ground, directed to the user, as shown in Figure. 4.6. A preliminary study determined the proper positioning of this sensor in a position in the intermediate area between feet and knees of a person of medium height. Placed at this height the incorrect detection of the tip of the shoe or of the knee is most likely to be avoided.

With the information obtained with this subsystem an estimation of the evolution of the march of the user can be extracted and thus determine parameters as speed, distance and angular position of the user with respect to the walker.
In [55], a previous work of the *Laboratório de Automaçao Inteligente* research group, an effective methodology for the estimation of the position of the center point between human legs and its angle relative to the walker during gait is proposed.
In this work, the proposed technique is divided into four parts:

- Data pre-processing, with considerations about the delimitation of the interest region;
- Transition detection comparing data from two consecutive measurements;
- Extraction and analysis of patterns considering the possibility of detecting "two legs separated", "two legs united" or "two legs overlapping", apart of the "error in detection" possible outcome;
- Leg coordinate estimation, as visible in Figure. 4.7(a), starting from the detection of each leg's middle point orientation and distance and their subsequent averaging. ($d1$,$a1$) and ($d1$,$a1$) are the polar coordinates of the left and right leg. (d,θ) are the coordinates of the middle point between the legs;



(a)



(b)

FIGURE 4.7: (A) Fuctional scheme of the detection of legs in the configuration of "two legs separated". (B) example of collected data analyzed in the detection of legs in the configuration of "two legs separated".

Figure. 4.7(b) shows one of the possible situations detected by the algorithm, "Perna direita" and "Perna esquerda" respectively represent the right and left leg detected.

Moreover, security rules were taken into considerations in the definition of the walkable area. If the distance read by the LRF is higher than $1m$ the walker immediately stops. This security measure was defined to limit dangerous situations in which the walker, for any reason, is not responding to the control and is moving away from the user.

4.2.2 IMU: Inertial Measurement Unit

This subsystem is responsible of collecting kinematic parameters of the walker and of the pelvic area of the user, such as: angular orientation and velocity. The sensor used in

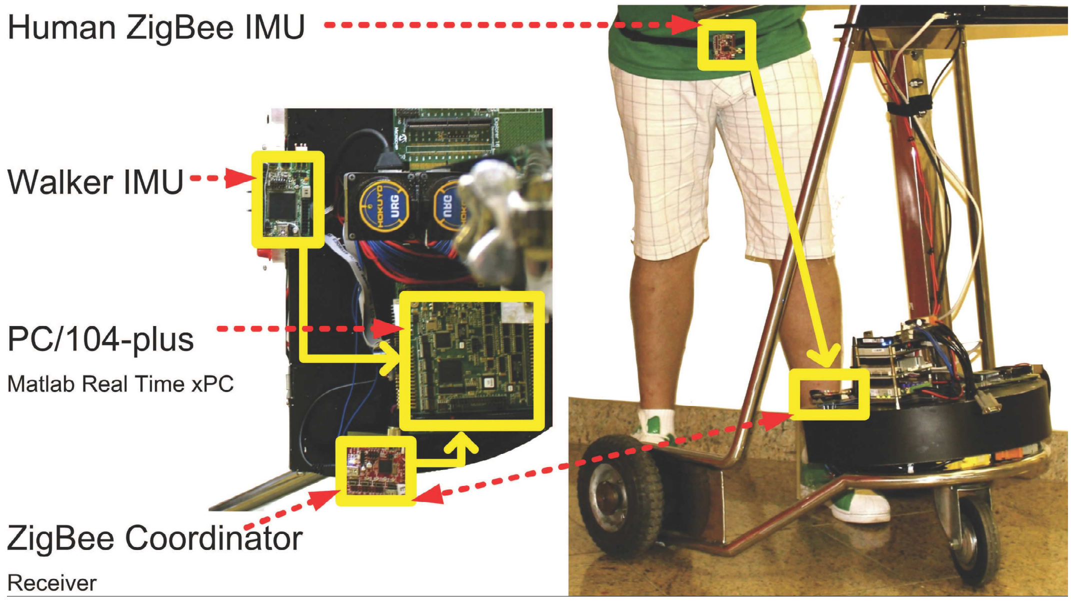


FIGURE 4.8: Positioning of the IMU sensors and their functional scheme of interaction.

the project has been developed in the *Laboratório de automação inteligente* and consists in an Inertial Measurement Unit, also called IMU, presented in [56]. The sensor works at a sampling frequency of $50Hz$.

