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MODELLING AND CONTROL
FOR HUMAN—ROBOT INTERACTION

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Tesi di Dottorato di Ricerca

Novembre 2007

Dipartimento di Informatica e Sistemistica

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Modelling and Control for Human–Robot Interaction

Research Doctorate Thesis

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Scuola di Dottorato in Ingegneria dell'Informazione
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Napoli, November 2007

Ago

Summary

In the growing area of human-centered application for robotic manipulators, human–robot interaction (HRI) poses new challenges for researchers and manufacturers in robotics. Physical HRI (pHRI) can be accepted only when safety and dependability issues are addressed as the central criteria for all the phases of design and control of robots for anthropic environments, while cognitive HRI (cHRI) is also relevant, due to the relationships that different people can have with robots. The contributions collected in this thesis are aimed at modelling and controlling robot manipulators for HRI. The framework is provided by the research activities carried out in two European projects related to pHRI. The most notable results of the work include proper modelling for simple geometric computation and real-time multiple-point control.

In detail, the contents of the thesis are organised as follows.

- Chapter 1 is an introduction which presents the relevance of human-centered robotics for service applications. The framework of the research work in the next section is introduced, i.e., the activities in the European projects PHRIDOM and PHRIENDS. The distinction between cHRI and pHRI is emphasised.

- Chapter 2 contains a discussion about the many aspects arising from pHRI. While traditional optimality for industrial robotics is related to speed and precision for maximizing production, the presence of a person in the robot's workspace asks for new optimality criteria such as safety and dependability. The need for cooperation neutralises the idea of enforcing safety by segregating machines and human users. After a review of tools for guaranteeing safety, ranging from robot design to sensors and actuators, a number of planning/control solutions are suggested.

- Chapter 3 presents the implementation of an approach to robot control with multiple control points, allowing desired motion trajectories in the workspace to such points. The Virtual-End-Effectors (VEEs) approach is introduced, which constitutes the base for an algorithm for choosing an arbitrary control point of the robot, namely, the so-called "skeleton algorithm". Force and velocity implementations

for the multiple-point control approaches are discussed.

- Chapter 4 discusses both reactive motion, which is necessary in HRI due to the difficulty of modelling the unstructured human environments, and evaluations which are proper of cHRI. Issues are addressed which are complementary to those introduced in the previous sections, together with issues arising form cognitive evaluation on HRI tasks.

- Chapter 5 is aimed at showing how the presented algorithms and HRI-centered strategies have been used for implementations on real robot manipulators, both industrial and advanced, for real-time operation. A discussion on the use of Virtual Reality (VR) for facing HRI from a cognitive point of view is addressed too. The "comfort" of the user, which is an important aspect from a cognitive viewpoint, provides an additional indicator for the evaluation of HRI system.

- Chapter 6 contains concluding remarks and proposals for possible developments.

1

Introduction

1.1 Human–robot interaction in service robotics

A robot can be a useful tool for the humanity: in a Western approach it is a servant, more than a companion, according to its ethimology (the czech world "robota" means "forced work"). It should help or substitute people in dangerous, repetitive, or boring tasks, enhance human possibilities, and be able to cooperate with humans in shared everyday 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 welfare applications, physical training, entertainment, warfare operations, while the inclusion of the last in "service" application of robotics is controversial. An analysis of application domain shows that service robotics is a growing market [1], and the most important point is the intrinsic need for direct human–robot interaction (HRI) in human environments (see, e.g., [2] and bibliography therein).

In the last 20 years, with the growing interest applications of artificial intelligence, autonomy and intelligence for robots has resulted interesting from an academic perspective. On the other hand, from an industry point of view, it has been clear that the robots were perfect without any autonomy: the brute force provided by manipulators was the key issue for automation applications. Industrial robotics is a developing area since more than 30 years, also without direct cooperation in HRI. Of course robots are not leaving industry, but better human–robot cooperation will certainly affect the industrial domain, where users are also more skilled in managing machines with reference to people who ask for robotic helpers or entertainers based on the easiness of interface and amusement for autonomous mobile robots.

In any case, close human–robot interaction and cooperation require robot which are "intelligent", with reference to "human-centered" properties more than to autonomy and classical AI reasoning capabilities. These properties are mainly related to the guarantees of safety and dependability [3] for the persons interacting with the robots. Therefore, performance of new robots is based on novel criteria, which focus both on the user and the robot, and not only on industry-derived objective precision metrics.

An "intelligent" robot is the one which mitigates fatigue and stress for human workers, and industrial domains present the necessity of integrating human experts in robotic cells. In this approach, supervision and cooperation of complex tasks can be accomplished by humans while, at the same time, robots increase human capabilities in terms of force, speed, and precision. In some applications which are not fully automatised, human–robot cooperation is rewarding, since the human can bring experience, global knowledge, and understanding for a correct execution of tasks.

Summarizing, the next generation of robots, both for service or cooperative work, is expected to interact with people more directly than today [4]. Human–Robot Interaction will certainly happen at the cognitive level (cHRI), fundamentally due to mental models of HRI, and concerning communication between human and robot through the many available channels of, e.g., video displays, sounds, mutual observation and imitation, speech, gaze direction tracking, facial expressions and hands' gestures.

However, robots are distinct from computers or other machines: they physically embody the link between perception and action, whose "intelligent connection" is a definition for robotics, and often have an anthropomorphic appearance. At the same time, they generate force and have a "body": hence, the most revolutionary and challenging feature of the next generation of robots will be 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. This approach is affordable if robots can be considered service tools which guarantee human safety and autonomy.

An effort is keeping the "physical viewpoint" while considering the importance of inferences and evaluation on unstructured environments. This viewpoint influences the new paradigms for the design and control of robot manipulators. Robots designed to cooperate with humans must fulfill different requirements from those typically met in conventional industrial applications. Typical conventional robot systems and applications require fast motions and absolute accuracy in positioning and path following and avoid using additional external sensing, provided that the application is performed in perfectly known designed and modeled environments.

The most important change of perspective is related to the optimality criteria for the considered manipulators: *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 [2].

Given such a discrepancy in requirements between old industrial manipulators and the next generation of service robots, robot design and control has to change to enable applications that require intrinsically safe pHRI.

Modelling of unstructured domain is a key issue for robotics in interaction with humans: the listed future application areas have to use sensory systems and trade in certain performance characteristics of the robot system to drastically increase dependability and overall safety in unpredictable dynamically changing environments.

Notice also that, right now, a sort of Descartes "duality" leads to accepting a dichotomy: the "brain" of robotic systems is usually studied by computer scientists and neuroscientists, whereas the study of mechanisms and their control is assigned to cybernetics, electronic, and mechanical engineers. Cognitive and physical interaction, however, are not independent: physical interaction can help in setting rules for cognitive evaluations of the environment during interaction tasks, while cognitive aspects may improve the physical interaction by setting suitable control interaction parameters. As a simple example, haptics can be used to "understand" the characteristics of an environment (soft or rigid), while cognitive-based inference rules can be considered for compliance control of manipulators physically interacting with humans (if the person is a child, then the compliance should be high).

This thesis is meant to provide contributions from planning/control viewpoints, exploiting both cHRI- and pHRI-related aspects. Such contributions have been made possible thanks to the current research activity on safety and dependability in pHRI, performed under European projects featuring collaboration between academic, research and industrial institutions.

1.2 European research projects and physical HRI

Research for analysis and possible standardisation of HRI applications is fastly growing in the last few years all around the world: the importance of international standards and their continuous revision, and the relevance of service application of robotics have lead to a discussion on safety design for human-centered robotics.

European research centers and industry are providing both technical tools and discussion about these issues, as better stressed in Section 2.1. The European Machine Directive 98/37/EC states that *all appropriate measures shall be taken to ensure that machinery or safety components may be placed on the market and put into service only if they do no endanger the health or safety of persons and, where appropriate, domestic animals or property*.

In general, industrial robot safety is enforced by strictly segregating the workspaces of humans and moving robotics and automation systems. This is clearly undesired when humans and robots need to share their workspaces for collaborative tasks.

It becomes evident that research has to focus on the possible introduction of robots for collaborative task in a way such to guarantee safety and dependability as central criteria for pHRI modelling and control. Focusing on the activity which constitutes the framework for this thesis, two research projects have been proposed for

facing the complexity of these topics, and for providing significant advances and insight in the territory of pHRI: the Prospective Research Project "Physical Human–Robot Interaction in anthropic DOMains (PHRIDOM)" [3], and the Specific Targeted Research Project (STReP) "Physical Human–Robot Interaction: depENDability and Safety (PHRIENDS)" [4], funded in the 6th European Research Framework Programme.

Recently, the 7th EU Research Framework Programme [5] has been introduced, and it addresses robotics and cognitive systems as a relevant track: results of the on-going cited project PHRIENDS are expected to give benefits to the next generation research projects.

1.2.1 PHRIDOM

The Prospective Research Project PHRIDOM, funded by the European Robotics Network of Excellence EURON, represents an exploratory work in analyzing safety and dependability issues in human-centered robotics, where machines have to closely interact with humans.The PHRIDOM project has investigated needs, related to technology and requirements, for safe and dependable robots in pHRI, by emphasizing the difference of human environments with respect to industrial applications. It is often the case, for instance, that accuracy requirements are less demanding.

On the other hand, a concern of paramount importance is safety of the robot system: under no circumstances should a robot cause harm to people in its surroundings, directly nor indirectly, in regular operation nor in failures. This suggest that standards of reliability must be rethought. From a system viewpoint, however, a pHRI machine must be considered as part of unpredictably changing anthropic environments. From this point of view, "failures" are events (e.g., contacts with a person, unexpected changes of mind or mistakes by the user) that cannot be ruled out in principle, and must rather be faced by suitable policies. The need hence arises for fault detection, and for fault management and recovery.

One important point to stress is the expertise of the user: unskilled users are expected to use robot assistant or prothesis, therefore they will have physical contact and interaction with the robot without clear awareness of risk and possible robot's behaviour.

In general, pHRI applications also raise critical questions of communication and operational robustness. These aspects can be captured by the concept of dependability, a crucial focus of PHRIDOM. Of course, user's safety is not one attribute like others for dependability. The next most crucial requirement for pHRI systems after dependability remains with their performance, meeting some of the old performance criteria, like accuracy, speed, repeatability.

To be useful, however, requirements must be quantified and/or formalised. The PHRIDOM Consortium started providing unambiguous definitions of concepts such as safety, fault robustness, dependability, performance, in relation with the different application domains. One result of the studies in PHRIDOM has been the preparation of a guide to the main topics for pHRI, which is the base for Section 2.1 of this thesis. The effort has been to consider together safety and dependability as the unified

optimality criteria for future technical challenges in the design of robots for human environments [6].

This analysis follows the idea of a geographic atlas [7], showing contact points and overlapping interests. In the PHRIDOM project issues and discussions resulting from different research groups about possible metrics for the evaluation of safety, dependability, and performance in pHRI lead to a huge preparatory work, which has been inherited by the PHRIENDS project.

1.2.2 PHRIENDS

There is a change in perspective for the role of control systems: they can add safety to heavy robots or give performance to intrinsically safe robots. While in the present this still depends on the available robots, in the future the approach suggested in the PHRIENDS project is quite novel and revolutionary.

In fact, the proposed integrated approach to the co-design of robots for safe physical interaction with humans revolutionises the classical approach for designing industrial robots —rigid design for accuracy, active control for safety— by creating a new paradigm: design robots that are intrinsically safe, and control them to deliver performance. In addition, control for safety on existing robots is addressed too.

In the framework of the PHRIENDS project, the involved research crew has the mission of developing key components of the next generation of robots, including industrial and service manipulators, whose application domains are, e.g., assistance, health care, and entertainment, designed to share the environment and to physically interact with people. Such machines have to meet the strictest safety standards, yet also to deliver useful performance: this poses new challenges to the design of all components of the robot, including mechanics, control, planning algorithms and supervision systems, sensing.

Although a single project cannot encompass the integration of a complete robot system, new actuator concepts and prototypes, new dependable algorithms for supervision and planning, new control algorithms for handling safe pHRI and for fault-tolerant behaviour will be explored. Moreover, meaningful subsystems will be integrated, also for contributing to the effort of international bodies towards the establishment of new standards for collaborative human–robot operation.

These ambitious objectives will be achieved through the presence in the consortium [4] of academic groups, research laboratories, and an industrial partner who has specific competence in HRI. The effort in modelling, design, and control, resulting by the complementary expertise provided by the involved team is meant lo lead to advance the state-of-the-art in two complementary directions:

1. integrate new algorithms in existing manipulators, and allow new paradigms for pHRI in service and industrial environments;
2. design, implement, test, and optimize the core components of the next-generation, intrinsically safer robot arms.

The first section of the project will lead to an experimental platform that is based on a revolutionary robot for pHRI both in industrial and service domains:

the KUKA light-weight robot arm (LWR, see Fig. 1.1), based on the third generation of the Lightweight Robot (LWR-III) [8], developed by the Institute for Robotics and Mechatronics of the German Aerospace Agency (DLR). Its controller will integrate in a prototypical fashion the newly developed algorithms.

Fig. 1.1. The KUKA LightWeight Robot (LWR) is a result of technology transfer by DLR

The second complementary part of the project will lead to test beds that will be used to evaluate and optimise safety and performance characteristics of a new generation of intrinsically safe robot arms. Eventually, all project activities will culminate in experimental platforms and test-beds.

Safe and dependable human-centered robotics has of course ethical motivations [9], but it also pays off. Results of the PHRIENDS project are expected to deeply impact applications where successful task completion requires people and robots to collaborate directly in a shared workspace. In fact, market pressures are about to reduce the separation between robots and people. New standards will deeply affect the robotics market. Current safety solutions are done by each robot producer in an individual way, under their responsibility with respect to legislation. The interest and involvement of robot manufacturers in the developments concerning standards is therefore even more important with the constant growth of application scenarios. According to preliminary results and discussion in the PHRIENDS consortium, the process of revising and creating new standards is expected to influence quantitative safety measures, risk assessment procedures, and collaborative assist devices. This

flow of information and contributions is planned to happen through active participation to specialised conferences and participation in the International Standards Organisation committees, summarizing the project's views and recommendations in a series of reports.

The approaches to modelling and control of robot manipulator for interaction with people presented in this thesis are collocated in the framework of PHRIENDS, and preliminary remarks are discussed in Chapter 2.

2

A review of human–robot interaction themes for anthropic domains

While traditional optimality criteria 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 present industrial robotics workspaces. The PHRIDOM and PHRIENDS consortia provided proposals and collected needs and starting points for solutions to contemplate the presence of human beings in robot's workspace. The problem of objective evaluation of safety and dependability is not yet solved: a review about the many aspects arising from physical interaction with robots is provided for presenting relevant issues which claim for a complete rethinking in all the phases of robot design and control approaches, in order to address the novel optimality criteria. Possible contributions from a planning/control viewpoint are suggested, which will be developed in the next chapters.

2.1 An atlas for physical HRI

Researchers worldwide are studying the social factors related to the introduction of robots in human environments and often their attention is focused on the cognitive interaction with machines. Since it is impossible to model every action in an unstructured anthropic environment, the "intelligent connection of perception with action" of robots implies the presence of autonomous behaviour, which is interesting per se and needed to solve real problems. However, this can result in dangerous situations for humans co-existing in the robot operational domain.

In order to spread the presence of robots in everyday life, personal robots just like personal computers, safety and dependability issues must be solved first [2]. However, it must be pointed out that safety standards for pHRI are still not well defined in the scientific community, and research evidences confirm the need for a renewed standardisation activity. In the next chapters, some contributions will be presented to address some of these issues.

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 worth noticing that, while robots should make "independent decisions", their designers must consider physical, social and ethical implications of such autonomy [2]. Efficient communication systems are crucial to have "wearable robots" analogous to "wearable" PCs, and their dependability is also relevant. While computers are no longer perceived as strange machines also because they do not pose evident threats to user's safety, current robots are still heavy and unsafe.

Moreover, the crucial point is to consider the current mechanical structure of the robots available on the market. 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. Especially in Europe, attention has recently been devoted to ethical issues, considering not only robotic/neural implants in human bodies, but also consequences of robot actions in an anthropic domain (see [9]).

One crucial capability of a robot for pHRI is the generation of supplementary 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. When determining the differences between computers and robots from a user point of view, one should also deeply consider the key problem of embodiment. People seem to perceive autonomous robots differently than they do with most other computer technologies: mental models are more anthropomorphic, and people attribute to robots human-like qualities and capabilities. During a physical interaction, if human-like robotic arms are used, motion capabilities can be simpler to understand ("legible"). In general, the user response to such an interactive system is always dominated by a specific mental model about how the robot behaves. If the robot looks like a living creature, the mental model of its behaviour may approach the mental model of humans or of pets, and there may also be unexpected social interactions [10]. A user mental model may result in a faked perceived robot "dependability": its zoomorphism or the human posture of a humanoid robot could give a wrong idea about the awareness of the robot, since it looks like a living creature. Indeed, mental models can be changed with experience, but anthropomorphism is still a forced consequence of our nature, especially for non-skilled users, because "our imagination cannot be anything but anthropomorphic" [11]. These mental models depend strongly on cultural approaches [12]: a robot can be a companion or a servant. Safety issues are usually considered more relevant for robot servants, while robot companions have typically a simpler mechanical design because the focus is on cognitive interaction and not on task execution.
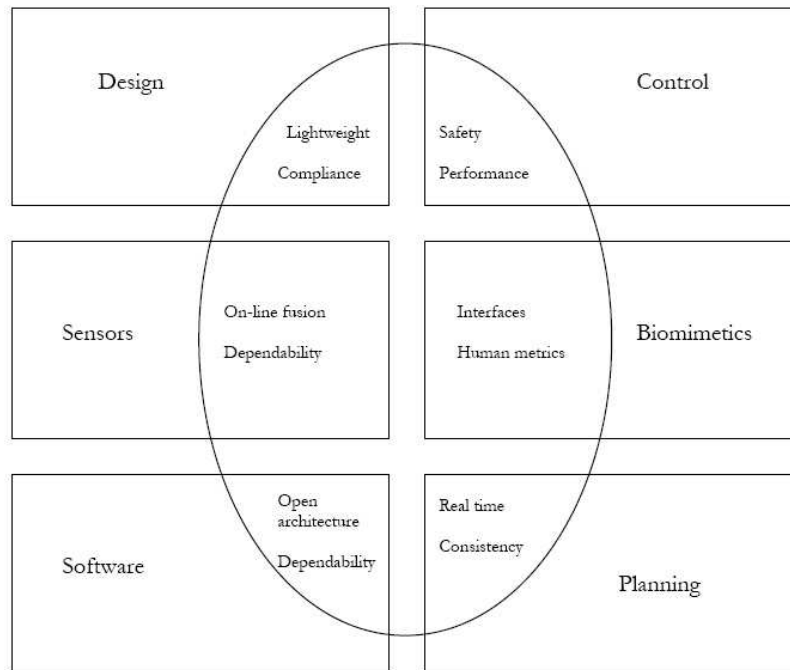
Fig. 2.1. This "map" of robotics for anthropic domains includes the main issues and superpositions for pHRI

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.

2.1.1 General aspects on safety and dependability in human-centered robotics

In the complexity of a HRI, the physical viewpoint 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. Severity indices of

injuries may be used to evaluate the safety of robots in pHRI. These should take into account the possible damages occurring when a manipulator collides with a human head, neck, chest or arm.

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 instantaneous 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. The latter allow the actuators rotor inertia to be dynamically decoupled from the links, whenever an impact occurs. The safety tactics involve mechanics (see Section 2.1.2), 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.

Indeed, 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 [13]. As clear from the previous discussion, safety metrics that consider only the brain" of the robot as an intelligent machine are inappropriate in this context. Asimov's famous "three laws of robotics" are mainly science fiction, since the "will" of the robots cannot be clearly mapped into motion behaviours, so that it is difficult for a robot to be aware of the potential damages.

The dependability of the system must be also understood. The "passive" safety is easy to understand: springs, rubber coverings, artificial skin, which have of course a real effect on reduction of damages, have also the additional property of being present in everyday life for the same purposes. The most obvious relation between cognitive "fear" related to physical injuries is the scary appearance of a robot, while the awareness of implemented safety systems could help. As an example of safety tools which are not visible, consider ABS, ESP and the other systems for safety in the cars. These safety devices are hidden, but they add dependability and people know that they can trust on them: "ubiquitous robotics" as well as ubiquitous computing can be guaranteed if safety and dependability are both guaranteed and understood. Moreover, consider that humanity came from a monster approach to the car and the train, present in lyrics and books of the first period of last century, to the human-like relation with this "everyday" ubiquitous machines, thanks to their (perceived) dependability.

The research in pHRI must consider any issue which could lead to define better evaluation criteria for the safety and dependability, considering "scores" or even "cost functions" to include the impact of different issues related to design and control of pHRI.

Safety standards and injury criteria

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

An important example of standard for robot safety in factories is the ANSI/RIA R15.06-1999 (American National Standard for Industrial Robots and Robot Systems – Safety Requirements). This standard addresses the requirements for personnel 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 hardware is 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.

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. It must be pointed out, however, 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 part document. Part 1, entitled "Design, Construction and Installation", is intended to be fully compliant with the European Machinery Directive and expected to replace the existing EN775 in due course. Part 2, work on which has recntly begun, has a working title of "Application and Use of Robots in the Work Place" and is intended to address work place safety requirements and is directed more to the end-user than the manufacturer. Most salient changes under consideration involve the following issues.

- Control Reliability: revised standards will allow safety-related control circuitry to use state-of-the-art electronic, programmable, and network based technology (including wireless).
- Safeguarding and Clearance: minor changes in clearance requirements are expected (from 18 inches to 0.5 meters), while attention is devoted towards completely removing the requirement for safeguarding in the presence of enhanced capabilities and features of the robot control system.
- New modes of operation: the committee is developing requirements for "synchronised" robot control, "mobile" robots mounted on Automated Guided Vehicles (AGV), and "assisting" robots which work in a "collaborative workspace" with the operator [4] .

It is worth pointing out that the ISO Technical Committee (TC 184/Subcommitee 2) dealing with standardisation activities on robotics is still working also on "Robots in Personal Care". For unstructured anthropic domains, available standards, before

their possible revision, are not very useful. 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 PHRIENDS partner 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 [14], [15], 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. The load is generally transmitted through the head-neck junction upon sudden changes in the motion of the torso. In order to quantify the injury severity produced by the impact with a robot, a scaling is needed. A definition of injury scaling developed by the automotive industry is the Abbreviated Injury Scale (AIS). If more than one part of the body is involved, the one with maximum injury severity is considered as the overall injury severity, which is indicated as Maximum AIS (MAIS). The type of injuries are divided in a classification, reported in [16], which relates the type of injury ("Minor", "Moderate", up to "Critical"), to its consequences ("Superficial", "Recoverable", "Not fully recoverable with care" and so forth), and gives a number in a scale from 0 to 6 (for fatal injuries) in the injury scale.

Such a qualitative scaling gives does not give any indication on ways to measure injury. This is provided by the so-called severity indices. Biomechanically motivated severity indices evaluated by impact tests are discussed in [14]. Briefly, among the theoretical basements of these criteria, there are the Vienna Institute Index and the so-called Wayne State Tolerance Curve (WSTC), which relates accelerations to skull fractures. The plot of the WSTC curve in log–log coordinates by Gadd [17] resulted in a straight line of slope -2.5, and the according severity index (Gadd Severity Index) is the integral of the head acceleration to the power of 2.5 during the relevant duration of collision. For the head quite many criteria are available for the first type of loading (direct interaction). In the various interpretations of the WSTC, a model of the head is usually assumed in the form of a mass–spring–damper system. The mostly used head severity index is the head injury criterion (HIC) [18], which considers together the effects of the impact duration δt and of the head acceleration during the specified time interval. Fixed values for δt define specific HIC criteria, i.e., limits to the maximum head acceleration without harm for pulses not exceeding a duration of δt.

The HIC focuses on the head acceleration and indicates that very intense acceleration is quite tolerable if very brief, while potentially harmful for pulse duration exceeding 10 or 15 ms (as time exposure to cranial pressure pulses increases,

the tolerable intensity decreases). The maximum power index (MPI) is instead the weighted change of kinetic energy of the human head before and after impacts, with the weighting carried out by two sensitivity coefficients in each direction. This injury criterion is suggested as alternative to the HIC since it is derived from the same underlying type of data (accelerations) but has physically relevant units. In the maximum mean strain criterion (MSC), a mass–spring–damper model of the head is used and expanded by the presence of a second mass; the average length of the head is considered as a parameter too. For torso injuries, the available criteria can be generally divided into four groups: acceleration-based criteria, force-based criteria, compression-based criteria, and soft-tissue-based criteria. For neck injuries, frontal and rear impacts have different effects and thus they are addressed separately. In general, the mechanisms of injury of the human neck are potentially related to the forces and bending moments acting on the spinal column. Two severity indices for the neck were often considered: the neck injury criterion for frontal impacts and the neck injury criterion for rear impacts (for details, please refer to [16]).

