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ROBOTIC INTERACTION AND COOPERATION

Industrial and rehabilitative applications

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Abstract

The main goal of the thesis is the development of human-robotic interaction control strategies, which enable close collaboration between human and robot. In this framework we studied two different aspects, with applications respectively in industrial and rehabilitation domains.

In the first part safety issues are examined on a scenario in which a robot manipulator and a human perform the same task and in the same workspace. During the task execution the human should be able to get into contact with the robot and in this case an estimation algorithm of both interaction forces and contact point is proposed in order to guarantee safety conditions. At the same time, all the unintended contacts have to be avoided, and a suitable post collision strategy has been studied to move away the robot from the collision area or to reduce the impact efforts.

However, the second part of the thesis focus on the cooperation between an orthesis and a patient. Indeed, in order to support a rehabilitation process, gait parameters, such as hip and knee angles or the beginning of a gait phase, have been estimated. For this purpose a sensor system, consisting of accelerometers and gyroscopes, and algorithms, developed in order to avoid the error accumulation due to the gyroscopes drift and the vibrations related to the beginning of the stance phase due to the accelerometers, have been proposed.

Contents

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Summary

The most revolutionary and challenging feature of the next generation of robots will be physical Human-Robot Interaction (pHRI).

pHRI robots will be designed to coexist and cooperate with humans in applications such assisted industrial manipulation, domestic work, entairtnment, rehabilitation or medical applications.

Therefore safety become the most important issue for a robot that has to share the workspace with a human.

The contributes of this thesis pursue the aim of improving the safety of a robot interacting with human operators. Furthermore, in the particular application of rehabilitation, a method for gait analysis is proposed, in order to achieve a better cooperation between an orthesis and a patient.

In addition this research activity has been involved in a research program of national interest.

In details the contents of this thesis are organised as follows.

- Chapter 1 is an introduction that presents the relevance of human-robot interaction and of safety. Furthermore is pointed out the difference between physical and cognitive interaction. Finally the framework of the research activity presented in the thesis, that is the national research project ROCOCO, is introduced.

- Chapter 2 contains a review about the different aspects of human-robot interaction. The interaction, in its simplest manifestation, implies a physical contact between the robot and the human, leading to the application of controlled forces between both actors. The actions of the two agents must be coordinated and adopted reciprocally since unexpected behaviour of one of them during interaction can result in severe injuries. Finally several methods to achieve safety are proposed.

- Chapter 3 deals with the problem of collision detection, that is an important issue both for collision avoidance and for the post collision reaction strategy. The aim of this chapter is to present algorithms

which allow the collision detection, and in particular the momentum-based method, that is the basis of the approach proposed in this thesis.

- Chapter 4 considers the problem of controlling a robot manipulator in the task space, while ensuring a compliant behavior in the circumstance of a collision occurrence. Furthermore, in the case of intentional contact, due to the execution of collaborative tasks, an algorithm for the estimation of both contact point and contact force is proposed, in order to predict human motion intentions.

- Chapter 5 is aimed at showing how the presented algorithms and HRI control strategies have been used on an industrial manipulator. Indeed, the control approach proposed has been tested on a scenario in which a robot manipulator is executing a motion task and a human operator enters in its workspace.

- Chapter 6 contains a review about gait analysis, that consists in a systematic study of human motion by instrumentation for measuring body movements, body mechanics, and the activity of the muscles. Finally wearable sensor systems, mainly used at this purpose, are introduced.

- Chapter 7 introduces a wearable sensor system, consisting of accelerometers and gyroscopes, in order to estimate hip and knee angles. The proposed algorithms pursue the aim of avoiding the error accumulation due to the gyroscopes drift and the vibrations related to the beginning of the stance phase due to the accelerometers.

- Chapter 8 is aimed at showing how the presented methods for the gait phase detection have been used.

- Chapter 9 deals with concluding remarks and possible developments.

Chapter 1

Introduction

A robot, according to its ethimology (the czech world *robota* means forced work) should help or substitute people in dangerous, repetitive, or boring tasks, enhance human possibilities, and be able to cooperate with humans in shared environment. The extension of application domains for robotics, from factories to human environments, is due to the elderly-dominated scenario of most industrialised countries, the desire of automatizing common daily tasks, and the lack or high cost of local human expertise.

Teleassistance and the use of computers and devices for remote medical care are already paving the way to the future use of robots in domestic environments. Suggested applications in service robotics include not only medical, domestic, personal assistance and home care domains, but also public-oriented service, cooperative material-handling, power extenders and rehabilitation devices for physical training, entertainment, and health-care applications.

For this reason robotic research is quickly moving its focus from *robots that can work in place of humans* to *robots that can collaborate with humans*. This trend has been supported by the recent progresses in robotic hardware and software technology that allow a safer physical Human-Robot Interaction.

Safety is the inherent and most important feature of a robot that has to work in an unstructured environment, sharing the workspace with a human operator and allowing a close physical cooperation. Indeed, the cooperation is the robot feature of performing a complete task with direct human interaction, namely an explicit and intentional contact with exchange of forces.

The key distinctive aspect of human-robot interaction is the intrinsic dual aspect of cognitive and physical interaction.

On the one hand, in physical Human-Robot Interaction (pHRI), humans and robots are supposed to share the same workspace, come in touch with each other, exchange forces, and cooperate in doing actions on the environment.

Therefore the classical solutions for preserving safety in industrial environments (using cages or stopping the robot in the presence of humans), are clearly inappropriate for pHRI. The current approach for reducing the possibility of injuries to the humans, as well as of damages to the robot, merges several internal and external safety-oriented features, at the mechanical, sensory and control levels.

The safest possible solution is namely to avoid any undesired contact (collision) with humans or environment obstacles. Unfortunately, collision avoidance may fail due to the limits of sensors and robot motion capabilities, e.g., if the human moves faster than the robot can sense or counteract. In this event, it is still possible to detect a physical collision and react to it so that the impact effect are reduced, or anyway the robot is immediately removed from the collision area.

On the other hand, one of the crucial roles of a cognitive human-robot interaction (cHRI) is to make the human aware of the possibilities of the robot while allowing him to maintain control of the robot at all times. Therefore cHRI concerns the communication between human and robot.

In the rehabilitation field, the key role of a robot in a physical human-robot interaction is the generation of supplementary forces to empower and overcome human physical limits ([12]), be they natural or the result of a disease or trauma. This involves a net flux of power between both actors, hence the pHRI is based on a set of actuators and a rigid structure that is used to transmit forces to the human musculoskeletal system. However, a cognitive human-robot interface (cHRI) in the human-robot direction is based on data acquired by a set of sensors to measure bioelectrical and biomechanical variables.

Therefore, wearable lower limb exoskeletons to assist patient to rehabilitate patterns of movement constitute a paradigm of very close Human-Robot Interaction. Human need robotic assistance to perform some task. Although the robotic control strategies used are based on physical interaction, the robot needs to know when to apply them and which the user needs at a given moment. Therefore a cognitive process is required so that the user can generate commands and select the control strategy to be applied.

In this framework the gait analysis is an efficient manner of providing useful information for several health-related applications.

Indeed, gait analysis is the systematic study of human motion by instrumentation for measuring body movements, body mechanics, and the activity of the muscles. Through this kind of analysis, the gait phase can be identified and afterwards it is possible to control properly the system in order to support the rehabilitation of gait patterns.

Summarizing, safety and dependability are the keys to a successful introduction of robots into human environments. Only dependable robot architectures can be accepted for supporting *human-in-the-loop* conditions and human-robot teams, and the safety of humans cooperating with robotic systems is the main need for allowing pHRI.

The main goal of the thesis is the development of human-robot interaction control strategies, which enable close collaboration between human and robot. The thesis is divided in two parts, developing the two different aspect of interaction presented above.

In the former safety during cooperation between human and robot is the most important issue. Cooperation means that human and robot perform together the same task in the same workspace. During the task execution the human should be able to get into contact with the robot, but, at the same time, all the unintended contacts have to be avoided, and when they occurs, suitable post collision strategies must be adopted to reduce the impact effects. Furthermore, by estimating contact forces, due to the intentional contacts, the robot can predict human motion intentions and react accordingly.

On the other hand, the latter deals with gait analysis. In order to support a rehabilitation process and improve the patient's pattern of movement suitable control strategies should be determined. For this purpose gait phases has to be identified, by means of the estimation of kinematic parameters, such as joint angles.

Focusing on the activity which constitutes the framework for this thesis, a research projects has been proposed for facing the complexity of these topics, and for providing significant advances and insight in the territory of cooperative robotics: the Research Program of National Interest named ROCOCO-COoperative and COollaborative RObotics. The project program dealt with the development of control solutions for robotic systems in cooperation, also with human beings, to execute different task.

In particular the unity of research of Palermo focused on the safety aspect of Human-Robot Interaction, contact estimation and reaction problems; furthermore the aim we intended to achieve in this field was the development of a mechatronic system, able to cooperate with the patient for the acquisition or rehabilitation of specific gait patterns.

Chapter 2

A review about Human-Robot Interaction

While traditional optimality critera for industrial robotics were meant to maximize production, the presence of a person in the robot's workspace neutralises the idea of enforcing safety by segregating machines and human users, like in the present industrial workspaces.

The interaction, in its simplest manifestation, implies a physical coupling between the robot and the human, leading to the application of controlled forces between both actors. The actions of the two agents must be coordinated and adopted reciprocally since unexpected behaviour of one of them during interaction can result in severe injuries.

2.1 Safety in Human-Robot Interaction

Since the very beginning of industrial robotics a great deal of attention has been paid to robot safety [1]. The first line of defense has always been to take all measures to enforce segregation between robot and people.

However, the segregation paradigm fails in cases where the human and the robot must share the physical environment and in applications in which successful task completion requires collaboration.

Data on industrial robot-related fatalities indicate that, even in traditional applications of industrial robots, safety is not a solved problem, especially because of all the operational phases, where the human operator is by necessity physically close to the mechanical arm or vehicle.

Furthermore the presence of autonomous behaviour, due to the fact that it is impossible to model every action in an unstructured anthropic environment, can result in dangerous situations for humans co-existing in the robot operational domain.

Many crucial points for robots in human environments can result in danger, such as natural motion, unexpected behaviours caused by the necessary autonomy, faults. It is clear how physical issues are crucial, since "natural" or unexpected behaviour of people during interaction with robots can result in very severe injuries caused by accidental collisions.

Therefore, safety and dependability are the keys to a successful introduction of robots into human environments. However, it must be pointed out that safety standards for HRI (Human-Robot Interaction) are still not well defined in the scientific community.

The characteristics of robots and humans and the necesity to work in the same workspace have led to a new generation of safe human-interacting machines known as Intelligent Assist Devices (IADs) ([1]). IADs serve principally to augment the strength of a human, but they may also serve to guide motion, via virtual surfaces, or tracking of a moving assembly line.

The value of robot-human collaboration is also being discovered in a variety of non industrial environments: from exoskeletons as human power amplifier([2]) or as haptic interfaces in virtual-reality environment ([3]), to medical assistants and telesurgery ([4]) and to rehabilitation ([5]- [6]).

2.1.1 General aspects on safety in human-centered robotics

In the complexity of a HRI, the physical view point is mainly focused on the risks of collisions occurring between the robot and its user: too high energy/power may be transferred by the robot, resulting in serious human damages.

In order to increase robot safety, among the numerous aspects of manipulator design to be considered, the elimination of sharp edges can reduce the potential for lacerations. The main solution for reducing the istantaneous severity of impacts is to pursue a mechanical design that reduces manipulator link inertia and weight by using lightweight but stiff materials, complemented by the presence of compliant components in the structure. Compliance can be introduced at the contact point by a soft covering of the whole arm with visco-elastic materials or by adopting compliant transmissions at the robot joints([7]- [8]).

The safety tactics involve mechanics, electronics, and software. Improvements for anticipating and reacting to collisions can be achieved through the use of combinations of external/internal robot sensing, electronic hardware and software safety procedures, which intelligently monitor, supervise, and control manipulator operation.

Finally, the problem of blending the requirements for safety while keeping "traditional" robot performance (speed and accuracy) high remains an open challenge for the designers of human-centered robotic manipulators.

Indeed, promptness of an elastically actuated arm is intrinsically severely reduced, if compliance is high enough to be effective for safety. In other words, even if optimal methods for controlling very compliant arms were available, there are inherent limitations on performance imposed by such hardware. To overcome these limitations, a recent trend in intrinsically safe robotics advocates the co-design of the mechanics and control of passively compliant, yet fast, strong and accurate arms. Very compliant transmissions may ensure natural and safe interaction but be inefficient in transferring energy from actuators to the links for fast motion.

2.1.2 Safety standards for Human-Robot Interaction

This section cannot be exaustive: it will just point out some aspects of physical interaction with robots which claim for risk assessment procedures which complement the undergoing revolution ofstandards.

An importante example of standard for robot safety is the ANSI/RIA R15.06-1999 (American National Standard for Industrial Robots and Robot Systems-Safety Requirements). This standard addresses the requirements for personal safety in industrial environments where robotic manipulators are employed. The complementary design standard ANSI/UL 1740 states hardware requirements and specifications, harmonised with R15.06: if the hardwareis built in compliance with UL 1740, the safeguarding requirements in R15.06 are met. Other standards are present worldwide, as the European standard EN 775, and their international equivalent is the ISO 10218 ([9]).

This standard has been revised in 2006, while the modifications are not already effective. The modifications allow cooperation with prescribed limits for speed and power. However, it must pointed out that the case when robots and people have to share the operational space is not clearly discussed. Actually, the standard poses human-robot segregation in the workplace as the way to obtain safety. Work has been ongoing since, gradually turning what started as a simple harmonisation effort into a genuine development effort introducing new concepts to the world of industrial robot safety.

The revised ISO 10218 ("Robots for Industrial Environment-Safety") will be a two parts document. The first part, entitled “Design, Construction and Installation”, is intended to be fully compliant with the European Machinery Directive. The second part, entitled “Applications and Use of Robots in the Work Place”, is intended to address work place safety requirements and is directed more to the end-user than the manufacturer([10]).

Most salient changes under consideration involve the folowing issues:

- *new modes of operation*: the standard finally allows the introduction in the workspace of advanced robotics concepts, such as *simultaneous control* of multiple manipulators, *mobile* robots mounted on vehicles for industrial automation and *collaborative operation* in which purposely designed robots work indirect cooperation with a human within a defined workspace with the operator;

- *control reliability*: revised standards will allow safety-related control circuity to use state-of-the-art electronic, programmable, and network based technology (including wireless);

- *safeguarding and clearance*: instead of fixed safeguard distance, these can be evaluated based on the assessment of stopping time and distance to be provided by the robot manufacturer in different load conditions. In collaborative mode, hard limits on either the maximum dynamic power or maximum static force at the end-effector apply, as well as on its maximum velocity.

Although the revision of ISO 10218 is already taking into consideration many more advanced features than in the past, evolution is still ongoing. In partcular the American National Standards Institute (ANSI) has established a comittee, T-15, that has published a draft safety standard for intelligent assist devices (IADs) [11]. Notable aspects of the standard include:

- *Risk assessments replace fixed rules*: instead of declarations regarding how to accomplish safe operation, risk assessment procedures were advised for IAD and pHRI robotic technologies, to identify and mitigate risks in proportionto their seriousness and probability;

- *Safety-critical software*: the greater complexity of human-robot interaction, and the observation that an abrupt power-down is not always a safe solution, necessitate a greater reliance on safety-critical software rather than safety-critical hardware. The T-15 draft standard requires that controllers, under any single component failure, lead to the shutdown of the system in a safe state, maintenance of a safe load position,and the prevention of subsequent automatic operation;

- *Dynamic limits*: Speed must not exceed 2.0 m/s, a fast walk; overforce or overload devices or techniques must be used that can reliably detect an impulse force of 267 N. These and similar limits could be further reduced to the extent practical as determined by arisk assessment;

- *Emergency stops*: in some unexpected situations one might want an IAD to continue to actively track a moving vehicle, rather than come immediately to a halt and possibly drag a part and a person engaged in a moving line. The T-15 draft standard demands a traditional e-stop, but also permits that an IAD may have one or more context-based safety stop circuits. When used, inputs should be provided to allow application- specific external devices to initiate context-based safety stops;

- *Man-Machine Interface*: IADs may operate in different modes (free-mode, hands-on-controls, hands-on-payload, line, tracking, etc.). The T-15 committee found that *mode misunderstanding* was a likely cause of safety problems.

Criteria for defining safety levels in HRI (inside and outside factories) are strictly related to the possible injuries caused by robots. Note that recently some European robot manufacturers (ABB, KUKA Roboter, Reis Robotics) have included software modules that monitor through external sensing the Cartesian space around the robot and stop operations in case of danger. In particular, the KUKA Roboter GmbH is leading these changes, having developed a safety system for industrial robots incorporating a safety-related fieldbus, (SafetyBUS) in a car production line.

Several standard indices of injury severity exist in other, non-robotic, domains. For evident reasons, the automotive industry was the first to define quantitative measures, indices and criteria for evaluating injuries due to impacts. These sets of studies have been suggested as a starting point for safety evaluation in robotics, using the automotive crash testing which considers two distinct types of loading concerning head injuries. The first type is a direct interaction, i.e., a collision of the head with another solid object at appreciable velocity. The second type is an indirect interaction, i.e., a sudden head motion without direct contact.

Recent evidences suggested by DLR show that values of severity indices from automotive industry computed for collision on the the DLR LWR-III are not very adequate for robotics: the robot does not case serious harms according to the scaling, since operating velocities in pHRI are low with respect to those considered in setting severity indices for automobile crashtests.

2.2 Dual aspects of human-robot interaction

The key distinctive aspect of human-robot interaction is the intrinsic dual aspect of cognitive and physical interaction.

On the one hand, the key role of a robot in a physical human-robot interaction (pHRI) is the generation of supplementary forces to empower and overcome human physical limits ([12]), be they natural or the result of a disease or trauma. This involves a net flux of power between both actors. On the other hand, one of the crucial roles of a cognitive human-robot interaction (cHRI) is to make the human aware of the possibilities of the robot while allowing him to maintain control of the robot at all times.

In wearable robotics, a cognitive human-robot interface (cHRi) is explicitly developed to support the flow of information in the cognitive interaction (possibly two-way) between the robot and the human. Information is the result of processing, manipulating and organizing of data, and so the cHRi in the human-robot direction is based on data acquired by a set of sensors to measure bioelectrical and biomechanical variables.

On the other hand, the cognitive interaction can be used to modify the physical interaction between human and robot, for instance to alter the compliance of an exoskeleton. One example is tremor suppression based on exoskeletonhuman interaction: the onset of a tremor can be inferred from the biomechanical data of limb motion (cognitive process); this is used to modify the biomechanical characteristics of the human limb (damping and apparent inertia), which in turn leads to tremor reduction.

Similarly, a physical human-robot interface (pHRi) is explicitly developed to support the flow of power between the two actors. The pHRi is based on a set of actuators and a rigid structure that is used to transmit forces to the human musculoskeletal system. The close physical interaction through this interface imposes strict requirements on wearable robots as regards safety and dependability. Cognitive and physical interactions are not independent.

In exoskeletons, there is an effective transfer of power between the human and the robot. Humans and exoskeletons are in close physical interaction. This is the reverse of masterslave configurations, where there is no physical contact between the slave and the human operator, which are remote from one another. However, in some instances of teleoperation, an upper limb exoskeleton can be used as the interface between the human and the remote robot. According to this concept, the exoskeleton can be used as an input device (by establishing a pose correspondence between the human and the slave or remote manipulator), as a force feedback device (by providing haptic interaction between the slave robot and its environment), or both.

The interaction between the exoskeleton and the human limb can be achieved through internal force or external force systems. Which of these force interaction concepts is chosen depends chiefly on the application.

On the one hand, empowering exoskeletons must be based on the concept of external force systems; empowering exoskeletons are used to multiply the force that a human wearer can withstand, and therefore the force that the environment exerts on the exoskeleton must be grounded: i.e. in external force systems the exoskeletons mechanical structure acts as a load-carrying device and only a small part of the force is exerted on the wearer. The power is transmitted to an external base, be it fixed or portable with the operator. The only power transmission is between the human limbs and the robot as a means of implementing control inputs and/or force feedback.

On the other hand, orthotic exoskeletons, i.e. exoskeletons for functional compensation of human limbs, work on the internal force principle. In this instance of a wearable robot, the force and power are transmitted by means of the exoskeleton between segments of the human limb. Orthotic exoskeletons are applicable whenever there is weakness or loss of human limb function. In such a scenario, the exoskeleton complements or replaces the function of the human musculoskeletal system. In internal force exoskeletons, the force is nongrounded; force is applied only between the exoskeleton and the limb.

Superimposing a robot on a human limb, as in the case of exoskeletons, is a difficult problem. Ideally, the human must feel no restriction to his/her natural motion patterns. Therefore, kinematics and control strategies for the physical interaction play a key role in wearable exoskeletons: if robots and humans are not kinematically compliant, a source of nonergonomic interaction forces appears.