The presented IMU is composed by a triaxial accelerometer, a triaxial gyroscope and a triaxial magnetometer; the combination of the information of these sensors allows the measurement of three-dimensional orientation of the device.

Figure. 4.8 represents the configuration used for the IMUs placed on the user and on the walker. On the left the ZigBee coordinator and the walker IMU with its physical communication with the *PC/104-plus*. On the right the human IMU that transmits to the coordinator through wireless communication.

In order to develop a sensor easy to use and to carry around the data is transmitted with a wireless connection. The communication technology used in this case is the ZigBee [57].

4.2.3 Central processing unit

This subsystem is the central processing unit and is based on the embedded architecture *PC/104-Plus*. This architecture is low power consumption and allows great flexibility in the hardware, since it is modular. Moreover, the size is reduced compared to a normal PC with the same processing capacity [58].

The user IMU signals and the LRF data, once pre-processed by a 16 bits microcontroller, are received by the ZigBee receiver and communicated to the *PC/104-Plus* through one serial interface. The motor control system and the walker IMU, pre-procesed with an 8 bits microcontroller, use the other serial interface of the *PC/104-Plus*.

This subsystem operates in real time and is programmed using the Matlab ToolBox *Real-Time xPC Target*. System programming is accomplished by an Ethernet port. This same port can be used for the storage of data from the system to perform analysis and processing. The code implemented in real time takes care of the low level control (PID, explained in Paragraph. 4.2.4) and high-level control (Inverse kinematics, explained in Paragraph. 4.3).

The processed data is sampled at 1 KHz. This unexpected feature is due to the fact that the walker is also used in other projects developed at the *Laboratório de automação inteligente*. In some of these projects force sensors placed on the forearm supports are used and their sampling time is 1KHz, for synchronization necessities all the on-board hardware is programmed with this sampling frequency.

4.2.4 Low level control: motors and encoders

The driving force responsible for the walker is a pair of DC motors of 40 rpm manufactured by DOGA[59]. The gear is self-blocking, so that any problem of power failure causes the engine block the walker. This is done in order to ensure user safety in case of electrical failure. Moreover, the sensors used are encoder with a resolution of 1200 pulses per revolution. Each encoder disk is fixed to the motor shaft and allows to have information about speed and position of the walker.

From the point of view of kinematics modeling, UFESsmart walker can be seen, simply, as a mobile robot with two wheels and differential traction, as modeled in Figure. 4.9.

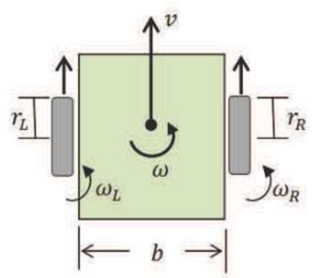


FIGURE 4.9: Model of a mobile robot with two differential wheels.

The linear velocity v and the angular velocity ω of the walker on the basis of the angular velocities of the wheels ω_r and ω_r can be obtained from Equation. 4.1, being r_L and r_R the radius of the left and right wheels and b the distance between the two wheels.

$$\begin{bmatrix} v \\ \omega \end{bmatrix} = \begin{bmatrix} \frac{r_R}{2} & \frac{r_L}{2} \\ \frac{r_R}{b} & -\frac{r_L}{b} \end{bmatrix} \cdot \begin{bmatrix} \omega_R \\ \omega_L \end{bmatrix} \tag{4.1}$$

In an ideal model, where all parameters of the two wheels and motors are identical and assuming perfect symmetry in the structure, the application of the same voltage to the two engines would cause the wheels to spin at the same speed and the walker to follow a straight line. However, this behavior is not observed in practice. This is due, among other factors, to the differences in size between the wheels and the asymmetries in the device. This also occurs because the behavior of the engines depend not only on the applied voltage, but also on the load to which they are subject. For these reasons, to ensure that the walker performs linear and angular velocities properly a low level controller has been programmed.

Then, by means of encoders, the wheel speeds are measured and compared with the desired value. The difference is the error that is used by the Proportional-Integral controller to calculate the new control action[60]. The control parameters have been defined empirically.