For coping with the conversion of severity indices to the probability of MAIS level, the National Highway Traffic Safety Administration specified empirical equations for converting e.g. HIC values to the probability of MAIS level. These conversions provide a scaling of injury severity. Recent evidences suggested by DLR [16] 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 crash-tests. PHRIENDS partners DLR and KUKA are leading experimental assessment for definition of novel injury criteria in pHRI. The new indices are expected to take into account improvements both in active and passive safety mechanisms.

2.1.2 Mechanics and control issues for a safe pHRI

The discussed novel additional optimality criteria for pHRI lead to redesign robots starting from the mechanics. The intrinsic or passive safety cannot be underestimated: "Rocks don't fly" synthesises the driving force in the mechanical design of lightweight robots.

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. Finally, 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 humanrobot 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.

An important point which is a base for his thesis is the complementarity of the work in modelling and control for improved safety. Safety tactics can be classified into intrinsic or mediated by control. 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 robot's 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 robot's 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 [8], which is capable of operating a payload equal to its own weight (13.5 kg). 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) [19], manifactured by Barrett Technology [20]. This is a very interesting cable-actuated robot, which is also backdrivable, i.e., by pushing on the links, it is possible to force motion of all mechanical transmission components, including the motors' rotors. 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.

More in general, a lightweight design and/or the use of compliant transmissions introduce link [21] and, respectively, joint [22] elasticity. In order to preserve performance while exploiting the potential offered by lightweight robot arms, one must consider the effects of structural link flexibility. Distributed link deformation in robot manipulators arises in the presence of very long and slender arm design (without
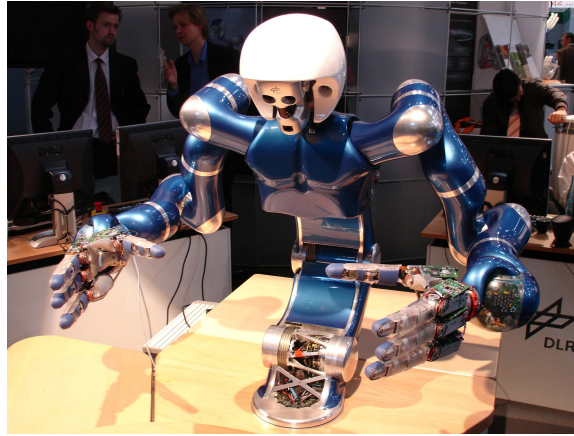
Fig. 2.2. The DLR humanoid manipulator Justin has an articulated torso, two DLR LWR–III arms, articulated head with vision system, two DLR–II Hands

special care on materials); notice that "link rigidity" is always an ideal assumption and may fail when increasing payload-to-weight ratio.

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. From the control point of view, there is a basic difference between link and joint elasticity. In the first case, we have non-colocation between input commands and typical outputs to be controlled; for flexible joint robots, the co-location of input commands and structural flexibility suggests to treat this case separately.

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) [23] 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 [24]. The optimal solution obtained analytically and numerically for single-dimensional systems shows that low stiffness is required at high speed and vice versa. This matches with intuition since most of the motion energy transfer from the motor should occur during the initial and final acceleration/deceleration phases. This ideal solution provides guidelines to be used also for multidimensional systems. Please refer to [23], [24], for design and implementation details.

Distributed macro-mini actuation

Another approach to reduce manipulators arm inertia for safety, while preserving performance, is the methodology of distributed macro-mini actuation DM^2 [25]. 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 DM^2 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) [26] . It is important to notice that often high-frequency torques are almost exclusively used for disturbance rejection. The effective inertia of the overall manipulator is reduced by isolating the reflected inertia of the actuators while reducing the overall weight of the manipulator.

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. For unstructured anthropic domains, such a detailed description of the environment is very difficult, if not impossible, to obtain. As a result, pure motion control may cause the rise of

undesired contact forces. On the other hand, force/impedance control [27] 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). The interaction between the robot and a human results then in a dynamic balance between these two "systems". This balance is influenced by the mutual weight of the human and the robot compliant features. In principle, it is possible to decrease the robot compliance so that it dominates in the pHRI and vice versa.

Cognitive information could be used for dynamically setting the parameters of robot impedance, considering task-dependent safety issues. Certain interaction tasks, however, do require the fulfilment of a precise value of the contact force. This would be possible, in theory, by tuning the active compliance control action and by selecting a proper reference location for the robot. 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.

In all cases, the control design should prevent introducing in the robot system more energy than strictly needed to complete the task. This rough requirement is related to the intuitive consideration that robots with large kinetic and potential energy are eventually more dangerous for a human in case of collision. An elegant mathematical concept satisfying this requirement is passivity. Passivity-based control laws [28], besides guaranteeing robust performance in the face of uncertainties, have thus promising features for a safe pHRI. 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 [29].

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.

Almost the totality of these issues are addressed in PHRIENDS: tools for modelling the scene and giving, in general, additional commands to the control algorithms for considering motion control of an arbitrary point of the manipulator will be presented in Chapters 3 and 4.

Real-time motion planning

Conventional robot motion planning is a typical off-line process that determines a feasible path (and a dynamically feasible timing), if one exists, connecting an initial and a final arbitrary robot configuration while avoiding obstacles. Complete knowledge of the geometry of the static environment is assumed. For high-dimensional configuration spaces, i.e., for robots with many degrees of freedom (DOF's) in crowded environments, the search for a feasible path is very complex and time-consuming; recently, probabilistic and randomised approaches have been developed to tackle this problem of the dimensionality [30].

When dealing with trajectory (path + timing) planning in anthropic domains, the additional features of intelligibility and acceptability of robot motion should be considered. The planner should produce robot trajectories which are easily recognised by the user and "natural" for the task to be executed, in the sense that they are similar to the motion that would be performed by a human. In particular, they should not generate a sense of fear due to unexpected appearance, overly fast speeds/accelerations, and lack of visibility. Within the context of off-line planning, one should include also an optimal or suboptimal definition of time variation for the stiffness properties of variable impedance actuation. Indeed, the intrinsic nature of service robotics is to deal with unstructured, time-varying environments, for which a model is hardly available. The major part of dynamicity is typically due to the unpredictable motion of a human user, and planning needs reactive techniques as well [31], [32].

Summarizing, a planner for HRI has to model the presence of humans for reasoning-based planning, but it also needs strategies for coping with situations where real-time emergency escape paths or stops must be considered. In this thesis, it will be emphasised the need for controlling multiple points whose motion can result in a collision, along proper paths.

2.1.3 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.

This section addresses the relevant dependability issues in pHRI, with emphasis on the robot side, where the key problems are caused by sensor capabilities and data fusion for inferring a correct characterisation of the scene and of the people in the robot environment. 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 [33].

- 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.

There are, indeed, strict relationships among these concepts. 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. In particular, it should be accepted that, in order to enforce a robot operation which is safe for the human, the completion of a programmed task may even be abandoned (this is also named survivability). To be useful, a robot must also be always ready to carry out its intended tasks, and able to complete those tasks successfully.

This is encapsulated in the dependability requirements of availability and reliability. There is evidently a trade-off between reliability/maintainability on one side, and safety on the other, since, in many applications, the safest robot would be one that never does anything. In some applications, however, the well being of humans requires robot availability and reliability. This is the case, for example, of robots used for surgery or for rescue operations. Robot integrity is a pre-requisite for safety, reliability, and availability. Integrity relates to the robots physical and logical resources, and requires appropriate mechanisms for protecting the robot against accidental and malicious physical damage, or corruption of its software and data. Finally, availability cannot be achieved without due attention to maintainability aspects. These concern again both the physical and logical resources of the robot, which should be easy to repair and to upgrade.

Sensors and dependability

The selection, arrangement, and number of sensors (as well as their single reliability) contribute to the measure of dependability of a manipulator for interaction tasks. Intelligent environments can be considered as dual to a robot equipped with multiple

sensors. On one hand, a properly sensorised environment incorporates the tools to perceive and understand what is happening, providing useful data to people and robots present in the environment. In this way, many robots can share the same sensory system. However, the large work needed for setting up such a global sensory system makes this approach unpractical (or cost-ineffective) for anthropic environments.

On the other hand, robots with built-in sensors provide a versatile platform, since their operation is not limited to a specific area. The construction of a good model of humans interacting with the robot is certainly one of the main purposes of a sensory system for pHRI: vision and other proximity sensors must be able to map the position of critical actors in the scene. These sensors must be robust to changing of environmental conditions like lighting, dust and other sources of uncertainty.

Sensor-based modeling of a person has a very common interpretation in cHRI as a tool for obtaining information about human intentions, by tracking and decoding movements and gestures. For pHRI, the focus is more on a robust modelling and creation and labelling of volumes in the workspace where the manipulator has different possibilities in terms of maximum speed, selected control algorithm, choice of control point (see Chapters 3 and 4).

For this, vision is the main sensory modality and stereo cameras can provide also depth information. Active exploration and selectivity of features are two important characteristics of the human vision which should be replicated in robot vision. With an on-board camera, robot motion can be used for active acquisition of data on humanrobot interaction. Basic capabilities include locating people in the operational space, predicting their incipient motion (based on a kinematic/dynamic model of the human) and detecting faces. Anticipated perception and anticipatory movements can help the robot to keep adequate postures during the interaction with human beings. An articulated human model should be considered, using at least simple skeletons of body components (neck, shoulders, torso, arms, forearms, hip, legs, see also Section 3.3).

As a minimum, a localisation/detection module should evaluate direction and distance of people present in the workspace. "Safety volumes" [34] can be generated so as to constrain the behaviour of the robot, in terms of speed and compliance, and depending on the specific phase of the interaction. In particular, this is relevant in the case of mobile service robots approaching humans (e.g., encountering them in a corridor). The selective visual tracking of the head is crucial [35], considering the presented injury criteria, but also monitoring arm positions is important, due to the possibility of dangerous collisions during cooperative tasks

A more precise localisation system can be built using additional sensing with markers, or radio frequency identification tags (RFID). For closer HRI, such as supporting people, handing over objects or shaking hands-all "physical" events, force/torque sensors and small "tactile" sensors distributed along the structure may be needed (just like in dextrous robotic hands). Of course, it is necessary to distinguish between intentional contacts and accidental collisions with human body and head.

Fusion of the information coming from multiple sensors may help in providing a coherent and reliable description of the world surrounding the robot. In general, it

is required to integrate sensor information based only on approximate models of the environment. Data fusion is particularly important when monitoring contacts, e.g., for selecting impedance parameters or for determining the most dangerous "control points" on the robot to be driven away from a human with higher priority. Unfortunately, there has been little work on achieving the fusion of contact and visual information. Taking as an example the problem of simultaneous localisation and mapping (SLAM) for a mobile service robot, the input from different sensors (laser scan, ultrasonic, vision) may be combined in order to drive prediction algorithms. The latter are based on Bayesian estimation, Kalman filtering, particle filters and so on, and cope with the occasional and systematic uncertainties of the observations. Artificial intelligence (AI) techniques can also be adopted for data fusion, e.g., fuzzy sets, neural networks, or first order logics. For the use of AI systems, there is often the need to define "symbolic" quantities that capture some relevant state of the HRI and/or of the environment to be used for high-level reasoning. Finally, inference systems may organize sensory sources and data taking into account the information about the specific phases of an interaction task. Indeed, only AI methods complying with real-time constraints are of interest for pHRI.

Fault handling and dependability

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 [36].

Dependability is related on the ability of the system to cope with failures. As an example, a model of failure taxonomy has been presented in [37] with reference to field robots. Reliability of the system is evaluated in terms of physical failures (of the effectors, sensors, power source, control system, and so on) and human communication failures.

It must be pointed out, however, that for application domains with pHRI, the picture is even more complex. 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 [33] [36]:

- 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, i.e., how to build a system that is fault-free. With respect to development faults, fault avoidance requires a rigorous approach to design through proven software engineering principles and the application of verification and validation procedures, such as formal verification and testing. Fault detection and isolation are parts of fault diagnosis. An early diagnosis allows an appropriate response of the system and prevents the propagation of the fault effects to critical components in the system. 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). Then, 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, i.e., how to live with the fact that the robotic system may contain or is actually affected by faults.

In pHRI, fault acceptance requires tolerance (or robustness) with respect to adverse environmental situations and other interaction faults, and incorporation of re-

dundancy 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. To judge whether the adopted robustness and tolerance techniques are necessary and sufficient, the achieved dependability needs to be assessed by an appropriate combination of analysis, e.g., failure modes, effects, and criticality analysis (FMECA), hazard analysis, and evaluation, e.g., through stochastic modeling or experimental fault injection.

Control architecture and dependability

Dependability of the robot control software for pHRI calls for a modular and hierarchical architecture, which is also advantageous for testing the single components and isolating possible faults so as to achieve operating robustness (availability, reliability, and maintainability [38]). Due to the need for continuous monitoring the environment and robot operation, as well as for on-line changes in planning Cartesian (and stiffness) trajectories, the operating system of a control architecture for pHRI must run in "real-time".

Since tasks need to be executed within a specified time constraint, multitasking, prioritised process threads, and multiple interrupt levels are to be considered. Deploying a control architecture for pHRI requires the proper organisation of the various software components. The type of onboard software for such robots will be very diverse, from low-level control loops up to high-level planners. Nonetheless, the expected overall properties of such an architecture are as follows.

- Programmability: the robot should be able to achieve multiple tasks described at an abstract level. Its basic functionalities should therefore be easily combined according to the task to be executed.
- Autonomy and adaptability: the robot should be able to carry out its actions and to refine or modify the task and its own behaviour according to the current goal and execution context as it perceives it.
- Reactivity: the robot has to take into account events with time bounds compatible with the correct and efficient achievement of its goals (including its own safety) and the dynamics of the environment.
- Consistent behaviours: the reactions of the robot to events must be guided by the objectives of its task.
- Robustness: the control architecture should be able to cope with failures, in particular by exploiting the redundancy of the processing functions and subsystems. Robustness will require the control to be decentralised to some extent.

The above requirements imply the coexistence of both deliberative and reactive behaviours in the system. The architecture should therefore embed interacting subsystems that perform according to different temporal properties. In general, the implementation of several task-oriented and event-oriented closed loops for achieving both anticipation capacities and real-time behaviour cannot be done on a single system with homogeneous processes, due to their different computational requirements.

A global architecture is needed, that enables the integration of processes with different temporal properties and different representations.

The PHRIENDS partner Laboratoire d'Automatique et d'Analyse des Systèmes (LAAS), proposed an architecture [39], which can be considered a good starting point for the work in PHRIENDS, composed by two hierarchical levels. The lowest level, namely the functional level, contains all the basic built-in functionalities of the system. Processing functions and control loops (e.g., image processing, obstacle avoidance, motion control, etc.) are encapsulated into controllable communicating modules. To make this level as hardware-independent as possible, and hence portable from one robot to another, it is interfaced with the sensors and effectors through a logical robot level. The modules are activated by the next level according to the task. The highest level is the decision layer, composed of a supervisor and a planner, which constitutes the main software component for autonomy. This level includes the capabilities for producing the task plan and supervising its execution, while being at the same time reactive to events from the functional level. The coexistence of these two features, a time-consuming planning process and a time bounded reactive execution process, poses the key problem of their interaction and their integration to balance deliberation and reaction at the decisional level.

Moreover, a solution to guarantee the safety properties is to integrate in the architecture a module that formally checks the validity of the low-level commands sent to the physical system and prevents the robot from entering an unsafe state. This check must verify consistency during execution without affecting the system basic functionalities: this mechanism is part of an execution control layer. Despite its clear role in the architecture, the execution control layer can actually be embedded in the

functional level, given its intricate interaction with its components. This results in an overall two-level architecture.

Case studies for benchmarking pHRI

In this section, simple case studies from [2] are reported, to highlight how safety issues are taken into account in practice. Incidentally, notice that some service robots either address the safety issues with simple solutions (bumpers in robotic vacuum cleaners) or present small intrinsic risks (such as small entertainment or pet robots). The definition of benchmarks is a general problem which becomes even more crucial in service robotics, where novel metrics are introduced without a clear standardisation. Robotic vacuum cleaners, soccer playing, general service or entertainment robots are compared on the basis of the fulfillment of a task: being anthropic domains quite different, it is difficult at this stage to propose a unique environment to assess dependability and performance of robots.

An example of physically interacting robot providing power augmentation to humans workers is Cobot [40]. 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 human's 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 [41].

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 [42] 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 DM^2 actuation scheme. In order to obtain a meaningful comparison, optimised SEA and DM^2 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 DM^2 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 DM^2. 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.

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 [43] [44]. A particularly efficient algorithm that uses only encoder positions is based on the monitoring of the generalised momentum of the mechanical system [45], [46], 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 [47], 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 [48]. 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 human–robot collisions is mandatory.

Revising safety metrics

Revised safety criteria, including the effects of the adopted reaction strategies on the reduction of risk, should be considered [49]. Examples have been recognised in some estimation of the danger depending on design or control parameters in [50], and [51], with reference to trajectory modifications for safer operations based on distances, inertia seen at possible collision instants, comfort.

In general, the common injury indices briefly cited in Section 2.1.1 originate in fact from fields other than robotics (e.g. automotive crash test, development of protection helmets) and were developed and tailored for those specific applications. Although they constitute a useful basis for starting the development and evaluation of safe robotic concepts, special attention has to be paid to the question whether the conditions under which these indices were formulated are indeed satisfied (and are general enough) in their robotic application.

As an example, consider the case of the head injury criterion (HIC). This widely adopted index in automotive crash tests was also successfully used so far in the pioneering pHRI literature in order to evaluate various hardware concepts for inherent safety mechanical design (VIA and DM [2]). This index is based on the evaluation of the time profile of the head acceleration. In the case of a car crash, the main source of injury for the head is the acceleration transmitted from the vehicle, through the body of the person, to its head. It is very likely that no direct impact of the head occurs during an accident and consequently the acceleration is the only quantity which can

always be reliably measured (e.g. by a test dummy). Nevertheless, the index applies also for impacts, if the head can freely move (accelerate) after the impact.

In robotics, however, the most dangerous injury would probably be produced always by a direct impact of the robot with the humans head. Moreover, it is possible that the head (or another part of the body) is even squeezed between robot and environment or between parts of the robot, leading to only reduced accelerations (and hence to an uncritical value of the HIC), but nevertheless constituting a high injury risk. This observation suggests that an index related, e.g., to the impact force or to the transmitted energy could describe more precisely the various types of injury which can arise in pHRI. This punctual example is given as a motivation for the need of further research for establishing a set of indices and measures that quantify as completely as possible the potential danger emanating from a robot.

One obvious possibility is to evaluate various existing indices (and possibly proposing new ones) based on simulation studies using existing models of the human body and of test robotic scenarios. Of course, the validation of the criteria is very problematic, one still has to rely here on empirical data (relating forces, accelerations, impact energy to real human injury) available from other fields. It is the implicit goal of the safe robotics research activities, to prevent the emergence of such a database of eerie accidents in robotics. The availability of standardised, well founded, and reliable criteria will considerably pave the way for making HRI safe and hence feasible and attractive from a practical point of view. Although some HRI taxonomies were proposed (see, e.g., [52]), the main issues considered (autonomy, human/robot presence ratio, level of shared interaction, available sensors and their fusion, task criticality) do not include safety in physical interaction. Very recently, researches from the Institute of Robotics and Mechatronics of the German Aerospace Research Center (DLR) have shown the need for taxonomy and criteria peculiar for the field [16]. A taxonomy for the evaluation of pHRI, with emphasis on safety and dependability issues, is still missing, and it is an expected outputs of PHRIENDS.

According to the discussion in this section, one may provide "scores" to the safety/dependability of the following robot components and functionalities: lightweight mechanical design, passive soft covering, (variable) compliant actuation and transmission, complete sensor suite/fusion, human-oriented off-line planning, reactive on-line planning, stable force/impedance control, motion control performance, fault diagnosis and tolerance, collision avoidance or detection, collision reaction tactics, modular control architecture. These individual scores should be combined with suitable weights and evaluated on a large sets of consistent experiments. A checklist associated to a typical robotic task involving pHRI should be considered. The scenario may include a robot manipulator mounted on a mobile base, used as an assistant for collecting an object in a large environment and handing it over to a human without damages or harm to humans present in the workspace.

Investigation and contributions come not only from academic institutions. The complexity of HRI fascinates also research centers and world-leading industrial companies. They are starting new research and application tracks in robotics for human environments which intrinsically need a study of safety and dependability in pHRI, since the novel proposed applications are in close vicinity with humans.

The cited work of KUKA Roboter in the PHRIENDS consortium is very important; at the same time, big names of technology like Toyota Motor company [53], interested in pHRI for the "Partner Robot" project, as well as Microsoft Co., with their robotics software platform, are addressing the field.

In addition to aspects mentioned in Section 2.1.1, notice that the American National Standards Institute (ANSI) has established a committee, T-15, that published a draft safety standard for Intelligent Assist Devices (IADs). The committee has defined as "single- or multiple-axis devices that employ a hybrid, programmable, computer-human control system to provide human strength amplification, guiding surfaces or both" and aims at directly assessing pHRI.

Main points here are:

- risk assessments in place of fixed rules;
- safety-critical software, to lead to the shutdown of the system in a safe state;
- dynamic limits, also determined via risk assessment;
- emergency stops;
- man-machine interface, for which the T15 committee found that "mode misunderstanding" was a possible cause of safety problems.

These point are often very close to those addressed in the PHRIDOM analysis [2] and in this thesis, and, to the best of our knowledge, no integrated initiative like PHRIENDS, which will address standardisation activities, focusing on both human and robot [4], has been started yet.

2.2 Some possible contributions from a planning/control viewpoint

The role of planning and control is evident both in cHRI and pHRI: while legible motion and smoothness of movements have also cognitive relevance, the possibility of having a very fast modelling and control of the interaction environment is a key issue for quickly detecting and moving interacting robots, giving control to different interfaces and control approaches at the same time.

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 DLR-III manipulator can provide solutions for all the considered steps. These points have been already partially verified for such robot, where the second aspect, mediated by modelling and control, needs proper sensing during interaction tasks. It has been pointed out that safety-critical collisions can be avoided very precisely with detailed models of the environment, while, at the same time, complexity of mesh-based modelling and of the algorithms for managing their calculation pose threats to dependability and to reactivity of the robot. Moreover, a person can move more quickly than expected for the sampling time of such algorithms.

The second step in the proposed approach to safety is the one addressed in this thesis, providing a manipulator's and world's model for fast deliberative/reactive motion, with arbitrary control points on the robot and the possibility of combining different trajectories for the fulfillment of different tasks, to be specified at an higher level.

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.

Moreover, if the modification to the trajectories are given in the operational space, there is the need for an appropriate inverse kinematics system to give the reference values for the velocity/force controllers of the manipulator, possibly considering kinematic redundancy and/or dynamic issues.

An approach to reactive planning could consider the on-line generation of the Cartesian path of multiple "control points" on the manipulator, possibly the closest one to obstacles. In this framework, it is useful to encompass the entire physical structure of the robot and of the obstacles (human or not) with basic geometrical shapes, which simplify distance computations.

Going on, the representation of the whole world with simple geometric primitives useful for distance computation and trajectory shaping seems to be an interesting resource for a quicker control, and then a safer interaction.

The spaces found in the interaction region, and possibly avoided during the motion, are considered "Safe (repelling) volumes" or "Goal (attractive) volumes" : their implementation is in the framework of modelling of the workspace with simple geometrical primitives, such as points, lines (segments), planes (limited regions), for computing distances and giving reference trajectories to manipulators, which are considered sequences of segments as well.

In detail, since pHRI has the two complementary directions of intrinsically safe (future) robots and safe by control (current) robots, the proposed contribution can be considered useful for completing the safety tactics for a service manipulator, and constitute a modelling base for multiple-point control.

In particular, it is worth noticing that the multiple control points modelled as introduced in Section 3.3, can move on the structure and require proper tools for computing corresponding joint motion (see Section 3.4).

Among the main aspects, the necessity of controlling multiple point of a robot in pHRI is central, both for multiple input channels to a robotic assistant (impedance

control, safety tactics, teleoperation, emergency paths), and for the presence of multiple possible colliding parts, e.g., of an humanoid. Humanoids are a special case because they intrinsically present multiple control points for grasping, moving the head for perception, assuming postures, walking, balancing, and so on.

Finally, whole-robot motion behaviour via multiple point control and reactive motion has to be cast into a task management policy, in order to complete a robot model for interaction.

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

- environment modelling for simple geometric computation,
- multiple-point approach both for multiple inputs and multiple outputs of the robot,
- arbitrary selection of the control points on the robot,
- reactive real-time control for safety,
- integration with deliberative tasks and other safety tactics.

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.

3

Multiple-point control

A central idea in HRI is the possibility of interacting with multiple control points of the robot via direct touch or remote operation. At the same time, every point on the robot can collide with the user. The goal of this chapter is to present tools which allow multiple-point control of robots for pHRI, by means of suitable motion trajectories in the workspace to be specified for such points.

3.1 Kinematic control of multiple points

As presented in the previous discussion, the motion of a robot manipulator can result in (even severe) damages to people present in the workspace. With respect to simple mobile robot control, articulated robot manipulators have to be controlled in different points in order to take into account the different postures that they can assume during their motion. These postures can pose threats in case of collision and scare the user, leading to unexpected movements and forcing the robot control architecture to react properly to unexpected behaviours.