The distinctive characteristic of wearable robots is dual cognitive and physical interaction with the human wearer. This immediately raises dependability and safety issues in robotics. Dependability and safety ultimately have a close bearing on control, sensor and actuator technologies, which interact directly with the human.

2.3 A survey of physical Human-Robot Interaction

The most revolutionary and challenging feature of the actual generation of robots is physical Human-Robot Interaction (pHRI). In pHRI humans and robots share the same workspace, come in touch with each other, exchange forces, and cooperate in doing actions on the environment.

One crucial capability of a robot for pHRI is the generation of supplemen-

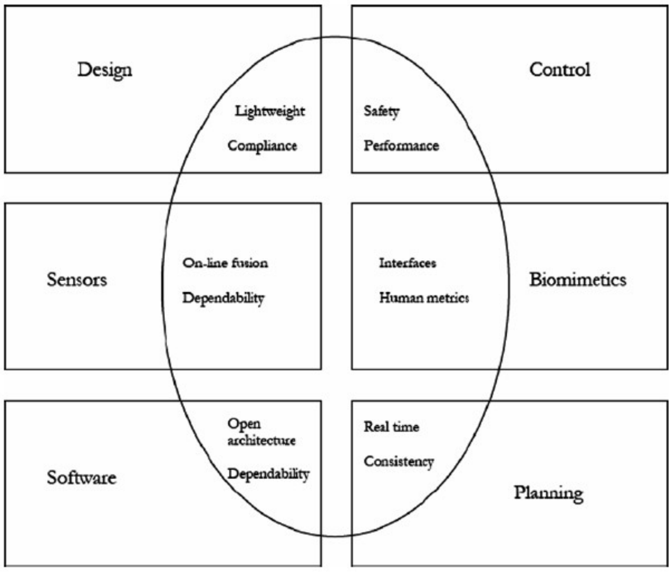


Figure 2.1: This map of robotics for anthropic domains includes the main issues and superpositions for pHRI

tary forces to overcome human physical limits. In anthropic domains, a robot may substitute the complex infrastructure needed for environments equipped with sensory systems capable of intelligent monitoring or telesurveillance. In these cases, instead of equipping the environment with many sensors and devices, a single robot could behave both as a sensor and as an actuator, able to navigate through different rooms, sense the environment, and perform the requested task.

Therefore, an improved analysis of the problems related to the physical interaction with robots becomes necessary. This topic must be addressed considering together the design of mechanism, sensors, actuators and control architecture in the special perspective for the interaction with humans.

Effective communication between a person and a robot may depend on whether there exists a common domain of understanding: HRI, which focuses on a complex combination of the user and the robot, including the relationship with the body of the robot, is different with respect to a simple human-computer interaction. Moreover, different roles of interaction with robots are possible since different people interact in different ways with the same robot, and the robot in turn reacts differently based on its perception of the world.

In addition, there are failure modes of the robot that can degrade the quality of the interaction and not only the safety. The interface design is crucial to let the human be aware of the robot possibilities and to provide her/him with a natural way to keep the robot under control at every time. With reference to Figure 2.1, it is worth noticing how numerous are research and development domains identified for a comprehensive approach to solutions for dependable robots in human environments.

2.3.1 Mechanics and control issues for a safe pHRI

The simple addition of a passive compliant covering in order to reduce impact loading is impractical and does not address the root cause of high impact loads due to the large effective inertia of most robotic manipulators. Moreover, protective skins or helmets for humans are normal only in industrial domains, and not natural in anthropic domains.

Modern actuation strategies, as well as force/impedance control schemes, seem to be anyway crucial in human-robot interaction. On the other hand, a more complete set of external sensory devices can be used to monitor task execution and reduce the risks of unexpected impacts. However, even the most robust architecture is endangered by system faults and human unpredictable behaviour. This suggests to improve both passive and active safety for robots in anthropic domains [7].

An important point which is a base for this thesis is the complementarity of the work in modelling and control for improved safety. The reduction of the possible effect of impacts depends on the minimisation both of the risk of collision and of consequences of collisions.

In particular, also planning/control approaches can have different strategies based on their role: very precise modelling of people and robot is precise and improves the task performance, reducing the limitations in robots motion for collision avoidance. However, it can be time-consuming; on the other hand, simple modelling can be too conservative, but very fast and possibly integrated into a variety of already implemented control systems, such force or impedance control for close interaction.

Mechanics and actuation for pHRI

Relevant service robots for pHRI

The first important criterion to limit injuries due to collisions is to reduce the weight of the moving parts of the robot. Moreover, the reduction of robots apparent inertia has been realised though different elastic actuation/transmission arrangements which include:

- relocation of actuators close to the robot base
- transmission of motion through steel cables and pulleys

- combination of harmonic drives and lightweight link design
- use of parallel and distributed macro-mini actuation with elastic couplings

A prototypical example of lightweight design is the DLR LWR-III [13]. Advanced light but stiff materials were used for the moving links, while motor transmission/reduction is based on harmonic drives, which display high reduction ratio and efficient power transmission capability.

In addition, there is the possibility of relocating all the relevant weights (mostly, the motors), at the robot base, like it has been done for the Whole Arm Manipulator (WAM) [14], manifactured by Barrett Technology. In the case of a collision, the lighter links display lower inertia and thus lower energy is transferred during the impact. On the other hand, compliant transmissions tend to decouple mechanically the larger inertias of the motors from those of the links. The presence of compliant elements may thus be useful as a protection against unexpected contacts during pHRI.

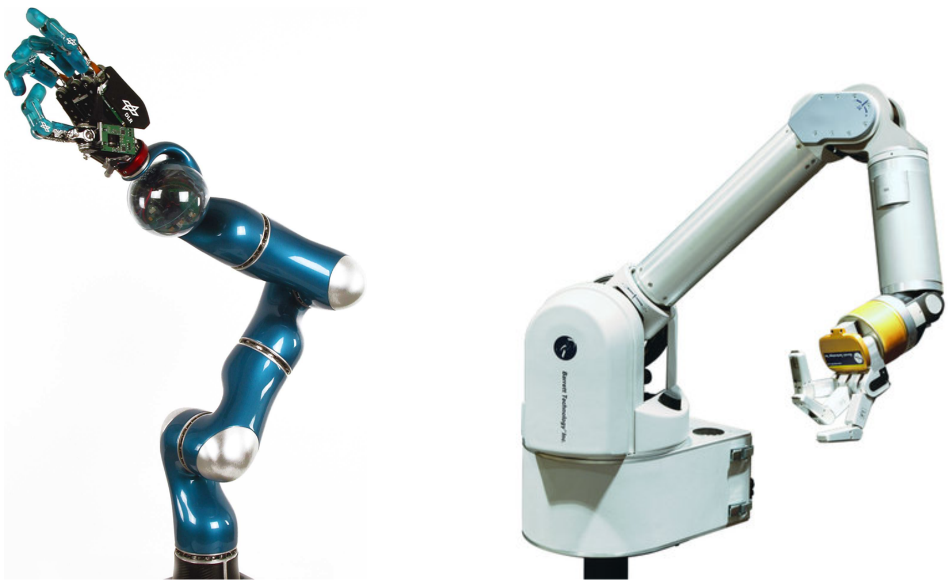


Figure 2.2: The DLR LWR-III arm (on the left) and the WAM (on the right)

On the other hand, in the presence of compliant transmissions, deformation can be assumed to be instead concentrated at the joints of the manipulator. Neglected joint elasticity or link flexibility limits static (steady-state error) or dynamic (vibrations, poor tracking) task performance. Problems related to motion speed and control bandwidth must be also considered. Flexible modes of compliant systems prevent control bandwidths greater than a limit; in addition, attenuation/suppression of vibrations excited by disturbances can be difficult to achieve. Intuitively, compliant transmissions tends to respond slowly to torque inputs on the actuator and to oscillate around the goal position, so that it can be expected that the promptness of an elastically actuated arm is severely reduced if compliance is high enough to be effective on safety.

Variable-impedance actuation

Very compliant transmissions may ensure safe interaction but be inefficient in transferring energy from actuators to the links for their fast motion. An approach to gain performance for guaranteed safety joint actuation is to allow the passive compliance of transmission to vary during the execution of tasks.

The variable impedance approach (VIA) ([15]-[16]) is a mechanical/control co-design that allows varying rapidly and continuously during task execution the value of mechanical components such as stiffness, damping, and gear-ratio, guaranteeing low levels of injury risk and minimizing negative effects on control performance. In this approach the best possible trade-off between safety and performance is desired. For a mechanism with given total inertia and actuator limits, one can formulate an optimal control problem to be used for comparing mechanical/actuation alternatives at their best control performance.

One interesting formulation is the following: find the minimum time necessary to move between two given configurations (with associated motion and impedance profiles), such that an unexpected impact at any instant during motion produces an injury severity index below a given safety level. This is called the Safe Brachistochrone problem [17]. The optimal solution obtained analytically and numerically for single-dimensional systems shows that low stiffness is required at high speed and vice versa.

Distribute macro-mini actuation

Another approach to reduce manipulators arm inertia for safety, while preserving performance, is the methodology of distributed macro-mini actuation DM2 [18]. For each degree of freedom (joint), a pair of actuators are employed, connected in parallel and located in different parts on the manipulator.

The first part of the DM2 actuation approach is to divide the torque generation into separate low and high frequency actuators whose torques sum in parallel. Gravity and other large but slowly time-varying torques are generated by heavy low frequency actuators located at the base of the manipulator. For the high-frequency torque actuation, small motors collocated at the joints are used, guaranteeing high performance motion while not significantly increasing the combined impedance of the manipulator-actuator system.

Finally, low impedance is achieved by using a series elastic actuator (SEA) [19], consisting of a relativelylarge actuator located atthe base of the manipulatorand connected to the axis through a spring, thus achieving low overall impedance. For the high-frequency torues needed, small motors collocated at the joints are used, providing high-performance motion while not significantly increasing the combined impedance of the manipulator-actuator system.

Control techniques for pHRI

Operational tactics can also actively contribute to safety, by means of suitable control laws, and more sophisticated software architectures may overcome some limitations of mechanical structure. Indeed, control methods cannot fully compensate for a poor mechanical design, but they are relevant for performance improvement, reduced sensitivity to uncertainties, and better reliability.

Typically, current industrial robots are position-controlled. However, managing the interaction of a robot with the environment by adopting a purely motion control strategy turns out to be inadequate; in this case, a successful execution of an interaction task is obtained only if the task can be accurately planned.

On the other hand, force/impedance control is important in pHRI because a compliant behaviour of a manipulator leads to a more natural physical interaction and reduces the risks of damages in case of unwanted collisions. Similarly, the capability of sensing and controlling exchanged forces is relevant for cooperating tasks between humans and robots.

Interaction control strategies can be grouped in two categories: those performing indirect force control and those performing direct force control. The main difference between the two categories is that the former achieve force control indirectly via a motion control loop, while the latter offer the possibility of controlling the contact force to a desired value, thanks to the closure of a force feedback loop. To the category of indirect force control belongs impedance control, where the position error is related to the contact force through a mechanical impedance of adjustable parameters. A robot manipulator under impedance control is described by an equivalent mass spring- damper system, with the contact force as input (impedance may vary in the various task space directions, typically in a nonlinear and coupled way).

If force measurements are available (typically through a robot wrist sensor), a direct force control loop could be also designed. Note that a possible way to measure contact forces occurring in any part of a serial robot manipulator is to provide the robot with joint torque sensors. The integration of joint torque control with high performance actuation and lightweight composite structure, like for the DLR LWR-III, can help merging the competing requirements of safety and performance.

As already mentioned, compliant transmissions can negatively affect performance during normal robot operation in free space, in terms of increased oscillations and settling times. However, more advanced motion control laws can be designed which take joint elasticity of the robot into account. For example, assuming that the full robot state (position and velocity of the motors and links) is measurable, a nonlinear model-based feedback can be designed that mimics the result of the well-known computed torque method for rigid robots, i.e., imposing a decoupled and exactly linearised closed-loop dynamics [20].

Moreover, in robots with variable impedance actuation, the simultaneous and decoupled control of both the link motion and the joint stiffness is also possible in principle, reaching a trade-off between performance and safety requirements.

2.3.2 Dependability in pHRI

One major problem for the introduction of robots (in particular with mobile bases) in unstructured environments is the possibility to rely on dependable sensors. Sensor data are needed for reactive planning, motion/ force control, visual servoing, fault diagnosis, and monitoring of safety levels. Due to the unstructured nature of anthropic domains and to the rather unpredictable movements of persons, a robot should be equipped with a complete set of sensors, including: range, proximity, touch, vision, sound, temperature, and so on.

Dependability of complex robotic systems in anthropic domains during normal operation is threatened by different kinds of potential failures or unmodeled aspects in sensors, control/actuation systems, and software architecture, which may result in undesirable behaviours. Due to the critical nature of pHRI, dependability must be enforced not only for each single component, but for the whole operational robot. Dependability is an integrated concept that encompasses the following attributes:

- *Safety*: absence of catastrophic consequences on the user(s) and the environment.

- *Availability*: readiness for correct service.

- *Reliability*: continuity of correct service, i.e., of completing tasks in a satisfactory manner.

- *Integrity*: absence of improper system alterations.

- *Maintainability*: ability to undergo modifications over time and repairs in case of failures.

In all pHRI situations, safety of robot operation is essential, given the presence of humans in contact with or in the vicinity of the robots. In this context, safety can be rephrased as "absence of injury to humans in the robots environment". Safety needs to be ensured both during nominal operation of the robot and in the presence of faults.

Fault handling

The possibility of conferring a proper degree of autonomy and safety to robots strongly depends on the capability to properly manage the possible occurrence of unexpected events, such as failures or abrupt changes of the environment. To preserve the safety of humans cooperating with robots during the execution of interaction tasks, fault handling and fault tolerant control have to be considered as fundamental functionalities [7].

Dependability is related on the ability of the system to cope with failures. To ensure acceptable levels of robot dependability attributes in pHRI, it is useful to define explicitly the types of faults that can affect the robot, and that need to be taken into account during development and deployment.

These can be very broadly described in terms of three non-disjoint fault classes:

- *physical (or internal) faults*, including both natural hardware faults and physical effects due to the environment (damage of mechanical parts, actuators and/or sensors faults, power supply failures, control unit hardware/software faults, radiation, electromagnetic interference, heat, etc.);

- *interaction (or external) faults*, including issues related to human-to-robot and robot-to-robot cooperation, robustness issues with respect to operation in an open, unstructured environment (such as sudden environmental changes and disturbances not usually acting during the normal system operation or exceeding their normal limits), and malicious interference with the robots operation;

- *development faults*, which may be introduced, usually accidentally, during the design or implementation of the hardware and software components of the robot.

All three faults classes need to be considered, with more or less emphasis depending on the application. One particularly delicate aspect in the context of robotics is that of development faults affecting the domain-specific knowledge embodied in robots world models and the heuristics in decisional mechanisms. Achieving dependability requires the application of a sequence of activities for dealing with faults:

- *fault prevention*, which aims at preventing the occurrence or introduction of faults;
- *fault removal*, which aims at reducing the number and severity of faults;
- *fault detection and isolation*, which aims at recognizing the occurrence of a fault and characterizing its type;
- *fault tolerance*, which aims at avoiding service failures in the presence of faults;
- *fault forecasting*, which aims at estimating the present number, the future incidence, and the likely consequences of faults.

Fault prevention and fault removal are collectively referred to as fault avoidance.

The robotic system has to be monitored during its normal working conditions so as to detect the occurrence of failures (fault detection), recognize their location and type (fault isolation), as well as their time evolution (fault identification).

Fault diagnosis methodologies are based on hardware redundancy, in the case of duplicating sensors, or on analytic redundancy, in the case that functional relationships between the variables of the system (usually obtained from the available mathematical model) are exploited. Usually, the output of a fault diagnosis algorithm is a set of variables sensitive to the occurrence of a failure (residuals), affected by a signature in the presence of a fault (fault signature). Therefore, the information from the signatures is processed to identify the magnitude and the location of the fault. Sometimes it is also possible to achieve a one-to-one relation between faults and residuals (decoupling), so that fault isolation is obtained, without further processing, after detection.

Existing analytical fault diagnosis techniques include observer-based approaches, parameter estimation techniques, and algorithms based on adaptive learning techniques or on soft computing methodologies. In practice, avoiding all possible faults is never fully achievable. Fault tolerance and fault forecasting are collectively referred to as fault acceptance.

In pHRI, fault acceptance requires tolerance (or robustness) with respect to adverse environmental situations and other interaction faults, and incorporation of redundancy to tolerate faults affecting robotic hardware or software. The concept of redundancy may be cast into a modular design philosophy, both hardware and software, that may guarantee that the effects of local faults remain internal to the modules, and also permits the reconfiguration of the system. In particular, fault tolerant control strategies can be separated into passive and active methods (possibly, to be combined).

The passive approaches are based on the adoption of robust control techniques to ensure that the controlled system remains insensitive to certain fault categories, considered as modelling errors and disturbances.

In the active approaches, when a failure occurs and is diagnosed (the fault has been isolated and possibly identified), the controller is reconfigured in order to preserve some properties of the controlled system, even though with degraded performance (adaptive control approaches belong to this class).

Another important aspect in the development of fault tolerant systems relies on the adoption of critical components redundancy. For robotic systems, redundancy can be introduced by adopting additional actuators, as in the case of duplicating joint actuators in spatial robots, or multiple sensory devices. Additionally, one may exploit kinematic redundancy of a manipulator; in such a case, a failed joint can be braked and the task accomplished by suitably modifying the trajectories of the healthy joints.

In the case of robotic systems interacting with humans, an intrinsically safe interaction and high tolerance to unexpected collisions can be guaranteed by imposing a suitable programmable compliant behaviour of the robotic system, e.g., via impedance control strategies. When a failure occurs, the robotic system should reach a configuration maximally safe for the humans.

2.3.3 Case studies for benchmarking pHRI

In this section, simple case studies from [7] are reported, to highlight how safety issues are taken into account in practice.

An example of physically interacting robot providing power augmentation to humans workers is Cobot [21]. In one of its basic implementations, it is a wheeled robotic platform that supports (typically heavy) parts to be manipulated by an operator. Virtual guiding surfaces are created, directing the constrained motion toward the appropriate environment location. The virtual guiding surfaces can be programmed in space and time and blended one into another. An assembly assist tool is made up of a guidance unit (the cobot) as well as conventional task-dependent tooling (e.g.,a door loader). Ergonomics is the performance criterion, with an improved inertia management leading to smaller operator applied forces. Safety is addressed via the intrinsic passivity of the cobot: the maximum energy in the system is limited by the humans capability. Also cobots with power assist have been developed: although these robots are not fully passive, safety is still preserved by appropriately limiting the power of the assisting motor. In this case study, the safety problem was solved enforcing a human-in-the-loop strategy.

Another example of application where safety is considered as a primary task are exoskeletons [22].

Related to dependability and robustness of safe robots, the possible failure modes of a simple robot with a Variable Impedance Actuation, based on antagonistic arrangement on nonlinear elastic elements, have been analysed in [23], under possible failures of some of its components. The ability of the system to remain safe in spite of failures has been compared with that of other possible safe-oriented actuation structures, namely, the SEA and the DM2 actuation scheme. In order to obtain a meaningful comparison, optimised SEA and DM2 implementations have been considered, with equal rotor and link inertias, yielding the same minimum-time motion performance for the considered task. Under the same failure modes, both SEA and DM2 lead to higher HIC values. An explanation of the apparently superior fail-safety characteristics of the antagonistic VIA is that such scheme achieves comparable nominal performance by employing two motors each of much smaller size than what necessary in the SEA and DM2. The basic stiff-and-slow/fast-and-soft idea of the VIA approach seems therefore to be more effective for realistic models of antagonistic actuation.

Another method to increase the safety of robots interacting with humans is to introduce mechanical compliance into the design, e.g., pursuing a lightweight robot design [13], or by using semi-active compliant actuation mechanism having magneto-rheological (MR) fluid based actuator that introduces reconfigurable compliance characteristics into the robot joints, is proposed in [24]. This enables high intrinsic safety coming from fluid mechanics as well as, it offers simpler interaction control strategy compared to other concurrent approaches.

Notice again that the problem of collisions is a central topic for research and experiment in pHRI, both for collision avoidance and for robot reconfiguration after collisions. Related to the second case, collision detection in the absence of external sensing devices can be realised in different ways by suitably comparing commanded motor torques and measured proprioceptive signals [25] - [26]. A particularly efficient algorithm that uses only encoder positions is based on the monitoring of the generalised momentum of the mechanical system [27], [28], which also allows identifying (isolating) the colliding link on the robot. Once the collision has been detected (more or less as a system fault), the robot may simply be stopped by braking or applying high-gain position feedback on the current joint position. However, the robot will remain in the vicinity of the collision zone with the human, producing thus a sensation of permanent danger. In [29], a different strategy has been implemented on a lightweight robot arm, by determining a direction of safe post-impact motion for the robot from the same signal used for collision detection.