4.2.5 High level software

The high-level software tool is done in Matlab/Simulink using the application *xPC Target*, which is a software package used in order to create control in real time. The environment *xPC Target* uses two computers: the first is a computer (*host*), with Matlab/Simulink installed to create models using blocks and flow diagrams. Models created can be executed *off-line*, to simulate and test the system response. The *host* uses the *Real-Time Workshop* and a C compiler to create an executable code from the model created, which will be used on a second computer embedded in the walker (*PC/104-Plus*) to execute the application in real time.

4.2.6 Power Supply

The UFES smart walker power supply system is composed by 3 cells of lead-acid rechargeable batteries of $6V$ voltage with $12A$ current each, which power the *PC/104-Plus*. Through the *PC/104-Plus* all other subsystems are fed.

4.3 Control Strategy based on IMU and LRF on horizontal ground

In [61], is presented a previous project developed at the *Laboratório de automação inteligente* with a Pioneer 3-AT [62]. This robot is controlled with the first version of the "following in front method". The motion asked to the robot is called "following in front" because the robot is always in front of the user, but it's attitude depends on human's intention, which physically follows the robot.

Based on the work exposed in [61] it has been developed a control strategy for the UFES smart walker. The human-robot interaction strategy is based on the analysis of human gait with the use of data fusion from a wearable IMU, an on-board IMU and a LRF sensor. This approach is focused on tracking human motion in order to obtain a controlled movement of the walker, in front of the user, dependent on natural parameters of the user.

The presented model of human-robot interaction is shown in Figure. 4.10, the most significant variables and parameters are drawn in the scheme and listed below: human linear velocity v_h, human angular velocity ω_h, human orientation ψ_h, robot linear velocity v_w , robot angular velocity ω_w, robot orientation ψ_w. Some interaction parameters are defined, such as the angle φ, the angle θ, the human-walker distance d between point W and H and the geometrical parameter a.

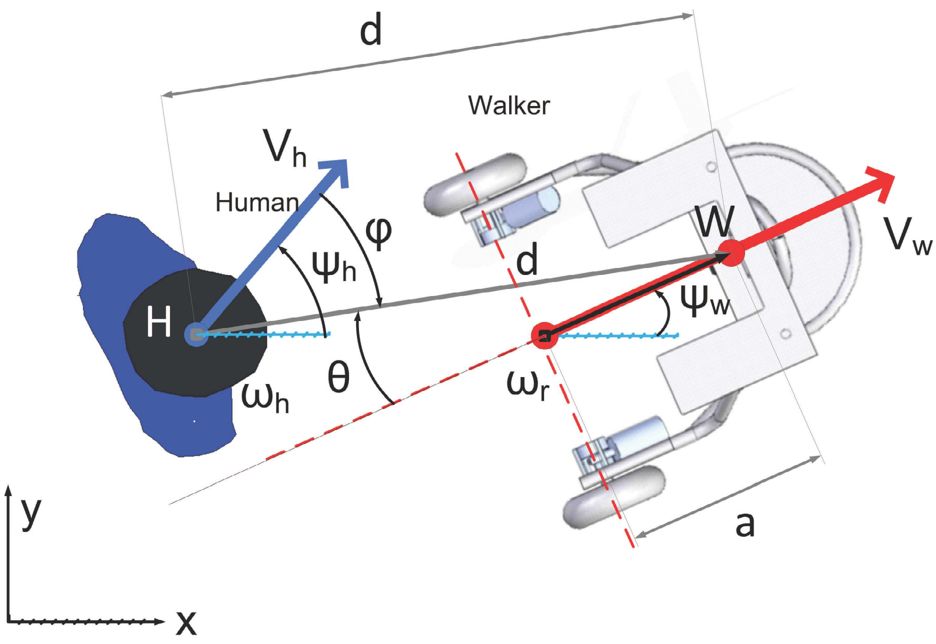


FIGURE 4.10: Human-walker interaction scheme in an upper view.

The basics of the proposed control is the inverse kinematics. Two variables are the ones to be controlled, the target of the control: the φ angle and the d distance. In this version of the control law the target is to achieve the φ angle to converge to the value 0 and the actual human-robot distance d to be equal to a desired value.