The approach presented in [54] takes into account the following issues, which are thought to be relevant in kinematic control of an articulated robot which has to interact with a dynamic anthropic domain, and which constitute the base for developments presented in this chapter:

- multiple-point control,
- desired path for every control point,
- nesting of the desired motion behaviours.

The first point depends on the possibility of having multiple possible input commands and, especially, multiple possible collisions. This means that the possible user has both to be able to control at the same time the motion of different parts of the robots (and not only the end-effector carrying objects or tools), and to be safe in case of multiple mechanical parts of an articulated manipulators approaching her/him (e.g., an hyper-redundant humanoid).

Moreover, the second point addresses the need for accomplishing different tracking tasks and legible and safe motion for parts of the robot which are not directly involved in the physical interaction or contactless collaborative task.

Finally, the third aspect is needed for giving importance and relevance to different tasks, whose priority can be managed according to the fact that cognitive aspects can have an influence on control parameters.

The implementation for giving the joint commands to the robotic system can be considered both in velocity or torque control, properly nesting other commands to the controller (e.g., a command coming from direct human touch at the end-effector in impedance control), in order to give priority to the path following.

The virtual end-effectors (VEEs) which have been introduced in [54] are parts of the manipulator structure, whose positions are to be controlled in addition to the control of the end-effector of the mobile robot manipulator. Since the focus is on redundant robots, the VEEs approach to inverse kinematics for multiple control points addresses this point first.

3.1.1 Inverse kinematics and redundancy

Redundancy resolution

Redundancy resolution is related to the problem of finding movements of available joints that respect the desired motion of the end-effector, while satisfying some additional task. The solution of the problem can be found on the basis of the well-known differential mapping

$$\dot{\boldsymbol{p}} = \boldsymbol{J}(\boldsymbol{q})\dot{\boldsymbol{q}} \tag{3.1}$$

where

$$\boldsymbol{p} = \begin{bmatrix} x\ y\ z \end{bmatrix}^{\mathrm{T}}$$
$$\boldsymbol{q} = \begin{bmatrix} q_1\ q_2\ ...\ q_n \end{bmatrix}^{\mathrm{T}}$$

are respectively the end-effector position vector and the joint position vector of an n-DOF mobile robot manipulator, and $\boldsymbol{J}$ denotes the usual Jacobian matrix.

Some assumptions are now introduced: for the purpose of obstacle-avoidance motion, the end-effector orientation is not considered. Of course, this can pose problem in case of carrying grasped objects. By focussing on a general case of a manipulator mounted on a mobile robot, we can consider $n = 8$, i.e. 2 DOF's for the mobile base and 6 DOF's for the manipulator.

Since the robot is redundant ($n > 3$), the simplest way to invert the mapping (3.1) is to use the pseudo–inverse of the Jacobian matrix, which corresponds to the minimisation of the joint velocities in a least-square sense [55]. Because of the different characteristics of the available DOF's, it could be required to modify the velocity distribution. This might be achieved classically by adopting a weighted pseudo–inverse $\boldsymbol{J}_W^{\dagger}$

$$\boldsymbol{J}_W^{\dagger} = \boldsymbol{W}^{-1}\boldsymbol{J}^{\mathrm{T}}(\boldsymbol{J}\boldsymbol{W}^{-1}\boldsymbol{J}^{\mathrm{T}})^{-1} \tag{3.2}$$

with the $(n \times n)$ matrix $\boldsymbol{W}^{-1} = \mathrm{diag}\{\beta_1, \beta_2, ..., \beta_n\}$, where β_i is a weight factor belonging to the interval $[0, 1]$ such that $\beta_i = 1$ corresponds to full motion for the i-th degree of mobility and $\beta_i = 0$ corresponds to freeze the corresponding joint [56]. These equations show that mobility distribution is a first tool which can be adopted for exploiting the available DOF's in a legible way for the user interacting with the robot.

Moreover, redundancy of the system can be further exploited by using a task–priority strategy [57], [58] corresponding to a solution to (3.1) of the form

$$\dot{\boldsymbol{q}} = \boldsymbol{J}_W^\dagger(\boldsymbol{q})\boldsymbol{v} + \left(\boldsymbol{I}_n - \boldsymbol{J}_W^\dagger(\boldsymbol{q})\boldsymbol{J}(\boldsymbol{q})\right)\dot{\boldsymbol{q}}_a \tag{3.3}$$

where $\boldsymbol{I}_n$ is the $(n \times n)$ identity matrix, $\dot{\boldsymbol{q}}_a$ is an arbitrary joint velocity vector and the operator $\left(\boldsymbol{I}_n - \boldsymbol{J}_W^\dagger\boldsymbol{J}\right)$ projects the joint velocity vector in the null space of the Jacobian matrix. Also in (3.3), $\boldsymbol{v} = \dot{\boldsymbol{p}}_d + k(\boldsymbol{p}_d - \boldsymbol{p})$ which provides a feedback correction term of $\boldsymbol{p}$ to the desired position $\boldsymbol{p}_d$, according to the well-known closed-loop inverse kinematics (CLIK) algorithm, being $k > 0$ a suitable gain [59]. This solution generates an internal motion of the robotic system (secondary task) which does not affect the motion of the end-effector while fulfilling the primary task [60].

For the purpose of multiple-point control, the kind of secondary tasks employed in the VEES approach algorithm are also task-space desired velocities for points of the robot itself, i.e., the secondary arbitrary joint velocity vector are based on the inverse kinematics of a reduced part of the structure. This is the way of controlling at the same time different points, provided that the nesting of the tasks and the number of DOF's allow the multiple desired paths: the policy for such a priority distribution will be discussed in next sections, and, more in general, it constitutes a base for discussion in Chapter 4.

As an example of positioning of different parts of manipulator (rather than only the actual end-effector), consider the human arm: the structure is redundant for the positioning of the hand, and thus it is possible to position the elbow (which can be considered a first VEE); the so-computed joint values can then be used as references for the positioning of the wrist (second VEE), and so far for the hand (real end-effector): please refer to Section 3.2.3, which is maninly based on [61] and [62]. Therefore, a hierarchical solution of redundancy is achieved, where the various lower-priority tasks are to be selected according to some suitable criteria.

3.2 The multiple VEEs approach

The multiple VEEs approach is hereby introduced in a general fashion, by adopting a multiple task priority strategy for specifying secondary tasks, along with a proper trajectory planning technique for the desired motion of each VEE.

In detail, let $\boldsymbol{q}_i$ denote the vector of the n_i joint variables which determine the position $\boldsymbol{p}_i$ of the i-th VEE. Therefore, the differential kinematics mapping for a generic VEE is

$$\dot{\boldsymbol{p}}_i = \boldsymbol{J}_i(\boldsymbol{q}_i)\dot{\boldsymbol{q}}_i \qquad\qquad (3.4)$$

where $\boldsymbol{J}_i$ denotes the associated Jacobian.

The result is a nested N-layer CLIK scheme, where N is the number of considered VEEs. To this regard, please notice that the end-effector is included in the counting of the VEEs; in fact, it may well be the case the highest priority be assigned to an intermediate VEE other than to the end–effector, say when an obstacle is obstructing the end–effector motion.

With this approach, the control of different points is not considered in a global matrix, but with multiple mappings. The VEEs approach can be used for maneuvering a kinematic structure in a volume, e.g., for tube inspections and endoscopy with snake robots, by considering the most critical edges of the structure as VEEs.
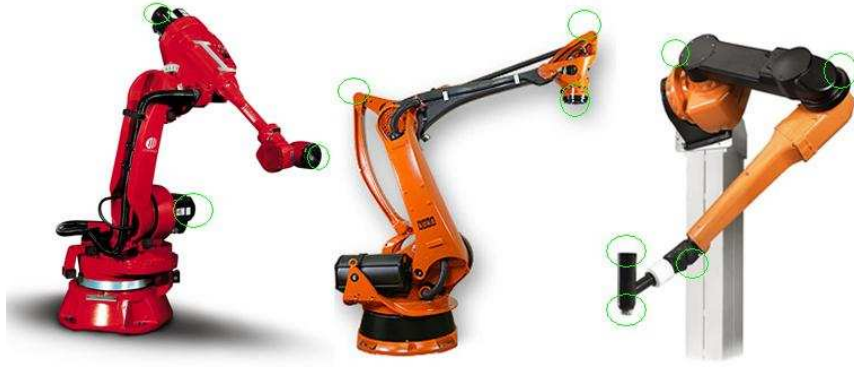
Fig. 3.1. Prominent parts of robots, including tools, have to be identified and labelled as VEEs

3.2.1 Nested closed-loop inverse kinematics

Inverse kinematics with the VEEs approach orders the VEE positioning tasks according to a priority management strategy. Since the trajectories of lower priority VEEs are assigned as secondary task, they will be followed only if they do not interfere with the higher priority task to be fulfilled. This point is crucial, and a different management of multiple tasks can be considered.

Following the algorithm presented in [54], a list of VEEs is considered, starting from the one with highest priority, i.e., the one which can possible collide first with an obstacle in the workspace. When a VEE gets close to an obstacle, its desired path following (necessary to avoid the obstacle) becomes of higher priority for the CLIK scheme and the priority order is switched with respect to the distance of each VEE from the obstacle. This can be achieved by considering the N-layer priority algorithm described in the following. The idea is summarised in Fig. 3.2, being N the lowest priority.

Fig. 3.2. Scheme of nested CLIK with VEEs

At the lowest layer, the differential mapping corresponding to the velocity of the VEE with lowest priority is considered, i.e. (3.4) with $i = N$. Hence, a CLIK algorithm with weighted pseudo-inverse is adopted to compute the inverse kinematics:

$$\dot{\boldsymbol{q}}_N = \boldsymbol{J}_N^{\dagger}(\boldsymbol{q}_N)\boldsymbol{v}_N, \tag{3.5}$$

with $\boldsymbol{v}_N = \dot{\boldsymbol{p}}_{Nd} + k_N(\boldsymbol{p}_{Nd} - \boldsymbol{p}_N)$, being $\boldsymbol{p}_{Nd}$ the desired position for the VEE with lowest priority and $k_N > 0$. The pseudo-inverse matrix is substantially weighted as in (3.2).

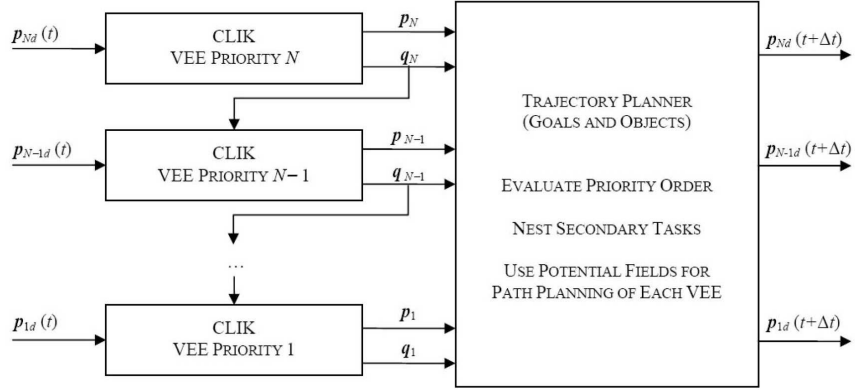At the generic i-th layer of the nested scheme, with $i = N-1, \ldots, 1$, the inverse kinematics is computed as in (3.3), i.e.

$$\dot{\boldsymbol{q}}_i = \boldsymbol{J}_{iW}^{\dagger}(\boldsymbol{q}_i)\boldsymbol{v}_i + \left(\boldsymbol{I}_{n_i} - \boldsymbol{J}_{iW}^{\dagger}(\boldsymbol{q}_i)\boldsymbol{J}_i(\boldsymbol{q})\right)\dot{\boldsymbol{q}}_{ia} \tag{3.6}$$

where

$$\boldsymbol{J}_{iW}^{\dagger} = \boldsymbol{W}_i^{-1}\boldsymbol{J}_i^{\mathrm{T}}(\boldsymbol{J}_i\boldsymbol{W}_i^{-1}\boldsymbol{J}_i^{\mathrm{T}})^{-1} \tag{3.7}$$

with $\boldsymbol{W}_i^{-1} = \mathrm{diag}\{\beta_{i1}, \beta_{i2}, ..., \beta_{in_i}\}$ and $\boldsymbol{v}_i = \dot{\boldsymbol{p}}_{id} + k_i(\boldsymbol{p}_{id} - \boldsymbol{p}_i)$, being $\boldsymbol{p}_{id}$ the desired position for the VEE with priority i, and $k_i > 0$. Further, $\dot{\boldsymbol{q}}_{ia}$ is the gradient of the objective function:

$$G_i = -\frac{1}{n_i}\sum_{j=1}^{n_i}\frac{q_{i,j} - q_{i+1,j}}{q_{i,jM} - q_{i,jm}}$$

where $q_{i,jM}$ ($q_{i,jm}$) is the maximum (minimum) value of the joint variable $q_{i,j}$, i.e. the j-th component of the joint vector $\boldsymbol{q}_i$. The above choice corresponds to achieving a joint motion for the joint variables as close as possible to that computed in the previous layer $\boldsymbol{q}_{i+1}$, which are fed as secondary reference values to the next layer,

providing a way to fulfill the desired inverse kinematics of different parts of the structure, with different priorities.

Going on, the nested CLIK algorithm computes the inverse kinematics for the structures ending with each of the considered VEEs. It is worth emphasizing that the order of priorities is dynamically changed during task execution.

The continuity of reference trajectories can be accomplished via proper modification of starting velocities for the novel selected higher-priority VEEs. As illustrated in Fig. 3.2, the scheme takes the desired positions for the ordered VEEs at time t; then, the output of the CLIK algorithms at the N levels are input to a trajectory planning block which re-evaluates the priority order among the various VEEs according to the positions of the goals and the obstacles in the environment, and thus generates the new ordered sequence of desired positions for the VEEs at time $t + \Delta t$, where Δt is the sampling time at which the CLIK algorithm is discretised for practical implementation; the planning aspects are discussed in the following section. The weights β_{ij} of the matrices $\boldsymbol{W}_i$ can be chosen according to the criterion described in [56].

In particular, with reference to the example cited in [54], the joints of the mobile base have a higher weight with the respect to the joints of the manipulator.

Consider a task where a mobile manipulator carries a 6-DOF anthropomorphic robot arm, reported in [54] and depicted in Fig. 3.3. It is clear that such a robot is unfit for HRI: it is considered because the VEEs approach can be used in industrial domains, where both the vehicle and the anthropomorphic manipulator are common. However, usually heavy robots are not carried by mobile carts. This comment is relevant in the perspective where control is an additional tool for safety, which has to be guaranteed starting from the design.

In Fig. 3.3 it is possible to see how trajectories are followed for various VEEs with different priorities. It is easy to recognize that planned trajectories for VEEs with lower priorities are abandoned when they interfere with the higher priority planned trajectories. With the priority strategy, which ranks the VEEs, it is possible to fulfill the most critical positioning problems on line.

The time history of a joint variable is also reported in Fig. 3.4; movements planned in the task space are abandoned if they interfere with higher-priority tasks, resulting in joint motions which can be different and, e.g., not legible by an interacting user.

The priority management strategy which gives preference to the closet point to obstacles is crucial: if a mobile robot manipulator is considered, which avoids the head of a person in a room with the end-effector, it is difficult to predict the possibility of hitting him/her with other parts of the structure, because a possible avoidance movement can be incompatible with the path of the real end-effector or of a VEE with higher priority. See Fig. 3.3(d) for an example of changing priority order for the considered manipulator, whose VEEs are labelled as in Fig. 3.3(a) . Multiple switching can be reduced if a filter is considered for changing smoothly the control VEE.

(a)

(b)

(c)

(d)
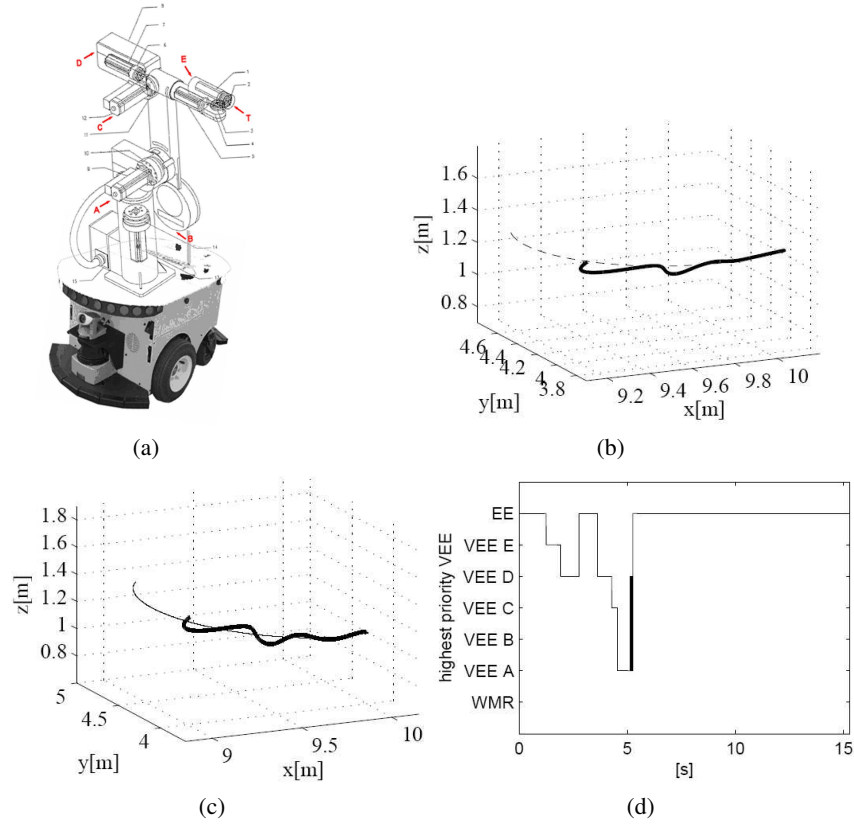
Fig. 3.3. Chosen robot model (a) and planned (gray) and actual (black) trajectory for the VEE labelled with A (b), and B (c), with resulting priority order in an HRI task (d)

3.2.2 Trajectory planning

For each VEE it should be possible to plan a complete trajectory off-line, but this approach is not satisfying, since the trajectories imposed to the VEEs, if planned a priori, do not have realistic application (most obstacles are moving and their trajectories are not known a priori).

Furthermore, the positioning of VEEs in task space is only a secondary task for the positioning of other VEEs with higher priority. On-line trajectory planning is needed: potential fields methods [31] can be used for such a planning: the manipulator moves in a field of forces; the position to be reached is an attractive pole for the end-effector, and obstacles are repulsive surfaces for the manipulator parts. The field of artificial forces F is produced by a differentiable potential function, with
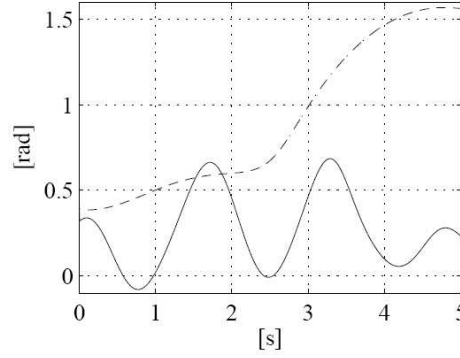
Fig. 3.4. Simulation results: planned (dashed) and actual (solid) trajectory for the position of the second joint of the considered manipulator

$F(\boldsymbol{p}_i) = -\nabla(U(\boldsymbol{p}_i))$, where $\nabla(U(\boldsymbol{p}_i))$ is the gradient vector of U at $\boldsymbol{p}_i$, that is the position of the VEE under the field effect.

This basic principle and its evolution, with possible consequences on control and physical interpretation of the resulting trajectory is discussed more in depth in Chapter 4. In a basic implementation, the potential U is constructed as the sum of two elementary potential functions: $U(\boldsymbol{p}_i) = U_{att}(\boldsymbol{p}_i) + U_{rep}(\boldsymbol{p}_i)$ In this relation $U_{att}$ is the attractive potential and depends only on the final position, whereas U_{rep} is the repulsive function and depends only on the obstacles position.

During the simulations shown in the figures of this section, the attractive potential field is chosen to be a parabolic well, centered in the goal positions, whereas a repulsive field is related to a distance of influence from obstacles. So, the goal is a source of an attractive potential field; obstacles are sources of repulsive potential fields.

Notice again the importance of the priority management in the CLIK schemes, as discussed above: even with on-line path planning, a desired path could be not executable, so it is necessary to switch the priority order, as emphasised by the trajectory planning block in Fig. 3.2. In addition, reactive motion can benefit of more complex potential functions. Additional considerations about the VEEs and some criticisms related to the limited number of VEEs, to be selected a priori by hand, lead to the skeleton approach, introduced in Section 3.3, where a more general whole-body modelling is considered.

3.2.3 An interesting biomimetic example

As an example of application of the VEEs approach, consider the multiple tasks, and the different joint involvement, performed by the human arm while drawing or writing.

Many anthropic tasks involve force and position constraints for the human arm. The inverse kinematics and the trajectory planning for human arm positioning may

depend on these constraints. The well-known manipulability ellipsoids may be used to study the relations between dexterity and efforts during handwriting, painting and other tasks where the human arm has to perform a precise motion while balancing forces acting on it. Moreover, the motion of the arm can be interpreted as a motion of different points, like elbow, and wrist.

This example is proposed according to the following analogies:

- *drawing* corresponds generically to *moving the end-effector,*
- *leaning the elbow* corresponds generically to an internal motion of a VEE,
- *different mobility of articulations* correspond generically to *joints' weighing*,
- *plans for trajectory* are based on *relevance of the points to be reached*,
- *foci of attention during writing* correspond to *crucial points as heuristics for the sensors*.

Notice that for many tasks such as writing on a surface, only three DOF's are required. In some cases, also orientation is important; however, the human arm is redundant to perform such tasks, even though a simplified 7-DOF kinematic model (not considering the hand articulated structure) is adopted (See Fig. 3.5). Using this simplified model, the lengths of the links have been set on the basis of anatomic evaluations: 0.3 m for the first link, 0.25 m for the forearm and 0.15 m for the hand-pencil link.

The solution to the inverse kinematics for a human-like arm during drawing tasks can be evaluated and compared with arm movements of human experimenters.
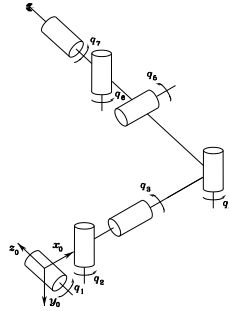
Fig. 3.5. Human-like 7-DOF robot arm

Biologically-motivated computer vision techniques are to be considered for trajectory planning in robotic systems whose aim is to execute draws in human-like fashion, also to infer mobility distribution in the human arm among available joints. The direction of gazes when a picture to be reproduced is observed is crucial for trajectory planning, and the postures assumed while executing an assigned task are strictly related to optimisations performed by the human evolution. Therefore, it is interesting to investigate human and animals' behaviours to infer laws for biomimetic

trajectory planning and inverse kinematics. When a 7-DOF anthropomorphic robot manipulator performs a drawing task or a handwriting task, the 4 redundant DOF's can be suitably used to perform secondary tasks.

A possible way of exploiting redundancy is that of mimicking the human arm movements. An example of application is rehabilitation robotics, where an exoskeleton may drive the correct movements of the injured arm of a patient. Moreover, in fine painting tasks, an anthropic behaviour implemented in the control law may produce a smoother end-effector trajectory resulting in higher quality lines. In [61], [62], following a biomimetic approach, the mobility of the last three joints, corresponding to the robot wrist, is suitably reduced with respect to the mobility of the other joints; moreover, if the task is at desk, the elbow and wrist are forced to stay close to the writing plane, in order to minimize the gravity acting on the structure.

Notes on biomimetic trajectory planning

The design of the trajectory has been considered first. Starting from a picture with a draw, the human experimenters and the robot are asked to reproduce it. Our capacity of perceiving information from an image involves a process of selection of the regions of interest in it. For an attentive visual inspection we move eyes (saccadic movements) in the world, three/four times per second. After that, the information across subsequent fixations (foveation points) is integrated in order to extract the features "perceiving" the image.

Biomimetics suggests finding a computational model that extracts the low-level features. Such a model was proposed in [63]; in the case of a gray map, the features are extracted from the intensity (I) and the orientation (O) pyramid, where center-surround differences, between a center fine scale and a surround coarser scale, yield the feature maps. The sequence of regions of interest gives the sequence of fixation regions (foci of attention, FOAs). The proposed task for a 7-DOF robot is to replicate a picture using human-like trajectory planning and inverse kinematics. First of all, the search of salient points in the picture to be drawn (Fig. 3.6) guides the trajectory planning. If a picture is shown for less than 2 seconds, only 5-6 saccadic movements (FOAs) are possible for the human eye to perceive the most important features needed to reconstruct main information (shape, texture, colour) about the picture. Considering the coding of the most important point to reproduce the shape, it could be observed that saccades are posed only on the points where tangential speed of drawn curves is rapidly variant, or where crossing of lines is observable. For the draws proposed to humans and robots (Fig. 3.6), the fixed points found by a system implementing the cited computational model, are reported in Fig. 3.7. These attention points are the same used during reading: humans filter only the information where the discontinuity is more relevant. After the selection of the FOAs, a simplified approach has been used, in order to generate the trajectory for the pencil, based only on codified information (orientation and intensity). Gabor filtering is a well-known technique for shape characterisation, edge detection and other useful image processing. Two-dimensional Gabor functions have been proposed to model the spatial summation properties in the visual cortex. They are widely used in image processing,

computer vision, neuroscience and psychophysics. It is possible, by such a filtering in 8 directions (with angular values $\{0, 22.5, 45, 67.5, 90, 112.5, 135, 157.5\}$), to give an estimation of the curvature of drawn lines in each region.