Finally, note that, if the collision is assumed to occur at the end-effector level (say, between the robot tool and the human user) kinematic redundancy of the arm may be used to minimize the instantaneous effect of an impact [47]. In fact, while executing a desired end-effector trajectory, the arm may continuously change its internal kinematic configuration in order to minimize the inertia seen at the end-effector.

Based on the previous discussion and on considered applications, it is clear that an assessment of the safety level for physical humanrobot collisions is mandatory.

2.4 Possible contribution

Summarizing, safety has many levels: compliance of the robot in case of contact, fast monitoring of the scene, precise collision checks with emergency stops. We can therefore consider 3 steps for safety tactics: those related to intrinsic safety, those which can prevent collisions, and those which are activated in the event of a crash.

The second step in the proposed approach to safety is the one addressed in this thesis, providing a manipulators model for fast deliberative/reactive motion.

For the purpose of a pHRI in a dynamic domain, the integration of a sensor-based on-line reactivity component into an off-line motion plan (needed for a global analysis of the scene) seems mandatory. Sensors can be used to acquire local information about the relative position of a manipulator arm (or a navigating mobile robot) with respect to the human user (or with respect to other arms or robots, in which case proprioceptive sensing may be enough). Based on this, the planner should locally modify a nominal path so to achieve at least collision avoidance or, in more sophisticated strictly cooperating tasks, keep contact between end-effector and human. The simplest modification of a nominal path in the proximity of an expected collision is to stop the robot. Even when a local correction is able to recover the original path, there is no guarantee, in general, that a purely reactive strategy may preserve task completion. For this, a global replanning based on the acquired sensory information may be needed.

We will focus in this thesis on a particular aspect of safety of robot manipulators, that of unexpected collisions of the manipulator with a human operator, which could happen anywhere on the manipulator structure and at any time during the execution of a planned trajectory. The approach proposed to detect collisions is based on the momentum-based method, proposed in [27].

After collision is detected, a reactive control strategy should switch as fast as possible from the control law associated to normal task execution to a reaction control law, where the joint torques due to the contact have to be reduced. The effect is that of a more compliance robot, suitable to move in the direction given by the human, or anyway by the contact. Indeed, robot compliance is useful in order to reduce the interaction forces both in the case of collision and during physical collaboration between humans and robots.

Finally, considering that our method is sensorless, an indirect evaluation of the contact force is required to predict human motion intentions and react accordingly.

Therefore in this thesis is also presented a method that allows to estimate both the contact force and the contact point for a n-link manipulator in point contact (with zero moment) with the environment, by means of a direct computation or an adaptive method.

Summarizing, a collection for suggested contributions addressing the listed problems will be reported in next chapters, with emphasis on:

- detect a collision of a robot with an unknown environment, using only the standard proprioceptive sensors (joint encoders), when collision can occurr at any point along the robot arm;
- reactive real-time control for safety;
- estimation of both contact force and contact point, in order to predict human motion intentions.

On the basis of the contents provided in this chapter, the above points will be developed in the next chapters, according to the scheme sketched in the summary.

Chapter 3

Collision detection

When a robot manipulator operates in an unstructured environment or shares its workspace with a human user, safety issues are of primary concern and collisions constitute one of the major source of risk for safety in pHRI. Therefore, the problem of collision detection is an important issue for research in pHRI, both for collision avoidance and for the reaction strategy after collisions. The aim of this chapter is to present algorithms which allow the collision detection, and in particular the momentum-based method, that is the basis of the approach proposed in this thesis.

3.1 Overview of collision detection algorithms

Detection of physical collisions is the basic feature for a safe control of the robot behavior since collision avoidance cannot be always guaranteed.

To be useful collision detection must be very efficient, in order to assure a promptly robot reaction. This limits the use of sensors, such as cameras, that are ineffective in the case of fast interaction, because of their low bandwidth.

Many injuries may occur from an accidental collision between the robot structure and the environment (or humans), due to the uncertain location of obstacles and/or unpredicted relative motion. Avoiding such collisions requires knowledge of the environment geometry and the use of computationally intensive motion planning techniques.

Preempting contact, between the human and the robot or between the robot and the environment, or detecting it in real-time is typically based on the use of external sensors, such as sensitive skin sensor [31]- [32], to detect nearby objects in an unknown or time-varying environment, on-board vision [33], based on images taken from several stationary cameras in the work cell, strain gauges [34], or tactile sensors [35] and force/torque sensors to identify a hazard when unplanned contact occurs [36].

A different method is to consider every object in the environment, including any humans, as an obstacle, and use a real-time obstacle avoidance strategy such as in [37].

An alternative approach for safety in pHRI is presented in [38]; it is called control-effort-based intent detection. It is used the principle of preservation of zero momentum: the momentum that is delivered by the human impact is just the negative of the momentum that is delivered by the control effort. Therefore the detection signal is fed into the control loop in a way such that it changes the reference position.

Furthermore in [39] is presented a method based on adaptive filtering of the residuals to address the issue of robustness towards modeling uncertainties. The evaluation algorithm is based on a gray-box modeling of the residuals, which takes into account acceleration-related uncertainties and speed-dependent non-linearities. The adaptive filtering is used to produce a dynamic threshold.

Collision detection in the absence of external sensing devices can also be realised by suitably comparing commanded motor torques and measured proprioceptive signals [25] - [26].

In addition, note that, if the collision is assumed to occur at the end-effector level kinematic redundancy of the arm may be used to minimize the instantaneous effect of an impact [47]. Indeed, while executing a desired end-effector trajectory, the arm may continuously change its internal kinematic configuration in order to minimize the inertia seen at the end-effector.

A notably efficient algorithm that uses only encoder positions is based on the monitoring of the generalised momentum of the mechanical system [27], [28], which also allows identifying (isolating) the colliding link on the robot.

In particular, the approach for the reaction strategy to a collision proposed in this thesis is based on the momentum-based method presented in [27]. The idea is to manage a collision at a generic point along the robot as a fault of its actuation system; during free motion, all residuals are practically zero. The rising of some residuals above a fixed threshold means that a collision occurs; when the contact is lost, residuals quickly return to zero.

3.2 The momentum-based method

In this section will be considered the problem of real-time detection of collisions between a robot manipulator and obstacles of unknown geometry and location in the environment without the use of extra sensors, taking in account that collision may occur at any point along the robot arm.

The main idea pursued in [27] is to handle the collision as a faulty behavior of the robot actuating system. In fact, the dynamic effect of a cartesian contact force is that of an additional joint torque with respect to the commanded one.

Therefore, robot actuator fault detection and isolation (FDI) technique [40] can be used. These do not require acceleration measurements nor inversion of the robot inertia matrix.

In particular, the FDI method based on generalized momenta [40] works independently of the generation scheme for the nominal torque, which may thus be any open-loop command or feedback law. This is particularly convenient when it is necessary to switch control strategy. The FDI scheme produces a residual vector which is filtered version of the joint torques resulting from cartesian contact forces.

3.2.1 Preliminaries

In the following robot manipulators are considered as open kinematic chains of rigid bodies, having n (rotational) joints with associated generalized coordinates $q \in \mathbb{R}^n$, that may undergo a possible contact with the environment at a generic point of the structure.

A spatial motion task for the robot is specified in terms of task coordinate variables $x \in \mathbb{R}^m$ with $m < n$ (e.g., the end-effector pose, or the position of a point along the robot structure). These coordinates are related by the direct and differential kinematic equations

$$x = f(q), \quad \dot{x} = J(q)\dot{q} \tag{3.1}$$

where $J(q) = \partial f(q)/\partial q$ is the so called task Jacobian matrix (obtained by analitical differentiation).

Using a Lagrangian approach the robot dynamic model is

$$M(q)\ddot{q} + c(q, \dot{q}) + g(q) = \tau + \tau_c \tag{3.2}$$

where $M(q)$ is the $(n \times n)$ symmetric positive definite inertia matrix, $c(q, \dot{q})$ is the $(n \times 1)$ Coriolis and centrifugal vector, $g(q)$ is the $(n \times 1)$ gravity vector, τ is the $(n \times 1)$ vector of the commanded joint torque, and

$$\tau_c = J_c^T(q)F_c \tag{3.3}$$

is the $(n \times 1)$ vector of the joint torque associated to a generalized contact force F_c. The Jacobian matrix $J_c(q)$ relates the linear and angular velocity of a frame Σ_c located at the contact point P_c to the joint velocity $\dot{q}$. Both terms in the right-hand-side of equation (3.3) are supposed to be unknown.

Furthermore, each component of vector $c(q, \dot{q})$ is quadratic in the velocities $\dot{q}$

$$c_i(q, \dot{q}) = \tfrac{1}{2}\dot{q}^T C_i(q)\dot{q}, \quad i = 1, \cdots, n \tag{3.4}$$

where the (symmetric) matrices $C_i(q)$ are computed through the Christoffel symbols as

$$C_i(q) = \left[\frac{\partial m_i(q)}{\partial q}\right] + \left[\frac{\partial m_i(q)}{\partial q}\right]^T - \left[\frac{\partial M(q)}{\partial q_i}\right] \tag{3.5}$$

being $m_i(q)$ the $i-th$ column of inertia matrix $M(q)$.

3.2.2 Collision Detection

The generalized momentum of the robot

$$p = M(q)\dot{q} \tag{3.6}$$

associated to the mechanical system in the equation (3.2) satisfies the first-order equation

$$\dot{p} = \tau + \tau_c - \alpha(q, \dot{q}) \tag{3.7}$$

where the components of α are given by [40]

$$\alpha_i = g_i(q) - \frac{1}{2}\dot{q}^T \frac{\partial M(q)}{\partial q_i}\dot{q}, i = 1, \cdots, n. \tag{3.8}$$

Note that in α only part of the Coriolis and centrifugal terms c are present. It is also evident from eq. (3.7) that each fault (and nominal input torque) affects one and only one component of p. In particular, this decoupling allows identifying separately concurent collisions.

The residual signal r is defined as

$$r(t) = K_I \left[\int_0^t (\alpha - \tau - r)\ ds + p(t)\right] \tag{3.9}$$

that can also be expressed as

$$r(t) = K_I \left[p(t) - \int_0^t \left(\tau + C^T(q, \dot{q})\dot{q} - g(q) + r\right)\ ds\right] \tag{3.10}$$

with $r\,(0) = 0$ and the diagonal matrix $K_I > 0$ [41].

Therefore, the residual dynamics satisfies

$$\dot{r} = -K_I r + K_I \tau_c \tag{3.11}$$

that is a first-order stable linear filter driven by the joint torques due to the collision.

Actually, for every component of the residual dynamics we can write a transfer function

$$\frac{r_i(s)}{\tau_{c,i}(s)} = \frac{K_i}{s + K_i}, i = 1, \cdots, n \tag{3.12}$$

having unitary gain.

Note that in order to be implemented equation (3.9) requires proprioceptive measures $(q, \dot{q})$ only, the knowledge of the current commanded input u, but no acceleration $\ddot{q}$ or inversion of the inertia matrix $M(q)$.

During free motion all the residuals are practically zero. In response to a generic collision, r raises exponentially with a time constant $1/K_I$.

A physical collision will then be detected as soon as $||r|| > r_{thres}$, being $r_{thres} > 0$ a suitable scalar threshold used to prevent false detection due to measurement noise and/or model uncertainties on r [29],[41].

In the ideal condition, for large value of K_I, the evolution of r will reproduce accurately the evolution of the contact torque $\tau_{c,i} = J_{c,i}^T(q)F_c$, being $J_{c,i}$ the $i-th$ column of the Jacobian matrix J_c.

Furthermore when the contact/collision is definitely over the residual will return rapidly to zero, according to equation (3.11).

3.2.3 Identification of the link in collision

A useful interpretation of this collision detection method is that, thanks to the residual computation, we are able to compensate for the coupled accelerations and dynamic motion of the robot and treat the problem as if it was a quasi-static one. In fact, using equation (3.11) only the component of the residual vector that are associated to joints placed before (in the robotic chain) the single colliding link will be influenced by the collision force F_c [41].

Therefore using the residual generator it is immediate identify the robot link that has collided. In fact, assuming that the robot is an open kinematic chain, if collision occurs on link k it is

$$r_i(t) \neq 0, \quad i = 1, \cdots, k, \quad r_j(t) = 0, \quad i = k+1, \cdots, n. \tag{3.13}$$

Assuming $r \approx \tau_c = J_c^T(q)F_c$, this follows from the fact that, for a collision on link k, the last $N-k$ columns of the Jacobian $J_{c,i}$ are identically zero. In view of the relations (3.13) r is called a *collision identification* signal [29], or simply a *residual* bearing this term from the fault detection literature. The first k components of vector r will be generically different from zero, at least for the time interval of contact, and will start decaying exponentially toward zero as soon as contact is lost.

The residual r will be affected only by Cartesian collision forces F_c that perform virtual work on admissible robot motion, i.e., those forces that do not belong to the kernel of $J_c^T(q)$.

More in general, the sensitivity to F_c of each of the affected residuals (proximal to the robot base) will vary with the arm configuration.

3.3 The error-based method

In this section is proposed a new approach for the estimation of the joint torques due to contact [42]. This simple alternative to the momentum-based method is based on the error estimation.

However, this method can be considered when a computed -torque control strategy like

$$u = M(q)\left[\ddot{q}_d + K_D(\dot{q}_d - q) + K_P(q_d - q)\right] + C(q, \dot{q})\dot{q} + g(q) \tag{3.14}$$

is supposed to track a desired position q_d.

Assuming that equation (3.14) holds true, it is possible to estimate the residual moments only by considering the linear feedback term

$$M(q)K_P\,(q_d - q) \approx \; \tau_c \tag{3.15}$$

as a residual approximation.

This method has a particular attraction due to the fact that is computationally effortless.

Furthermore, as we can see in the following chapter by means of suitable experiments, comparing the residual torques estimated by means of error-based method and momentum-based method, it is easy to see that the latter are more noisy.

However, the computation of the residual does not depend on the particular control law and can be useful also for other applications, for example for collision detection. The price to pay is the dependance on the complete dynamic model of the robot.

Chapter 4

Post-impact motion and contact estimations

Unlike the industrial robots, which are stiff to guarantee high precision, the robots used in anthropic environments must be designed with high degree of compliance to ensure safety. This is especially true for the applications requiring physical human-robot interaction, not only because of unexpected impacts of robots with humans but for the execution of collaborative tasks requiring intentional exchange of forces as well [43].

This chapter considers the problem of controlling a robot manipulator in the task space, while ensuring a compliant behavior in the circumstance of a collision occurrence.

Furthermore an algorithm for the estimation of both contact point and contact force is proposed, in order to predict human motion intentions.

4.1 An overview on reactive motion control

Among the possible contributions to safety and dependability of robots for pHRI, it is worth noticing that a central point is the design of the trajectories. They have to provide escape paths in short time from dangerous situations, or reconfiguration paths for letting the manipulator assume postures which are less dangerous in the event of an impact.

Reactive collision avoidance is necessary in both robot-robot and human-robot interaction. The first is simpler, because of the high reliability of sensory data. For reactive collision avoidance in human-robot interaction, tracking of important parts of the human body is necessary, while a reactive control system acts on the interacting robot for forcing it to move away from possible collisions. Sensor dependability and integrated planning/control become central in order to safely interact with people and environment.

The reaction strategies are aimed at immediately removing the robot from the collision area. Almost they focus on either slowing down or stopping when a hazardous situation is identified [44], moving to evade contact [45] or trying to minimize the impact force if contact occurs [46]. Nevertheless, in the case of redundant robots, it is possible to preserve as much as possible the execution of the end effector task by projecting the reaction torques into the null space of the main task [47].

An alternative approach is proposed in [48], where a measure of danger during interaction is computed, based on factors affecting the impact force during a potential collision between the human and the robot. This danger index is then used as an input to real-time trajectory generation when the index exceeds a predefined threshold. The alternate trajectory generated by a safety module tries to lower the danger present in the interaction; therefore, the goal of the safety module is to generate a plan to move the robot to the safest possible location in real-time, and then issue a request to the planner module to generate a global plan, either for retraction or to continue the initiated task.

Impedance control represents an effective approach to control actively the robots compliance. The impedance behavior usually is given to the task variables to control the interaction of the end effector [49][51], also during the execution of visual servoing tasks [52]. However, an active compliance behavior can be also imposed to the joint variables to enhance safety [53][56]. The Cartesian impedance control for torque controlled flexible joint and redundant robots was investigated thoroughly in [57]. The impedance control problem with null-space stiffness control for 7 degree-of-freedom (DOF) flexible joint arms, based on singular perturbation approach and passivity based approach was addressed in [58] and [59], respectively. Furthermore a novel safety control method, incorporating fuzzy logic is proposed in [60] so as to guarantee safety and robustness of a upper-limb rehabilitation robot control system by means of a position-based impedance controller, implemented in order to achieve compliance between the end-effector and the impaired limb in the meanwhile of the rehabilitation training.

Recently, problems and solutions related to kinematic redundancy have gained new interest because of the application of robotic systems with a high number of DOFs, such as humanoid and dual-arm robots. A theoretical and empirical evaluation of different operational space control techniques for redundant manipulators has been presented in [61]. A well-established framework to deal with highly redundant robots is multipriority control, which can be performed both at the kinematic [62] and dynamic levels [63]. Within this framework, it is possible to control the behavior of several interaction points on the body of the robot.

An alternative algorithm, proposed in [64], is based on a simplified sensorless estimation of external forces and saturation of joint control torques to keep the effective external forces under safety level, which can be efficiently integrated in robotic position control systems. Finally an interesting approach is presented in [29]. In particular the post-impact phase is solved by switching to a hybrid force/motion controller that regulates the interaction forces. The directional information on interaction forces provided by the identification scheme is used to safely drive the robot away from the human: the PD control applied during pre-impact phase switches in the reflex strategy, more friendly, after a collision detection.

Summarizing robot compliance is useful in order to reduce the interaction forces, both in the case of collision and during physical collaboration between humans and robots. An example of application scenario is depicted in figure 4.1, where a robot, working on a table, experiences a contact with a human. This contact may produce errors on the main task of the robot if active compliance is used to achieve a safe interaction [43].

Figure 4.1: Robot working close to a human

The goal of this chapter is to improve the performance during impact and at the same time to ensure safe interaction through active compliance.

4.2 Post collision strategy

In the post-impact phase, the first task is to detect the collision occurrence, which may have happened at any location along the robot arm. The controller should then switch to an appropriate reaction strategy, the most simple one being to stop the robot.

However, this would not remove the arm from direct contact with a human, generating an unpleasant feeling of permanent danger or even squeezing the person in a narrow environment.

Instead, once an undesired physical collision has been detected the robot switches as fast as possible from the control law associated to normal task execution to a reaction control law, where the joint torques due to the contact have to be reduced (see figure 4.2)[41].

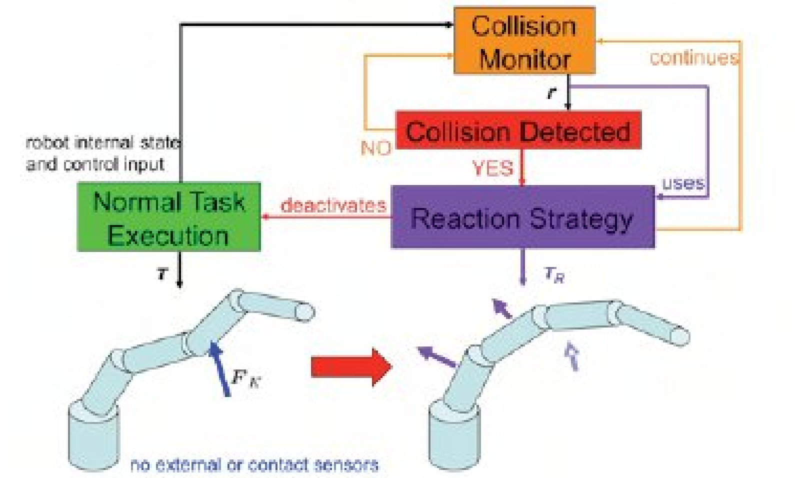


Figure 4.2: Collision detection and reaction scheme

4.2.1 Joint space impedance control

Impedance control is one of the most adopted methods of controlling the interaction between a manipulator and the environment. While the Cartesian or task-space impedance control regulates the mechanical impedance of the robot end effector [65], [43], the joint space impedance control guarantees a compliant behavior of the robot joints.

The joint space impedance equations are

$$M_d(\ddot{q}_d - \ddot{q}) + B_d(\dot{q}_d - \dot{q}) + K_d(q_d - q) = \tau_c \tag{4.1}$$

where $q_d(t)$ is a desired trajectory, while M_d , B_d , and K_d are $(n \times n)$ positive-definite matrices, representing the desired inertia, damping, and stiffness, respectively.