Equation 4.2 represents the direct kinematics of the robot, where $\tilde{\varphi}$ and $\tilde{d}$ are the difference between the desired and the measured values.

$$\begin{pmatrix} \dot{\tilde{d}} \\ \dot{\tilde{\varphi}} \end{pmatrix} = \begin{pmatrix} \cos(\theta) & -a\sin(\theta) \\ -\frac{\sin(\theta)}{d} & -a\frac{\cos(\theta)}{d} \end{pmatrix} \overbrace{\begin{pmatrix} v_w \\ \omega_w \end{pmatrix}}^{u} + \begin{pmatrix} -v_h\cos(\varphi) \\ \omega_h + v_h\frac{sin\varphi}{d} \end{pmatrix} \tag{4.2}$$

Starting from this kinematics model, it is possible to write the inverse kinematics controller shown in equations 4.3 and 4.4, which are the two components of the u-vector.

$$v_w = \cos(\theta) \left[-k_d\tilde{d} + v_h\cos(\varphi)\right] - dsin(\theta)\left[-k_\varphi\tilde{\varphi} - \omega_h - \frac{v_h}{d}\sin(\varphi)\right] \tag{4.3}$$

$$\omega_w = -\frac{\sin(\theta)}{d}\left[-k_d\tilde{d} + v_h\cos(\varphi)\right] - \frac{d}{a}\cos(\theta)\left[-k_\varphi\tilde{\varphi} - \omega_h - \frac{v_h}{d}\sin(\varphi)\right] \tag{4.4}$$

At this point it is necessary to introduce a heavy hypothesis that simplifies widely the complex problem that we are facing: dynamic effects are not taken into account in the control strategy [5], which makes the problem much lighter and easier to solve. This hypothesis is introduced because of the very limited speed at which the walker will be pushed in his prescribed tasks. A perfect velocity tracking ability is assumed and no dynamic effect is considered.

Based on the presented model of the human-walker interaction and the hypothesis, it's shown that the control errors $\tilde{d}$ and $\tilde{\varphi}$ converge to the desired value.

This conclusion becomes clear after substituting eq. 4.3 and eq. 4.4 into eq. 4.2, thus obtaining,

$$\begin{pmatrix} \dot{\tilde{d}} \\ \dot{\tilde{\varphi}} \end{pmatrix} = \begin{pmatrix} -k_d\tilde{d} \\ -k_\varphi\tilde{\varphi} \end{pmatrix} \rightarrow \begin{cases} \dot{\tilde{d}} + k_d\tilde{d} = 0 \\ \dot{\tilde{\varphi}} + k_\varphi\tilde{\varphi} = 0 \end{cases} \tag{4.5}$$

Therefore, the control system is exponentially asymptotically stable,

$$\tilde{d}\,(t) = \tilde{d}\,(0)\, e^{-k_d t} \tag{4.6}$$

$$\tilde{\varphi}\,(t) = \tilde{\varphi}\,(0)\, e^{-k_\varphi t} \tag{4.7}$$

4.3.1 Parameters extraction

The control strategy proposed needs the following parameters as input in order to control the walker. All of them are observable in the upper view of Figure. 4.10.

angle θ and human-robot distance d
: represent the human orientation seen from the LRF on-board and the human robot distance. The algorithm for their extraction using the LRF sensor has already been explained in paragraph 4.2.1.

human and walker orientations ψ_h and ψ_w
: are extracted by the IMUs orientation angles, respectively positioned on the human pelvis and on the walker, with the technique explained in paragraph 4.2.2.

φ Angle
: is extracted from Equation. 4.8 and is defined only if the magnitude of v_h is greater than zero.

$$\varphi = \theta - \psi_w + \psi_h \tag{4.8}$$

Human angular velocity ω_h
: is directly extracted by the IMU on the walker with the technique explained in paragraph 4.2.2.

Human linear velocity v_h
: is determined with an adaptive estimation algorithm, that is described in the next paragraph.

Robot linear velocity v_w and robot angular velocity ω_w
: are the outputs of the controller and are fed back into the control loop.

4.3.2 Linear velocity estimation

In [63] it's exposed a method for estimation of linear velocity developed in the *Laboratório de automação inteligente*, applied on the UFES smart walker. This method has been developed on passive mode, meaning without the use of propulsion on walker's wheels, but it is useful to extract parameters in any configuration of the walker.

The proposed method is based on the detection of the position of user's legs with the LRF embedded in the walker and proposes a filtering strategy, with the use of adaptive algorithms, such as WFLC (Weighted Frequency Fourier Linear Combiner) and FLC (Fourier Linear Combiner) [64] to extract gait parameters: cadence, amplitude and linear velocity of the user, to be used as control parameters in real time.