Finally, it is possible to plan a trajectory for the pencil, based on manual selection of sequence of the FOAs, which can be different by the natural succession, due to the reorganisation, (i.e. top-down evaluations or quicker solutions). The goal-directed attention is important in gaze shifts for planning. These shifts can depend also on cognitive evaluations about the shown picture: this is the reason why handwriting is a very interesting task for automatic systems that can be implemented also for orthosis-assisted movements. It should be interesting also to compare goal-directed planning for movements of fingers (e.g., handwriting) and feet (locomotion).
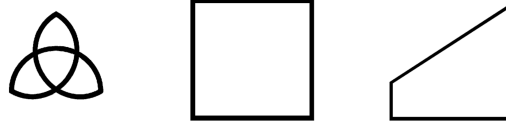
Fig. 3.6. Draws proposed for observation and reproduction
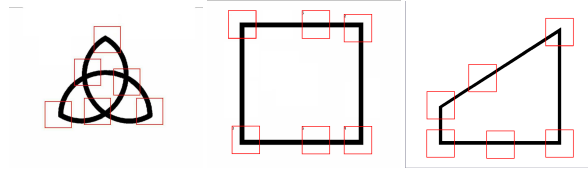
Fig. 3.7. Observed objects with evaluated foci of attention

Closed-loop control systems were emphasised since the cybernetics of Wiener as a functional analogy between men and machines. The CLIK schemes lead to obtaining joint variables of a robot manipulator starting from a differential mapping between task-space and joint-space values.

Biomimetic inferences may be considered to evaluate how humans and animals distribute the motion required by a trajectory planned in the task space among the available degrees of freedom offered by the joints, especially when redundancy is present, i.e., when there are more DOF's than those required for the description of a task in the task space.

The trajectories for wrist and elbow, considered as VEEs, are planned in the task space. Moreover, according to the VEEs approach, in order to confer a biomimetic behaviour to the arm during the execution of a writing task, the weights β_i in (3.2) and the vector $\dot{q}_{ia}$ in (3.12) must be suitably chosen.

Observing a human writer, it can be recognised that the joints of the shoulder and of the elbow shall have higher mobility with respect to the joints of the wrist. This can be easily obtained by choosing the weights β_i close to 1, for $i = 1, 2, 3, 4$ and close to 0 for $i = 5, 6, 7$. These values could be modified during task execution using, e.g., soft computing techniques [56].

Moreover, during the action of writing at a desk, the elbow and the wrist are usually taken close to the desk, in order to minimize the effects of the gravity on the arm. This behaviour can be enforced to the arm by assigning to the elbow and the wrist a position close to the writing plane without modifying the trajectory of the pencil: these positions are planned in the task space, based on dynamics considerations. The desired behaviour can be achieved by considering the three-layer priority algorithm, described in the following

At the low layer, the differential mapping corresponding to the velocity of the elbow along the y axis is considered, i.e.,

$$\dot{y}_e = \boldsymbol{J}_e(\boldsymbol{q}_e)\dot{\boldsymbol{q}}_e \tag{3.8}$$

where $\dot{\boldsymbol{q}}_e = [\, q_1 \ q_2 \ q_3\,]^\mathrm{T}$ and $\boldsymbol{J}_e(\boldsymbol{q}_e)$ is a (1×3) row vector. Hence, a CLIK algorithm with weighted pseudo-inverse is adopted to compute the inverse kinematics:

$$\dot{\boldsymbol{q}}_e = \boldsymbol{J}_{We}^\dagger(\boldsymbol{q}_e)v_e, \tag{3.9}$$

with $v_e = \dot{y}_{de} + k_e(y_{de} - y_e)$, being y_{de} the desired elbow position and $k_e > 0$. The pseudo-inverse matrix in (3.9) is

$$\boldsymbol{J}_{We}^\dagger = \boldsymbol{W}_e^{-1}\boldsymbol{J}_e^\mathrm{T}(\boldsymbol{J}_e\boldsymbol{W}_e^{-1}\boldsymbol{J}_e^\mathrm{T})^{-1} \tag{3.10}$$

with $\boldsymbol{W}_e^{-1} = \mathrm{diag}\{\beta_1, \beta_2, \beta_3\}$.

At the middle layer, the differential mapping corresponding to the velocity of the wrist along the y axis is considered, i.e.,

$$\dot{y}_w = \boldsymbol{J}_{Ww}(\boldsymbol{q}_w)\dot{\boldsymbol{q}}_w \tag{3.11}$$

where $\dot{\boldsymbol{q}}_w = [\, q_1 \ q_2 \ q_3 \ q_4\,]^\mathrm{T}$ and $\boldsymbol{J}_{Ww}(\boldsymbol{q}_w)$ is a (1×3) row vector. Again, a CLIK algorithm with weighted pseudo-inverse and secondary task is adopted to compute the inverse kinematics:

$$\dot{\boldsymbol{q}}_w = \boldsymbol{J}_{Ww}^\dagger(\boldsymbol{q}_w)v_w + \left(\boldsymbol{I}_4 - \boldsymbol{J}_{Ww}^\dagger(\boldsymbol{q}_w)\boldsymbol{J}_w(\boldsymbol{q}_w) \right) \dot{\boldsymbol{q}}_{aw}, \tag{3.12}$$

The pseudo-inverse matrix in (3.12) is

$$\boldsymbol{J}_{Ww}^\dagger = \boldsymbol{W}_w^{-1}\boldsymbol{J}_w^\mathrm{T}(\boldsymbol{J}_w\boldsymbol{W}_w^{-1}\boldsymbol{J}_w^\mathrm{T})^{-1} \tag{3.13}$$

with $\boldsymbol{W}_w^{-1} = \mathrm{diag}\{\beta_1, \beta_2, \beta_3 \ \beta_4\}$ and $v_w = \dot{y}_{dw} + k_w(y_{dw} - y_w)$, being y_{dw} the desired wrist position, $k_w > 0$; $\dot{\boldsymbol{q}}_{aw}$ is the gradient of the objective function:

$$G = -\frac{1}{6}\sum_{i=1}^{3} \frac{q_i - q_{ei}}{q_{iM} - q_{im}}$$

where q_{iM} (q_{im}) is the maximum (minimum) value of the joint variable q_i. The above choice corresponds to achieve a joint motion for the first 3 joint variables close to that computed in the first step. This is imposed as a secondary task, hence it is fulfilled only if it does not interfere with the primary task.

Finally, at the high layer, the complete manipulation structure with the CLIK algorithm is considered, where $\dot{\boldsymbol{q}}_a$ is chosen as the gradient of the objective function:

$$G = -\frac{1}{8} \sum_{i=1}^{4} \frac{q_i - q_{wi}}{q_{iM} - q_{im}},$$

corresponding to a motion for the first 4 joints close to that computed in the second step.

Notice that the weights β_i of the matrix $\boldsymbol{W}$, and thus of $\boldsymbol{W}_e$, $\boldsymbol{W}_w$, are chosen according to the criterion described above.

When the task is performed on a vertical plane, the secondary task of minimizing the gravity torques on the joints are to be transformed to the joint space, where reference values for the joint positions are provided to fulfill this requirement. Usually this constraint leads the arm to keep a posture attached to the body. Notice that, in order to seek for suitable kinematics postures to optimize the movements, information on the force acting on the end effector should be provided; as an example, the manual use of a camcorder is a typical task where positioning on a plane might be helpful; in such a task, in order to minimize the torques on the human arm, usually the forearm is kept close to the arm.
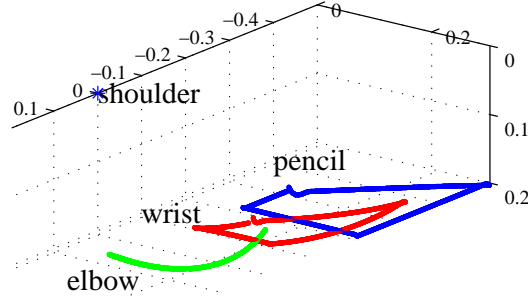
Fig. 3.8. Position of elbow, wrist and pencil for the robot during a drawing task at a desk

In order to better show the effectiveness of the CLIK scheme, also the joint angular positions can be evaluated via simple trigonometric calculations [61]. As an example, the angle between the arm and forearm can be evaluated from Carnot's cosine theorem knowing the positions of the arm and forearm and the distance between the wrist and the shoulder. The automatic system, in order to reproduce the first picture in Fig. 3.6, inferred a trajectory, based on active vision, and results of simulations for the positioning of the robot in the task space are shown in Fig. 3.9.
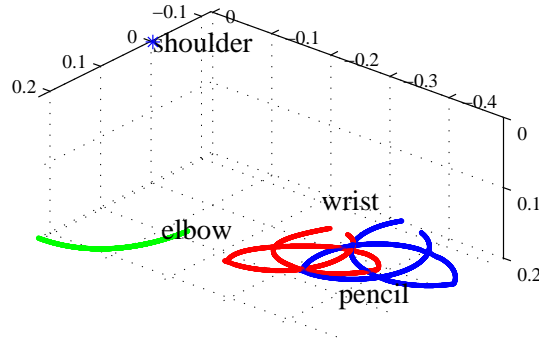
Fig. 3.9. 3D traces of elbow, wrist and pencil in simulation for the 7-DOF manipulator

The acquired trajectory of the pencil is used as input to the CLIK scheme (the trace of the pencil is reported in Fig. 3.9), and the resulting time histories of joints, not reported for brevity, are qualitatively following [62] those recorded on human writers, with errors due to modelling: as an example, the angle q_3 for the model in Fig. 3.5 is more difficult to evaluate from measurements, due to the volume of the arm, while robot links are considered without a volume; in some cases the angle can be different, due to the position and orientation of the robot elbow, which is not exactly laid on the desk in every case, during the task.

Also the sequence of drawn parts of the pictures is relevant: in the presented example, if the robot starts drawing towards the lower extremity first, joint movements change, but the task-space strategy is preserved.

This VEEs-based integrated system for trajectory planning and inverse kinematics for a robot capable of reproducing human draws with similar movements can lead to a better understanding of the optimisation performed by the human brain for the positioning of the arm.

The VEEs approach leads to summarize important points which are to be addressed as significant ideas for pHRI:

- plan and control for different control points,
- influence of biomimetic inferences and dynamics on desired trajectories,
- joint involvement and legibility of motion trajectories.

Moreover, relevant issues for improving the approach arise, e.g., from:

- whole-body modelling for arbitrary control point selection,
- reactive motion in case of unstructured environments.

3.3 Whole-body modelling and multiple control point

3.3.1 Need for multiple control points

The idea of separated control points for the same robot presents a serious drawback: control points have to be chosen manually before the experiments.

An approach which automatically selects a control point on a whole kinematic structure, based on sensor information, could result more effective for pHRI applications. In addition, these control points should be computed fast, based on a model of the environment which leads to simple distance computation and trajectory determination.

With focus on the model of the robot for fast multiple-point control, these considerations lead to the so-called "skeleton algorithm" [64], which can be considered as an extension of the Virtual End-Effectors approach, composed of these four steps:

- build a proper model of the robot, namely the skeleton, useful for analytical computation;
- find the closest points to a possible collision along the skeleton, namely the collision points;
- generate repulsion forces;
- compute avoidance torque commands to be summed to the nominal torques for the controller.

These steps are illustrated in the following, with reference to the problem of self-collision avoidance of a robot, which is simple since the involved model uses only segments, and the sensory data can be considered absolutely dependable (proprioceptive), with respect to interaction with external objects, tracked with slower and less dependable exteroceptive sensors.

Related works include researches on self-collision avoidance for a humanoid robot with fixed control points [65], external object avoidance for a 7-DOF arm [66], adopting elastic forces for the repulsion fulfilled via perturbations of desired position and inverse kinematics for completing the task. Discretisation of the robot structure has been proposed for self-collision avoidance also related to humanoid leg [67] motions, where polyhedral models have been adopted.

3.3.2 Skeleton-based modelling

In order to have a real reference manipulator designed for interaction with humans, this presentation is referred to the DLR Justin manipulator [68] (see Fig. 2.2), and is mainly based on [64], while implementation on industrial robots is possible too [34]. The setup and details on experiments will be presented in Chapter 5.

In order to avoid collisions between the arms and the torso of a humanoid manipulator like Justin, one should consider all the points of the articulated structure which may collide (and injure people in pHRI). The problem of analyzing the whole volume of the parts of a manipulator is simplified by considering a *skeleton* of the structure (Fig. 3.10), and proper volumes surrounding this skeleton. The adopted geometrical

model leads to using a very simple and fast computation rule for distance evaluation and modification of the trajectories for each point of the manipulator.

In general, one could derive the skeleton automatically from a proper kinematic description, e.g. via a Denavit–Hartenberg (D–H) table. This point will be considered in the following.

However, it is more efficient, and also intuitive and straightforward, to set up the skeleton by hand, as done below: let us consider the design of a skeleton by focusing on Justin, it is easy to notice that such a skeleton can be composed by considering segments lying on the links of the arms and the torso.

In this way, segments are built that "span" the whole kinematic structure of the manipulator. In Fig. 3.10 it is possible to observe ten segments in which the manipulator is decomposed, where the segment ends located at the Cartesian positions of the joints are computed via simple direct kinematics. Notice that, due to the kinematics of the DLR LWR-III, the joint motion in the roll axes of the arms does not affect the position of the shoulder-elbow and elbow-wrist segments.

Moreover, depending on how the control point on the segments produce attract or repelling forces/velocities, some segments could be discarded if they already benefit (going away from obstacles) of the resulting motion caused by other segments.

Automatic skeleton building form D–H parameters is a point which emphasises how the approach can be considered general for an articulated robot. The underlying idea is that a solid of revolution can express the shape of a link, but this can be partially modified using properly the repulsion functions from every point of the link, which in a sense create a safe volume around the point, and the result of these multiple volumes for the whole robot creates a safe region which has to approach the real volume of the considered part of a manipulator.

In other words, if it possible to control every point on the skeleton, at the same time repulsion forces from such points with respect to any object in the task space for collision avoidance have to reflect the shape of the mechanical structure around that point.

A general D–H table gives the possibility of computing the *Cartesian position of each joint*. These positions can constitute the ends of the segments of the skeleton (*nodes*), and some of this possible nodes will be discarded if they coincide with other nodes already present in the skeleton.

Moreover, the possibility of having robot where D–H parameters are variable has to be considered carefully, in order to understand what this means in terms of the skeleton building. Depending on whether such value change together or sequentially while moving *on the spine of the links* from the Cartesian position of a joint to the next, it is possible to approximate a link which has a "square wave" shape or another which is a straight segment between two successive nodes.

Of course, it is important to consider segments which cover the spine of all the mechanical parts: this has a reflex on D–H tables when manipulator links have parts on both sides of a revolute joint as, e.g., for counterbalances or for allocating motors (see Fig. 3.1 and 5.6).

Summarizing, in general, after the definition of the nodes by hand for Justin, application of the following sequence is expected for automatic skeleton building:

(a)

(b)
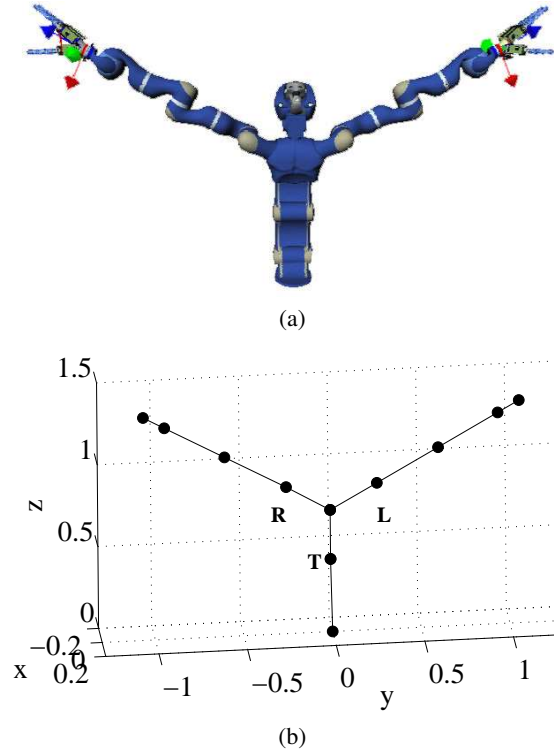
Fig. 3.10. For the DLR Justin (a), a skeleton can be found (b) by considering the axes of the arms and the spine of the torso. Segments are drawn between the Cartesian positions of some crucial joints

- compute the Cartesian position of each joint;
- compute the Cartesian position of each mechanical end of the robot;
- select nodes discarding coincident points;
- build segment between adjacent nodes.

Built the skeleton, the focus is then on distance evaluation on the robot for self-collision avoidance, which is the base for motion in an unstructured domain, with computation of distance from geometric figures.

With an analytical technique, it is always possible to find the two closest points for each pair of segments of the structure. This information can be used in order to avoid a collision between these two points, e.g., by pushing the closest points whenever their distance becomes lower than a threshold.

If hysotropic repelling functions are used for every control point, spheres centered at these *collision points* can be considered as protective volumes, where repulsion has to start. Since the closest point can vary between the two ends of the segment, on the assumption of a fixed radius, the resulting protective volume will be a cylinder with two half spheres at both ends (see Fig. 3.11(a)). Of course, this

a special case: in general, by varying the radiuses of the spheres centered in arbitrary points of the skeleton, any solid of revolution can be obtained from a segment, provided that there is a law to specify the intensity or the starting distance of forces which mimic the effect of collisions, or the presence of virtual elastic elements on the surface of such a solid.

With reference to the structure in Fig. 3.10, the volumes constructed around the torso point T and the points L and R for the left and the right arm, respectively, encompass the two segments from T to L and T to R which thus can be discarded, leading to consideration of a total of eight segments, i.e. two for the torso and three for each arm.

Again, in the design of the skeleton, some heuristics can help in discarding useless computation; nevertheless, the general case of computing all possible distances between simple objects like segments, regions of a plane (circles, rectangles) or points has the only limit of the time complexity for modelling the interaction environment.

(a)   (b)
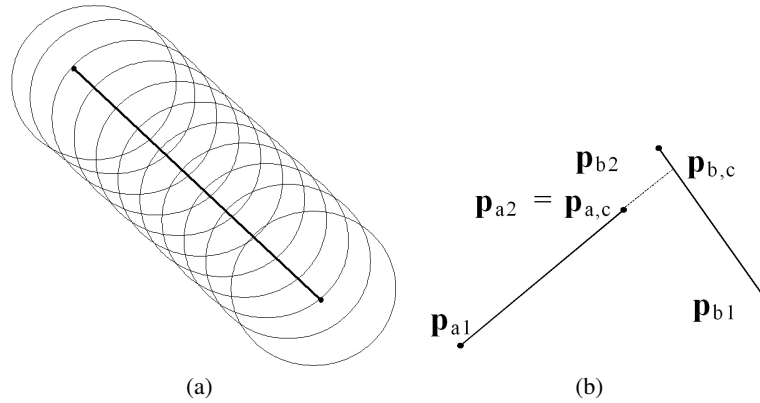
Fig. 3.11. Segments are protected by spheres centered in the collision points (a); a simple case of distance evaluation on a plane is reported (b)

3.3.3 Finding the possible collision points

A modelling of the scene for pHRI should take into account the necessity for computing distances between possible colliding bodies. This implies that simple models like the skeleton can be used for speeding up the analysis of the scene for navigation and interaction. With reference to an explanation of the skeleton algorithm, the considered world model is composed by segments, e.g., for self-collision avoidance of the manipulator.

As anticipated above, the collision points move along the segments of the skeleton designed on the spine of the robot links. Hence, the direct kinematics computation can be carried out in a parametric way for a generic point on each segment

by simply replacing the link length in the homogeneous transformation relating two subsequent frames with the distance of the collision point from the origin of the previous frame.

For each segment in which the structure is decomposed, the distance to all the other segments is calculated with a simple formula. Let $\boldsymbol{p}_a$ and $\boldsymbol{p}_b$ denote the positions of the generic points along the two segments, whose extremal points are $\boldsymbol{p}_{a1}$, $\boldsymbol{p}_{a2}$ and $\boldsymbol{p}_{b1}$, $\boldsymbol{p}_{b2}$, respectively. One has:

$$\boldsymbol{p}_a = \boldsymbol{p}_{a1} + t_a \boldsymbol{u}_a \tag{3.14}$$

$$\boldsymbol{p}_b = \boldsymbol{p}_{b1} + t_b \boldsymbol{u}_b \tag{3.15}$$

where the unit vectors $\boldsymbol{u}_a$ and $\boldsymbol{u}_b$ for the two segments are evaluated as follows:

$$\boldsymbol{u}_a = \frac{1}{||\boldsymbol{p}_{a2} - \boldsymbol{p}_{a1}||}(\boldsymbol{p}_{a2} - \boldsymbol{p}_{a1}) \tag{3.16}$$

$$\boldsymbol{u}_b = \frac{1}{||\boldsymbol{p}_{b2} - \boldsymbol{p}_{b1}||}(\boldsymbol{p}_{b2} - \boldsymbol{p}_{b1}) \tag{3.17}$$

and $\{t_a, t_b\}$ are scalar values, with

$$\frac{t_a}{||\boldsymbol{p}_{a2} - \boldsymbol{p}_{a1}||} \in \{0, 1\} \qquad \frac{t_b}{||\boldsymbol{p}_{b2} - \boldsymbol{p}_{b1}||} \in \{0, 1\}.$$

The collision points $\boldsymbol{p}_{a,c}$ and $\boldsymbol{p}_{b,c}$ are found by computing the minimum distance between the two segments (see, e.g., Fig. 3.11(b)). If the common normal between the lines of the two segments intersects either of them, then the values $t_{a,c}$ and $t_{b,c}$ for the parameters t_a and t_b can be computed as follows:

$$t_{a,c} = \frac{(\boldsymbol{p}_{b1} - \boldsymbol{p}_{a1})^T (\boldsymbol{u}_a - k\boldsymbol{u}_b)}{(1 - k^2)} \tag{3.18}$$

$$t_{b,c} = \frac{t_{a,c} - \boldsymbol{u}_a^T (\boldsymbol{p}_{b1} - \boldsymbol{p}_{a1})}{k} \tag{3.19}$$

with

$$k = \boldsymbol{u}_a^T \boldsymbol{u}_b. \tag{3.20}$$

It is understood that in the case the common normal does not intersect either of the two segments, i.e. $t_a/(||\boldsymbol{p}_{a2} - \boldsymbol{p}_{a1}||)$ and $t_b/(||\boldsymbol{p}_{b2} - \boldsymbol{p}_{b1}||)$ are both outside the interval $\{0,1\}$, then the distance between the closest extremal points becomes the minimum distance. Simple modifications have to be adopted for taking into account parallel or orthogonal segments, and a continuous motion of the control point in such situations has to be enforced via proper techniques (see, e.g., the suitability of techniques proposed in Section 3.4.3).

This analytical approach leads to computing in real-time the collision points $\boldsymbol{p}_{a,c}$ and $\boldsymbol{p}_{b,c}$ for each pair of segments, and the related distance

$$d_{\min} = ||\boldsymbol{p}_{a,c} - \boldsymbol{p}_{b,c}||. \tag{3.21}$$

Obviously, the technique is suitable for point-to-segment distance, with minor modifications.