The impedance behavior (4.1), with a freely chosen desired inertia matrix M_d , can be achieved only if a measure or estimation of the external torque is available and is used in the feedback control law. Namely, we have the following control law:

$$\tau = M(q)\ddot{q}_c + C(q, \dot{q})\dot{q} + g(q) + \tau_c \tag{4.2}$$

with the command joint acceleration $\ddot{q}_c$ chosen as

$$\ddot{q}_c = \ddot{q}_d + M_d^{-1}\left(B_d\dot{\tilde{q}} + K_d\tilde{q} - \tau_c\right) \tag{4.3}$$

where $\tilde{q} = q_d - q$ leads to the closed loop dynamics (4.1).

In the case that τ_c is not available or is not used in the controller, the joint impedance behavior (4.1) can be achieved only with $M_d = M(q)$, using the control law

$$\tau = M(q)\ddot{q}_d + B_d\dot{\tilde{q}} + K_d\tilde{q} + C(q, \dot{q})\dot{q} + g(q) \tag{4.4}$$

Notice that the joint space impedance control can be applied to both redundant and nonredundant manipulators, since it is achieved in the joint space.

4.2.2 Post-impact reaction control

An alternative to the joint space impedance control is proposed in [42]. In order to implement a reaction strategy it is possible to consider the Computed-Torque as a proper control strategy

$$u = M(q)\left[\ddot{q}_d + K_D(\dot{q}_d - \dot{q}) + K_P(q_d - q)\right] + C(q, \dot{q})\dot{q} + g(q) \tag{4.5}$$

which usually provides accurate trajectory tracking of a desired position q_d in free motion.

Therefore, after simple algebra

$$M\ddot{e} + K_D^{'}\dot{e} + K_P^{'}e = \tau_c \tag{4.6}$$

where the error $e = q_d - q$ and $K_D^{'} = MK_D$ and $K_P^{'} = MK_P$.

During collision we adopt the same control strategy, by redefining the desired trajectory as

$$q_r = q_d - K_C K_P^{-1} \tau_c. \tag{4.7}$$

Hence the previous control law become

$$u = M(q)\left[\ddot{q}_r + K_D(\dot{q}_r - \dot{q}) + K_P(q_r - q)\right] + C(q,\dot{q})\dot{q} + g(q) \tag{4.8}$$

After some algebraic manipulation, in the same way of the equation (4.6),

$$M\ddot{e}_2 + K_D^{'}\dot{e}_2 + K_P^{'}e_2 = \tau_c \tag{4.9}$$

where $e_2 = q_r - q$.
The (4.9), considering (4.7), leads to the closed loop dynamics

$$M\ddot{e} + K_D^{'}\dot{e} + K_P^{'}e - K_C^{'}\tau_c = \tau_c \tag{4.10}$$

where $K_C^{'} = MK_C$.

$$M\ddot{e} + K_D^{'}\dot{e} + K_P^{'}e = (I + K_C^{'})\tau_c \tag{4.11}$$

Therefore a more compliant behavior is obtained

$$(I + K_C^{'})^{-1}M\ddot{e} + (I + K_C^{'})^{-1}K_D^{'}\dot{e} + (I + K_C^{'})^{-1}K_P^{'}e = \tau_c \tag{4.12}$$

Indeed, the (4.12) suggest that the effect of the post collision strategy (4.7) is that of a decreased equivalent inertia, damping and stiffness matrices by a factor larger than one [42].

By a comparison between the joint space impedance control and the reaction strategy proposed in [42], it is possible to point out that, although the former allows a compliant behavior of the robot, as it is evident in the relation (4.1), the error dynamic turns out to have a limitation due to the fact that depends by the matrix K_d that is supposed to guarantee the compliance of the robot. However, even if relation (4.12) depends on the inertia matrix, when the contact joint torque is null the dynamic error become the same relation as in the pre-collision case.

The expected outcome is that the robot become more suitable to move in the direction given by the human, or anyway by the contact. When the contact is lost, and in absence of further collisions, the residual will return to zero, than the robot bounces back in the pre-impact motion.

4.3 Contact point and force estimations

Physical collaboration is characterized by force exchanges between human and robot, which may occur at any place of the robot structure. In the absence of a distributed force/tactile measurement system, an indirect evaluation of the contact force is required to predict human motion intentions and react accordingly. Therefore, we have provided an algorithm to estimate both the contact point and interaction forces for a $n - link$ manipulator in point contact (with zero moment) with the environment, when collision occurs in an unknown point of the robot manipulator [42].

The method, starting from residual joint torque estimation, allows both direct and adaptative computation of the contact point and force, based on a principle of equivalence of the contact forces.

With reference to Fig. 4.3 let us consider that a contact force F_c occurs at an unknown point P_c of the link j.

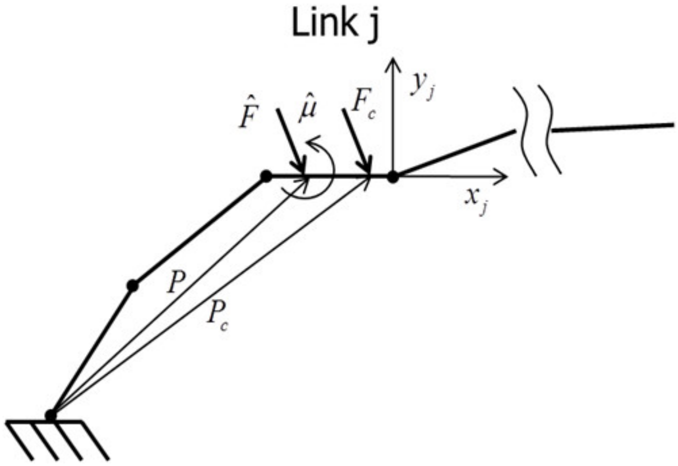


Figure 4.3: Equivalence of the force-torque contact on the link j

Althoug a point wise collision can occur at any point along the robot arm, the contact can be estimated considering the Jacobian matrix in any fixed point, such as point P, provided that

$$j \geq 6 \tag{4.13}$$

In order to estimate the contact force, corresponding to the contact point P, the mapping should be inverted and the simplest way is by using the pseudo-inverse of the Jacobian matrix

$$\hat{\gamma} = \left(J^{l_j T}\right)^{PI} \tau^j \tag{4.14}$$

where $\hat{\gamma} = \begin{pmatrix} \hat{F} \\ \hat{\mu} \end{pmatrix}$ is the vector of estimated forces and moments and equation (4.14) corresponds to the minimisation of γ in a least-square sense. The condition (4.13) implies that

$$\hat{F} = F_c \tag{4.15}$$

$$\hat{\mu} = (P_c - P) \times \hat{F}. \tag{4.16}$$

Therefore the residual contains an indirect estimate of $\hat{F}$.

Anyway the estimate will be limited to only those components of F_c that can be detected by the residual r, hence all forces $F_c \in \mathcal{N}(J_c^T(q))$ will not be recovered in $\hat{F}_c$.

However, this should not be considered as a serious limitations since such force components do not produce active work in the robot coordinates q.

Furthermore, in the framework of a collaboration between human and robot, carried out as an intentional contact, it could be useful to localize the impact. Actually, if the contact point belongs to the allowed collaborative parts of the robot and the human, both the collision avoidance and the robot reaction based on the residual should be disabled.

Therefore, it is shown next how to estimate the contact point respectively by means of a direct and an adaptive method.

By (4.16) it is possible to estimate the contact point in the planar case with $j \geq 3$ as

$$P_c = \frac{\hat{\mu}_{z_j}}{\hat{F}_{y_j}} x_j + P \tag{4.17}$$

being

$$\hat{\mu} = x_j^T \left(P_c - P\right) \hat{F}_{y_j} z_j = \hat{\mu}_{z_j} z_j \tag{4.18}$$

where $\hat{F}_{y_j}$ is the y_j component of $\hat{F}$ and $\hat{\mu}_{z_j}$ is the z_j component of $\hat{\mu}$.

Furthermore, although in the planar case moment $\hat{\mu}$ is parallel to z_j axis, in the general case moment $\hat{\mu}$ lies on the plane $y_j - z_j$. Therefore, an equation similar to (4.17) also holds in the general case, but with components of the projection of $\hat{F}$ and $\hat{\mu}$ on the plane $y_j - z_j$, instead of $\hat{F}_{y_j}$ and $\hat{\mu}_{z_j}$.

Due to the fact that the moment in the contact point is zero, an adaptive approach can be considered whose purpose is to minimize the estimated moment. Considering both (4.17) and (4.18) and choosing

$$\hat{P}_c\left(t\right) = \delta p\left(t\right) x_j + \hat{P}_c\left(0\right) \tag{4.19}$$

with

$$\delta \dot{p}\left(t\right) = k \frac{\hat{\mu}_{z_j}}{\hat{F}_{y_j}} \tag{4.20}$$

it is simple to prove that $\hat{P}_c(t) \rightarrow P_c$ asymptotically.

Note that in case of the 2-DOF planar robot, to apply this algorithm we must decrease the problem dimension, by adding a further information of the contact force, i.e., that the contact force is directed along the normal to the obstacle surface. In this case, we obtain a square jacobian matrix simply projecting the original jacobian matrix on frame j and canceling the first row of the obtained matrix, corresponding to the first column of the transpose, which multiply a null force component by hypothesis.

Chapter 5

Applications of post-collision strategies

This chapter is aimed at showing how the presented algorithms and HRI-centered strategies have been used for real implementations on an industrial manipulator.

The control approach proposed in this thesis has been tested on a scenario in which a robot manipulator is executing a motion task and a human operator enters in its workspace.

5.1 Experimental setup

Experiments for evaluation of the proposed reaction strategies have been performed at the Robotic laboratory of the Department of Energy, Information technology and Mathematical models, at the University of Palermo.

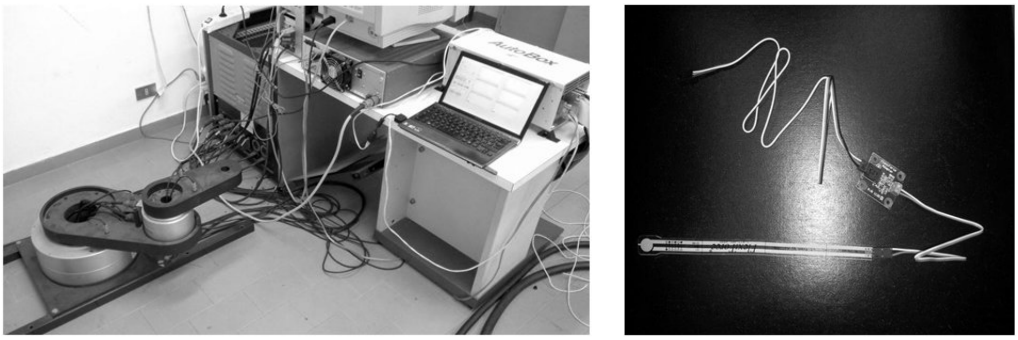
The experimental setup consist of a two link planar robotic manipulator directly driven by variable reluctance motors (NSK Megatorque: stall torque 250 Nm for link 1 and 40 Nm for link 2), shown in figure 5.1.a. Furthermore the manipulator is equipped with two resolvers and resolver-to-digital converter boards equivalent to a 19,200 ppr incremental encoder.

The robot is controlled by a dSpace DS1103 PPC Controller Board and industrial controllers designed for torque control loops, with ± 10 volt torque command signals.

An advanced real-time interface software from dSpace and a simulation environment have been also used, which permit fast, safe and reliable prototyping of planning and control algorithms.

Indeed, this interface automatically generates real-time code from Simulink models and implements this code on dSPACE real-time hardware.

Finally the manipulator has been controlled to constant joint angles and a normal force (measured with a FlexiForce piezoresistive force sensor, in figure 5.1.b) has been applied near to the tip in an unknown position.



(a) The 2DOF planar robot

(b) The flexi-force sensor to measure the contact force

Figure 5.1: Experimental setup

In addition, in the following figure it is shown the schematic structure of the control system:

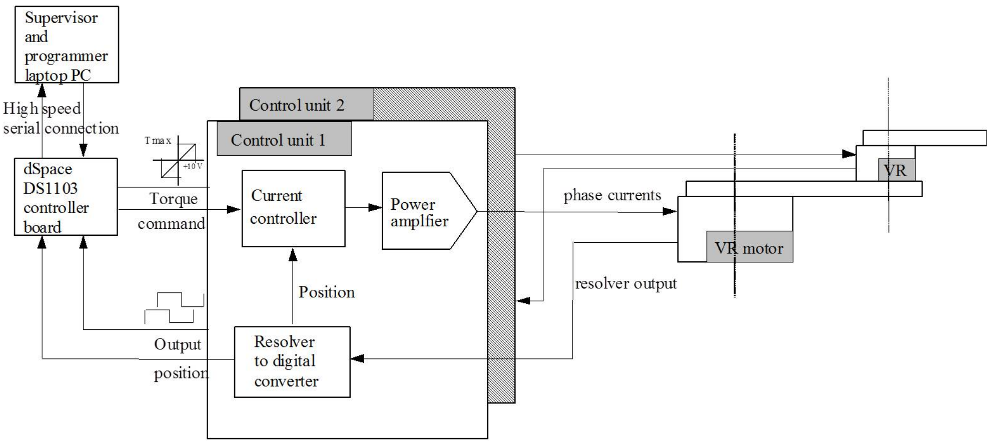


Figure 5.2: Schematic structure of the control system

5.2 Experimental evaluation

One aim of the experiments performed on the industrial manipulator is the comparison of estimating contact point and contact force by means of both the momentum-based method and the error-based method. In addition, another purpose of these experiments is the comparison between the different ways of estimating the contact point, namely the direct computation (4.17) and the adaptive method(4.19- 4.20).

Furthermore, two different sets of experiments are considered; in the latter it is evaluated the performance of the reaction strategy proposed in the chapter 3 pursuing a more compliance robot, in a scenario in which an human experiences a contact with the industrial robot.

5.2.1 Experiment 1:

The same experiment is repeated to show the performance of the estimation algorithms, namely by using both the momentum-based method, proposed in [27] and the error-based method, presented in this thesis [42].

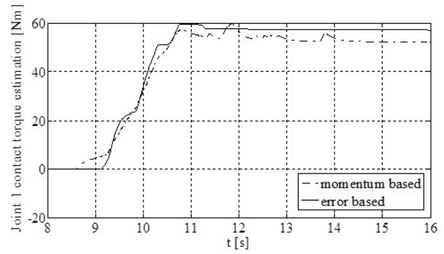
The comparison of estimating contact point and contact force is shown in the Figure 5.3.

In the figure 5.3.a and figure 5.3.b it is shown the estimation of the torques due to the contact, for both joint 1 and joint 2; both the momentum-based method (3) and the error-based method (6) perform the same shape, however in the momentum-based method the identified residual torques are more noisy and, therefore, the identified contact force and contact point. This is due to the fact that the momentum-based method uses the control torques signal to estimate the residual. However, the computation of the residual does not depend on the particular control law and can be useful also for other applications, such as collision detection.

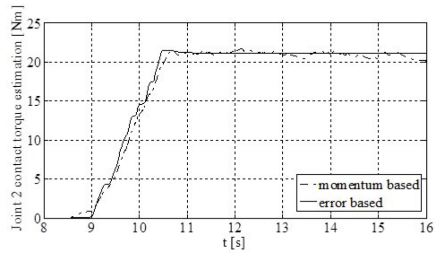
In the figure 5.3.c the comparison between the measured contact force and the estimation with both momentum and error-based methods can be observed.

The contact point, estimated by means of both momentum-based and error-based algorithm, at this stage is made only considering the adaptive method. Observing figure 5.3.d it can be observed the convergence of the contact point estimates to its true value, except for a constant error in the case of error-based method, significantly small. However, the error remains non null, especially during the interaction, because of the presence of a considerable amount of joint friction.

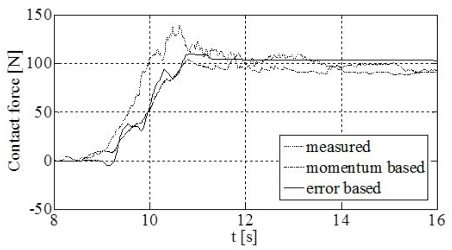
Furthermore, comparing the plot of the time histories of the estimated contact point (see figure 5.4.a) and the estimated contact torque (see figure 5.4.b) through the different ways of estimating the contact point, namely the direct computation (18) and the adaptive method (20), (21), it can be observed that the adaptive method is able to drive the estimated moment to zero as well as allows convergence of the contact point estimates to its true value. In particular for the figure 5.3.d has to be noticed the difference considering direct computation and adaptive method, due to the totally different



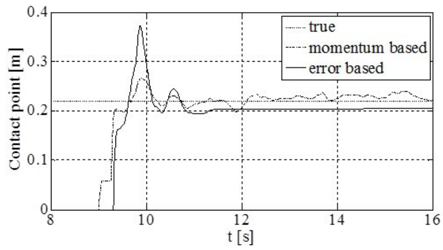
(a) Joint 1 contact torque estimation



(b) Joint 2 contact torque estimation



(c) Estimation of the contact force

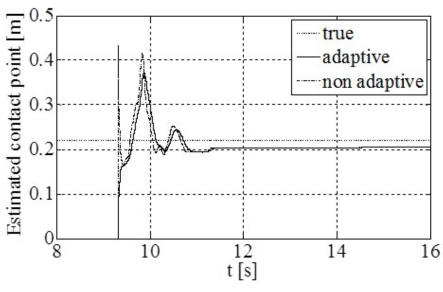


(d) Estimation of the contact point

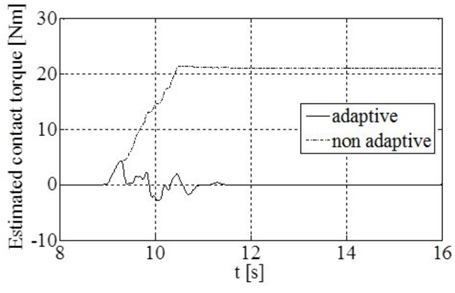
Figure 5.3: Estimation by means of momentum-based method and error-based method

way of estimating. Indeed, in the direct method the estimation is made on an momentum-based algebraic computation in each instant, however in the adaptive case the estimation is based on the variation of the contact point pursuing the minimization of the momentum.

The shape of the estimated contact force is the same because of the relation (16) for both method, and thus it is not reported for brevity.



(a) Estimation of the contact point



(b) Estimation of the contact torque

Figure 5.4: Estimation by means of direct computation and adaptive method

Finally, for completeness the time history of the estimated contact torque is reported as well (see figure 5.5).

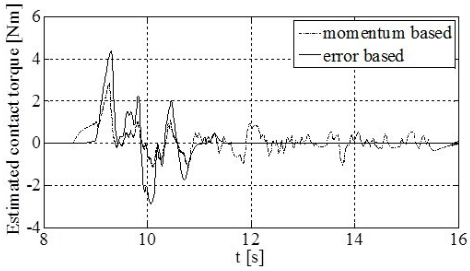


Figure 5.5: Estimation of the contact torque

5.2.2 Experiment 2

The main aim of this experiment is the validation of the reaction strategy proposed in this paper, namely the increased compliance of the robot after a contact with the human in an unknown point of the robot.

This purpose is achieved in figure 5.6, where is shown the position errors for both joints, and in figure 5.7, where is shown the estimated force, only with the error-based method, for brevity. As a matter of fact it can be noticed that the force-error ratio is equivalent to the assigned compliance.

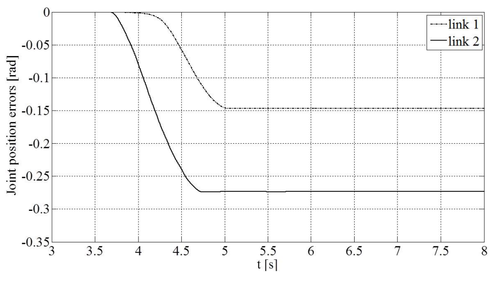


Figure 5.6: Joint position errors

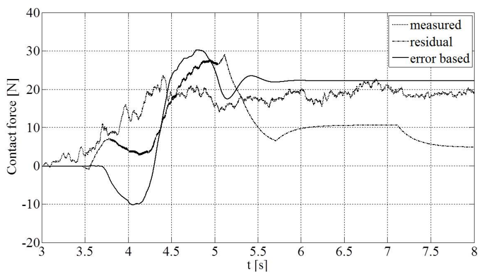


Figure 5.7: Estimation of the contact force

Furthermore in figure 5.8 and in figure 5.9 are comparised both methods of estimating the contact point presented in this work, that are the direct computation and the adaptive method. In these figures, as well as for the first experiment, it is pointed out that the adaptive method allows the convergence of the contact point estimates to its true value.