The estimation algorithms are used in the configuration shown in the scheme in Figure. 4.11 to determine user's linear velocity. The two signal corresponding to user's legs distances D_{pe} and D_{pd} are subtracted one with the other, the obtained differential signal Dif is passed to the WFLC algorithm that manages to extract the gait cadence from it. Then the FLC algorithm estimates the amplitude coefficients of the Fourier Series, selecting just the frequency found by the WFLC, the gait cadence, determining the amplitude of the differential signal. Once cadence and amplitude are available, it is possible to determine user's linear velocity simply multiplying them[65].

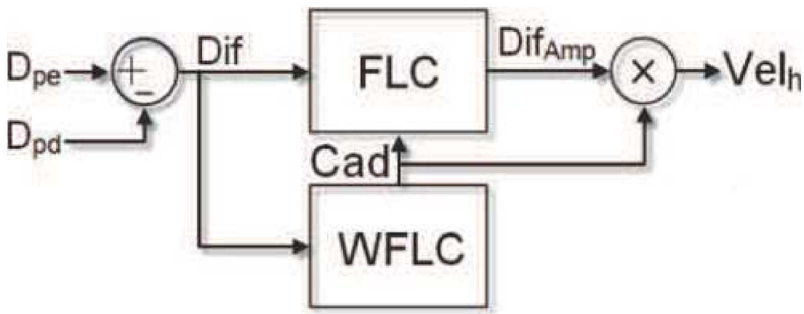


Figure 4.11: Scheme of the adaptive algorithms used in the estimation of linear velocity of the user, based on LRF data

The FLC and WFLC algorithm are briefly described in this paragraph. For more detailed information refer to [65].

The FLC adaptive algorithm, shown in Figure. 4.13, allows the estimation of the amplitude and phase of an almost-periodic signal with known frequency. The estimation of the coefficients of the Fourier series is made dynamically with a recursive Least Squares Algorithm (LMS)[66]. The FLC provides an output of phase 0 and low computational cost, thus allowing its implementation in real time[67]. The Fourier model of M harmonics is given by equation 4.9.

$$s = \sum_{r=1}^{M} [w_r sin\ (r\omega_0 k)\ +\ w_{M+1} cos\ (r\omega_0 k)]$$

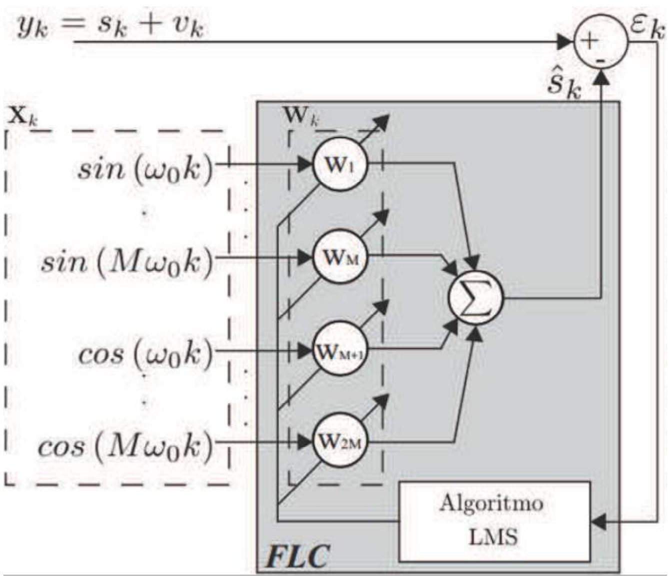


FIGURE 4.12: Adaptive algorithm Fourier Linear Combiner (FLC)

The recursive algorithm of Least Mean Square (LMS) adapts the vector of coefficients of the Fourier Series, the W_k, which are used to produce a linear combination of sines and cosines which are orthogonal to the components of the vector of input X_k. The FLC algorithm can be defined as:

$$x_{r_k} = \begin{cases} \sin(r\omega_0 k)\ ,\ \ 1 \le r \le M \\ \cos((r - M)\,\omega_0 k)\ ,\ \ M+1 \le r \le 2M \end{cases} \tag{4.10}$$

$$\varepsilon_k = y_k - W_k^T X_k \tag{4.11}$$

$$W_{k+1} = W_k + 2\mu\varepsilon_k X_k \tag{4.12}$$

There are M parameters to define, one per each harmonic that we want to estimate, in our case just 1.
The selected weight used to update amplitude μ is equal to $1.8 * 10^{-3}$. These weights have been obtained experimentally, testing people without locomotion disabilities.