For later computation of the avoidance torques, it is necessary to compute the Jacobians associated with the collision points, i.e. the matrices $\boldsymbol{J}_{a,c}$ and $\boldsymbol{J}_{b,c}$ describing the differential mapping of $\dot{\boldsymbol{p}}_{a,c}$ and $\dot{\boldsymbol{p}}_{b,c}$ with the joint velocities $\dot{\boldsymbol{q}}$ of the whole structure, i.e. in compact form

$$\begin{bmatrix} \dot{\boldsymbol{p}}_{a,c} \\ \dot{\boldsymbol{p}}_{b,c} \end{bmatrix} = \begin{bmatrix} \boldsymbol{J}_{a,c} \\ \boldsymbol{J}_{b,c} \end{bmatrix} \dot{\boldsymbol{q}}. \tag{3.22}$$

It is worth noticing that the positions of $\boldsymbol{p}_{c,a}$ and $\boldsymbol{p}_{c,b}$ vary along the segments as the manipulator is moving. Hence, the associated Jacobians depend on the positions of the two pairs of segment ends, i.e. $\boldsymbol{p}_{a1}, \boldsymbol{p}_{a2}, \boldsymbol{p}_{b1}, \boldsymbol{p}_{b2}$, through (3.19). Thus, Eq. (3.22) can be rewritten as

$$\begin{bmatrix} \dot{\boldsymbol{p}}_{a,c} \\ \dot{\boldsymbol{p}}_{b,c} \end{bmatrix} = \boldsymbol{J}_t \begin{bmatrix} \dot{\boldsymbol{p}}_{a1} \\ \dot{\boldsymbol{p}}_{a2} \\ \dot{\boldsymbol{p}}_{b1} \\ \dot{\boldsymbol{p}}_{b2} \end{bmatrix} = \boldsymbol{J}_t \begin{bmatrix} \boldsymbol{J}_{a1} \\ \boldsymbol{J}_{a2} \\ \boldsymbol{J}_{b1} \\ \boldsymbol{J}_{b2} \end{bmatrix} \dot{\boldsymbol{q}} \tag{3.23}$$

where $\boldsymbol{J}_{a1}, \boldsymbol{J}_{a2}, \boldsymbol{J}_{b1}, \boldsymbol{J}_{b2}$ obviously relate the joint velocities to the velocities of the two pairs of segment ends, and

$$\boldsymbol{J}_t = \begin{bmatrix} \dfrac{\partial \boldsymbol{p}_{a,c}}{\partial \boldsymbol{p}_{a1}} & \dfrac{\partial \boldsymbol{p}_{a,c}}{\partial \boldsymbol{p}_{a2}} & \dfrac{\partial \boldsymbol{p}_{a,c}}{\partial \boldsymbol{p}_{b1}} & \dfrac{\partial \boldsymbol{p}_{a,c}}{\partial \boldsymbol{p}_{b2}} \\[3mm] \dfrac{\partial \boldsymbol{p}_{b,c}}{\partial \boldsymbol{p}_{a1}} & \dfrac{\partial \boldsymbol{p}_{b,c}}{\partial \boldsymbol{p}_{a2}} & \dfrac{\partial \boldsymbol{p}_{b,c}}{\partial \boldsymbol{p}_{b1}} & \dfrac{\partial \boldsymbol{p}_{b,c}}{\partial \boldsymbol{p}_{b2}} \end{bmatrix} \tag{3.24}$$

whose terms can be computed by suitable differentiations of (3.15) through (3.19).

These equations are based on the known mutual influence of the segments, based on the presented distance model. In general, this can be extended to a more complete modelling, based on the idea that the environment can be described by simple geometry, based on the use of points, segments and planar delimited regions.

3.3.4 Generating repulsion trajectories

The third point of the approach is related to generate proper reference motion for the control points. A more comprehensive discussion on trajectories will be presented in Chapter 4. However, in general, potential fields or different optimisation techniques can be used in order to generate the forces which will produce the self-collision avoidance motions.

The two opposite forces acting on the two possibly colliding closest points $\boldsymbol{p}_{a,c}$ and $\boldsymbol{p}_{b,c}$ can be chosen as follows:

$$\boldsymbol{f}_{a,c} = \frac{h(d_{\min}, d_0, d_{\text{start}})}{d_{\min}} (\boldsymbol{p}_{a,c} - \boldsymbol{p}_{b,c}) \tag{3.25}$$

$$\boldsymbol{f}_{b,c} = \frac{h(d_{\min}, d_0, d_{\text{start}})}{d_{\min}} (\boldsymbol{p}_{b,c} - \boldsymbol{p}_{a,c}) = -\boldsymbol{f}_{a,c} \tag{3.26}$$

where h is a nonlinear function of the arguments; $d_{\min}$ is the minimum distance computed as in (3.21), d_{start} is the starting distance where the force has to act: points farther than d_{start} are not subject to any repulsion. Moreover, d_0 is the limit distance around the skeleton where a collision may occur: in the case of cylindrical links, d_0 can be fixed as the radius of the section of the link. Notice that $h > 0$ gives the amplitude of the force along the direction between the two collision points.

Further, in order to properly smoothen the manipulator motion upon the action of the repulsion forces, it is appropriate to add damping terms as follows:

$$\boldsymbol{f}_{a,c} = \frac{h(d_{\min}, d_0, d_{\text{start}})}{d_{\min}}(\boldsymbol{p}_{a,c} - \boldsymbol{p}_{b,c}) - \boldsymbol{D}_a \dot{\boldsymbol{p}}_{a,c} \qquad (3.27)$$

$$\boldsymbol{f}_{b,c} = \frac{h(d_{\min}, d_0, d_{\text{start}})}{d_{\min}}(\boldsymbol{p}_{b,c} - \boldsymbol{p}_{a,c}) - \boldsymbol{D}_b \dot{\boldsymbol{p}}_{b,c} \qquad (3.28)$$

where $\boldsymbol{D}_a$ and $\boldsymbol{D}_b$ are suitable positive definite matrices. Notice that, if damping is the same for the two segments, the forces have the same intensity in two opposite directions.

It is worth pointing out, indeed, that multiple collision points on the same segment have to be considered, whenever more segments are close to a possible collision. Nevertheless, since the computation is very fast, considering all segments without using any heuristics for reducing the number of involved parts is not mandatory, and it depends only on limits on the computation time.

In next chapter it will be shown that repulsion forces can be derived from a potential function. These forces can be naturally used to compute avoidance torques at the manipulator joints via the Jacobian transpose. Nevertheless, it should be pointed out that suitable repulsion velocities could be likewise generated in lieu of repulsion forces (see Section 3.4). In such a case, these velocities could be used to compute avoidance joint velocities via a pseudo-inverse of the Jacobian.

This alternative solution has not been considered since Justin is endowed with a torque controller which naturally allows summing the avoidance torques to those needed to execute a given task.

However, the interesting implementation in velocity control will be presented, since the differential kinematics equation has an important modification, due to the fact that not only the joint angles, but also other kinematics parameter on the D–H table change during the task.

3.3.5 Computing avoidance joint commands

As introduced, desired trajectories can be transformed in joint velocities or torques, also according to some rule for considering multiple tasks. In view of the kineto-statics duality for robotic systems with holonomic constraints, it is straightforward to compute the *avoidance torques* corresponding to the repulsion forces via the transpose of the Jacobian matrices defined in (3.22), leading to

$$\boldsymbol{\tau}_c = \begin{bmatrix} \boldsymbol{J}_{a,c}^T & \boldsymbol{J}_{b,c}^T \end{bmatrix} \begin{bmatrix} \boldsymbol{f}_{a,c} \\ \boldsymbol{f}_{b,c} \end{bmatrix}. \qquad (3.29)$$

The use of the transpose of the Jacobian matrix for the evaluation of the avoidance torques does not allow a weighing of the joint involvement for the generation of the avoidance motions. A posture behaviour, e.g., can be enforced only via proper null-space projection [32].

Null-space techniques can be used to enforce master-slave behaviours for the two arms of the humanoid manipulator, e.g., the "master" arm can have the goal reaching as primary task, and the collision avoidance is in its null-space, while the "slave" arm must guarantee the collision avoidance (main task), while trying to follow a prescribed trajectory (the slave is not trajectory task-preserving, meaning that its main task is safety). This approach is suitable for pHRI: both arms are "slave" with respect to the position of the arm of a human operator.

3.4 Torque-based and velocity-based control

In general, the approach can be used not only for reactive motion, but also for goal-directed trajectory planning, as indicated by an higher level planner. In every case, the quasi-static approach discussed before must be implemented including the full dynamics of the system.

It is worth pointing out that the control of points on the same robots can benefit of an important tool: the symbolic computation of the forward kinematics equation, and the corresponding differential kinematics equation. If this approach is adopted, the position and the Jacobian of every point can be computed by feeding to these symbolic objects the values of the D–H parameters for the specified point, and setting to 0 the other parameters after that point in the kinematic structure.

Summarizing, the suggested tools for velocity implementation are:

- modular Jacobian,
- moving control point,
- legible and safe desired motion.

The last point benefits of the first two tools and has of course cognitive aspects, related to the notion of "legibility". The need for a modular Jacobian comes from the number of matrix multiplication which are necessary for an arbitrary number of DOF's. The possibility of varying the control point has been considered right now via automatic distance computation. Nevertheless, effects on differential kinematics for the control point of such a motion affects velocity-based implementations.

Experiments showing good results with the presented quasi-static implementation of motion command in the presence of moving control point using the skeleton approach will be shown in Chapter 5. The avoidance torques corresponding to the repulsion forces via the transpose of the Jacobian matrices, discussed in the previous sections, are just summed to other nominal torques for the controller.

Moreover, the tools for coping with moving control points in velocity-level implementation will be provided below, and have been tested in simulation.

3.4.1 Modular Jacobian

In order to have a moving control point on the structure of a robot manipulator, a possible approach is to consider every point as the end-effector of a manipulator, whose symbolic direct kinematics function can be computed from D–H parameters with variable value. This is meant to speed up the computation time, both in torque and velocity control, since the real-time check of distances and corresponding computed trajectories have to fit in the time slot for the control law that they complement.

This symbolic approach is based on the consideration that, if we consider a manipulator and its direct kinematics equation, changing the value of its D–H parameters results in the kinematics equations of another manipulator, whose end-effector is situated before the real end-effector: that is equivalent to move the control point of the structure.

If the displacements vary continuously and sequentially, from the tip of the robot towards the base, the whole skeleton can be spanned, and an arbitrary control point can be used as a VEE. For the purpose of control, the Jacobian matrix is the cornerstone: similarly to the previous discussion, a symbolic Jacobian can be used, where the kinematic parameters in the D–H table change as introduced, allowing the motion of the control point. The crucial aspect is that derivation of the differential kinematics equation is affected by the motion of the multiple control points. This can be also taken into account in a symbolic expression.

3.4.2 Inverse kinematics with moving control points

Considering the direct and differential mappings with the standard D–H parameters, the equations reported in Section 3.2 do not take into account the possibility of varying kinematic parameters. A complete model is as follows. The direct kinematics equation can be written in the form

$$p_i = k(q_i) \tag{3.30}$$

where the vector q_i contains the D–H variables vectors $d_i, a_i, \theta_i, \alpha_i$. The differential mapping, discarding possible variations of the values in α_i, is therefore

$$\dot{p}_i = \frac{\mathrm{d}k}{\mathrm{d}t} = \frac{\partial k}{\partial \theta_i}\frac{\partial \theta_i}{\partial t} + \frac{\partial k}{\partial a_i}\frac{\partial \alpha_i}{\partial t} + \frac{\partial k}{\partial d_i}\frac{\partial d_i}{\partial t} =$$
$$= J_{\theta,i}(\theta_i, a_i, d_i)\dot{\theta}_i + J_{a,i}(\theta_i, a_i, d_i)\dot{a}_i + J_{d,i}(\theta_i, a_i, d_i)\dot{d}_i \tag{3.31}$$

Given a control point p_i, in Eq. 3.31, the matrices $J_{a,i}$ and $J_{d,i}$ are the Jacobians which express the contribution to the motion of the control point of the variations of the D–H values which characterise the control point. Moreover, θ_i expresses the vector of the joint values which contribute to the motion of the control point. Notice that $J_{\theta,i}$ is the ordinary Jacobian up to the control point, for a given set of D–H parameters.

There are proper ways [55] for reducing the number of nonnull values in the d_i and a_i vectors of D–H parameters. Often, this is intrinsically forced by the manipulator's design. As a simple case, consider a manipulator kinematics where only some values in the vector d_i change. In this situation, the way to compute the joint variables starting for a moving point on the skeleton of the robot is the following:

$$\dot{\boldsymbol{\theta}}_i = \boldsymbol{J}_{\theta,W,\mathbf{i}}^{\dagger}(\dot{\boldsymbol{p}}_i - \boldsymbol{J}_{d,i}(\boldsymbol{\theta}_i, \boldsymbol{a}_i, \boldsymbol{d}_i)\dot{\boldsymbol{d}}_i) \qquad (3.32)$$

where the subscript W is referred to possible joint involvement weighing. Based on these simple modifications, multiple-point control, which has shown to be central in interaction with robots, can be accomplished easily both in force and velocity control, with some additional notes for the second approach, which are discussed below.

The main point is that the control points, with the associated Jacobian, move on the robot, e.g, depending on automatic distance computation: therefore, this motion is taken into account in the differential kinematics.

3.4.3 Continuity of moving control points

While a control point is computed automatically based, e.g., on the distance from the closest obstacle to the skeleton of the manipulator, there is the possibility that, due to multiple obstacle and articulation of the robot, its position changes in a discontinuous fashion.

If every segment is monitored with respect to all other segments, this problem has an intrinsic solution if multiple torque commands result from contemporary multiple "pushing", considering all the combination of segments (see [64]). However, some heuristics or the need for a reduced number of control points can result in some sudden change of control point, and therefore of the corresponding D–H values.

In order to avoid this problem, the D–H values for the control point have to be forced to vary with continuity and *in the right sequence*: this corresponds to move to next control point *always lying on the skeleton*. This can achieved, e.g., via spline interpolation between the current control point and next node of the skeleton, and then from there to the new control point, via sequent Cartesian position of the joints, i.e., nodes of the skeleton. The sequence of variation of the D–H parameters is important for simulating such a motion on the spine of the links, and the use of spline interpolation is suggested for specifying values of the higher-order derivatives of D–H values. The time specifications for reaching the new control point via interpolation have to be related to the maximum acceptable delay before reaching the new desired set of D–H values.

Second-order inverse kinematics schemes [69] can be easily modified in the way introduced in Section 3.32 for taking into account the presence of the moving control point with variable kinematic parameters.

This tool is useful also for forcing the motion of the control point on the skeleton in case of distance computation between parallel segments, where the closest point computed according to Section 3.3.3 can move from an end to the other of the segment of the skeleton, in case of motion of an obstacle segment passing through a
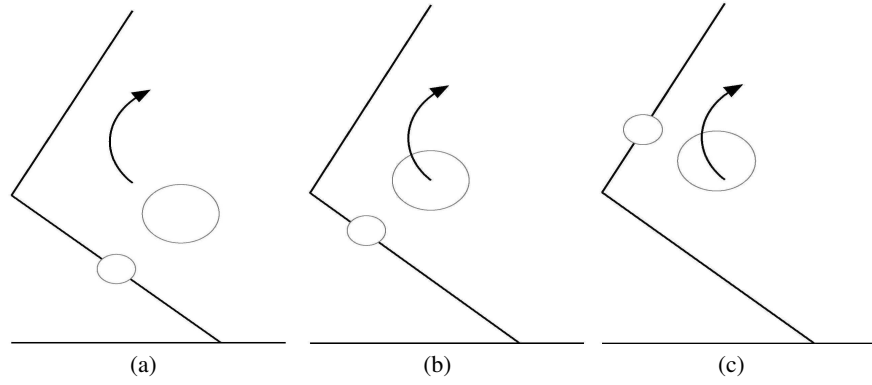
Fig. 3.12. The control point (small circle) on the skeleton, automatically computed as the closest to a moving object (big circle), can give a discontinuity to reference trajectories, moving abruptly on a new segment

configuration which results in a parallelism with respect to the segment on the manipulator's skeleton. This, as mentioned, introduces an adjustable delay to the change of control point, which has to be compatible with the current motion of the robot, i.e., it has to be compatible with the time-to-collision.

This concept, while simple, is central for the application of the skeleton approach in velocity control, where maximum velocities are provided as metrics for maximum energy in case of contact or for computing the minimum time before a complete stop of the manipulator.

Fig. 3.13. When a control point's position is expected to change, e.g. from p_1 to p_2 (a), the desired new D–H parameters are to be reached sequentially and with continuity (b)

With reference to Figure 3.12, it can be seen that a single control point which is automatically computed based on environment modelling, can move abruptly on the articulated structure. The use of different filters for the motion on the control point 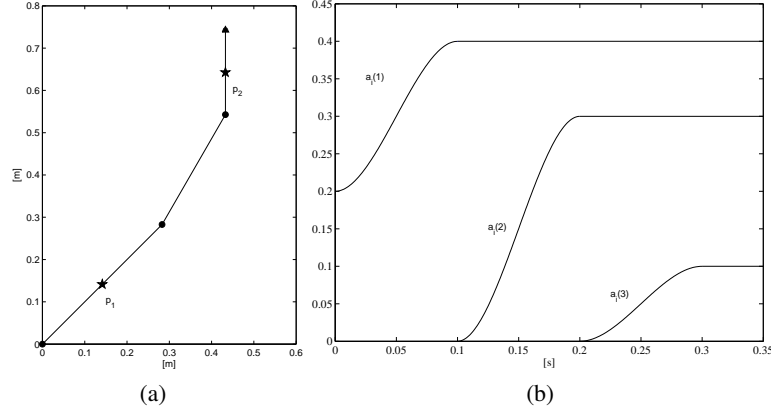depends on the control algorithm too: if the control uses higher order derivatives of the position, motion has to be smooth enough to ensure continuity of these data.

Figure 3.13 shows an example of variation of the D–H parameters which identify the control point for a three-link planar manipulator, whose lengths are 0.4 m, 0.3 m, 0.2 m. In such a manipulator, only the values in the vector $\boldsymbol{a}_i$, i.e., $a_i(1)$, $a_i(2)$, $a_i(3)$, change for a control point $\boldsymbol{p}_i$ on the skeleton. If the control points moves from the middle of the first link ($\boldsymbol{p}_1$) to the middle of the third link ($\boldsymbol{p}_2$), the resulting continuous and sequential change in the D–H parameters, obtained via cubic spline interpolation, is reported. The time for reaching the desired final value for each parameter has been set always equal to 0.1 s. This means that the new desired control point is reached in 0.3 s. In the meanwhile, the control point is moving on the skeleton and its motion is taken into account as described above.

4

Reactive motion and specifications for HRI

Reactive motion is necessary in HRI due to the difficulty of modelling the unstructured human environments; a simple and fast model is used for the crucial aspect of relative distance computation of the robot from the interaction environment. Reactive trajectories based on potential fields will be introduced, useful for collision avoidance. Moreover, rules for fulfilling tasks in anthropic environments have to benefit of evaluations which are proper of cHRI. Issues are addressed in this chapter, which are complementary to those introduced in previous sections, together with suggestions coming form cognitive evaluation on HRI tasks.

4.1 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.

Some desired paths can be unfeasible for a given manipulator, and also dynamic limits can modify the trajectory tracking. It is intended that nonholonomic constraints are managed separately, and also other aspects as workspace and joint limits deserve special attention and modifications, e.g., for wheeled mobile bases. Therefore, the planning system should take into account such limitations, including them via proper modifications of desired trajectories. Reactive motion control is meant to provide an additional tool to off-line planning, able to cope with changes in the environment through fast operations: simple modelling for inferences about the environment is therefore necessary. Following the discussion in the above chapters, motion control can benefit of the idea of modelling the whole body of the robot with simple geometry and of giving the possibility of designing an arbitrary trajectory for any given control point.

Several reactive approaches to planning are used in robotics, mostly based on artificial potential fields and their algorithmic or heuristic variations, and have been

applied both to mobile and articulated robots navigation [32]. It is natural to express the motion of the robot during interaction as a combination of task-dependent trajectories and effects of a potential field (see also Chapter 3) influencing forces pushing the manipulator or desired velocities for a control point. It has been shown that the skeleton approach leads to computation of forces for any given control points: the controller has then to properly merge the effects of forces coming from potential fields with other desired motion/force behaviours. The possibility of an energetically passive behaviour is an important aspect from the control viewpoint for improved safety of an interacting human.

Collisions constitute one of the major source of risk for safety in pHRI. While the discussed recent promising researches, which are going to be merged in the framework of the PHRIENDS project, show that a lightweight robot could be safe also in the presence of collisions [14], [47], a complete scheme for safe pHRI should also consider that the use of highly redundant multi-arm robotic manipulators (like humanoids) cannot be faced only via deliberative planning/control schemes.

Reactive collision avoidance is therefore 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.

For the purpose of fast real-time collision-free motion, reactive control is required for an arbitrary control point, which is possible to identify from D–H parameters, as seen in Section 3.4. It will be considered the case of controlling, e.g., the closest points to a collision or to a goal, letting them move continuously on the manipulator and allowing different control modalities, exploiting also a computationally effective symbolic Jacobian, and possibly also heuristics on the interaction scenario.

This gives emphasis also to the electronic hardware and software safety procedures, to monitor, supervise, and control robot operation. Moreover, by focusing on the collision avoidance trajectories, variable kinematic configurations may be used to minimise the instantaneous effect of an impact for a redundant robot, where changes in the internal kinematic configuration are aimed at minimizing the inertia seen at the end-effector [48], via null-space techniques and additional potential functions.

In general, one can summarise a list of needed tools for reactive motion in pHRI, with emphasis on collision prediction for generting avoidance motion, as follows:

- geometric models of the environment,
- proper prediction of collisions,
- vectorial fields for reactive motion.

4.2 Collision avoidance trajectories

4.2.1 Notes on collisions

Models for collisions between arbitrary bodies can be very complex, taking into account partially plastic or elastic impacts. With reference to a simple skeleton model, collision avoidance is performed by considering anticipated virtual elastic impacts occurring in the direction connecting the two closest point on each pair of segments, considering the possible combinations. This means that a force command proportional to the distance of two approaching parts is commanded to a control point on the robot before the real collision between the robot and the environment. Complex behaviours as multiple rebounds due to multiple collisions has to be considered also, and the possibility of merging additional trajectories in order to escape from local minima deserves special attention.

Rigid collisions have to be modelled with impulsive forces, while simple springs (linear o non linear) allow rendering the effect of the virtual collision as rebounds with continuity. The selected direction for repulsive motion, as introduced, is meant to push the robot away from the path which eventually results in an impact.

In brief, the repelling forces are computed on orthogonal directions and, when summed, they result in a contribution to motion in that direction. The effect of virtual springs, even nonlinear spring, have been considered with reference to continuous reference commands. Rendering of rigid contacts, which has to be faced carefully for avoiding discontinuities, as often needed in haptics, is not necessary: compliant impacts are simulated with the potential functions.

4.2.2 Multiple-point control resulting from potential fields

As introduced above, force or velocity fields are to be used instead of specified timed paths (trajectories) for facing unstructured or only partially known environments, and collisions have to be avoided between modelled parts in the environment.

As briefly mentioned in Section 3.3, it is not difficult to show that the introduced *repulsion forces* for collision avoidance on the skeleton may be derived from a potential function

$$U_c = -\int_{d_{\min}}^{\infty} h(\delta, d_0, d_{\text{start}}) d\delta \tag{4.1}$$

by differentiation with respect to $\boldsymbol{p}_{a,c}$ and $\boldsymbol{p}_{b,c}$, i.e.

$$\boldsymbol{f}_{a,c} = -\frac{\partial U}{\partial \boldsymbol{p}_{a,c}} \qquad \boldsymbol{f}_{b,c} = -\frac{\partial U}{\partial \boldsymbol{p}_{b,c}}, \tag{4.2}$$

leading to the expressions in (3.25),(3.26).

In the case of a linear function

$$h = \begin{cases} k\,(d_{\text{start}} + d_0 - d_{\min}) & \text{if } d_{\min} < d_0 + d_{\text{start}} \\ 0 & \text{elsewhere} \end{cases} \tag{4.3}$$

with $k > 0$, the repulsion potential becomes

$$U_c = \begin{cases} \frac{1}{2}k\left(d_{\text{start}} + d_0 - d_{\text{min}}\right)^2 & \text{if } d_{\text{min}} < d_0 + d_{\text{start}} \\ 0 & \text{elsewhere} \end{cases} \tag{4.4}$$

and the expressions of the repulsion forces follow simply.

In Fig. (4.1), three choices for h are proposed, where the amplitude of the force can:

- grow to infinity when the distance to a possibly colliding point approaches zero (hyperbolic function, solid line), or
- be limited to a finite value (linear function as in (4.3), dashed line), provided that this value causes an avoidance motion faster than any other planned motion for the manipulator, or else
- be piece-wise: exponential (dotted line) up to a given distance d_1, and from there linear.
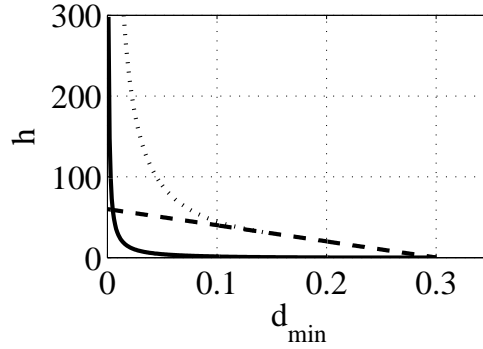
Fig. 4.1. Examples of varying amplitude for the repulsion force (for simplicity, d_0=0)

The function h can be shaped according to many considerations: maximum allowable speed, implementation of linear springs for providing towards the user a repulsive motion which is easy to understand and anticipate: this can be a definition of "legible" trajectory for a human. In general, these considerations can be related both on cHRI-based rules or on quantitative evaluations in pHRI, as discussed below.

Going on with the reference to the application to self-collision avoidance for the Justin manipulator, since in the proposed approach the repulsion forces for a generic segment have been derived from a potential as in (4.2), a torque-based collision avoidance strategy fits within the passivity-based control framework developed at DLR for the LWR–III [71, 72].

Within this framework, a joint torque feedback (using the torque signal sensed by the torque sensor after the gear-box in each joint) is used to reduce the friction

as well as the apparent inertia of the actuator. The inputs to the controller are the interaction torques $\boldsymbol{\tau}_i$ generated by, e.g., an impedance controller.