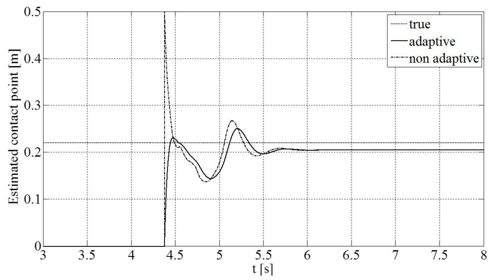


Figure 5.8: Estimation of the contact point by means of direct computation and adaptive method

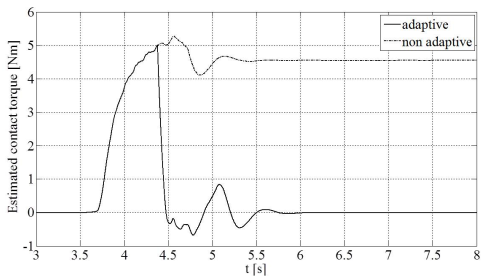


Figure 5.9: Estimation of the contact torque by means of direct computation and adaptive method

Chapter 6

A review about Gait Analysis

Robot-assisted human gait costitutes a very close human-robot interaction paradigm, that requires a critical process of sensing and actuating.

Gait analysis is the systematic study of human motion by instrumentation for measuring body movements, body mechanics, and the activity of the muscles.

The current chapter provides an introduction of gait analysis, in particular reviews available wearable sensors and ambulatory gait analysis methods.

6.1 Basis of Human Gait Analysis

Gait analysis is the systematic study of human locomotion. This type of analysis involves the measurement, description, and assessment of quantities that characterize human locomotion. Through gait analysis, the gait phase can be identified, the kinematic and kinetic parameters of human gait events can be determined, and musculoskeletal functions can be quantitatively evaluated.

As a result, gait analysis has been employed in sports, rehabilitation, and health diagnostics, but also to the field of robotics, especially humanoid robotics.

Gait patterns of humans and humanoid robots are often described by analysing changes in angular rotation of hip, knee and ankle joints during one gait cycle. Indeed, estimation of gait parameters is also a valuable measure for the detection of irregularities in gait patterns of human and humanoid robots.

Gait analysis has attracted an increasing amount of attention from the researchers and clinicians since the 1970s. With the utilization of video cameras, gait analysis based on highly accurate computer-based force plates was established in the 1980s and was applied in specialized motion laboratories.

However, this standard gait analysis requires specialized locomotion laboratories, expensive equipment, and lengthy set up and post-processing times. Moreover, limitations in terms of the moving area and gait cycles for the observed subject/patient have been observed. To mitigate these problems, an alternative gait analysis method based on wearable sensors, which are inexpensive and can be applied outside the laboratory environment, was studied and has shown great prospects in the recent two decades. Indeed, the term *wearable* implies that such system is portable, lightweight and safe. In order for such a device to be accesible for home use, the additional implications are that the wearable robot has to be economical and easy to operate.

In gait analysis using wearable sensors, motion sensors are worn or attached to various parts of the patients body and the movement signal recorded by these sensors can be used to perform the gait analysis.

6.1.1 Application of Gait Analysis

With the development of sensor technology and gait data analyzing techniques, gait analysis using wearable sensors has become a widespread and useful tool for both clinical practice and biomechanical research. Using small, low-power, and low cost wearable sensors, ambulatory gait analysis can be used conveniently in sports, rehabilitation, clinical diagnostics, and humanoid robotics, as summarized in the following [66].

Sports

In sports, gait analysis based on wearable sensors can be used for sport training and analysis for the improvement of athlete performance. An athletes faulty performance can be recognized and further corrected by the ambulatory gait analysis, which can promote performance improvement.

The prevention of sport injury is an alternative application of gait analysis using wearable sensors. Combining gait analysis with sport training can effectively prevent many injuries from overuse or incorrect posture and motion, thus maintaining the athletes high level of running and jumping.

Rehabilitation

The application of gait analysis in rehabilitation has been widely studied and realized in numerous hospitals and healthcare centers with subjects of different ages.

Gait analysis based on wearable sensors is an effective clinical tool for treatment planning, outcome assessment, and longitudinal studies on maintenance and progress. As a clinical tool, motion analysis of the lower extremities during gait is applied in pre-operative planning for patients with cerebral palsy [67] and can alter surgical decision making. After the application of gait analysis, the cost of care can be reduced by decreasing the number of pre- and post-operative clinic visits and subsequent surgical or other interventions.

Ambulatory gait analysis can also provide a quantitative description of the gait cycle, which complements and augments the standard observational analysis. The ambulatory gait analysis results can also assist in interventions to determine whether or not a particular course of treatment is appropriate for a patient. For people with neurological conditions, such as Parkinsons disease and stroke, the ambulatory gait analysis is an important step in their recovery process and can provide low-cost and convenient rehabilitation monitoring. Parkinsons disease is commonly characterized by motor dysfunctions, such as resting tremors, slowing of movement, gait difficulty, and limb rigidity. Hence, gait has been verified as one of the most reliable diagnostic signs of this disease. Accordingly, studies on the use of gait analysis as an alternative measure of the severity of Parkinsons disease have been increasing. Salarian et al. [68] performed gait measurement in patients with Parkinsons disease using a developed wearable sensor device and concluded that stride length is highly correlated with the severity of the disease.

In the rehabilitation of stroke patients, gait analysis using wearable sensors also play an important role. Many stroke patients who regained their walking ability do not have sufficient locomotion capacity for independent mobility in their community and need to undergo gait rehabilitation for the recovery of their independent mobility.

In the field of joint arthroplasty, clinical and instrumental data can be obtained through gait analysis based on wearable sensors. Such data can be used to evaluate the patients progress before and after hip or knee arthroplasty. Aminian and Najafi [69] tested and validated the application of gait analysis based on body-fixed sensors in hip osteoarthritic patients as a progress assessment method before and after surgery.

Clinical Diagnosis and Healthcare Monitoring

Based on the estimation results of the lower extremities, the disease and its severity can be determined, and clinicians can establish a proper treatment scheme for the patients. In healthcare monitoring, gait analysis based on wearable sensors can also be applied in various occasions, such as in the detection of gait abnormalities, the assessment of recovery, fall risk estimation, and so on. In the healthcare environment, gait information is used to detect walking behavior abnormalities that may indicate the onset of adverse health problems or the progression of neurodegenerative diseases [70].

Fall risk estimation is also an important application of gait analysis using wearable sensors. As the most common type of home accident among elderly people, fall is a major threat to health and independence. The importance of this threat facilitated studies on fall risk estimation to provide adaptive assistance and preventive measures to subjects deemed at risk.

Humanoid robotics

Humanoid robotics includes a rich diversity of projects where perception, processing and action are embodied in a recognizably anthropomorohic form in order to emulate some subset of the physical, cognitive and social dimensions of the human body and experience.

Humanoids should interact socially with people in typical, everyday environments. One of the crucial characteristics of humanoid robots is bipedal walking. For nearly the whole of the 20th century, bipedal robots were very difficult to construct and robot locomotion involved only wheels, treads or multiple legs. Giving legs to a robot instead of wheels attributes a lot more to it than just resemblance to a human being.

A robot system aiming to simulate the human gait must receive gait information that allows the system to mimic this action. Therefore, gait analysis has not only proved to be relevant to research fields like biomechanics, sport analysis and rehabilitation engineering, but also to the field of robotics, especially humanoid robotics [71].

Detection of irregularities: Gait Index

The design of robotic bipedal gait simulations and the successful implementation of these movements in a mechatronic structure requires comprehensive techniques for the analysis of the kinematics and kinetics of the human gait. Some of these techniques are oriented toward detections and analysis of irregularities in human gait with the aim of providing diagnostic tools to clinicians in the rehabilitation process.

These techniques could also be of great importance in humanoid robotics, because they could provide the tool for detection of irregularities in robot bipedal walking. Afterward, the controlling process of the robots walk could be improved with the aim of overcoming the previously detected irregularities.

By the way, even with the assistance of advanced gait analysis systems, objective quantification of the amount by which an individuals gait differs from the normal gait still remains difficult.

To accurately evaluate the extent of gait deviations from normal gait, or to assess the changes in a gait resulting from a specific treatment, it is important to consider not only how each feature of the gait pattern has changed but also how the relationship between the features changed. To evaluate whether a specific gait variable is normal, abnormal, or improved following treatment, the natural correlation that exists between gait variables must be determined. For this reason multivariate statistical techniques are used to develop a measure of how closely an individual gait pattern approaches normality [71].

In order to pursue this aim, many index are defined, whose purpose is to find a single number that reflects the amount by which a subjects gait deviates from an average normal gait.

The Gillette gait index (GGI), defined by Schutte et al. [72], has become one of the most popular indices in paediatrics and clinical routine, and is used to assess therapeutic outcomes for normal and pathological subjects. The Gait Deviation Index (GDI) is a new multivariate measure of overall gait pathology [73]. It is defined as a scaled distance between the 15 gait feature scores for a subject and the average of the same 15 gait features. The GDI offers an alternative to the GGI as a comprehensive quantitative gait pathology index, and is replacing the GGI index in practice.

Another proposed gait index is the Gait Profile Score (GPS), which is a single index measure that summarizes the overall deviation of kinematic gait data relative to normative data [74]. The GPS can be decomposed to provide Gait Variable Scores (GVS) of nine key component kinematic gait variables, which are presented as a Movement Analysis Profile (MAP).

While all the above mentioned methods are useful in the detection and classification of gait irregularities, their main disadvantage is the inability to detect and indicate the presence of an irregularity inside the gait cycle.

6.1.2 Introduction of gait phases

Generally, human walking is a periodic movement of the body segments and includes repetitive motions.

To understand this periodic walking course better and easier, the gait phase must be used to describe an entire walking period.

In the past, normal events were conventionally used as the critical actions of separated gait phases. However, this practice only proved to be appropriate for amputees and often failed to accommodate the gait deviations of

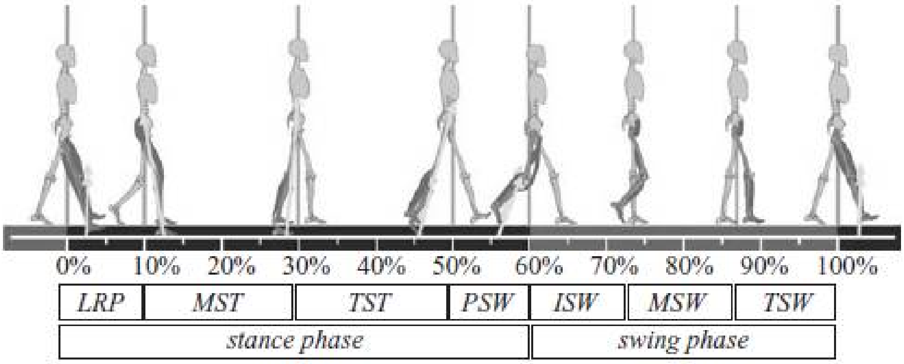


Figure 6.1: Human gait phases and period

patients impaired by paralysis or arthritis. However, to avoid areas of confusion, the Rancho Los Amigos gait analysis committee developed a generic terminology for the functional phases of gait [75].

Analysis of the human walking pattern by phases more directly identifies the functional significance of the different motions generated at the individual joints and segments.

Human gait can be regarded as a cyclic process comprising a stance phase and a swing phase (see figure 6.1). [12]. This process is described mechanically by kinetic (momentum and torques), or kinematic (angles) variables of the human lower limb articulations. Other time-related parameters, such as step length, cadence and speed are also important.

The stance phase is divided into four periods: loading response (LRP), midstance (MST), terminal stance (TST) and preswing (PSW). The swing phase in turn is divided into three periods: initial swing (ISW), midswing (MSW) and terminal swing (TSW). The beginning and end of each period are defined by specific *events*.

Detailed definitions of the gait phases are described in the following:

- *Initial contact*: This phase preceeds the beginning of stance phase and comprises the moment when the foot touches the floor. The joint postures presented at this time determine the limbs loading response pattern.

- *Loading response*: This phase is the initial double-stance period. The phase begins with initial floor contact and continues until the other foot is lifted for swing. Using the heel as a rocker, the knee is flexed for shock absorption. Ankle plantar flexion limits the heel rocker through forefoot contact with the floor.

- *Midstance*: This phase is the first half of the single-limb support interval. In this phase, the limb advances over the stationary foot through ankle dorsiflexion (ankle rocker), while the knee and hip extend. Midstance begins when the other foot is lifted and continues until body weight is aligned over the forefoot.

- *Terminal stance*: This phase completes the single-limb support. The stance begins with the heel rising and continues until the other foot strikes the ground, in which the heel rises and the limb advances over the forefoot rocker. Throughout this phase body weight moves ahead of the forefoot.

- *Pre-swing*: This final phase of stance is the second double-stance interval in the gait cycle. Pre-swing begins with the initial contact of the opposite limb and ends with the toe-off. The objective of this phase is to position the limb for swing.

- *Initial swing*: This phase is approximately one-third of the swing period, beginning with a lift of the foot from the floor and ending when the swinging foot is opposite the stance foot. In this phase, the foot is lifted, and the limb is advanced by hip flexion and increased knee flexion (up maximum 40-60 degree).

- *Mid-swing*: This phase begins as the swinging limb is opposite the stance limb and ends when the swinging limb is forward and the tibia is vertical (i.e., hip and keen flexion postures are equal). The knee is allowed to extend in response to gravity, while the ankle continues dorsiflexion to neural.

- *Terminal swing*: This final phase of swing begins with a vertical tibia and ends when the foot strikes the floor. Limb advancement is completed as the leg (shank) moves ahead of the thigh. In this phase, limb advancement is completed through knee extension. The hip maintains its earlier flexion and the ankle remains dorsiflexed to neural.

To summarize, the human gait phases may be described by a series of initial evens and a number of characteristics that may be reflected in the lower limb articulations, as shown in Table 6.1.

Each gait phase has a functional objective and a critical pattern of selective synergistic motion to accomplish its goal. The sequential combination of the phases also enables the limb to accomplish three basic tasks, namely,

Table 6.1: Gait phases and parameters

Gait phase	Initial event	Phase characteristics
Initial contact	The foot touches the floor	Limbs loading response pattern
Loading response	Initial foot contact	Knee flexing around 15 degree, plantar flexion
Midstance	Opposite toe-off	Reduction on knee flexion(around 12 degree), dorsal flexion
Terminal stance	Heel rise	Complete knee extension
Preswing	Opposite foot initial contact	Second period of double limb support
Initial swing	Toe-off	Ends with maximum knee flexion
Midswing	Feet adjacent	From maximum knee flexing until tibia perpendicular to the ground
Terminal swing	Tibia vertical	Change from knee flexion to complete extension

weight acceptance, single-limb support, and limb advancement. Weight acceptance begins the stance period through initial contact and loading response. Single-limb support continues the stance through the midstance and terminal stance. Limb advancement begins in the pre-swing phase and continues through initial swing, mid-swing, and terminal swing. Based on the above analysis of the gait phases and basic tasks of limb movement, the gait phases may be detected effectively after orientations of the leg segments are accurately obtained.

6.2 Wearable sensor systems for Gait Analysis

There are mainly two kind of systems for gait analysis: outside observation systems and wearable sensor systems. In outside observation an optical 3D motion analysis system with electronic goniometers or camera system method ([76]- [77]) are used to detect walking motion; gait analysis with these methods is expected to really improve rehabilitation training, since they are highly accurate and appropriate instruction can be realized based on exact and quantitative evaluation; however, it is expensive, needs sophisticated instrumentation and specialized personnel, and considerable workspace. Furthermore the devices are expensive, and pre-calibration experiments and off-line analysis of recorded pictures are especially complex and time consuming. Therefore this method is limited in laboratory research or clinical environments, and is difficult to be applied in daily life applications.

In recent years wearable sensors have been used in measurement of human movements and in gait analysis; these sensors have the properties of lower cost, efficient manner of providing the estimation of gait parameters, small size robustness, and easiness for settings; moreover the kinematic data obtained from inertial sensors can be directly used as inputs of control algorithms.

6.2.1 Sensors for Gait Analysis

Recently gait analysis has used different types of motion sensors and systems, such as the accelerometer, gyroscope, magnetoresistive sensors, flexible goniometer, electromagnetic tracking system (ETS), sensing fabric, force sensor, and sensors for electromyography (EMG). Based on these sensors, a single type or a combined sensor system of multiple types of sensors may be used for various gait analysis applications. The basic principles and features of these motion sensors and systems are described in the following [66].

Inertial sensors

Inertial sensors like acceleroometers and gyroscopes have been frequently used in navigation and augmented reality modeling, because they have the properties of low cost, small size robustness, and easiness for settings.

An accelerometer is a type of inertial sensor that can measure acceleration along its sensitive axis.

The common operation principle of accelerometers is based on a mechanical sensing element that comprises a proof mass attached to a mechanical suspension system, with respect to a reference frame.

Three common types of accelerometers are available, namely, piezoelectric, piezoresistive, and capacitive accelerometers.

A gyroscope is an angular velocity sensor. The micro-machined gyroscope is based on the concept of measuring the Coriolis force, which is an apparent force proportional to the angular rate of rotation in a rotating reference frame. By detecting the linear motion from the Coriolis effort and performing an integration of the gyroscopic signal, the angular rate can be obtained.

A gyroscope can be applied for the measurement of the motion and posture of the human segment in gait analysis by measuring the angular rate. For example, by attaching a gyroscope to human feet or legs, the angular velocity and angle of feet or legs during the gait can be determined to realize the reorganization of the various gait phases. In the gait analysis, a gyroscope is usually combined with an accelerometer to construct a complete initial sensing system.

However, the position and angle of an inertial sensor cannot be correctly determined, due to the fluctuation of offset and measurement noise, leading to integration drift. Therefore, designing drift-free inertial systems is the main target of the current research.

Magnetoresistive sensors

Magnetoresistive sensors are based on the magnetoresistive effect. If a magnetic flux is applied, a Lorentz force proportional to the magnetic flux density will deflect the current path. As the current path is deflected, the current flows through the plate for a longer distance, causing the resistance to be increased. That is, the magnetoresistive effect refers to the change in the resistivity of a current carrying ferromagnetic material resulting from a magnetic field, with the resistance change proportional to the tilt angle in relation to the magnetic field direction. Based on this magnetoresistive effect, magnetoresistive sensors can estimate changes in the orientation of a body segment in relation to the magnetic North or the vertical axis in the gait analysis.

Flexible Goniometer

Unlike the inertial sensor, the flexible goniometer is operated by measuring the change in the physical signal resulting from the angular change. A flexible goniometer can be used to measure the relative rotation between two human body segments. The flexible goniometers used in gait analysis can be divided into strain gauges, mechanical flexible, inductive, and optical fiber goniometers.

Electromagnetic Tracking System (ETS)

The electromagnetic tracking system is a kind of 3D measurement device based on Faradays law of magnetic induction. When an object carrying sensor coils performs a motion inside controlled magnetic fields, the induced voltages in the sensor coils will change, with respect to the change of the objects position and orientation, relative to the source of controlled magnetic fields. In the ETS, the controlled magnetic fields are generated by a fixed transmitter and detected by the receivers fixed on the object in motion. Therefore, the positions and orientations of the object in relation to the transmitter can be calculated. Based on this working principle, some developed commercialized ETSs have been applied in bioengineering, including gait analysis.

Force Sensors

Force sensors can be embedded into footwear to realize ambulatory measurements of GRF during the gait. This GRF is a 3D vector, with the actual direction depending on the nature of the interface between the foot and the ground.

Electromyography (EMG)

To measure the action of the muscles in the lower extremity in a human gait, the EMG was developed to perform an indirect measurement of muscle activity using surface or wire electrodes. These electrodes are a kind of sensor for EMG and can detect voltage potentials to provide information on the timing and intensity of muscle contraction.

EMG sensors can be used to realize the assessment of muscle activity in human gait and play an important role in evaluating the walking performance of individuals with problems in their lower extremities.

6.2.2 Gait analysis methods based on wearable sensors

The achievements of human gait analysis can be divided into three areas, namely, kinematics, kinetics, and EMG. The kinematics of the human gait describes the movements of the major joints and components of the lower extremity in the human gait. Gait kinetics focuses on the study of forces and moments that result in the movement of human segments, in which the orientation of all the leg segments obtained from gait kinematics is often required. The EMG of the human gait is used to detect and analyze muscle activity during human walking [66].

6.3 Open issue on Gait Analysis

Wearable sensors have been widely used in measurement of human movements and in gait analysis; these sensors provide quantitative and repeatable results over extended time periods with low cost and good portability, showing great progress in recent year.

However, a significant problem on measurement of joint angles with inertial sensors, and in particular with gyroscopes is the error accumulation in the integral value due to the pronounced drift.

6.3.1 An atlas of inertial sensor-based systems

There are two types of inertial sensor-based systems. The former estimates gait parameters by installing inertial sensors on the foot.

In [78] by installing accelerometers and gyroscopes on a shoe foot kinematics can be estimated, while the gait parameters can be estimated by means of a regression model; however in [79] is proposed an inertial sensor-based two feet motion system for gait analysis. An inertial sensor is attached on each shoe and an inertial navigation algorithm, including an indirect kalman filter, is used to estimate the movement of both feet, while the position and attitude between two shoes can be estimated using a camera on one shoe and infrared leds on the other shoe.

The other kind of inertial sensor-based systems estimates gait cycle parameters, such as joint angles, installing gyroscopes and accelerometers on the legs.