An extension of the FLC is also used, the adaptive algorithm Weighted-frequency Fourier Linear Combiner WFLC, shown in Figure. 4.13. The filter allows to estimate amplitude, frequency and phase of an almost-sinusoidal signal using a truncated Fourier series, where the Fourier coefficients will be adjusted dynamically by using the recursive LMS algorithm.

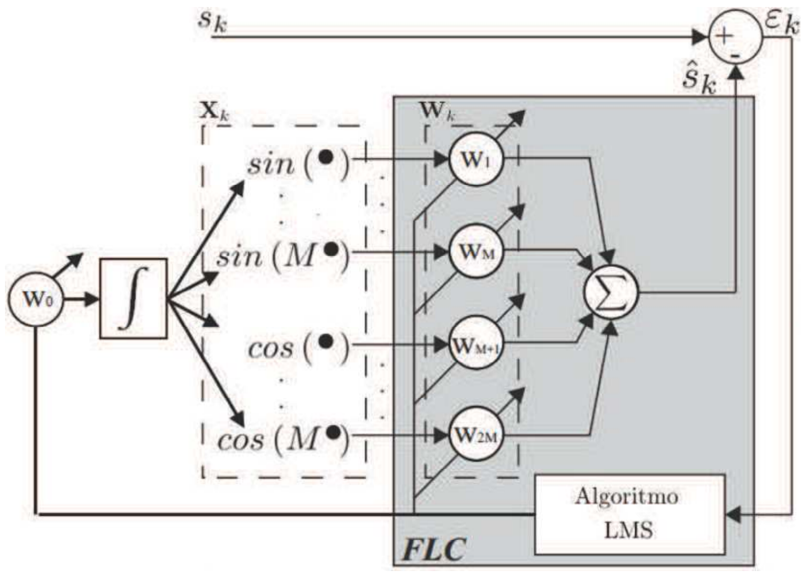


FIGURE 4.13: Adaptive algorithm Weighted-frequency Fourier Linear Combiner (WFLC)

WFLC is described by the following equations, from 4.13 to 4.16

$$\mathrm{x_{r_k}} = \begin{cases} \sin\left(\mathrm{r}\sum_{\mathrm{t}=1}^{\mathrm{k}} \omega_{0_\mathrm{t}}\right), & 1 \leq r \leq M \\ \cos\left(\mathrm{r}\sum_{\mathrm{t}=1}^{\mathrm{k}} \omega_{0_\mathrm{t}}\right), & M+1 \leq r \leq 2M \end{cases} \tag{4.13}$$

$$\varepsilon_\mathrm{k} = \mathrm{s_k} - \mathrm{W_k^T X_k} - \mu_\mathrm{b} \tag{4.14}$$

$$\omega_{0\mathrm{k}+1} = \omega_{0\mathrm{k}} + 2\mu_0 \varepsilon_\mathrm{k} \sum_{\mathrm{r}=1}^{\mathrm{M}} \mathrm{r}\left(\mathrm{w_{r_k} x_{M+r_k} - w_{M+r_k} x_{r_k}}\right) \tag{4.15}$$

$$\mathrm{W_{k+1}} = \mathrm{W_k} + 2\mu_1 \varepsilon_\mathrm{k} \mathrm{X_k} \tag{4.16}$$

From these equations we are able to extract amplitude, frequency and phase. Equation 4.13 defines a sinusoidal signal of fundamental frequency ω_{0t}. Equation 4.14 has as output the error used for the adaptation in the LMS algorithm, error in between the actual signal and the estimated one. Morevoer, equation 4.15 and 4.16 have the role to update for every iteration with the LMS algorithm the weights ω_{0t} and W_t respectively for frequency and amplitude estimation.

The parameters that had to be defined experimentally are the following:

- M, which is the number of harmonics to be estimated. For this work it is equal to 1 being one the cadence of the gait to be found,
- ω_0, the instantaneous frequency to begin with. In this case it has been used $1\frac{rad}{s}$,
- μ_0 and μ_1 which are parameters used in order to update correctly the amplitude and frequency weight, respectively. μ_0 is equal to $2 * 10^{-5}$and μ_0 is equal to $1.5 * 10^{-3}$,
- μ_b, necessary to compensate the low frequency drift, in this case equal to 0[68].