By assuming a flexible joint model for the manipulator, the entire control structure can be put into the passivity framework, allowing also a Lyapunov-based convergence analysis [71, 72]. Such controller can incorporate the collision avoidance by just adding the proper avoidance torques to the interaction torques, i.e.

$$\boldsymbol{\tau}_{i,c} = \boldsymbol{\tau}_i + \boldsymbol{\tau}_c = \begin{bmatrix} \boldsymbol{J}^T & \boldsymbol{J}_{a,c}^T & \boldsymbol{J}_{b,c}^T \end{bmatrix} \begin{bmatrix} \boldsymbol{f}_{\mathrm{TCP}} \\ \boldsymbol{f}_{a,c} \\ \boldsymbol{f}_{b,c} \end{bmatrix}. \tag{4.5}$$

These torques need to be summed to the gravity (and inertial) torques generated by the motion controller. In (4.5), $\boldsymbol{J}$ is the Jacobian related to the positions of the end-effectors arms, while $\boldsymbol{f}_{\mathrm{TCP}}$ is the force generated by the impedance controller at the tool-center point (TCP). It should be clear that both the case of a single TCP —when only one arm is in contact with a human or the environment— and the case of two TCP's can be considered with reference to (4.5).

In order to show passivity of the controller including collision avoidance, the sum of all repulsion potentials $U_{c,\mathrm{tot}} = \sum_i U_{ci}$ (for all pairs of segments involved in possible collisions) has to be added to the storage function related to the manipulator and the controller, leading to

$$V(\boldsymbol{q}, \dot{\boldsymbol{q}}) = T(\boldsymbol{q}, \dot{\boldsymbol{q}}) + U(\boldsymbol{q}) + U_{c,\mathrm{tot}}.$$

Herein $T(\boldsymbol{q}, \dot{\boldsymbol{q}})$ is the kinetic energy of the manipulator and the virtual energy of the torque controlled actuator, $U(\boldsymbol{q})$ contains the potential energy of the arm (gravity, elasticity) and of the controller and $\boldsymbol{q}$ describes the configuration of the manipulator. The function $V(\boldsymbol{q}, \dot{\boldsymbol{q}})$ can be also used as a Lyapunov function for showing stability or asymptotic stability, depending on the choice of either a task-space or a joint-space controller. The derivative of $V(\boldsymbol{q}, \dot{\boldsymbol{q}})$ along the system trajectories is namely

$$\dot{V} = -\dot{\boldsymbol{q}}^T \boldsymbol{D} \dot{\boldsymbol{q}} - \sum_i \left(\dot{\boldsymbol{p}}_{a,c}^T \boldsymbol{D}_a \dot{\boldsymbol{p}}_{a,c} + \dot{\boldsymbol{p}}_{b,c}^T \boldsymbol{D}_b \dot{\boldsymbol{p}}_{b,c} \right)_i$$

and contains all dissipative elements of the manipulator, the controller and the collision avoidance. Energetically-passive interaction is therefore achieved. Details about the control adopted for Justin are reported in [68].

4.3 Additional modelling for real-time whole-body control

4.3.1 Environment and interacting persons

A more complete model of the environment is necessary for real-time computation of corresponding joint commands, namely, a model able to generalise the skeleton for a robot manipulator, where planes, segments and points are considered in a limited

region, based on sensory information. Moreover, adjustable parameters in the potential field shaping also result in a more accurate modelling. The complexity of such world modelling is affected by the possibility of exploiting heuristics for reducing computation and checks.

For anticipating a collision and for reactive avoidance motion, in general, objects in the environment can be delimited by volumes which, in turn, can be expressed as *points*, *lines*, *planes*.

For the purpose of generating continuous reference trajectories, mutual distance computation between the geometric quantities in the world model has to be performed fast. The distance computation for couples of segments presented in Section 3.3 and point-to-segment distances have to be complemented with analytical formulas for the distance from planes. This is a straightforward generalisation which can be easily obtained considering a point on a plane. Consider the equation of a plane in the form:

$$ax + by + cz + d = 0. \tag{4.6}$$

The distances between the extremal points of a segment on the robot and such a plane are then considered on the direction orthogonal to the plane, which is actually colinear to the vector $[a, b, c]^{\mathrm{T}}$. The repelling force will act on one of the ends of the robot's segment. If the closest point on the plane is outside from the considered polygonal regions, distances from the sides of the polygon are computed.

In addition, the tools for the continuous motion on the skeleton avoiding jumps (see Section 3.4) have to be implemented also, for discarding abrupt changes of closest points in the case of parallel segments, or segments parallel to a plane.

In order to keep the repelling regions limited, the closest point on a plane can be discarded if it is not inside a user-defined polygon, which can coincide with surfaces in the workspace. Then, such a polygon becomes the limit for a repelling (or attracting) region. These simple but powerful tools for real-time distance computation result in the computation of points as summarised in Figs. 4.2, 4.3. With reference to Fig. 4.2, the closest points to a rectangular regions from the segments of a skeleton are shown. Another simple solution is to adopt circular regions. considering only the distance from the center of the computed closest point on the plane. Figure 4.3 shows how the closest points on a plane (gray dots) are found. If one of these points is not inside the circular region, i.e., its distance from the center is bigger than the radius, the intersection (black dot) between the circumference and a line connecting the point with the center (dashed black line) is considered as the closest point to the considered segment.

Similarly to the case with segments, note that a point in the considered regions can then be protected with volumes whose shape results from the parameters in the cited function h, as discussed in Section 4.3.2 .

Two additional points are then important: the resulting possible multiple rebounds coming from local specifications about reactive motion (see Section 4.3.3), and the use of heuristics both for giving different amplitudes to the forces and for discarding some computation, as discussed above.
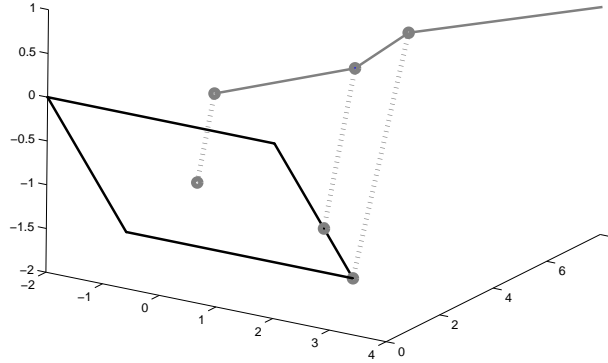
Fig. 4.2. The distances from segments (gray) to a rectangular regions (black) are computed as a straightforward extension with respect to the introduced distance formulas for segments
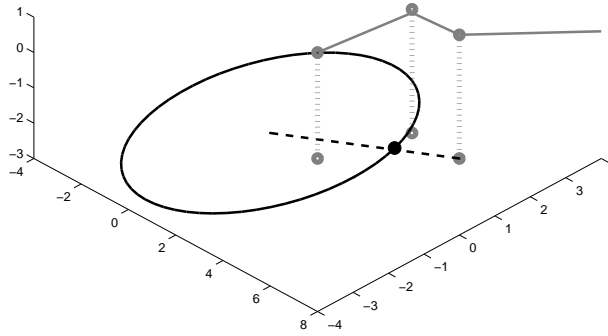
Fig. 4.3. Distances from a circular regions are computed by considering distances to a plane, and then from there to the center of the considered region

Heuristics can be used for discarding points which cannot collide due to mechanical limits of the robot. For scene monitoring, distances have to be computed in any case. However, the computation of joint commands can be skipped for segments which are not likely to collide, due to high distances and low speed.

As heuristics for reducing the number of contemporary segments which push a robot segment, one may also fictitiously increase the values in the associated damping matrices for all those points but the closest one, so as to obtain one collision point

per segment and thus one repulsion force. As seen before, more general solution is to consider all the possible combinations of segments.

The amplitude of the forces depends on design choices about the intensity of the repulsion between the arms, which affect the values of the amplitude of h and $\boldsymbol{D}_a$, $\boldsymbol{D}_b$. Inference systems can be helpful in order to dynamically modify the starting and limit distances and the shaping of the function h. In pHRI, the tuning of these parameters may depend on the part of the human body that is close to the manipulator.

Consider the model of an interacting person present in the workspace. According to the steps of the skeleton algorithm, the Cartesian position of human joints have to be identified (elbow, neck, knees, ...), in order to compute distances on segments which connect these points. For this purpose, face and hand detection algorithm have to be implemented (see Section 5.2).

After this phase, choices of h are feasible, e.g. on the basis of performance criteria like the Head Injury Criterion, where accelerations and velocities of the arms during the avoidance motions can be kept under a threshold in order to reduce the risk of injury for the body of a human user present in the workspace of the manipulator. If the focus is only on self-collision avoidance, such real-time inferences are not necessary, while collisions with the user are considered only in "after-impact" strategies.

For the purpose of world modelling, the use of exteroception is a central point. Reliability of cameras, proximity and touch sensors is relevant for assessing the positions of points used for modelling complex figures. This is the case, for instance, of the important model of an interacting person. The human head has to be protected at least, and sensory systems have to be able to detect the head and the hands, distinguishing them from the faces, for creating safe protecting regions, as seen above.

Additional heuristics can drive such evaluations: skin detection can help in finding head and hands, information about the maximum reach of used robot can also be used for skipping some computation. It is worth noticing that ordinary exteroception is much slower with respect to proprioception.

For a very precise model of the robot, the idea of using detailed meshes with polygons has the limitation of the computation time needed for all the checks: the skeleton approach has however to be refined for allowing less conservative region "wrapping". Therefore, it is worth noticing that the attracting or repelling force which originate from any point of these areas (which can be indeed goals or forbidden regions) can be shaped according to additional information on the environment, such as level of danger of specified collision, level of intrinsic safety additional tactics (robot's edges wrapping, post-collision management, and so on).

4.3.2 Limit distances and object shaping

The way for obtaining complex shapes for objects in pHRI scenarios can be based on the properties of the reactive force which attracts or repels the control points. With reference to the h function describing a repulsion force, the shape of an object to

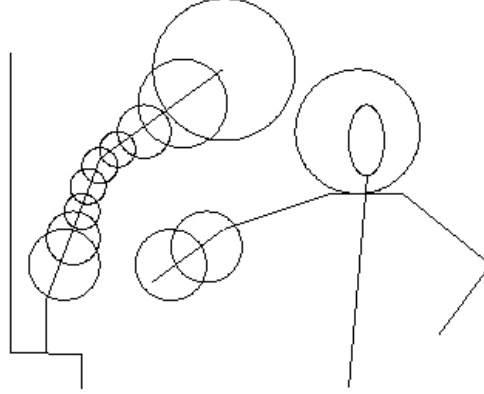be avoided can be reproduced with increasing fidelity by varying parameters of the potential function.

Fig. 4.4. Adjustable parameters like amplitude and distances of the sources of the repelling forces result in a more precise modelling for reactive motion

Summarizing, with reference to Fig. 4.4, among the available strategies for changing the protective volumes, the ones that are used in the presented HRI applications of Chapter 5 are:

- modifying the amplitude of h for creating more or less stiff virtual elastic walls,
- changing the limit distance d_0 which identifies the source of the repelling effect with respect to the spine of the considered part.

These two issues are complementary: the modification of d_0, resulting in a shift of the origin of repelling force from the skeleton, is based on the exact knowledge of the shape of the robot, and can help in obtaining a more precise wrapping of the volumes to be protected. As an example, for links with circular section, it is enough to consider such radius as d_0, i.e., to subtract its value from the computed value of the distance $d_{\min}$. The value of d_0 can be modified arbitrarily and continuously; therefore, the changing repulsion can result in an always better approximation of the contours of the objects represented with simple geometric entities, while still using analytical formulas.

Eventually, for structured domains, or when dependable sensing is available, precise shaping can be obtained also around external objects by shifting the starting distance. This tool gives the possibility of delimiting in a more detailed fashion the borders of the robot links and of environment parts, such as a wall or the floor. On the other hand, the augmentation of the amplitude of the force is meant for giving additional safety to the repelling volumes wrapping, e.g., a moving object, by accepting

a persistent presence of reactive movements due to the covering of wider areas by the effects of the potential fields.

In turn, the variation of the amplitude of the repelling function can be directly related to possible danger which can be caused by approaching objects whose shape is not perfectly known. For instance, the intensity could increase when a sharp edge is approaching the user if only centroids of user's head and body are extracted by sensors. This tool is thought to be more conservative than the previous one (isotropic spherical regions are created), and directly related to some safety danger criterion during the interaction. Again, this is related to the reliability of sensory data and to availability of meaningful safety criteria.

In principle, also the starting distance d_{start} is an available parameter for discarding some sources for object motion. Since the motion on the skeleton is continuous, also such variations give continuous reference to the controllers.

Summarizing, the manipulator is a skeleton of segments, the world is composed of segments and planar regions; the distance between segments and the distance from segments to rectangle or circles on the plane are the main indicator of an approaching collision. The precision during motion can be increased via proper shifting repulsion sources or decreasing the size of forbidden regions. The important point is the suitability for real-time operation, since the distances are computed in any case from the skeleton, using analytical formulas.

Note that forces/velocities can be related also explicitly to the variation of the parameters in Eqs. (3.25),(3.26)), giving

$$\boldsymbol{f}_{a,c} = \frac{h(d_{\min}, \dot{d}_{\min}, d_0, \dot{d}_0, d_{\text{start}}, \dot{d}_{\text{start}})}{d_{\min}}(\boldsymbol{p}_{a,c} - \boldsymbol{p}_{b,c}) \tag{4.7}$$

$$\boldsymbol{f}_{b,c} = \frac{h(d_{\min}, \dot{d}_{\min}, d_0, \dot{d}_0, d_{\text{start}}, \dot{d}_{\text{start}})}{d_{\min}}(\boldsymbol{p}_{b,c} - \boldsymbol{p}_{a,c}) = -\boldsymbol{f}_{a,c} \tag{4.8}$$

The suitability for inverse kinematics benefit of the modifications to the differential kinematics equation described in Section 3.4.

4.3.3 Attractive and repulsive trajectories

The collision avoidance paths can also be seen as general paths among attracting and repelling objects, which can constitute a base for gross motion of interacting robots, while fine motion can be accomplished after checks on possible impacts.

Deliberative/reactive motion can therefore be accomplished using models where selected regions of the environments are labelled as attracting or repelling volumes

One tool for this purpose, which is also a solution for avoiding local minima due to motion among multiple goals and obstacles, is the *moving virtual target*, which represents a fictitious target to be introduced in the workspace for letting the robot leave some postures: it could be, e.g., the hand of the user, possibly wearing a glove with markers, which allows the robot to reach some posture where local minima problems are abandoned.

This approach has been considered for experiments (see Section 5.2). The use of a virtual target corresponds to situations where manual guidance in torque control is used for moving the robot towards a desired posture.

4.3.4 Skeleton-based whole-arm grasping

The idea of grasping big objects with the arms instead that the hands, depending on dynamic limit or balancing of a manipulator, can be afforded with the introduced tools. It is based on a simple approach where grasping is performed using a virtual attractive target on the object, which corresponds to virtual springs put in proper positions on object and manipulator. The skeleton approach allow locating everywhere these control points. Of course, theory about grasping, including closure and friction properties of the grasp has to be properly considered for defining such control points.

After this stage, however, the steps of the skeleton algorithm apply, using both attractive repulsive force around the object, for approaching the grasp position and for aligning with the desired control point configuration, before removing the repulsive force and grasping the object via attraction of control points.

With reference to Fig. 4.5, a repelling area (indicated by the big circle) can be created around the object to be grasped (small circle), while the manipulator is attracted so as to preshape around the object. Finally, repulsion is removed and the grasp can be performed.
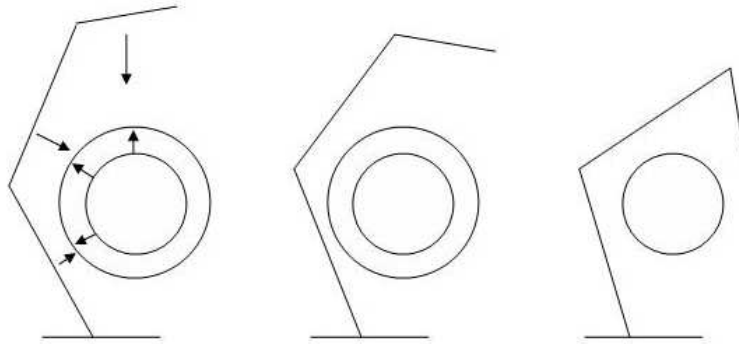

Fig. 4.5. Whole-arm grasping can be performed via multiple-point control and potential fields

It is worth noticing that also internal stress on an held object can be reduced using the repulsive forces on the control points, balancing the attraction which can result in squeezing the grasped object.

4.4 Multiple tasks and cognitive aspects in HRI

Safety tactics have different abstraction levels, from passively safe robots to intelligent procedures for safety by means of control. Cognitive evaluation is mainly related to pre-collision phases in pHRI, for managing multiple tasks, anticipating impacts, and providing legible motion behaviours.

4.4.1 Priority and mobility distribution

In the presence of redundant DOF's, the importance of automatic adjusting the priority order for multiple tasks has widely been addressed in robotics, as discussed above (see Section 3.2). In human environments, some tasks have to be fulfilled with an adjustable priority order which is related to the possible consequences of motion on a human users.

The number of available DOF's also defines whether the manipulator is functionally redundant for a given task. For a given sequence of tasks, a way for stacking them in an order which allows a "global" task fulfillment "at the best" depends on the considered optimality criterion, i.e., the definition of safety/performance trade-off for the considered HRI application.

Moreover, the main idea of reactive control is to give priority to some emerging task, possibly discarding the others or summing them with minor modification to the main trajectory. With reference to previous sections, redundancy can be solved for allowing multiple tasks, based on projection in the null-space, or not considered, by just summing concurrent motion commands.

Rules have to be chosen for trying to accommodate concurrent needs in joint motion generation. A purely reactive strategy presents the problem of local minima and no guarantees for task completion in some configurations of goals and obstacles.

An additional tool which can be used in velocity control is the weighting of joint involvement already introduced in Section 3.2. The involvement of motors in a task can vary according to specifications which freeze the motion of some joints, and increment the contribution of other joints. Dynamical limits for the joints, reduction of the inertia seen at the link and cognitive evaluation on the sense of fear of robot motion can drive this decision process. In [56], [70], fuzzy sets are used for translating linguistic concepts in weights which influence priority order, trajectory scaling, or joint involvement.

Another important aspect, from the examples with VEEs and whole-body control on a skeleton, is the choice of the control points. The solution of considering more relevant the point nearest to a collision can be exploited for automatically giving priority to that point, provided that the closest point tracking preserves continuity of commands for the control system. Moreover, such tracking has to be fast enough for allowing motion commands to be in time for avoiding collisions. This behaviour has to be complemented with evaluation of the effect of the motion of the control point (see Section 3.4).

More in general, task nesting can be related to the kinematics and dynamics of the robot: indicators of proximity to singularities, nonholonomic constraints and so

on can be used not only for scaling trajectories, but also for abandoning paths which are not feasible from a safety viewpoint.

In the presence of singular configuration of the manipulator, the inertia seen in case of an an impact can be very high, and redundancy resolution has to be used for avoiding singularities instead of accommodating different positioning task. Moreover, joint limits also can result in forces absorbed by the structure.

In such cases, the robot has to stop and ask for a global replanning from the planning system.

4.4.2 Legibility of motion and smoothness of movements

Smoothness and anticipation of the motion of a collaborative colleague increase the sense of comfort during cooperative operations. This intuition can be proposed as a desired criterion for motion trajectories of robots in the presence of humans. Sudden motion can lead the user to react as a reflex, moving in such a way to hit objects in the environment and cause that the exteroceptive sensory systems, which maps human positions for the robot controller, possibly loose the tracking of the user.

If the robot's trajectories can be *anticipated*, i.e., the user can understand where the robot is going, for a task-driven operation, comfort augments. This is one of the aspects which define a "mental" safety [73]. According to the presented models, reaction forces implemented as virtual springs can be easy to understand and anticipate (see also Chapter 5).

The listed cognitive aspects are meant to emphasise that, for human environments, the notion of safety includes also psychological effects on the user coming from the robot's motion. It is understood that fault management strategies are meant to limit consequences of faults also in terms of "strange" motions which results in high forces and in discontinuous motion and scare on the user.

An application where some kind of perceived safety is more relevant is rehabilitation robotics: Virtual Reality-based simulation has been considered in Section 5.3 for coping with the perceived safety, after experiments on collision anticipation according to the presented models.

The understandability of robot motion during HRI is necessary for addressing the property of legibility of trajectories. In the pHRI scenario, the presence of humans suggest some biomimetic solutions for operations. Human-like motion can be easy to understand, and also bimanual operation is natural for cooperation: this allows the user to better understand what is going on during the cooperation with the robot, and allows a simpler human supervision.

Humanoid shapes for robots in HRI appear therefore natural, both for allowing more natural cooperation, and for to the possibility of using tools designed for humans. Learning algorithms are then to be considered for forcing human-like postures in collaborative tasks between humans and humanoid robots. A gesture-based communication and intuitive interfaces are another important point. Moreover, the physical viewpoint addressed in PHRIENDS can be helpful for avoiding postures which are unsafe due to inertia seen at possible impact points.

4.4.3 Rules based on proxemics

Control of pHRI tasks has to focus on the user as well as on the robot: among the main points for robot control, risk assessment has to consider both objective and perceived safety, both depending on the proximity to the robot. A user can start becoming familiar with the interacting robot and trust it, and this can result in closer approach to the robot, like in human–human interaction. According to previous discussion, some repelling functions can be discarded for allowing close cooperation. However, this poses of course bigger threats, especially for users with reduced mobility, who could be slow to exit from the robot's workspace.

The framework of *proxemics* [74] is interesting: it addresses change in behaviour related to the spacing with respect to another person.

Like for potential fields encompassing the collision points in the skeleton approach, area can be found and labelled based on *intimate distance*, *personal distance*, *social distance* and *public distance*. While in human–human relations these distances depend on cultural aspects, in HRI these can be related to safety, both intrinsic and mediated by control.

It is worth noticing that the amplitude of repelling force and maximum allowed joint speed can vary in the different zones, while these limitations can be removed for skilled users: going on with the proxemics metaphor, the personal distance in Europe and in Asia is set at different numeric values. This corresponds, in HRI, to let professional users go at less than 0.5 m from the robot while it keeps higher average speeds, while the same distance corresponds to almost frozen joints for tasks aimed at contactless human–robot cooperation, e.g., for assembling. Social effects in crowded environment have to be taken into account for mobile manipulators, whose navigation has not to scare people.

A classification of the human–robot collaborative workspace is expected also in the standard definition. Right now, the defined robot control modality related to higher or lower sharing of the workspace (far, close, touching, supporting, invasive) correspond of course to different safety levels.

A central problem for pHRI is the phase where users and robots are in touch. The tools presented in previous chapter for multiple-point reactive motion during HRI are based on objective indicators of proximity for close cooperation. They can be complemented with comfort measures which have to be estimated via experiments with users.

5

Applications

This chapter is aimed at showing how the presented algorithms and HRI-centered strategies have been used for real implementations on both a standard, industrial manipulator, and an advanced service robot. With reference to interaction with intrinsically unsafe robots, it has to be pointed out that dependability of sensory data is crucial to cope with unpredictable user's motion. Moreover, there will be also a discussion on the use of Virtual Reality (VR) for facing HRI from a cognitive point of view while implementing the proposed control algorithms and considering the consequent reactive motion of the manipulator. While real experiments help in giving quantitative warrantees about the use of reactive multiple-point control with the proposed simple modelling, Virtual Reality allows the verification of possible system faults and unexpected user behaviours without the risk of real collisions and injuries, as results from preliminary experiments in an immersive environment. The "comfort" of the user, which is an important aspect from a cognitive viewpoint, provides an additional indicator for the evaluation of HRI system. This results in an additional useful criterion for interface design and choice of some control parameters.

5.1 Application to a human-friendly humanoid manipulator

5.1.1 Safety concepts and experimental setup at DLR

Experiments for evaluation of the proposed multiple-point control, considering self-collision avoidance of a humanoid manipulator as a benchmark, have been performed at the Institute of Robotics and Mechatronics of the German Aerospace Agency Research Center (DLR). Self-collision avoidance allow testing the algorithms assuming perfect sensing about the position of the possibly colliding parts.

Moreover, this set of experiments benefits of "Safe Robotics" concepts and integration developed by DLR. The choice of the DLR LWR-III (and its equivalent KUKA LWR, see Fig. 1.1), as the reference robot for pHRI, confirmed by the research activity in the framework of PHRIENDS, depends on its lightweight design,

its unitary load-to-weight ratio (with a weight of 13.5 Kg), together with the implementation of passivity-based control laws and tactics for collision detection, which allow to interact safely with the robot.

In addition, the humanoid two-arms–hands–torso system Justin, recently developed by DLR [68], inherits such tools. It is composed by a sensorised articulated head, two DLR LWR-III arms and an articulated torso with 3 active and 1 passive DOF's. Such unique platform both satisfies the safety requirements addressed for its arms and provides the advantage of two-handed manipulation, using the DLR Hand-II [75]. The total number of DOF's (active and passive) of the robotic system is 18, plus 24 for the hands and 2 for the neck.