Morris [80] identified the beginning and the end of the walking cycle and made the signals at the beginning and at the end of the cycle equal. Sabatini et al. [81] proposed a method using quaternions for calculating body segment orientations from angular velocity data of a body mounted gyroscope; however the proposed method used the cyclic properties of gait to compensate the drift. Another approach using quaternions is proposed in [82]: the initial orientation of the sensor units were estimated using acceleration data during upright standing position and the angular displacements were estimated using angular velocity data during gait. An algorithm based on quaternion calculation was implemented for orientation estimation of the sensor units, which were converted afterwards to the orientation of the body segments by a rotation matrix obtained from a calibration trail.

Tong et al. [83] derived segment inclinations and knee angle from segment angular velocities and applied a low cut high pass filter on the shank and thigh inclination angle signals; however in this way he removed low-frequency information, therefore this method cannot be applied to real-time processing. However Favre et al. used acceleration data to compensate for the drift in the angular velocity data, but this compensation could only be implemented in situations where gravitational acceleration is the only component measured [84]. Another method to estimate joint angles from measured accelerations is the estimation of the inclination angles between the sensor and the vertical, and after that the subtraction of the angles for adjacent segments. This results are not accurate if the segment accelerations are as large as the gravity ([85]- [86]). A different approach was presented in [87], where each single gait phase was detected by means of gyroscopes and accelerometers; the former measured the angular velocity of each segment, the latter measured the inclination of the leg segment in every single gait cycle for periodic recalibration: an orientation estimation algorithm was used continuously for the orientation estimations obtained by mathematical integration of the angular velocity obtained from gyroscopes.

Furthermore Willemsen et al. [88] estimated joint angles without integration; his method is based on the comparison of signals deduced from two accelerometers mounted on adjacent segments of the leg. However, a low pass filter is requested, therefore is introduced a delay. In many applications the offset drift is solved by means of Kalman filter: Cikajlo proposed an algorithm where the Kalman filter is used to correct the shank inclination measured by the gyroscope [89]; in addition, the extended Kalman filter [90] and Gaussian particle filter [91] were also used to evaluate the hip angle in a walking cycle from the measurements of the wearable sensors, thus improving accuracy. Also the neural network [92] was applied for the estimation of ankle, knee, and hip joint angles, obtaining a good accuracy; however, this method needs a training for individual settings before measurements in order to estimate with a good accuracy.

Popovic [93] proposed a new method for estimation of absolute segment and joint angles during the gait; absolute angles of each segment were determined by band pass filtering the difference between signals from two accelerometers, while joint angles were evaluated by subtracting absolute angles of the neighboring segment. The offset drift was minimized with a Butterworth filter and it can be additionally reduced if a high-pass filter is used in conjunction with the low-pass filter. This approach is similar to the method based on multi-rate complementary filtering theory developed in [94] for a navigation system. However the method encounters an accuracy problem if the gait is slow, therefore is not acceptable for patients with an high level of disability. Another method of gait parameters recognition in real-time is proposed in [95] where the wearable system consists of tri-axial accelerometer and an autocorrelation procedure estimates the repeating characteristics over the gait periodic signal.

An interesting method was proposed by Watanabe ([96]- [97]- [98]) where signals from the sensor attached on the foot were used in the gait length estimation and joint angles were calculated as integral of difference between angular velocities measured from two gyroscopes attached on adjacent segments. Outputs of accelerometers are filtered with Butterworth low pass filter and used to measure inclination, and the offset drift problem was solved by the Kalman filter, used to estimate the error of the joint angle measured by gyroscopes form differences between angles obtained by gyroscopes and those by accelerometers.

6.3.2 A possible contribution

We will focus in this thesis on a particular aspect of gait analysis by means of inertial sensors, that of error accumulation due to the pronounced offset drift.

In order to avoid this drawback we have developed an accurate, but simple algorithm and sensor system to estimate hip and knee angles both in gait and in stand phase of the human movement.

Therefore in this thesis is presented a second order algorithm, proposed in [99] , that allow to obtain a relation between measured accelerations and angular velocities and the joint angles between two consecutive x-axes.

Furthermore gait cycle parameters, such as joint angles and the beginning of the stance phase, are estimated upon the idea of [99] and we validated our algorithm under walking on short distance pathway [100].

Finally in this thesis are proposed two more methods to estimate gait parameters, in order to solve the problem of vibrations caused by the contact of the foot with the ground; the former merges the method proposed in [99] with the complemetary filters method [94]. Namely, the estimation from ours algorithm is used in the complementary filter method instead of measurements from accelerometers. However, the latter merges the complementary filters method with the integrated gyros signals. [100].

Summarizing, in the next chapters will be reported some algorithm and experiment in the field of gait analysis in order to estimate joint angles by overcoming the particular issue of gyroscopes, that is the error accumulation due to the drift, and the vibrations caused by the accelerometer at the beginning of stance phase.

Chapter 7

Gait parameters estimation with inertial sensors

Gait analysis using wearable sensors is a convenient and efficient manner of providing useful information for multiple health-related applications.

In this chapter a wearable sensor system, consisting of accelerometers and gyroscopes, has been studied in order to estimate hip and knne angles. The proposed algorithms pursue the aim of avoiding the error accumulation due to the gyroscopes drift. Furthermore two more methods have been proposed in order to solve the problem of vibrations caused by the contact of the foot with the ground.

7.1 An overview on inertial sensors issues

In this section we present some results about the study of a wearable sensor system, in order to support the rehabilitation of patients with a motor impairment, training in health care, monitoring of the patient healing progress, sport training and analysis of the improvement of athlete performance, or in humanoid robotics.

In this fields, the improvement of a patient, or anyway the motor ability of the operator, are normally evaluated just by a visual information of the movements or by measurement of the time for a task; on the other hand quantitative evaluations of movements with a measurement system can be obtained.

The standard methods for human motion analysis are an optical 3D motion analysis system with camera system methods; gait analysis with these methods is supposed to be improved, since they are highly accurate; however, this kind of measurement system is expensive, and it is limited in laboratory or clinical environments, because it needs sophisticated instrumentations and an huge workspace.

For this reason lately wearable sensors such as accelerometers and gyroscopes have been used in measurement of human movements and in gait analysis.

Indeed, as a clinical tool applied in rehabilitation and diagnosis of medical conditions and sport activities, gait analysis using these inertial sensors shows great prospects due to their properties of lower cost, efficient manner of providing the estimation of gait parameters, small size robustness; furthermore the kinematic data obtained from inertial sensors can be directly used as inputs of control algorithm.

However, the measurement of gait cycle parameters with gyroscopes leads to the significant problem of error accumulation in its integral value caused by offset drift. In order to reduce the offset, several methods have been proposed.

Willemsen [88] estimated joint angles without integration of gyroscopes signal, but by means of the comparison of signals deduced from two accelerometers mounted on adjacent segments of the leg. However, a low pass filter is requested, therefore is introduced a delay. In many applications the offset drift is solved by means of Kalman filter [89]. Furthermore Favre used acceleration data to compensate for the drift in the angular velocity data, but this compensation could only be implemented in situations where gravitational acceleration is the only component measured [84].

In addition Popovic [93] proposed a method for estimation of absolute segment, by band pass filtering the difference between signals from two accelerometers, while joint angles were evaluated by subtracting absolute angles of the neighboring segment. The offset drift was minimized with a Butterworth filter and it can be additionally reduced if a high-pass filter is used in conjunction with the low-pass filter. This approach is similar to the method based on multi-rate complementary filtering theory developed in [94] for a navigation system. However the method is not accurate if the gait is slow, therefore is not acceptable in the fields of rehabilitation or health care. Finally an interesting method was proposed by Watanabe ([96]- [97]- [98]) where signals from the sensor attached on the foot were used in the gait length estimation and joint angles were calculated as integral of difference between angular velocities measured from two gyroscopes attached on adjacent segments. Like in the Popovic's method, outputs of accelerometers are filtered with Butterworth low pass filter in order to measure inclination, and the offset drift problem was solved by the Kalman filter, used to estimate the error of the joint angle measured by gyroscopes from differences between angles obtained by gyroscopes and those by accelerometers.

The aim of this chapter is to propose other methods in order to estimate hip and knee angles avoiding the gyroscopes drift. In particular it is presented an estimation algorithm able to estimate gait parameters, such as hip and knee angles, without the integration of gyroscopes signal. Furthermore it is introduced the complementary-filters method since during experiments both methods are comparised and afterwards bound together. Finally another method is proposed where the complementary filters method is properly mixed with the integrated gyros signals.

7.2 Acceleration Propagation Based method (APB)

In this section it is shown the estimation algorithm originally proposed in [99]. The kinematic scheme of each leg of the sensor system, based only on low cost inertial sensors such as accelerometers and gyroscopes is shown in the figure 7.1.

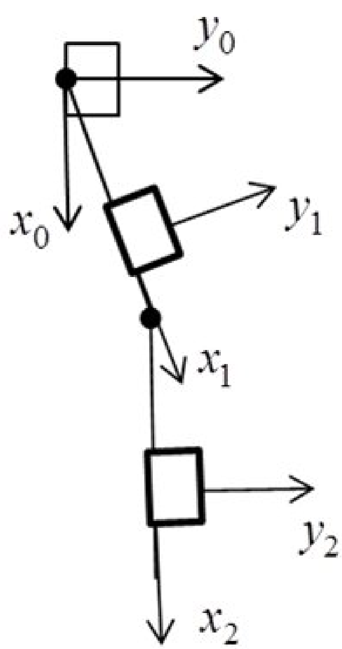


Figure 7.1: Kinematic scheme of a leg

In order to avoid the gyroscopes drawback we studied a second order kinematic model and we obtained a relation between measured accelerations and angular velocities and the joint angles between two consecutive x-axes.

The kinematic relation that express the position of the knee accelerometer it is considered

$$P_0 = P_0^1 - l_1 x_1 \tag{7.1}$$

where l_1 is the position of the knee accelerometer (with respect to the coordinate frame 0) and the rotation matrix is defined as $R_1^0 = (x_1 \quad y_1 \quad z_1)$.

The second order kinematic model was obtained from (7.1) making the derivative and decomposing on the x_0 and y_0 axis

$$\ddot{P}_{0,mx} x_0 + \ddot{P}_{0,my} y_0 = \ddot{P}_{1,mx} x_1 + \ddot{P}_{1,my} y_1 + l_1 \dot{\theta}_1^2 x_1 - l_1 \ddot{\theta}_1 y_1 \tag{7.2}$$

where $\ddot{P}_{i,m}$ is the measure from accelerometers, and $\dot{\theta}_1$ the measure from the knee gyroscope.

Projecting in the frame 1 the second order kinematic relation expressing the knee acceleration, we found relations such that we need only measurements from the accelerometers and the gyroscope to estimate the hip angle θ_1 .

$$\begin{aligned} \ddot{P}_{0,mx} c_1 + \ddot{P}_{0,my} s_1 - l_1 \dot{\theta}_1^2 = \ddot{P}_{1,mx} \\ -\ddot{P}_{0,mx} s_1 + \ddot{P}_{0,my} c_1 + l_1 \ddot{\theta}_1 = \ddot{P}_{1,my} \end{aligned} \tag{7.3}$$

where c_1 and s_1 are the cosine and the sin of the hip angle.

In the same way for the second link, considering the position kinematic relation of the ankle accelerometer

$$P_0 + l_{01} x_1 + l_2 x_2 = P_2 \tag{7.4}$$

where l_{01} is the position of the origin O_1 (with respect to the coordinate frame 0), l_2 is the position of the ankle accelerometer (with respect to the coordinate frame 1) and the rotation matrix is defined as $R_2^0 = (x_2 \quad y_2 \quad z_2)$.

For the second link, the second order kinematic relation is

$$\begin{aligned} \ddot{P}_{0,mx} x_0 + \ddot{P}_{0,my} y_0 - l_{01} \dot{\theta}_1^2 x_1 - l_2 (\dot{\theta}_1 + \dot{\theta}_2)^2 x_2 + l_{01} \ddot{\theta}_1 y_1 + l_2 (\ddot{\theta}_1 + \ddot{\theta}_2) y_2 = \\ = \ddot{P}_{2,mx} x_2 + \ddot{P}_{2,my} y_2 \end{aligned} \tag{7.5}$$

where $\ddot{P}_{2,m}$ is the measure from the ankle accelerometer, and $(\dot{\theta}_1 + \dot{\theta}_2)$ the measure from the ankle gyroscope.

As in the case of the first link we projected in the frame 2 the kinematic relation (7.5), expressing the ankle acceleration, and we multiplied (7.5) by x_2^T and y_2^T, obtaining respectively

$$\begin{aligned} \ddot{P}_{0,mx} c_{12} + \ddot{P}_{0,my} s_{12} - l_{01} \dot{\theta}_1^2 c_2 - l_2 (\dot{\theta}_1 + \dot{\theta}_2)^2 + l_{01} \ddot{\theta}_1 s_2 = \ddot{P}_{2,mx} \\ -\ddot{P}_{0,mx} s_{12} + \ddot{P}_{0,my} c_{12} + l_{01} \dot{\theta}_1^2 s_2 + l_{01} \ddot{\theta}_1 c_2 + l_2 (\ddot{\theta}_1 + \ddot{\theta}_2) = \ddot{P}_{2,my} \end{aligned} \tag{7.6}$$

where c_{12} and s_{12} are the cosine and the sin of the angle $(\theta_1+\theta_2)$. With some algebraic manipolation the (7.6) become

$$\begin{aligned}[\ddot{P}_{0,mx}c_1 + \ddot{P}_{0,my}s_1 - l_{01}\dot{\theta}_1^2]c_2 + [\ddot{P}_{0,my}c_1 - \ddot{P}_{0,mx}s_1 + l_{01}\ddot{\theta}_1]s_2 = \ddot{P}_{2,mx} + l_2(\dot{\theta}_1 + \dot{\theta}_2)^2 \\ [\ddot{P}_{0,my}c_1 - \ddot{P}_{0,mx}s_1 + l_{01}\ddot{\theta}_1]c_2 - [\ddot{P}_{0,mx}c_1 + \ddot{P}_{0,my}s_1 - l_{01}\dot{\theta}_1^2]s_2 = \ddot{P}_{2,my} - l_2(\ddot{\theta}_1 + \ddot{\theta}_2)\end{aligned} \tag{7.7}$$

where c_2 and s_2 are the cosine and the sin of the knee angle.

Considering the kinematic relation (7.3) we found a second order kinematic relation that allows to estimate the knee angle θ_2 only by measurements from the knee and ankle accelerometers and the ankle gyroscope, avoiding the error accumulation due to the integration of the gyroscopes signals.

$$\begin{aligned}[\ddot{P}_{1,mx} + (l_1 - l_{01})\dot{\theta}_1^2]c_2 + [\ddot{P}_{1,my} - (l_1 - l_{01})\ddot{\theta}_1]s_2 = \ddot{P}_{2,mx} + l_2(\dot{\theta}_1 + \dot{\theta}_2)^2 \\ [\ddot{P}_{1,my} - (l_1 - l_{01})\ddot{\theta}_1]c_2 - [\ddot{P}_{1,mx} + (l_1 - l_{01})\dot{\theta}_1^2]s_2 = \ddot{P}_{2,my} - l_2(\ddot{\theta}_1 + \ddot{\theta}_2)\end{aligned} \tag{7.8}$$

The kinematic relations (7.8) are analogous to the relations (7.3), unless for the compensation terms, which depends on the difference (l_1-l_{01}),namely the distance between the knee accelerometer and the origin of the frame 1. Therefore, if the knee accelerometer is put as $l_1 = l_{01}$, the system will become more robust, and the joint angle computation is a simple propagation of the same formula.

7.3 Complementary filters method

The results obtained from the approach presented in [99] are compared in this work, under walking on short distance pathway, with direct measurement from encoder and with results provided using complementary filters theory. Furthermore others method proposed in this work are based on the complementary filters method and are compared with previous methods.

Complementary filters arise in the context of signal estimations based on measurements from sensors over both distinct and complementary regions of frequency [94]. In this application the estimation of the position is based on measurements provided by accelerometers and gyroscopes. Indeed, accelerometers provide accurate informations at low frequency, however gyroscopes show drift phenomena in the same frequency band, therefore they are useful at higher frequencies.

Let us consider the expression of filtered position

$$PW_{PB} + \frac{v}{s}(1 - W_{PB}) = P \tag{7.9}$$

where

$$W_{PB} = \frac{\tau_z s + 1}{\tau_p s + 1} \tag{7.10}$$

is a low-pass filter for measured accelerations, whereas

$$1 - W_{PB} = \frac{\tau_p - \tau_z}{\tau_p s + 1} s \tag{7.11}$$

is an high pass filter for the integrated gyroscope signals, however it can be seen as a low-pass filter for the direct measured velocities from gyroscopes.

7.4 Mixed Complementary Filter-APB (CF-APB)

In this section it is shown the estimation algorithm originally proposed in [100].

The mixed complementary filter consists of a modified complementary filters method where the measurement from accelerometer has been replaced from the APB method, proposed in the first place in [99].

Indeed, the APB algorithm, as well as the classic complementary filters method, shows a good performance save for the time interval right after the beginning of the stance phase, namely the contact of the foot with the ground, where there are vibrations.

To solve this problem a new complementary filters method has been introduced, consisting in the APB method, more accurare than the accelerometer measurement, and the gyros information, respectively at the low and high frequency.

Furthermore the cut-off frequency can be adjusted according to the reliability of both the two estimation methods. In particular the cut-off frequency could be decreased to a low frequency as soon as a contact of the foot with the ground is detected, in order to place more trust on the gyroscope measurement and therefore avoid vibrations, caused by the accelerometer signal.

7.5 Intelligent Complementary Filter (ICF)

In this section it is shown the estimation algorithm originally proposed in [100].

This method is based on the complementary filters with rate limiter and the integrated signal from gyros blended together.

The APB algorithm, as well as the complementary filters method, as it is shown in the next section, has an accurate performance in the walking tests where there are not considerable fast variations of joint angles nor contacts of the foot with the ground, the latter bringing to oscillations of the system for a short time interval. This method has been proposed in order to solve this drawbacks.

To improve the complementary filters performance, at least to solve the problem of fast angles variations and vibrations, we introduce the rate limiter in the complementary filters method, in other words freezing the estimated angular velocity considering the sensors features of gyroscopes.

The general idea of the method proposed in this section is that the accelerometer signal, bringing oscillations in the time interval right after the contact of the foot with the ground, should not be considered in this circumstance; however the integrated gyroscope signal is enough accurate for short time interval.

Therefore, this method estimates joint angles by means of complementary filters method with the rate limiter until a gap between this method and the complementary filters method is detected. At this stage the integrated gyroscope signal has to be used, considering the initial condition identified at this instant.

Finally, when the gap will be over, the joint angles could be estimated again by means of the complementary filters signal with rate limiter.

In order to explain better the ICF method, a scheme is shown in the figure 7.2.

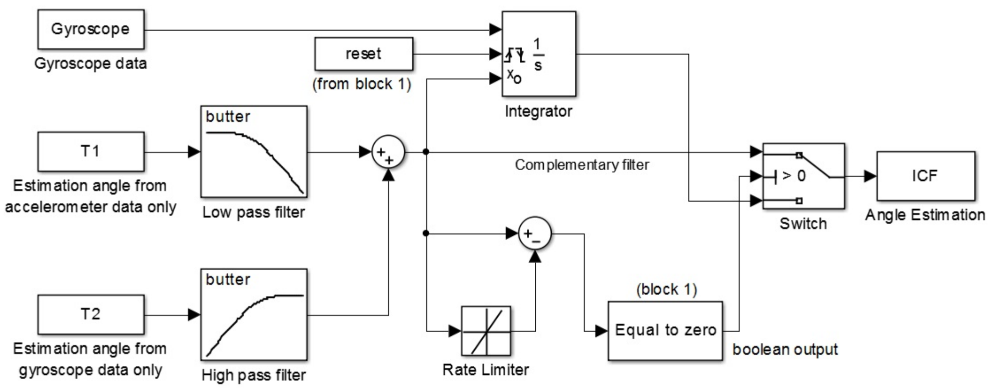


Figure 7.2: Schematic structure of the ICF method

Chapter 8

Applications of gait analysis algorithms

The aim of this chapter is to show how the presented methods for the gait phase detection have been used.

The algorithms proposed in this thesis have been tested on a real overground walking trial.

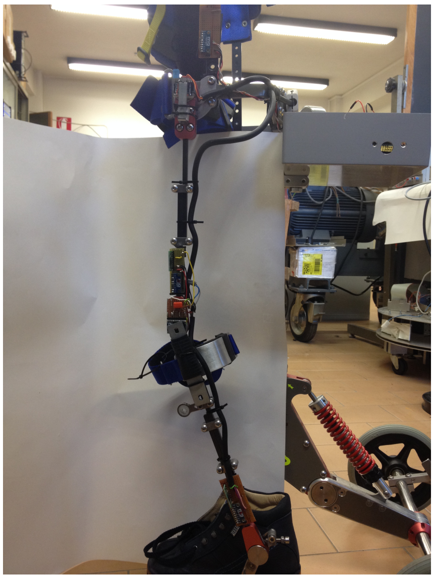
8.1 Experimental setup

Experiments for evaluation of the proposed methods have been performed at the Robotic laboratory of the Department of Energy, Information technology and Mathematical models, at the University of Palermo.