These parameters have been tuned to estimate the cadence of the input signal.

4.3.3 Validation of the linear velocity estimation algorithm

To validate the linear velocity estimation algorithm 6 users without pathology associated with gait were chosen. These have the following characteristics: two have a height exceeding 180 cm (High - Figure. 4.14a), two are between 170 cm and 180 cm (Medium - Figure. 4.14b) and two are lower than 170 cm (Short - Figure. 4.14c). Each user performed eight repetitions of a straight path of 12 m length with the Walker.

FIGURE 4.14: 3 Users while performing the test, on the picture are marked the four point that allow to calculate the corrective coefficient CC. Respectively are representing: (a)a tall person, (b)an average height person (c)a short person.

Of the repetitions, four were made using a 0.5 step per second rate and the other four with a 1 step per second rate. The pace of the march was set by a metronome and the ground was marked every 500 mm with tape. Thus, we defined two walking speeds: 250 mm/s and 500 mm/s for the validation of the proposed methodology.

4.3.3.1 Corrective Coefficient (CC)

As can be seen in Figure. 4.14, the largest amplitude of each step is given by $distance_{3-4}$ corresponding to the marks on the floor, but the value measured by the laser sensor is $distance_{1-2}$.

All experiments were video-recorded in order to measure offline the ratio between the two distances, and make adjustments to the depicted extracted parameters and so to minimize the position error of the laser sensor. After analyzing the data from the 6 patients it has been averaged a constant ratio between the two, defined by the relation: $distance_{3-4} = k{*}distance_{3-4}$. This constant is used to multiply the amplitude estimated by the FLC block to obtain the actual amplitude of the step. The value found for k is 1.6 .

4.3.3.2 Experimental Results

In Figure. 4.15 one can observe an experiment done with cadence of one step per second as an example.

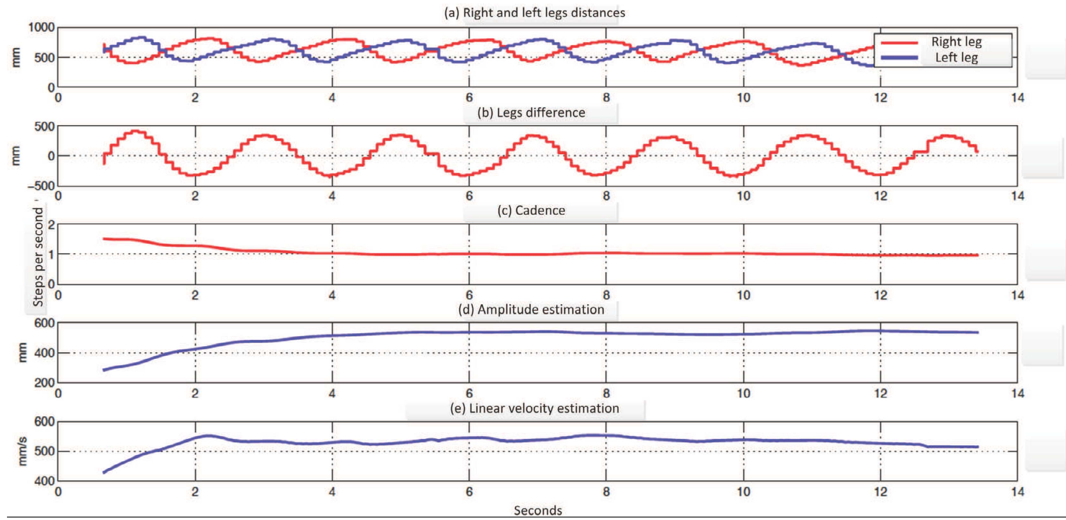


FIGURE 4.15: Results of test done with 1 step/sec walking speed.(a) Distance from the LRF of the legs, the right one in red and the left one in blue, (b) Difference in between the position of the two legs, (c) cadence estimated by the algorithm WFLC (d) Amplitude estimated by the algorithm FLC (with the CC); (e) speed obtained by the product of the amplitude and the estimated cadence.

Figure. 4.15a shows the position of the legs, in red the right leg and in blue the left leg. The difference in position of the legs, which is the input for the speed estimation algorithm, is shown in Figure. 4.15b. Figure. 4.15c shows the cadence estimated by the WFLC algorithm. As defined in the specifications of the experiment, the amplitude of