5.1.2 Application of the skeleton algorithm for the Justin manipulator

Experiments have been performed in order to test the effectiveness of the skeleton algorithm for self-collision avoidance of the DLR Justin manipulator and, in general, for the LWR-III arm. The extension to external objects avoidance is trivial if the exteroception is assumed to be dependable.

(a)   (b)

(c)   (d)

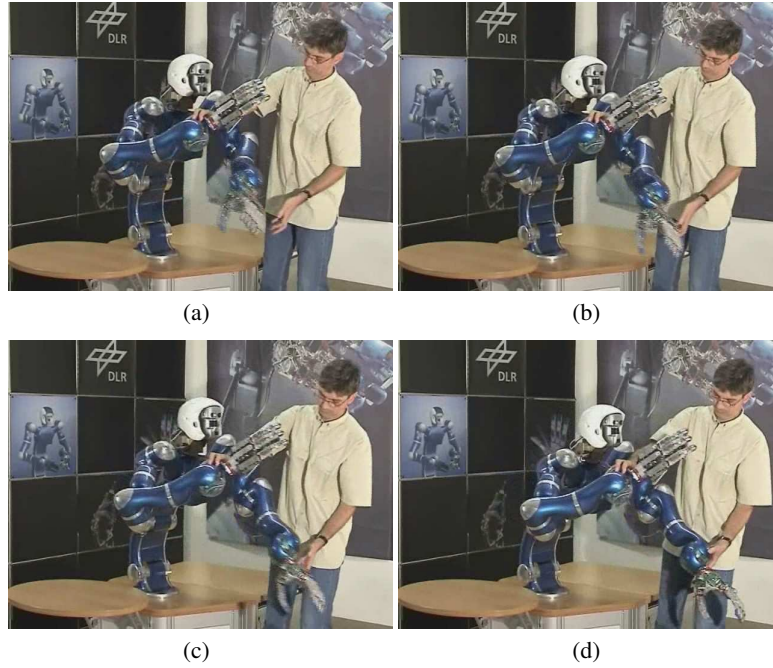**Fig. 5.1.** Reactive movements of the manipulator in order to avoid a collision between the arms (preliminary experiments, see also *http://www.prisma.unina.it/public/videos.htm*)

Current trajectories have been acquired during manual guidance of the manipulator in torque control, where gravity has been suitably compensated. The manipulator

has successfully avoided all collisions, and different potential functions have been tested. The critical distance d_{start} where the effect of the repulsion vanishes has been varied from 20 to 30 cm.

According to models in Chapters 3 and 4, damping has been considered. This allows slowing down the lightweight robot arms after repulsion forces moved them away, avoiding collisions. From the repulsion force, the corresponding torques have been computed only on the basis of distance computation in Section 3.3.
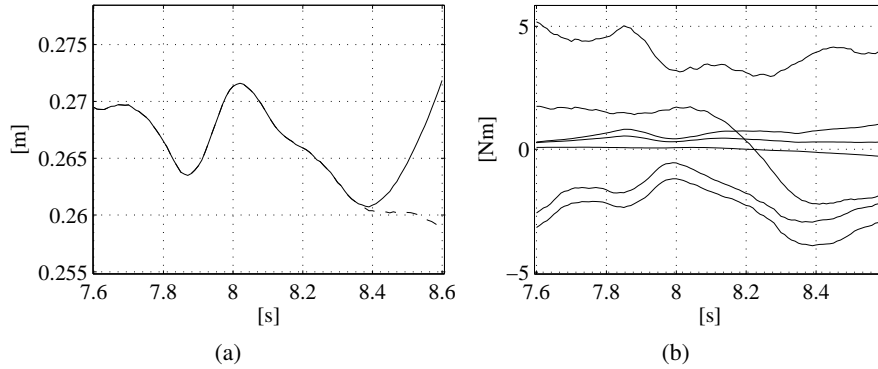

Fig. 5.2. (a) distances of the two last segments of the left arm to the other segments of the manipulator; (b) corresponding avoidance torques

In Fig. 5.1, the reaction of the manipulator in real-time for collision avoidance can be observed. The user drives the right arm towards the left arm. The system finds the closest point between the segments of the skeleton and, when the distance becomes lower than the fixed threshold, the left forearm moves away along a proper direction, with a repulsion force proportional to the distance and a proper damping in order to stop safely. Notice that the right arm is pushed by the same force, but the user is keeping the right wrist, compensating this force.

The presence of torque sensors allows the simultaneous computation of proper torques for the manipulators, to cope with the force applied by the human user and the forces generated with the skeleton algorithm. The reactive motion of the manipulator can be better appreciated in the videos which can be downloaded from *http://www.prisma.unina.it/public/videos.htm.*

From Fig. 5.2 it is possible to notice how, in another phase of the experiments, the approach of the two arms results in a distance lower than the threshold set to 30 cm, which implies the presence of two opposite repulsion forces. These forces cause the variation of the avoidance torques needed to push the closest points away. In this case, the torques, whose values are shown in Fig. 5.2(b), depend only on the effect of the elbow-wrist and wrist-hand segments, whose minimum distance from the rest of the structure are shown in Fig. 5.2(a) for the left arm.

It is possible to see how the reactive effect remains activated, since it happens that the users applies forces on the hands, keeping them closer then the distance where the force starts to act, namely, d_{start}.

A good point to notice is the symmetry of the structure, leading to cancellation of equivalent movements in different directions caused by the double repulsion of the pairs of collision points which are considered by the control system. For instance, if the two hands are going to collide, the involvement of the joints of the torso is significantly reduced with respect to the arms' joints.

Different repulsion functions and different values in the damping matrices have been adopted, leading to faster or slower reaction of the manipulator when approaching the starting distance for the repulsion effects, but the results are not reported here for brevity. The shape of such a function is important for studying the initial distance and velocity which are to be adopted for different avoidance tasks, from self-avoidance to object avoidance, up to human body avoidance.

As introduced in Chapter 3, an alternative to the presented technique, the skeleton algorithm could be applied also for a velocity control based implementation, i.e. by generating repulsion velocities for the collision points, and thus computing the joint velocities via proper inverse kinematics [34].

Notice again that tracking of interacting people, e.g., via markers in elbow and wrist [62] can be used for building a robust skeleton-based model for human avoidance. Nevertheless, as already introduced, additional tools based on [45] are available for detecting collisions with users.

Multiple interaction is shown in the snapshots from experimental activity in Fig. 5.3. Multiple touches and multiple repulsion result in a comfortable interaction without robot self-collision. Exteroception is not present in the interaction shown in Fig. 5.3: torque control is in charge of accomodating forces applied on the arms.

The world model can be arbitrarely complicated, according to suggestions in Chapter 4. Computation time has to preserve real-time constraints: for the presented experiments at DLR with torque control, the complete monitoring of the scene, with Jacobian computation, torque command calculation, and sum to nominal torque fit in the controller sampling time (1 ms), providing real-time operations.

In detail, the implemented blocks, with a modular approach, are:

- direct kinematics for skeleton building,
- distance and force computation in the collision prediction phase,
- modular Jacobian.

To be more general, the Jacobian is not specialised for different regions of the structure: as an improvement from the computational viewpoint, the Jacobian for segments closer to the skeleton could already contain, in the symbolic form, the simplifications due to the null value of the D–H parameters beyond the control point.

The starting distance for the repulsion force in the experiments in Fig. 5.3 is set to 0.25 m: again, protecting volumes which follow the shape of the arms can be obtained by varying the limit distance d_0.

As a final example of applications with the DLR Justin humanoid in the presence of external obstacles, consider experiments in Fig. 5.4, where the left arm of the
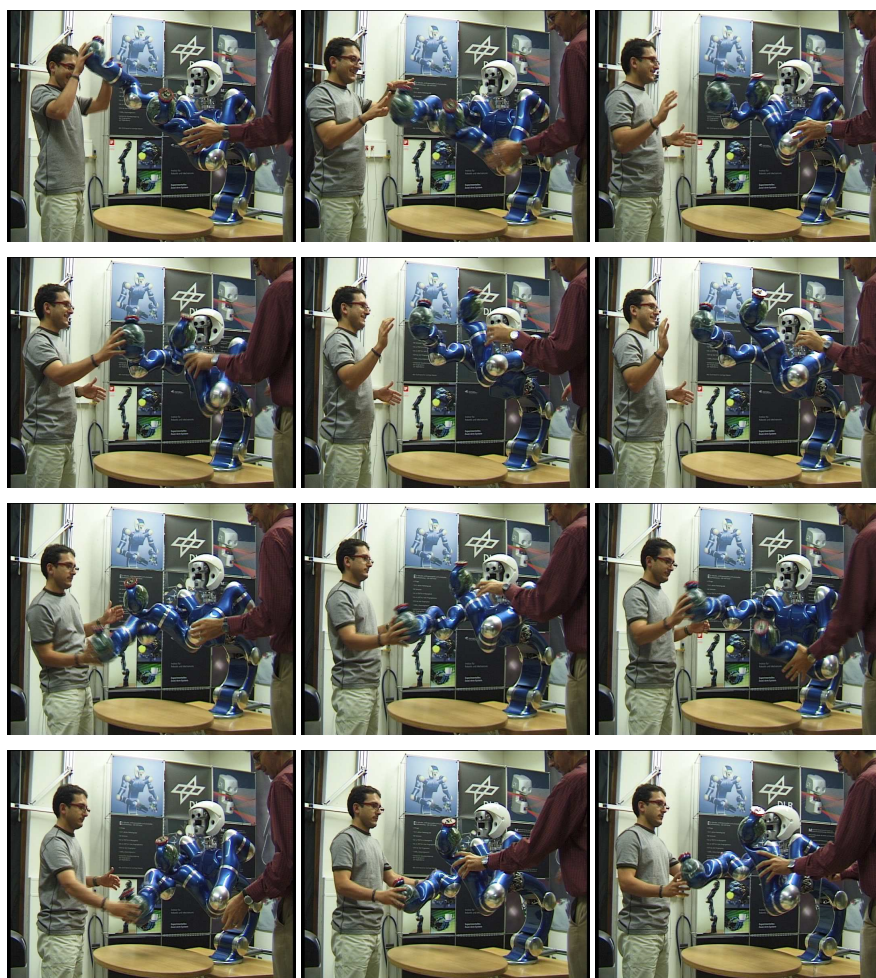
Fig. 5.3. Multiple interaction with the robot in the presence of self-collision avoidance (please refer also to *http://www.prisma.unina.it/public/videos.htm*)

humanoid manipulator approaches to the can (a), modelled as a segment. Then, the repelling force lets the arm bounce towards the chest (b), and from there again outwards (c), until the system is stopped by the interacting user (d) or due to damping. The touch by the user can actually be detected with proper techniques developed by DLR. Notice that users can leave the robot arms freely move, because they anticipate the bouncing effect and wait for the arm to come back.

It is just the case to stress again how the integration in PHRIENDS allows merging multiple tactics to cope with collisions, leading to a safer and more dependable HRI. In fact, strategies include:
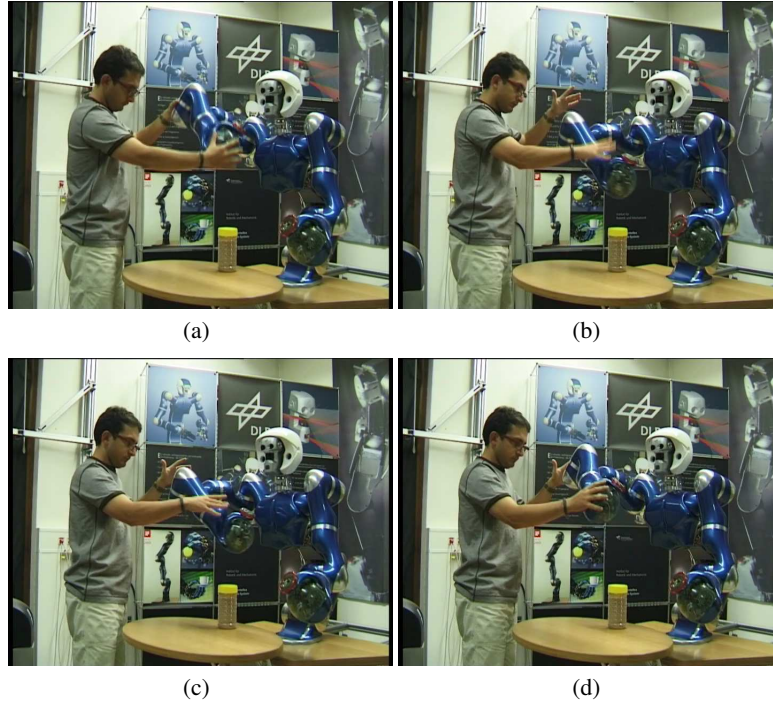
(a)   (b)

(c)   (d)

Fig. 5.4. In this sequence the can is an obstacle, modelled as a segment

- pre-impact models (addressed in this thesis),
- impact effect reduction by lightweight design,
- post-impact management, i.e., reaction to collisions.

5.2 Application to small industrial domains

The idea of a simple world model based on points, lines and planes has been tested in an industrial robotics scenario, where it can be enforced by the partially known structure of the environment. In fact, with a classical industrial layout, the skeleton can be built perfectly, knowing the position of all the equipment; moreover, in interaction with human co-workers, the robot can use exteroception to build a model of the interacting persons.

Unfortunately, the complex strategies available for previous experiments are not present in current industrial domains. Therefore, a proposed velocity-based implementation has to cope with the inherent limitations of heavy and unsafe used manipulators

According to previous sections, safety in pHRI is more than a generic attribute of the wider concept of dependability with the same importance, e.g., than maintainability. The skeleton approach does not take into account intrinsically the full

dynamics of the robot, while this can be faced via modification of the potential fields used for shaping the amplitude of the repelling force. The approach is suitable for a wide class of robot manipulators, but the risk of harm during reactive motion is more acceptable where dependability for the system is guaranteed by the human compatible safety levels at the possible collision instant, resulting from the lightweight link design, compliant transmissions, post-collision tactics. In the following, the reactive algorithm will be considered in its implementation on a heavy industrial robot. Again, it will be clear that models and controls for HRI cannot be considered without additional specifications on manipulator's design and actuation.

5.2.1 Experimental setup at PRISMA Lab

The setup in the PRISMA Lab consists of two industrial robots Comau SMART-3 S (see Fig. 3). This manipulator has a six-revolute-joint anthropomorphic geometry with nonnull shoulder and elbow offsets and non-spherical wrist. One of the two robots has an additional DOF provided by a base prismatic joint.

The robot is controlled by the C3G 9000 control unit which has a VME-based architecture with two processing boards (Servo CPU and Robot CPU) both based on a Motorola 68020/68882. Upon request, COMAU supplies the proprietary controller unit with a BIT3 bus adapter board, which allows the connection of the VME bus of the C3G 9000 unit to the ISA bus of a standard PC with MS-DOS operating system, so that the PC and C3G controller communicate via the shared memory available in the Robot CPU. In this way the PC can be used to implement control algorithms, and time synchronisation is achieved by means of a flag set by he C3G and read by the PC. A closed proprietary C library (PCC3Link produced by Tecnospazio SpA) is available to perform communication tasks.

In the new open controller available at the PRISMA Lab, named RePLiCS [76], the software running on the PC has been completely replaced by a real-time control environment based on RTAI–Linux operating system. RePLiCS allows advanced control schemes to be designed and tested, including force control and visual servoing. An advanced user interface and a simulation environment have been also developed, which permit fast, safe and reliable prototyping of planning and control algorithms. A noticeable feature of RePLiCS, which is an enhancement of the existing industrial multi-robot controllers, is that it allows not only the time synchronisation of the sequence of operations executed by each robot, but also real cooperation between the robots.

5.2.2 An application with exteroception

As presented in the central chapters, a reactive technique for collision avoidance, where repulsion forces can be shaped arbitrarily and the Jacobian matrices for computation of the corresponding joint motions/torques is a useful tool for completing a human/robot dependable interaction scheme. Nevertheless, better results depend on sensor dependability for locating the position of human beings with respect to the robot.

In order to use the skeleton algorithm, simple fixed cameras have been employed to detect the positions of face and hands of an operator in the operational space of the robot. In assembly tasks in cooperation with the robot, the operator does not move fast, simplifying the tracking by means of cameras. In preliminary experiments, markers have been used to help the detection and tracking. The detected positions of the human operator are tracked in order to keep a safety volume around him/her, repelling the robot when it approaches too much. Safety by means of control is translated in scaling trajectories and stopping the robot when the face detection fails.

The frame rate for the preliminary experiments in the PRISMA lab is quite low, and therefore errors on distance computation can be important if the robot is fast as in automatic operations. The time which is necessary to complete a task is an objective indicator of performance; therefore, a trade-off between maximum allowable speed and safety level has to be reached. An estimation of the time to a possible collision, given the current speed and acceleration of the robot, can be used for limiting the control point's speed or, possibly, to stop the robot if the distance is decreasing too fast for a possible recovery.

In the experiments in the PRISMA Lab, users interacting with the industrial manipulators used for experiments, even skilled, were however not fully confident while the robot moved towards the goal point and reconfigured itself in order to comply with the planned repulsion strategy. Due to the quality of exteroception, risk assessment is move at the sensing level. Errors in sensing cannot be tolerated like for a lightweight robot. Also the dependability of the computation of the control point (and the corresponding planned torques or velocities) may be affected by a wrong evaluation of the closest point to a collision. Sensor fusion algorithms are therefore to be considered together with a model of their accuracy.

Anticipation of robot movement by the user is a good feature for improving safety. The repelling force can be identified as a virtual spring from the user, who can anticipate the forthcoming motion of the robot, provided that she/he has an idea of the type of "bouncing" behaviours implemented on the robot (e.g., linear spring).

Figure 5.5 shows how face detection debug has been performed with printed pictures: according to standards, users are not allowed to enter in the workspace during automatic robot operation. Real face tracking in the manipulator's workspace has been then performed with reduce maximum operating velocity.

With reference to Fig. 5.6, the skeleton which contains the possible control points goes also over the spine of the links: in fact, motors are present, which can result in impacts. The inclusion of additional parts (like, e.g., tools handled by the manipulator) in the skeleton, can be related to the volume of the repelling region wrapping a control point on the skeleton (see Fig. 5.6 and Section 4.3.2).

Experiments performed for self-collision avoidance of a manipulator correspond to an ideal case where positions of the possibly colliding bodies are known almost exactly. This is the case of the presented results with the Justin manipulator. Software and communication dependability are to be guaranteed for approaching this ideal case. Experiments at PRISMA Lab show how effective the technique can be also with traditional robots. In fact, head avoidance and gola-directed movements
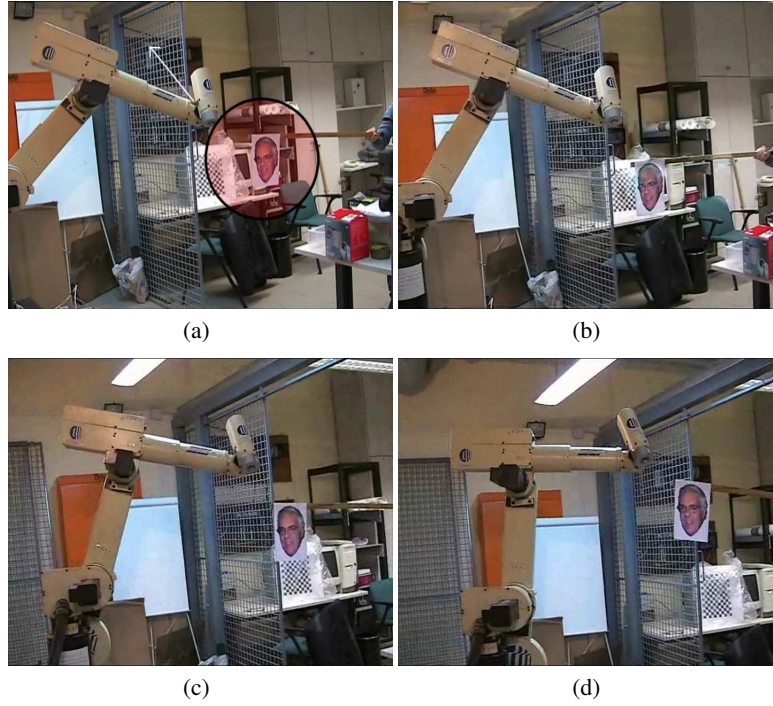
Fig. 5.5. Face detection for the creation of a safe volume (a), which results in manipulator's avoidance motion (a–d)

were fulfilled; however, a trade-off with performance is needed (e.g., slowing down the maximum repulsion motions), since the intrinsic nature of heavy industrial manipulators gives less robustness with respect to consequences of sudden motions in case of malfunctioning (which has to be related with probabilistic aspects).

These concepts can be explicitly captured via cost functions, including the injury level. However, an implementation of such indicators will be more effective after the ongoing revision of safety criteria for collaborative HRI.

Comparing the results of experiments with advanced and ordinary robots, from the dependability viewpoint, it is clear that the proposed technique is intended to offer an additional tool for safety in pHRI, but cannot be the only safety procedure. The simple software implementation for the skeleton algorithm does not pose additional software dependability problems, but can be inadequate when intrinsic safety is poor.

If a vision system (e.g., the one considered for the experiments at PRISMA Lab based on [35]) is adopted, dependable estimation of the head position must cope with issues related to: vision hardware speed and synchronisation, camera calibration, model of the face detection, maximum allowable errors and delays in the considered probabilistic framework. These issues are under investigation for a more quantitative
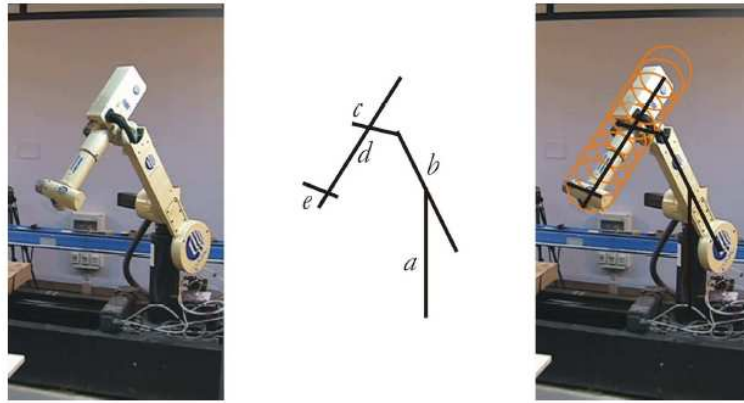
Fig. 5.6. Skeleton including dangerous appendices (e.g., point labelled with "e")

evaluation of the safety in the proposed approach. In order for a robot to be perceived as safe, cognitive aspects as the appearance can play an important role. However, a friendly appearance can result in an illusory sense of dependability.

Summarizing, also partially unstructured domains can benefit of the proposed modelling approach. The application with industrial robots shifts the attention on the dependability of many components like sensors and software procedures. The algorithm is robust, modular and with the possibility of adapting different shapes of the repelling functions (also on-line and based on cognitive evaluation).

For risk assessment, not only sensors, but also communication and the application domain strongly affect possible dangers for interacting people. Possible fault detection and dependability assessment of sensors become central before reasonable acceptance of such a reactive approach in everyday industrial and service environment.

Despite the importance of active control, it is not possible to understand all the possible movement and reaction of a user. This becomes more relevant for manipulators designed for special users, like impaired persons. A reactive approach, even robust, has to be accompanied by an architecture where also the possible post-collision phase is managed in order to reduce the exposure of a user to a crash.

5.3 Application to rehabilitation robotics in Virtual Reality

5.3.1 Rehabilitation robotics and Virtual Reality

Cognitive evaluation of HRI applications can be performed with the help of Virtual Reality (VR) tools. In addition to ergonomics evaluation and user-friendly design in the presence of dynamic events [77], VR allows subjective comfort measures related to the use of a robotic manipulator.

For human-centered applications, these evaluations complement the objective physical metrics that are investigated, e.g., in the PHRIENDS framework. Both cognitive and physical parameters can be chosen for comparing physical HRI solutions: moreover, experiments with real candidate users can help to set the perceived importance of such indicators.

The performed research activity in HRI using Virtual Reality (VR) tools is related to a possible rehabilitation robotics application.

Fig. 5.7. The immersivity is a key issue for capturing subjective evaluation about the virtual model, which can be useful for the design of a physical prototype

The considered application is a wheelchair-mounted manipulator, using a standard motorised wheelchair, available in the VR laboratory. The real wheelchair is meant to let the potential user sitting while superimposing virtual models of manipulators in the immersive VR scenario (see Fig. 5.7. In this way, operating conditions are better simulated.

Assistive robots can be divided in fixed structures and moving platforms. While the first solution often requires modifications of the infrastructures in order to provide a known environment, manipulators mounted on mobile vehicles or on wheelchairs offer higher flexibility. A good discussion of these issues has been addressed in [78]. It is worth noticing that often disabled people with upper-limb limitations also present mobility impairments which force them to use wheelchairs. Wheelchair-mounted robotic arms (WMRA) [79], [80] can be effective helpers but, on the other hand, realistic simulations of the environment and extensive experimental activities have to be conducted for testing the effectiveness of their applications in unstructured domains. Moreover, safety issues have to be addressed in depth.