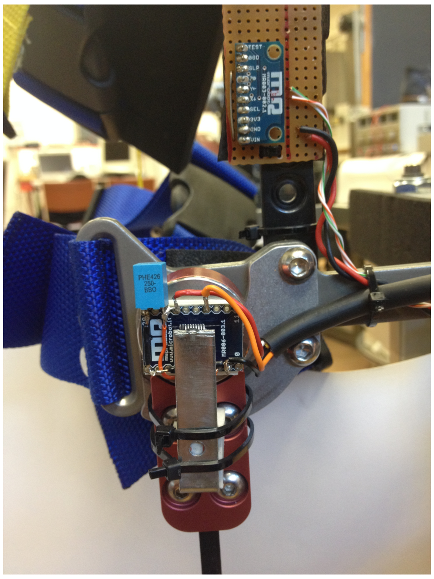
The wearable sensor system consists of accelerometers and gyroscopes put near to the knee and the ankle (see Figure 8.1); we put also encoders on the hip and knee joints only to compare their angular measurements with results of our algorithm.

The experimental equipment comprises of:

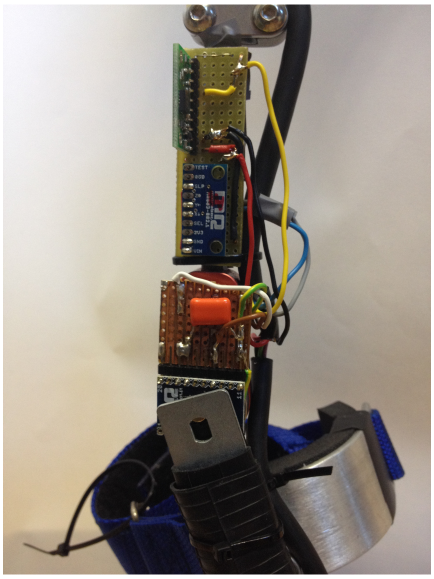
- LPY510Al (ST), an analog low-power dual-axis micro machined gyroscope, capable of measuring angular rate along pitch and yaw axes. It provides excellent temperature stability and high resolution. The gyroscope allows band limiting the outuput rate response through the integrated low pass filter.
- MMA7361L (FreeScale), a capacitive low power 3-axis accelerometer, integrating a voltage regulator and a low pass filter.
- ARDUINO DUE, a microcontroller board based on the Atmel SAM3X8E ARM Cortex-M3 CPU, providing 54 digital input/output pins, 12 ana-



(a) Left leg of the NF-walker used in the experiments



(b) Particular of the hip accelerometer and encoder



(c) Particular of the knee gyro, accelerometer and encoder

(d) Particular of the ankle gyro and accelerometer

Figure 8.1: Wearable sensor system

log inputs (12 bits of resolution), 4 UARTs (hardware serial ports), a 84 MHz clock, 96 KBytes of SRAM, 512 KBytes of Flash memory for code, a DMA controller.

- AS5045, the encoder chosen for comparison, a contactless magnetic rotary sensor for accurate angular measurement over a full turn of 360. It is a system-on-chip, combining integrated hall elements, analog front end and digital signal processing in a single device.
- a commercial device for assisted gait, the NF-Walker [101].

8.2 Experimental evaluation

The experiments performed have the main purpose of comparing the different way of estimating hip and knee angles, namely the APB method, CF method, APB-CF method, ICF method and direct angular measurement from encoders.

In addition, in experiments 2 and 3, these algorithm are evaluated on a over-grounded walking trial. However, due to limited laboratory size (therefore limited walking distance), this kind of measurement was restricted to only a few steps.

8.2.1 Experiment 1

This experiment shows the performance of the joint angles estimation algorithm, namely by using both the proposed second order algorithm and the complementary filters method and comparing them with the encoder measurement.

In the figure 8.2 it is shown respectively the estimation of the hip and knee angles through the algorithm proposed in [99] and the comparison with direct encoder measurement.

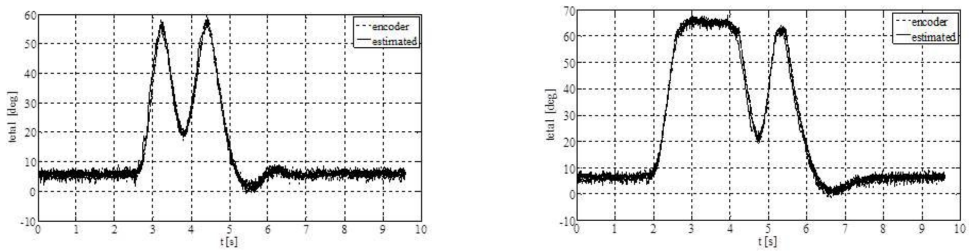


Figure 8.2: *a)* Estimation of the hip angle vs. encoder measurement; *b)*Estimation of the knee angle vs. encoder measurement

Even though it is possible getting accurate angular measurement using only encoders, the kinematic data, such as angular velocity and acceleration, obtained from inertial sensors, could be directly used as inputs of some control strategy; therefore it is more advantageous to use accelerometers and gyroscopes in gait analysis.

Furthermore in the figure 8.3 the estNODYN shape is obtained without gyroscope signal, and without any second order coupling, only with a simple gravity projection; therefore, in the NODYN case the angle joint estimation occurs in static conditions.

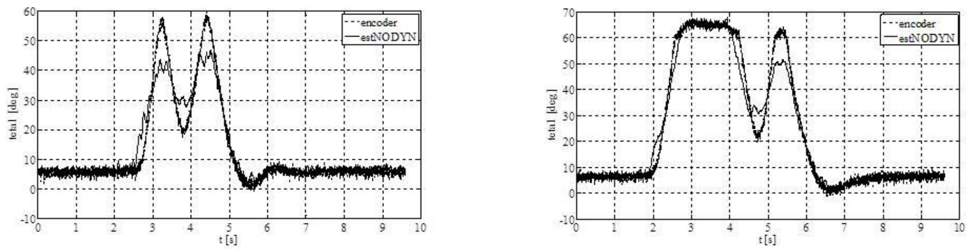


Figure 8.3: *a)* Static estimation of the hip angle vs. encoder measurement; *b)* Static estimation of the knee angle vs. encoder measurement. The estNODYN shape is obtained without gyro signal.

The figure 8.4 shows the comparison between the direct encoder signal and the results provided from complementary filtering approach. The best results were obtained by choosing $\tau_z = \frac{1}{20\pi}$ and $\tau_p = \frac{1}{0.6\pi}$. From the figure 8.4 it is easy to see that the estimation through complementary filters is accurate in the frequency of the gyroscope signal, however it is not accurate in the first instants or vice versa.

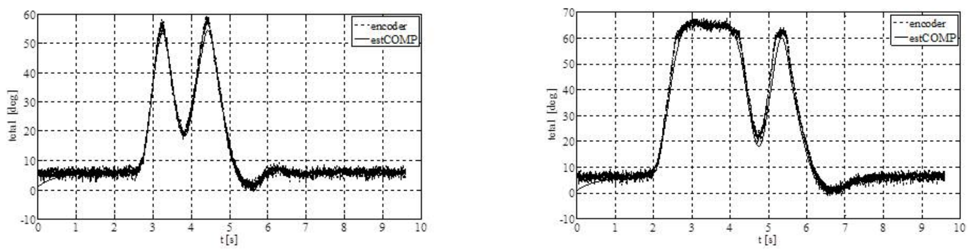


Figure 8.4: *a)* Estimation of the hip angle through complementary filters method vs. encoder measurement; *b)* Estimation of the knee angle through complementary filters method vs. encoder measurement.

Finally the figure 8.5 shows sensors output of the knee joint, while the figure 8.6 shows acceleration and angular velocity from ankle sensors.

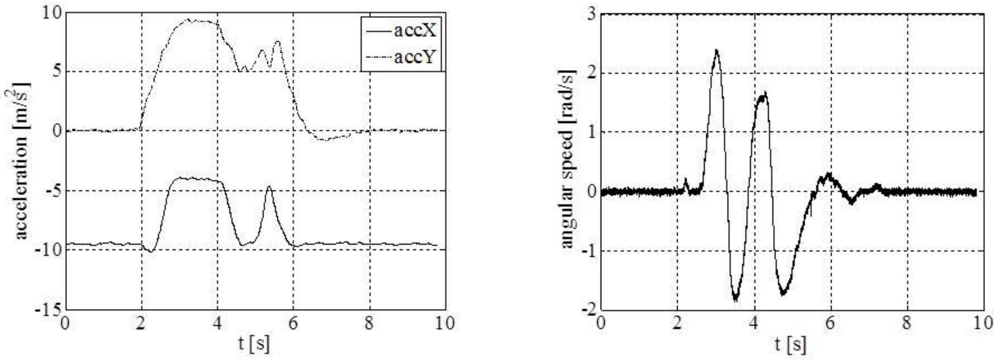


Figure 8.5: *a)* Knee acceleration measurement components; *b)* Femur angular speed measurement.

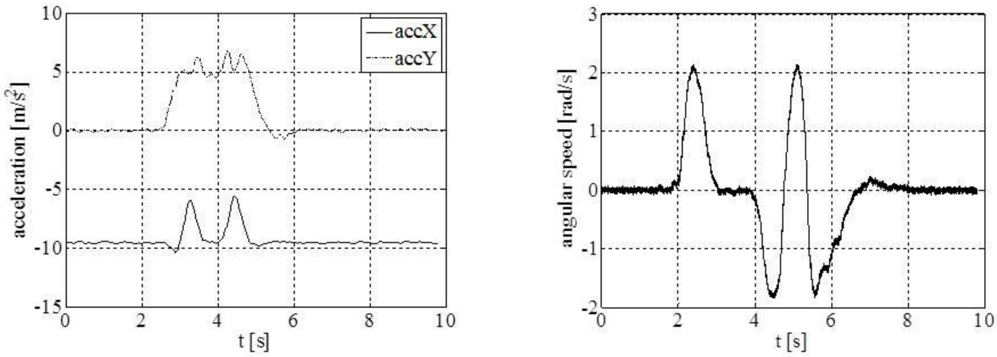


Figure 8.6: *a)* Ankle acceleration measurement components; *b)* Tibia angular speed measurement.

The results have pointed out a good accuracy of the angle estimations, above all in high angular rate movement, as well as the possibility to use this method instead of direct encoder measurement, considering that accelerometer and gyroscope outputs could be used in control strategy.

8.2.2 Experiment 2

This experiment is performed to evaluate the performance of the mixed Complementary Filter - APB (CF-APB) algorithm on a over-ground walking trial.

In the figure 8.7 there is a comparison of the performances of the APB method, encoder measurements, the integration of the gyros signal, and the mixed complementary filtering approach proposed in this work (CF- APB).

From this figure it is pointed out that the APB algorithm shows a good accuracy of the angles estimation, save for a time interval after the contact, where there are vibrations. This problem is presented by the complementary filters method as well.

For this purpose, a new complementary filters algorithm has been proposed, developed with the APB algorithm, more accurate than accelerometer signal, and gyroscopes. The main advantage respect the classic complementary filter is that as soon as the contact is detected, moving the pole position it is possible to obtain estimations without vibrations.

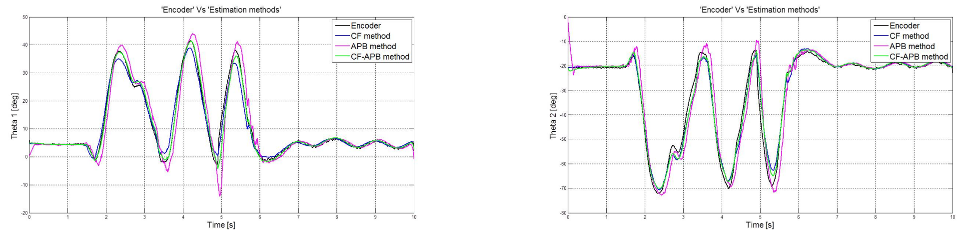


Figure 8.7: *a)* Estimation of the hip angle; *b)* Estimation of the knee angle

8.2.3 Experiment 3

This experiment is performed to evaluate the performance of the Intelligent Complementary Filter (ICF) algorithm on a over-ground walking trial.

In the first place from figure 8.8, that points out the sensors signal, respectively for the hip and knee angles, it is possible to detect the beginning of the stance phase, namely the instant where a contact of the foot with the ground occurs, by means of the trigger signal of the accelerometer.

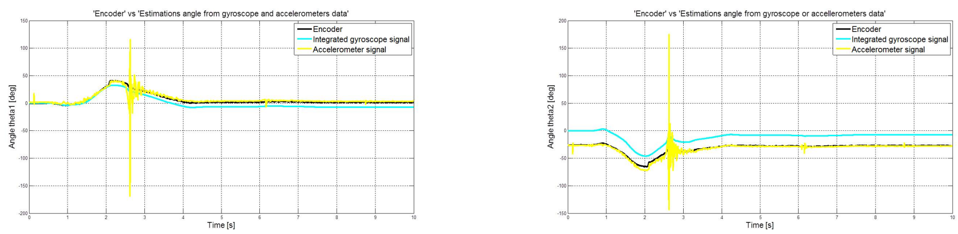


Figure 8.8: *a)* Sensors signals of the hip angle; *b)* Sensors signals of the knee angle.

In the figures 8.9.a-8.9.b it is shown a comparison between the complementary filters method with rate limiter, the CF method, and the encoder measurement for both hip and knee angles. In particular, in the figures 8.9.c-8.9.d it is pointed out the occurrence of a gap between both the estimation methods, in the same time interval when there is the contact of the foot with the ground and the related vibrations.

Finally in figure 8.10.a-8.10.b there is a comparison of the performances of the APB method, CF method, encoder measurement, and ICF method. In particular in figure 8.10.c-8.10.d it is evident the improvement of the performance of the ICF method, especially in the time interval concerning the contact issues.

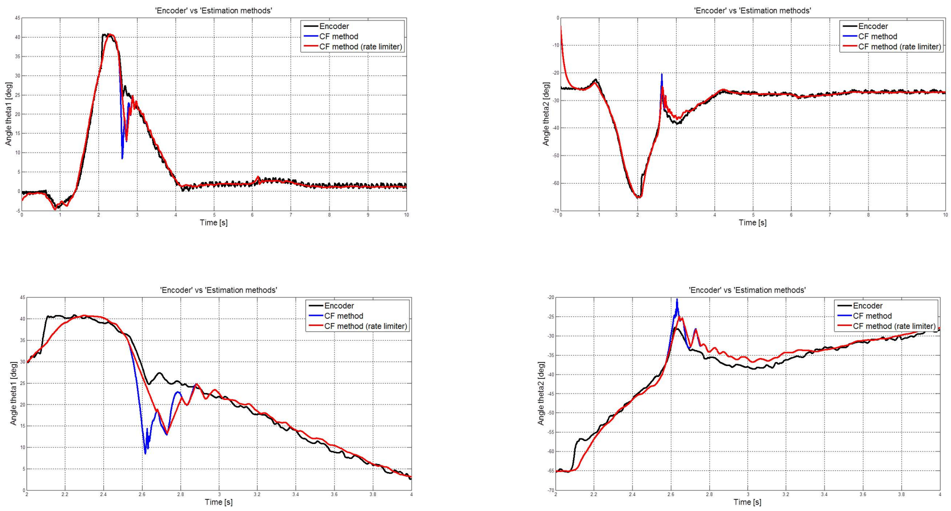


Figure 8.9: *a)* Estimation of the hip angle by means of CF methods vs. encoder measurement; *b)* Estimation of the knee angle by means of CF methods vs. encoder measurement; *c)* Particular of the hip angle estimation by CF methods; *d)* Particular of the knee angle estimation by CF methods.

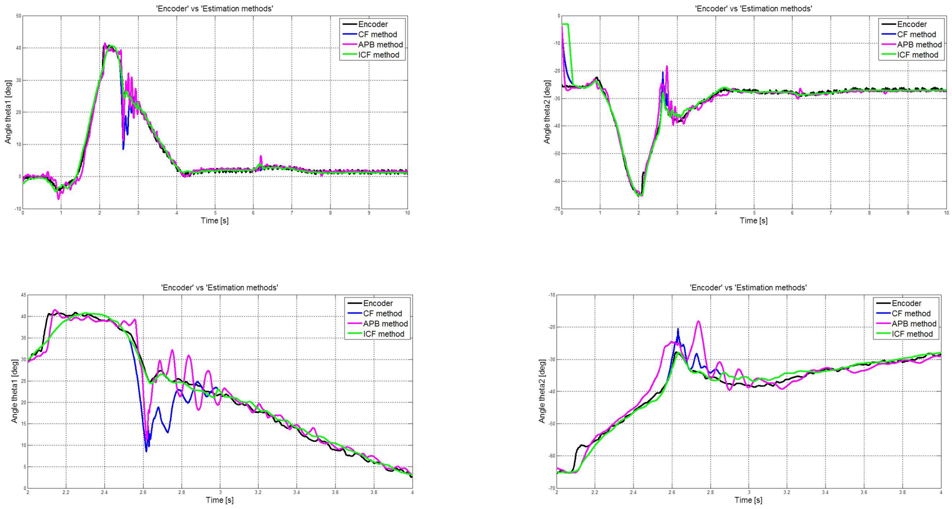


Figure 8.10: *a)* Comparison of hip angle estimation methods vs. encoder measurement; *b)* Comparison of knee angle estimation methods vs. encoder measurement; *c)* Particular of the comparison between estimation methods for the hip angle; *d)* Particular of the comparison between estimation methods for the knee angle

Chapter 9

Conclusions

The research themes at issue in this thesis concern with robotics interaction and cooperation. In this framework we studied two different aspects, with real applications respectively for industrial and rehabilitation domains.

In the former safety issues are examined on a scenario in which a robot manipulator and a human perform the same task and in the same workspace. During the task execution the human should be able to get into contact with the robot and in this case safety conditions have to be guaranteed. At the same time, all the unintended contacts have to be avoided, and suitable post collision strategy must be adopted to reduce the impact efforts.

However the second part of the thesis deals with issues of the cooperation between an orthesis and a patient. Indeed, in order to improve the cooperation between health-related devices and operator and to support a rehabilitation process, gait parameters, such as joint angles or the beginning of a gait phase, have to be estimated.

Contributions presented in this thesis are listed and summarized in the following sections.

9.1 Robotics interaction in the industrial domain

This section considers the problem of controlling a robot manipulator in the task space, while ensuring a compliant behavior when a collision occurs. Once an undesired physical collision has been detected (by means of algorithm presented in the Chapter 3), the robot switches as fast as possible from the control law associated to normal task execution to a reaction control law.

Therefore, for the purpose of moving the robot manipulator away from collision, a reaction control law is proposed, where the joint torques due to the contact have to be reduced.

The effect of this strategy is to obtain a more compliant robot, predisposed to move in the direction given by the human, or anyway, by the contact.

Furthermore, in the framework of intentional contact, the interaction force estimation is important to predict human motion and react accordingly. For this purpose a method has been proposed for the estimation of both the contact force and the contact point for a n-link manipulator in point contact (with zero moment) with the environment.

9.2 Robotics cooperation in the rehabilitation domain

In the rehabilitation fields, the key role of a robot in interaction with the patient is the generation of supplementary forces to empower and to overcome human physical limit, be they natural or the result of a disease or trauma.

However, this process is based on data acquired by a set of sensors to measure kinematic variables, namely the gait analysis.

In this framework a wearable low cost sensor system, based on accelerometers and gyroscopes measurements, has been proposed in this thesis. Furthermore some algorithm has been proposed in order to estimate hip and knee angles both in gait and in stand phase.

The purpose that this work intends to achieve is the estimation of gait parameters avoiding the significant problem of measurement of joint angles with inertial sensors, namely the error accumulation due to the offset drift of the gyroscopes. In addition the thesis dealt with the accelerometer issue, that is the vibrations related to the time interval right after the contact of the foot with the ground.

Furthermore the trigger signal of accelerometers has been used in order to detect the beginning of the stance phase, namely the initial contact of the foot with the ground.

The results have pointed out a good accuracy of the angle estimations, above all in high angular rate movement, as well as the possibility to use this method instead of direct encoder measurement, considering that accelerometer and gyroscope outputs could be used in control strategy.

Future developments of this algorithm will be the development of a mechatronic system for walking assistance of motor impaired child. In particular the estimation of joint angles allows the detection of gait phases in a totally wearable system and afterwards the development of a proper control law to activate pneumatic muscles, put on the orthoses, in order to support the rehabilitation gait patterns.

Bibliography

[1] B. Siciliano, O. Kathib, "Springer Handbook of Robotics," 31 August 2008.