5.3.2 Experiments at TEST Lab

Experiments have been carried out using the facilities in the VR–TEST (Technology, Environment, Safety and Transport) laboratory of the Competence Centre for the Qualification of Transportation Systems, set up by the Regional Authority of Campania in Caserta. VR–TEST is a semi-immersive VR laboratory, which is endowed with a powerwall (Fig. 5.7), three Digital Light Processing (DLP) projectors and shutter glasses for active stereoscopic view. The Simulation Manager software is Virtual Design 2, by vrcom. This application provides a user-friendly interface to handle all VR devices used in the laboratory. Moreover, the availability of a software development kit allows enhancing and customizing the basic functionalities of the Simulation Manager with new software modules, that are fully integrated with the underlying VR framework. In order to simulate the movement of a kinematic chain in VR, a new module has been developed [81].

The use of Virtual Reality (VR) could speed up the design of such robotics solutions, because it is possible to set systems parameters based on feedback from experimenters, involving also cognitive aspects of the interaction with the robots. Such instrument can be used for a fast comparison of interface, appearance, kinematic parameters. VR technolgy can been adopted for evaluating the perceived safety during robot motion, depending on robot's shape, speed and posture [73].

Two stages can be emphasised, namely, a concept stage in which the functional parameters of the wheelchair and the robotic arm have been defined, and an evaluation stage in which a VR architecture has been developed in order to analyze the safety issues and to evaluate the usability of the system.

These tools allow a comparison of manipulators for pHRI, based not only on the central physical viewpoint, which has been emphasised in previous discussion. A cognitive viewpoint is useful in order to understand the possible fallacy of the perceived dependability. It happens that some manipulators can be judged favorably only based on their friendly appearance. It is important to note that there are crucial ethical aspects related to the fact that users want to keep control of robotic extenders.

In the considered application in Virtual Reality, the evaluation of the comfort for the users plays a complementary role to the quantitative safety assessment, and constitutes an additional criterion for the performance of robots physically interacting with humans. For the purpose of user's centered simulation, different manipulators have been considered as candidate wheelchair-mounted robotic arm, with a velocity-level implementation, according to the approach discussed in Chapter 3. Only light-weight manipulators have been considered, with a kinematic structure similar to the KUKA LWR, which represents the reference manipulator for PHRIENDS.

A key point for wheelchair-mounted manipulators is the possibility for the robot of moving around the seat, and extending this way its workspace around the user, without passing trough the front part of the wheelchair [82]. In order to obtain a wider workspace for the robotic arm mounted on the wheelchair, a sliding rail has been considered around the powered wheelchair (see Fig. 5.8), with proper kinematic modelling of such a joint for exploiting it as an additional degree of freedom available for the control of the robot. Moreover, the rail is able to rotate around an horizontal
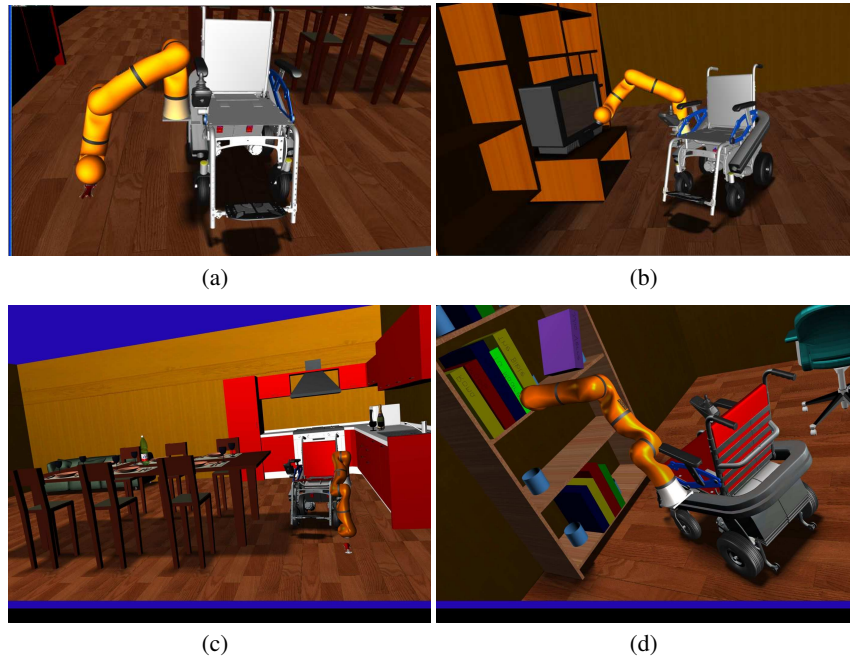
(a)   (b)

(c)   (d)

Fig. 5.8. The base rail allows the robot to extend its workspace for reaching different points in the virtual environments

axis, providing a way to change its inclination, for adapting the workspace to user's needs (e.g., better dexterity on the ground).

With reference to Fig. 5.8, note that the base joint is modelled as a prismatic joint on the left, right and rear side of the wheelchair, while the sections between these segments are modelled as rotary joints. Smooth transitions between different segments have been considered. User and environment are modelled as in Chapter 4.

For environment modelling and motion control of every point of the robotic systems, the skeleton algorithm has been adopted. The user (or an automatic module for safety procedures) can control the position not only of the end-effector, but also of an arbitrary point on the articulated structure of the manipulator, moving on the robot.

For instance, a control point can be the point of the robot which is closest to a collision (monitored with exteroception), or a point (e.g., the "elbow") that it is wished to move away from its current position. The control interface gives reference directions, which are interpreted as desired velocities, and a CLIK scheme is adopted for computing the reference joint values.

With reference to the control of the end-effector, the differential kinematics mapping may be inverted using the pseudo-inverse of the control point's Jacobian matrix. As introduced in Section 3.4, if a moving control point is considered, other parameters besides the joint value change during motion. Therefore, a Jacobian for taking into account the motion of the control point on the structure has to be considered.

Looking at the D–H kinematics parameters of the considered manipulators, only the d_i parameters may change while the control point moves. Therefore, in this case Eq. 3.32 holds.

In past experimental sessions, only the control of the end-effector position has been considered. Notice that the Jacobian matrix has to be computed for every possible control point. Therefore, a symbolic expression for the matrix has been provided, where one must substitute the kinematic parameters corresponding to the considered control point for getting the particular solution needed, while simulations have been completed for modelling the whole interaction scenario and implementing a skeleton-based collision avoidance between manipulator and the sitting user, encapsulated in a safety volume.

Some properties for the evaluation of the considered robots can be described via objective indicators such as the well-known manipulability measure [55], which gives an indication of the ability of the robot to change posture and, therefore, of its ability in manipulation from the current position (and orientation). With a dynamic model of the arms, it is also possible to compute a dynamic version of such indicator and additional safety measures [48].

However, the main point for the use of virtual reality is the evaluation of user's sense of comfort during HRI. The implementation of the presented planning/control strategies was meant to verify how safety is perceived by potential users. In the case of rehabilitation robotics, safety procedures are relevant but, at the same time, users could prefer to take control via the interface device in order not to be bypassed by a control system, even safe. It has been noticed during experiments related to the presented applications that users can underestimate the importance of intrinsic safety.

Users' feedback about the importance that they give to proposed possible evaluation criteria (like, e.g., usability, design, maximum allowed payload, or safety) can be used for modifications to manipulator design for pHRI. Notice that the autonomy of the user is a clear indicator of the perceived comfort, while automatic safety policies seem to subtract autonomy. This is an additional aspect which helps in understanding how much interdisciplinary is the field of design and control of HRI solutions, from modelling of robotic systems to evaluation of users' behaviours.

6

Conclusion and future research directions

The research themes at issue in this thesis concern with the framework of human-centered robotics. The scientific foundations for pHRI and cHRI have been studied and exploited for defining collaborative tasks, models and techniques for human-robot cooperation. The proposed modelling and control tools have been tested in real HRI applications, and they pave the way for interesting future developments.

6.1 Summary of tools for robotics in anthropic domains

This thesis has been conceived for providing planning/control tools with reference to real applications of HRI both for service and industrial domains. Contributions range, according to the metaphor in [7], from charting the territory of pHRI, up to models and experiments for robot motion in the presence of humans.

A central need is to have multiple control points, possibly arbitrarily changing and moving towards directions which can be planned in different fashions (timed trajectories, force/velocity fields). Presented contributions are listed, with brief additional notes, in the following sections.

6.1.1 Planning and control tools

For the purpose of moving a robot manipulator away from possible collisions, or driving it towards a desired goal, the need for controlling all the parts of the articulated structure has been faced via multiple point control in Chapter 3. An arbitrary control point can be selected, according to the introduced skeleton algorithm. The trajectories, resulting from timed paths or potential fields, can be scaled according to distances. Of course, other indicators such as inertia and danger from sharp edges can be considered. New insights about injury criteria are expected to identify cost-functions for such purpose.

6.1.2 Real-time operation

The need for real application of proposed tools suggests resorting to a computationally effective implementation of the model for distance evaluation and trajectory generation for pHRI. Symbolic implementations of the direct and differential kinematics functions have then been considered for speeding up the computation and allowing real-time operation with the considered tools, as shown in Chapter 5. Every control point is represented via its D–H values, as if it were the end-effector of a smaller manipulator. The importance of keeping in short time slots the environment modelling and monitoring results crucial; in fact, if the monitoring procedures are to be integrated in control frameworks, a central requirement is to keep the computation time in the limits imposed by the sampling period of the main controller.

6.1.3 Cognitive aspects

The presence of a human in the robot's workspace poses problems related to unpredictability of his/her motion and to ethical evaluation about the acceptable level of risk for HRI. The legibility of trajectories is a point which allows a more natural interaction, and user's comfort has to be estimated also via simulation tools like Virtual Reality environments.

6.2 Developments

The proposed work allows integration in:

- collision management tactics,
- higher level task/path planning,
- evaluation of objective and perceived safety.

Such integrations are expected to be simple and natural, since all the design tools have been explicitly provided (see Chapters 3, 4). The theoretical foundations have been complemented by the experiments presented in Chapter 5, showing their potential impact and their limitations.

Among the expected developments of the introduced tools, the most relevant in the next future is the integration with the safety tactics and the human-aware planner which are ongoing activities in PHRIENDS.

For the definition of planning/control parameters, both collision prevention strategies and cognitive evaluation of the environment will be used. In the presence of novel danger criteria, trajectories will be designed on the basis of the presented approaches.

Sensor dependability is expected to be characterised for taking into account uncertainty in sensing for reliable user's tracking, and more complex task management will be addressed in new experiments.

The perceived safety during robot motion, based on shape and size, will be deeply invesigated with the help of Virtual Reality, where modelling will be completed with second-order CLIK schemes, already tested in numerical simulations.

The possible application to mobile manipulators and legged humanoid is a fascinating challenge.

References

1. International Federation of Robotics – Statistical Department, 2007 World Robotics Survey, *http://www.ifrstat.org/*.
2. A. De Santis, B. Siciliano, A. De Luca, A. Bicchi, "An atlas of physical Human–Robot Interaction", *Mechanism and Machine Theory*, Elsevier, in press.
3. PHRIDOM Research Project Home Page, *http://www.piaggio.ccii.unipi.it/phridom/index.htm*.
4. PHRIENDS Research Project Home Page, *http://www.phriends.eu*.
5. European Seventh Framework Programme for Research and Technology Development (FP7), *http://cordis.europa.eu/fp7*.
6. Proceedings of the *IARP/IEEE RAS Joint Workshop on Technical Challenges for Dependable Robots in Human Environments*, G. Giralt, P. Corke (Eds.), Seoul, Korea, 2001.
7. A. Albu-Schäffer, A. Bicchi, G. Boccadamo, R. Chatila, A. De Luca, A. De Santis, G. Giralt, G. Hirzinger, V. Lippiello, R. Mattone, R. Schiavi, B. Siciliano, G. Tonietti, L. Villani, "Physical Human–Robot Interaction in Anthropic Domains: Safety and Dependability", *4th IARP/IEEE-EURON Workshop on Technical Challenges for Dependable Robots in Human Environments*, Nagoya, J, 2005.
8. G. Hirzinger, A. Albu-Schäffer, M. Hahnle, I. Schäfer, N. Sporer, "On a new generation of torque controlled light-weight robots", *2001 IEEE International Conference on Robotics and Automation*, Seoul, K, 2001.
9. ETHICBOTS Research Project Home Page, *http://ethicbots.na.infn.it*.
10. K. Severinson–Eklundh, A. Green, H. Huettenrauch, "Social and collaborative aspects of interaction with a service robot", Workshop on "Robot as Partner: An Exploration of Social Robot", *2002 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Lausanne, CH, 2002.
11. I. Calvino, "Six Memos for The Next Millennium", Harvard University Press, 1988.
12. Proceedings of the Italy–Japan 2005 Workshop "The Man and the Robot: Italian and Japanese Approaches", *http://www.robocasa.net/workshop2005/index.php?page=program*.
13. O. Khatib, K. Yokoi, O. Brock, K. Chang, A. Casal, "Robots in human environments: Basic autonomous capabilities", *International Journal of Robotics Research*, vol. 18, pp. 684–696, 1999.
14. S. Haddadin, A. Albu-Schäffer, G. Hirzinger, "Dummy crashtests for evaluation fo rigid human–robot impacts", *5th IARP/IEEE RAS/EURON Workshop on Technical Challenges for Dependable Robots in Human environments*, Rome, I, 2007.

15. A. Bicchi, G. Tonietti "Fast and 'soft-arm' tactics", *IEEE Robotics and Automation Magazine*, vol. 11(2), pp.22–33, 2004.

16. S. Haddadin, A. Albu-Schäffer, G. Hirzinger, "Safe physical human–robot interaction: Measurements, analysis & new insights ", *13th International Symposium of Robotics Research*, Hiroshima, J, 2007.

17. C.W. Gadd, "Use of weighted impulse criterion for estimating injury hazard," *10th Stapp Car Crash Conference*, New York, 1966.

18. J. Versace, "A review of the severity index", *15th Stapp Car Crash Conference*, New York, 1971.

19. K. Salisbury, "Whole arm manipulation", *4th International Symposium of Robotics Research*, Santa Cruz, CA, 1987.

20. Barrett Technology, WAM, *http://www.barretttechnology.com/robot/products/arm/armfram.htm*.

21. A. De Luca, "Feedforward/feedback laws for the control of flexible robots", *2000 IEEE International Conference on Robotics and Automation*, San Francisco, CA, 2000.

22. A. De Luca, P. Lucibello, "A general algorithm for dynamic feedback linearization of robots with elastic joints", *1998 IEEE International Conference on Robotics and Automation*, Leuven, B, 1998.

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

24. 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.

25. M. Zinn, O. Khatib, B. Roth, J.K. Salisbury, "A new actuation approach for human-friendly robot design", *8th International Symposium on Experimental Robotics*, S. Angelo d'Ischia, I, 2002.

26. G. Pratt, M. Williamson, "Series elastic actuators", *1995 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Pittsburgh, PA, 1995.

27. B. Siciliano, L. Villani, *Robot Force Control*, Kluwer Academic Publishers, Boston, MA, 1999.

28. A. Albu-Schäffer, C. Ott, G. Hirzinger, "A unified passivity based control framework for position, torque and impedance control of flexible joint robots", *12th International Symposium of Robotics Research*, San Francisco, CA, 2005.

29. M.W. Spong, "Modeling and control of elastic joint robots", *ASME Journal of Dynamic Systems, Measurement, and Control*, vol. 109, pp. 310–319, 1987.

30. S.R. Lindemann, S. M. LaValle, "Current issues in sampling-based motion planning", *11th International Symposium of Robotics Research*, Siena, I, 2003.

31. O. Khatib, "Real-time obstacle avoidance for robot manipulators and mobile robots", *International Journal of Robotics Research*, vol. 5(1), pp. 90–98, 1986.

32. O. Brock, O. Khatib, "Elastic strips: A framework for motion generation in human environments", *International Journal of Robotics Research*, vol. 21, pp. 1031–1052, 2002.

33. A. Avizienis, J.-C. Laprie, B. Randell, C. Landwehr, "Basic concepts and taxonomy of dependable and secure computing", *IEEE Transactions on Dependable and Secure Computing*, vol. 1, pp. 11–33, 2004.

34. A. De Santis, B. Siciliano, "Reactive collision avoidance for safer human–robot interaction", *5th IARP/IEEE RAS/EURON Workshop on Technical Challenges for Dependable Robots in Human Environments*, Roma, I, 2007.

35. P. Viola, M. Jones, "Robust real-time face detection", *International Journal of Computer Vision*, vol. 57, pp. 137–154, 2004.

36. F. Caccavale, L. Villani, *Fault Diagnosis and Fault Tolerance for Mechatronic Systems: Recent Advances*", Springer Tracts in Advanced Robotics, vol. 1, Heidelberg, D, 2003.
37. J. Carlson, R. R. Murphy, A. Nelson, "Follow-up analysis of mobile robot failures", *2004 IEEE International Conference on Robotics and Automation*, New Orleans, LA, 2004.
38. "Safely among us", *IEEE Robotics and Automation Magazine*, vol. 11(2), Special Issue on Dependability of Human-Friendly Robots, 2004.
39. R. Alami, R. Chatila, S. Fleury, M. Ghallab, F. Ingrand "An architecture for autonomy", *International Journal of Robotics Research*, vol. 17, pp. 315–337, 1998.
40. R.B. Gillespie, J.E. Colgate, M.A. Peshkin, "A general framework for cobot control", *IEEE Transactions on Robotics and Automation*, vol. 17, pp. 391–401, 2001.
41. H. Kazerooni, A. Chu, R. Steger, "That which does Not stabilize, Will only make us stronger", *International Journal of Robotics Research*, vol. 26, pp. 75–89, 2007.
42. 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.
43. 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.
44. 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. 230–236, 1997.
45. 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.
46. 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.
47. A. De Luca, A. Albu-Schäffer, 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.
48. I.D. Walker, "Impact configurations and measures for kinematically redundant and multiple armed robot systems", *IEEE Transactions on Robotics and Automation*, vol. 10, pp. 670–683, 1994.
49. J. Heinzmann, A. Zelinsky, "Quantitative safety guarantees for physical human–robot interaction", *International Journal of Robotics Research*, vol. 22, pp. 479–504, 2003.
50. K. Ikuta, H. Ishii, M. Nokata, "Safety evaluation method of design and control for human-care robots", *International Journal of Robotics Research*, vol. 22, pp. 281–297, 2003.
51. D. Kulic, E.A. Croft, "Real-time safety for human–robot interaction", *12th IEEE International Conference on Advanced Robotics*, Seattle, WA, 2005.
52. H. Yanco, J.L. Drury, "A taxonomy for human–robot interaction", *AAAI Fall Symposium on Human–Robot Interaction*, Falmouth, MA, 2002.
53. Y. Ota, T. Yamamoto, "Standardization activity for service robotics", *5th IARP/IEEE RAS/EURON IARP International Workshop on Technical Challenges for Dependable Robots in Human environments*, Rome, I, 2007.
54. A. De Santis, P. Pierro, B. Siciliano, "The virtual end-effectors approach for human–robot interaction", in *Advances in Robot Kinematics*, J. Lenarcic and B. Roth (Eds.), Kluwer Academic Publishers, Dordrecht, NL, pp. 133–144, 2006.
55. L. Sciavicco, B. Siciliano, *Modelling and Control of Robot Manipulators*, 2nd Ed., Springer-Verlag, London, UK, 2000.

56. A. De Santis, B. Siciliano, L. Villani, "Fuzzy trajectory planning and redundancy resolution for a fire fighting robot operating in tunnels", *2005 IEEE International Conference on Robotics and Automation*, Barcelona, E, April 2005.

57. Y. Nakamura, *Advanced Robotics: Redundancy and Optimization*, Addison-Wesley, Reading, MA, 1991.

58. B. Siciliano, J.J. E. Slotine, "A general framework for managing multiple tasks in highly redundant robotic systems, *5th International Conference on Advanced Robotics*, Pisa, I, 1991.

59. B. Siciliano, "A closed-loop inverse kinematic scheme for on-line joint-based robot control", *Robotica*, vol. 8, pp. 231–243, 1990.

60. S. Chiaverini, B. Siciliano, O. Egeland, "Redundancy resolution for the human-arm-like manipulator", *Robotics and Autonomous Systems*, vol. 8, pp. 239–250, 1991.

61. A. De Santis, V. Caggiano, B. Siciliano, L. Villani, G. Boccignone, "Anthropic inverse kinematics of robot manipulators in handwriting tasks", *12th Conference of the International Graphonomics Society*, Fisciano, Italy, 2005.

62. V. Caggiano, A. De Santis, B. Siciliano, A. Chianese, "A biomimetic approach to mobility distribution for a human-like redundant arm", *1st IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics*, Pisa, I, 2006.

63. L. Itti, C. Koch, E. Niebur, "A model of saliency based visual attention for rapid scene analysis", *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 20, pp. 1254–1259, 1998.

64. A. De Santis, A. Albu-Schäffer, C. Ott, B. Siciliano, G. Hirzinger, "The skeleton algorithm for self-collision avoidance of a humanoid manipulators", *2007 IEEE/ASME International Conference on Advanced Intelligent Mechatronics* , Zürich, CH, 2007.

65. F. Seto, K. Kosuge, R. Suda, H. Hirata, "Real-time control of self-collision avoidance for robot using RoBE", *2003 IEEE International Conference on Humanoid Robots*, Karslruhe–München, D, 2003.

66. B. Bon, H. Seraji, "On-line collision avoidance for the Ranger telerobotic flight experiment," *1996 IEEE International Conference on Robotics and Automation*, Minneapolis, MN, 1996.

67. J. Kuffner, K. Nishiwaki, S. Kagami, Y. Kuniyoshi, M. Inaba, H. Inoue, "Self-collision detection and prevention for humanoid robots", *2002 IEEE International Conference on Robotics and Automation*, Washington, DC, 2002.

68. C. Ott, O. Eiberger, W. Friedl, B. Bäuml, U. Hillenbrand, C. Borst, A. Albu-Schäffer, B. Brunner, H. Hirschmüller, S. Kiehlöfer, R. Konietschke, M. Suppa, T. Wimböck, F. Zacharias, G. Hirzinger, "A humanoid two-arm system for dexterous manipulation", *2006 IEEE International Conference on Humanoid Robots*, Genova, I, 2006.

69. F. Caccavale, S. Chiaverini, B. Siciliano, "Second-order kinematic control of robot manipulators with Jacobian damped least-square inverse: Theory and experiments", *IEEE/ASME Transactions on Mechatronics*, vol. 2, pp. 188–194, 1997.

70. G. Antonelli, S. Chiaverini, "Fuzzy redundancy resolution and motion coordination for underwater vehicle–manipulator systems", *IEEE Transactions on Fuzzy Systems*, vol. 11, pp. 109–120, 2003.

71. C. Ott, A. Albu-Schäffer, G. Hirzinger, "A passivity based Cartesian impedance controller for flexible joint robots — Part I: Torque feedback and gravity compensation", *2004 IEEE International Conference on Robotics and Automation*, New Orleans, LA, 2004.

72. A. Albu-Schäffer, C. Ott, G. Hirzinger, "A passivity based Cartesian impedance controller for flexible joint robots – Part II: Full state feedback, impedance design and exper-

iments, *2004 IEEE International Conference on Robotics and Automation*, New Orleans, LA, 2004.

73. S. Nonaka, K. Inoue, T. Arai, Y. Mae, "Evaluation of human sense of security for co-existing robots using Virtual Reality", *2004 IEEE International Conference on Robotics and Automation*, New Orleans, LA, 2004.

74. E.T. Hall, *The Hidden Dimension*, 4th Ed., Anchor Books, New York, 1990.

75. C. Borst, M. Fischer, S. Haidacher, H. Liu, G. Hirzinger, "DLR Hand II: Experiments and Experiences with an Anthropomorphic Hand", *2003 IEEE International Conference on Robotics and Automation*, Taipei, TW, 2003.

76. F. Caccavale, V. Lippiello, B. Siciliano, L. Villani, "RePLiCS: An environment for open real-time control of a dual-arm industrial robotic cell based on RTAI-Linux", *2005 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Edmonton, CND, 2005.

77. G. Burdea, P. Coiffet, "Virtual reality and robotics," in *Handbook of Industrial Robotics*, 2nd Ed., pp. 325–333, Wiley, New York, 1999.

78. A. Gimenez, C. Balaguer, A. Sabatini, V. Genovese, "The MATS system to assist disabled people in their home environments", *2003 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Las Vegas, NV, 2003.

79. H. Eftring, K. Boschian, "Technical results from Manus user trials", *1999 International Conference on Rehabilitation Robotics*, Stanford, CA, 1999.

80. M. Hillman, A. Gammie, "The Bath institute of medical engineering assistive robot", *1994 International Conference on Rehabilitation Robotics*, Wilmington, DE, 1994.

81. G. Di Gironimo, A. Marzano, A. Tarallo, "Human robot interaction in Virtual Reality", *5th EUROGRAPHICS Italian Chapter Conference*, Trento, I, 2007.

82. C. Balaguer, A. Gimenez, A. Jardon Huete, A.M. Sabatini, M. Topping, G. Bolmsjö "The MATS robot. Service climbing robot for personal assistance", *IEEE Robotics and Automation Magazine*, vol. 13(1), pp. 51–58, 2006.