[2] A. Chu, H. Kazerooni, A. Zoss, "On the biomimetic design of the Berkeley lower extremity exoskeleton (BLEEX)," *Proc. IEEE Int. Conf. Robot. Autom. 2005*,21, pp. 4345-4352.

[3] M. Bergamasco, A. Frisoli, "A new force-feedback arm exoskeleton for haptic interaction in virtual environments," *World Haptics Conf. WHC 2005*,Pisa, pp. 195-201.

[4] J. Guiochet, A. Vilchis, "Safety analysis of a medical robot for tele-echography," *IARP IEEE/RAS Joint Workshop Tech Challenge Dependable Robots Human Env.*,Toulouse 2002.

[5] T. Noritsugu, T. Tanaka, "Application of Rubber Artificial Muscle Manipulator as a Rehabilitation Robot," *IEEE/ASME Transaction on Mechatronics*,Vol. 2, No. 4, December 1997.

[6] M. Peshkin, J. E. Colgate, W. Wannasuphoprasit, C. Moore, B. Gillespie "Cobot architecture," *IEEE Trans. Robot. Autom. 2000*, 17 (4), pp. 377-390.

[7] A. De Santis, B. Siciliano, A. De Luca, A. Bicchi, "An atlas of physical human-robot interaction," *ScienceDirect, Mechanism and Machine theory, 2008*, 43, pp. 253-270.

[8] R. Alami, A. Albu-Schaeffer, A. Bicchi, R. Bischoff, R. Chatila, A. De Luca, A. De Santis, G. Giralt, J. Guiochet, G. Hirzinger, F. Ingrand, V. Lippiello, R. Mattone, D. Powell, S. Sen, B. Siciliano, G. Tonietti, L. Villani, "Safe and Dependable Physical Human-Robot Interaction in Anthropic Domains: State of Art and Challenges," *Proceedings of the IROS' 06 Workshop on pHRI-Physical Human-Robot Interaction-in Anthrpic Domains.*

[9] ISO 10218: *Manipulating Industrial Robots- Safety*(International Organization for Standardization, Geneva 1992.

[10] ISO 10218-1: *Robots for industrial environments- Safety requirements. Part 1*(International Organization for Standardization, Geneva 1992.

[11] Robotic IndustriesAssociation: T15.1. Draft standard for trial use for intelligent assist devices- personnel safety requirements (2002).

[12] "Wearable Robots: Biomechatronic Exoskeletons," *Edited by Jose' L. Pons*, CSIC, Madrid, Spain.

[13] G. Hirzinger, A. Albu-Schaeffer, M. Hahnle, I. Schaefer, N. Sporer, "On a new generation of torque controlled light-weight robots," *2001 International Conference on Robotics and Automation*, Seoul, K. 2001.

[14] K. Salisbury, "Whole Arm Manipulation," *4th International Symposiumof Robotics Research*, Santa Cruz, CA, 1987.

[15] A. Bicchi, G. Tonietti, M. Bavaro, M. Piccigallo, "Variable stiffness actuators for fast and safe motion control," *11th International Symposiumof Robotics Research*, Siena, I. 2003.

[16] G. Tonietti, R. Schiavi, A. Bicchi,"Design and control of a variable stiffness actuator for safe and fast physical human/robot interaction, *IEEE International Conference on Robotics and Automation*, pp. 528-533, 2005.

[17] A. Bicchi, S. Lodi Rizzini, G. Tonietti, "Compliant design for intrinsic safety: General issues and preliminary design," *2001 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Maui, HI. 2001.

[18] M. Zinn, O. Khatib, B. Roth, "A New Actuation Approach for Human Friendly Robot Design," *2004 IEEE International Conference on Robotics and Automation*,New Orleans, La, April 2004.

[19] G. Prett, M. Williamson, "Series elastic actuators," *1995 IEEE/RSJ International Conference on Intelligent Robots and Systems*,Pittsburgh, PA, 1995.

[20] M. W. Spong, "Modeling and control of elasticjoint robots," *ASME Journal of Dynamic Systems, Measurement and Control*,vol. 109, pp. 310- 319, 1987.

[21] R.B. Gillespie, J.E. Colgate, M.A. Peshkin,“A general framework for cobot control, *IEEE Transactions on Robotics and Automation*, vol. 17, pp. 391401, 2001.

[22] H. Kazerooni, A. Chu, R. Steger,“That which does Not stabilize, Will only make us stronger, *International Journal of Robotics Research*, vol. 26, pp. 7589, 2007.

[23] G. Boccadamo, R. Schiavi, S. Sen, G. Tonietti, A. Bicchi, “Optimization and fail safety analysis of antagonistic actuation for pHRI, *First European Robotics Symposium*, Palermo, I, 2006.

[24] M. R. Ahmed, I. Kalaykov, “Semi-Active Compliant Robot Enabling Collision Safety for Human Robot Interaction, *IEEE International Conference on Mechatronics and Automation*, August 4-7, 2010, Xi’an, China.

[25] K. Suita, Y. Yamada, N. Tsuchida, K. Imai, H. Ikeda, N. Sugimoto, “A failure-to-safety kyozon system with simple contact detection and stop capabilities for safe human autonomous robot coexistence, *1995 IEEE Internationl Conference on Robotics and Automation*, Nagoya, J, 1995.

[26] Y. Yamada, Y. Hirasawa, S. Huang, Y. Uematsu, K. Suita,“Human-robot contact in the safeguarding space, *IEEE/ASME Transactions on Mechatronics*, vol. 2, pp. 230236, 1997.

[27] A. De Luca, R. Mattone, “Sensorless robot collision detection and hybrid force/motion control, *2005 IEEE International Conference on Robotics and Automation*, Barcelona, E, 2005.

[28] H.B. Kuntze, C.W. Frey, K. Giesen, G. Milighetti,“Fault tolerant supervisory control of human interactive robots, *IFAC Workshop on Advanced Control and Diagnosis*, Duisburg, D, 2003.

[29] A. De Luca, A. Albu-Schaeffer, S. Haddadin, G. Hirzinger, “Collision detection and safe reaction with the DLR-III lightweight manipulator arm, *2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Beijing, PRC, 2006.

[30] I.D. Walker, “Impact configurations and measures for kinematically redundant and multiple armed robot systems, *IEEE Transactions on Robotics and Automation*, vol. 10, pp. 670683, 1994.

[31] V. J. Lumelsky, E. Cheung, "Real-Time Collision Avoidance in Teleoperated Whole-Sensitive Robot Arm Manipulators, *IEEE Transaction on Systems, Man, and Cybernetics*, vol 23, no. 1, January/February 1993.

[32] G. Cannata, S. Denei, F. Mastrogiovanni, " Towards automated self-calibration of robot skin", *Robotics and Automation (ICRA), 2010 IEEE International Conference on*, 4849-4854

[33] D. Ebert, D. Henrich, "Safe Human-Robot- Cooperation: Image-based collision detection For Industrial Robots, *IEEE/RSJ International Conference on Intelligent Robots and Systems*, Lausanne, September 30th-October 5th, 2002.

[34] A. Garcia, V. Feliu, J. A. Somolinos, "Experimental testing of a gauge based collision Detection mechanism for a new three-degree-of-freedom flexible robot, *J. of Robotic Systems*, vol.20, no.6, pp.271-284,2003.

[35] G. Cannata, S. Denei, F. Mastrogiovanni, "Tactile sensing: Steps to artificial somatosensory maps", *RO-MAN, 2010 IEEE*, 576-581

[36] Y. Yamada, Y. Hirawawa, S. Huang, Y. Umetani, K. Suita, "Human-robot contact in the safeguarding space, *IEEE/ASME Transactions on Mechatronics*, 2,(1997) 230-236.

[37] O. Kathib, "Real-time obstacle avoidance for manipulators and mobile robots, *The International Journal of Robotics Research*, 5, (1986) 90-98.

[38] M. S. Erden, T. Tomiyama, "Human-Intent Detection and Physically Interactive Control of a Robot Without Force Sensors, *IEEE Transaction on Robotics*,vol.26, no. 2, April 2010.

[39] A. Caldas, M. Makarov, M. Grossard, P. Rodriguez-Ayerbe, D. Dumur, "Adaptive Residual Filtering for Safe Human-Robot Collision Detection under Modeling Uncertainties, *IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)* Wollongong, Australia, July 9-12, 2013.

[40] A. De Luca, R. Mattone, "Actuator Failure Detection and Isolation Using Generalized Momenta, *2003 IEEE International Conference on Robotics and Automation*,Taipei, Taiwan, September 14-9, 2003.

[41] A. De Luca, F. Flacco, "Integrated control for pHRI: Collision avoidance, detection, reaction and collaboration, *The Fourth IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics*, Roma, Italy, June 24-27, 2012.

[42] F. Alonge, E. Cucco, F. D'Ippolito, "Contact estimation in robot interaction, submitted to *International Journal of Advanced Robotics Systems*

[43] H. Sadeghian, L. Villani, H. Sadeghian, M. Keshmiri, B. Siciliano, "Task-Space Control of Robot Manipulators With Null-Space Compliance, *IEEE Transaction on Robotics*.

[44] Y. Yamada, Y. Hirawawa, S. Huang, Y. Umetani, K. Suita, "Human-robot contact in the safeguarding space, *IEEE/ASME Transactions on Mechatronics*, 2,(1997) 230-236.

[45] V. J. Traver, A. P. del Pobil, M. Perez-Francisco, "Making service robots human-safe, *IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2000*, pp. 696-701.

[46] J. Y. Lew, Y. T. Jou, H. Pasic, "Interactive control of human/robot sharing same workspace, *IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2000*, pp. 535- 539.

[47] A. De Luca, L. Ferrajoli, "Exploiting robot redundancy in collision detection and reaction, *in Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2008, pp. 32993305.

[48] D. Kulic, E. A. Croft, "Real-time safety for human-robot interaction, *Robotics and Autonomous Systems*, 54 (2006) 1-12.

[49] A. Albu-Schaffer, G. Hirzinger, "Cartesian impedance control techniques for torque controlled light-weight robots, *in Proc. IEEE Int. Conf. Robot. Autom.*, 2002, pp. 657663.

[50] B. Siciliano, L. Villani, "An inverse kinematics algorithm for interaction control of a flexible arm with a compliant surface, *Control Eng. Practice*, vol. 9, no. 2, pp. 191198, 2001.

[51] F. Caccavale, P. Chiacchio, A. Marino, L. Villani, "Six-DOF impedance control of dual-arm cooperative manipulators, *IEEE/ASME Trans. Mechatronics*, vol. 13, no. 5, pp. 576586, Oct. 2008.

[52] V. Lippiello, B. Siciliano, L. Villani, "A position-based visual impedance control for robot manipulators, *in Proc. IEEE Int. Conf. Robot. Autom.*, 2007, pp. 20682073.

[53] D. Tsetserukou, N. Kawakami, S. Tachi,"iSoRA: Humanoid robot arm for intelligent haptic interaction with the environment, *Adv. Robot.*, vol. 23, pp. 13271358, 2009.

[54] Y. Li, S. S. Ge, C. Yang, "Impedance control for multi-point human robot interaction, *in Proc. 8th Asian Control Conf.*, 2011, pp. 11871192.

[55] Y. Li, S. S. Ge, C. Yang, X. Li, K. P. Tee, "Model-free impedance control for safe human robot interaction, *in Proc. IEEE Int. Conf. Robot. Autom.*, 2011, pp. 60216026.

[56] Y. Li, S. S. Ge, C. Yang, "Learning impedance control for physical robot-environment interaction, *Int. J. Control*, vol. 85, no. 2, pp. 182193, 2012.

[57] C. Ott, "Cartesian impedance control of redundant and flexible joint robots, *in Springer Tracts in Advanced Robotics*, vol. 49. New York, NY, USA: Springer, 2008.

[58] A. Albu-Schaffer, C. Ott, U. Frese, G. Hirzinger, "Cartesian impedance control of redundant robots; recent results with theDLR-Light- Weight arms, *in Proc. IEEE Int. Conf. Robot. Autom.*, 2003, pp. 3704 3709.

[59] A. Albu-Schaffer, C. Ott, G. Hirzinger, "A unified passivity based control framework for position, torque and impedance control of flexible joint robots, *Int. J. Robot. Res.*, vol. 26, pp. 2339, 2007.

[60] L. Pan, A. Song, G. Xu, H. Li, H. Zeng, B. Xu, "Safety Supervisory Strategy for an Upper-Limb Rehabilitation Robot Based on Impedance Control, *International Journal of Advanced Robotic Systems*,vol.10, 2013.

[61] J. Nakanishi, R. Cory, M. J. Peters, S. Schaal, "Operational space control: A theoretical and empirical comparison, *Int. J. Robot. Res.*, vol. 27, pp. 737757, 2008.

[62] B. Siciliano, J. J. Slotine, "A general framework for managing multiple tasks in highly redundant robotic systems, *in Proc. 5th Int. Conf. Adv. Robot.*, 1991, vol. 2, pp. 12111216.

[63] O. Khatib, L. Sentis, J. H. Park, J. Warren, "Whole-body dynamic behavior and control of human-like robots, *Int. J. Human. Robot.*, vol. 1, pp. 2943, 2004.

[64] A. Vick, D. Surdilovic, J. Kruger, “Safe Physical Human-Robot Interaction with Industrial Dual-Arm Robots, *International Workshop on Robot Motion and Control*, Wasowo, Poland, July 3-5, 2013.

[65] B. Siciliano, L. Sciavicco, L. Villani, G. Oriolo, “Robotics: Modelling, Planning and Control”. New York, NY, USA: *Springer-Verlag, 2009.*

[66] W. Tao, T. Liu, R. Zheng, H. Feng, “Gait Analysis Using Wearable Sensors”. *Sensors 2012*, 12 2255-2283.

[67] R.E. Cook, I. Schneider, M.E. Hazlewood, S.J. Hillman, J.E. Robb, “Gait analysis alters decision-making in cerebral palsy”. *J. Pediatr. Orthop. 2003*, 23, 292295.

[68] A. Salarian, H. Russmann, F.J. Vingerhoets, C. Dehollain, Y. Blanc, P.R. Burkhard, K. Aminian, “Gait assessment in Parkinsons disease: Toward an ambulatory system for long-term monitoring”. *IEEE Trans. Biomed. Eng. 2004*, 51, 14341443.

[69] K. Aminian, B. Najafi, “Capturing human motion using body-fixed sensors: Outdoor measurement and clinical applications”. *Comput. Animat. Virtual Worlds 2004*, 15, 7994.

[70] M. El Sayed, A. Alsebai, A. Salaheldin, N. El Gayar, M. ElHelw, “Ambient and wearable sensing for gait classification in pervasive healthcare environments”. *In Proceedings of the 12th IEEE International Conference on e-Health Networking Applications and Services (Healthcom)*, Lyon, France, 13 July 2010; pp. 240245.

[71] I. Stancic, T. Grujic Supuk, M. Bonkovic “New Kinematic Parameters for Quantifying Irregularities n the Human and Humanoid Robot Gait”. *International Journal of Advanced Robotics Systems 2012*, vol 9, 215.

[72] L.M. Schutte, U. Narayanan ,J.L. Stout , P. Selber , J.R. Gage , M.H. Schwartz “An Index for Quantifying Deviations From Normal Gait”. *Gait and Posture (2000).* 11(1): 25-31.

[73] M.H. Schwartz, A. Rozumalski ,“ The Gait Deviation Index: a New Comprehensive Index of Gait Pathology. Gait Posture (2008). 28(3): 351-357.

[74] S. Beynon , J.L. McGinley, F. Dobson, R. Baker, “Correlations of the Gait Profile Score and the Movement Analysis Profile relative to Clinical Judgments”. *Gait Posture (2010).* 32(1): 129-132

[75] "Observational Gait Analysis Handbook", The Professional Staff Association of Rancho Los Amigos Medical Center: Downey, CA, USA, 1989.

[76] M. Casadio, P.G. Morasso, V. Sanguineti, "Direct measurement of ankle stiffness during quiet standing: Implications for control modeling and clinical application". *Gait Posture 2005*, 21, 410-424.

[77] M. I. Chacon-Murguia, R. Sandoval-Rodriguez, O. Arias-Enriquez, "Human Gait Feature Extraction Including a Kinematic Analysis Toward Robotic Power Assistance". *International Journal of Advanced Robotic Systems 2012*, 9, 68-76.

[78] B. K. Santhiranayagam, D. Lai, A. Shilton, R. Begg, M. Palaniswami, "Regression Models for Estimation Gait Parameters Using Inertial Sensors". *ISSNIP 2011*, 46-51.

[79] T. Nhat Hung, Soo Suh, Y., "Inertial Sensor-Based Two Feet Motion Tracking for Gait Analysis". *Sensors 2013*, 13, 5614-5629.

[80] J. R. W. Morris, "Accelerometry- A technique for the measurement of human body movements". *J. Biomech 1973*, 6, 729-736.

[81] A. M. Sabatini, "Quaternion based attitude estimation algorithm applied to signals from body-mounted gyroscopes". *Electron. Lett. 2004*, 40, 584-586.

[82] S. Tadano, R. Takeda, H. Miyagawa, "Three Dimensional Gait Analysis Using Wearable Acceleration and Gyro Sensors Based on Quaternion Calculations". *Sensors 2013*, 13, 9321-9343.

[83] K. Tong, M. H. Granat, " A practical gait analysis system using gyroscopes". *Med. Eng. Phys. 1999*, 21, 87-94.

[84] J. Favre, B. M. Jolles, O. Siegrist, K. Animian, "Quaternion-based fusion of gyroscopes and accelerometers to improve 3D angle measurement". *Electron. Lett. 2006*, 42, 612-614.

[85] H. Dejnabadi, B. M. Jolles, K. Aminian, "A New Approach to Accurate Measurement of Uniaxial Joint Angles Based on a Combination of Accelerometers and Gyroscopes". *IEEE Transactions on Biomedical Engineering* August 2005, Vol. 52, No. 8.

[86] H. Dejnabadi, B. M. Jolles, E. Casanova, P. Fua, K. Aminian, "Estimation and visualization of sagittal kinematics of lower limbs orientation using body-fixed sensors". *IEEE Trans. Biomed. Eng. 2006*, 53, 1385-1393.

[87] T. Liu, Y. Inoue, K. Shibata, "Development of a wearable sensor system for quantitative gait analysis". *Meaasurement 2009*, 42, 978-988.

[88] A. T. Willemsen, J. A. van Alste, H. B. K. Boom, "Real-time gait assessment utilizing a new way of accelerometry". *J. Biomech 1990*, 23, 859-863.

[89] I. Cikajlo, Z. Matjai, T. Bajd, "Efficient FES triggering applying Kalman filter during sensory supported treadmill walking". *J. Med. Eng. Technol 2008*, 32, 133-144.

[90] L. Dong, J. Wu, X. Bao, "A Hybrid HMM/Kalman filter for tracking hip angle in gait cycle". *IEICE Trans, Inf, Syst. 2006*, 7, 2319-2323.

[91] Z. Zhang, Z. Huang,J. Wu, "Ambulatory hip angle estimation using Gaussian particle filter". *J. Signal Process. Syst. 2009*, 58, 341-357.

[92] A. Findlow, J. Y. Goulermas, C. Nester, D. Howard, L. P. J. Kenney, " Predicting lower limb joint kinematics using wearable motion sensors". *Gait and Posture 2008*, vol. 28, no. 1, 120-126.

[93] M. D. Djuric-Jovicic, N. S. Jovicic, D. Popovic, "Kinematics of Gait: New Method for Angle Estimation Based on Accelerometers". *Sensors 2011*, 11, 10571-10585.

[94] P. Oliveira, A. Pascoal, "Navigation Systems Design: An Application of Multi-Rate FIltering Theory". *IEEE 1998.*

[95] C. C. Yang, Y. L. Hsu, K. S. Shih, J. M. Lu, "Real-Time Gait Cycle Parameter Recognition Using a Wearable Accelerometry System". *Sensors 2011*, 11, 7314-7326.

[96] T. Watanabe, H. Saito, E. Koike, K. Nitta, "A preliminary Test of Measurement of Joint Angles and Stride Length with Wireless Inertial Sensors for Wearable Gait Evaluation System". *Computational Intelligence and Neuroscience 2011.*

[97] T. Watanabe, H. Saito, "Tests of Wireless Wearable Sensor System in Joint Angle Measurement of Lower Limbs". *IEEE EMBS, Boston, Massachusetts*, August 30-September 3, 2011.

[98] H. Saito, T. Watanabe, A. Arifin, "Ankle and Knee Joint Angle Measurements during Gait with Wearable Sensor System for Rehabilitation". *IFMBE 2009*, 506-509.

[99] F. Alonge, E. Cucco, F. D'Ippolito, "Use of accelerometers and gyros for hip and knee angle estimation". *IEEE International Conference on Mechatronics and Automation 2013*, August 4-7, Takamatsu, Japan,*Best Paper Finalist.*

[100] F. Alonge, E. Cucco, F. D'Ippolito, A. Pulizzotto, "The use of accelerometers and gyroscopes to estimate the gait phase". Submitted to *Sensors*

[101] http://madeformovement.com/products/nf-walker