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Robust and Adaptive Approaches

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Adam: To my parents, Tiki and Vince, for encouraging me to pursue a career in my childhood passion of robotics

Said: To my parents, family and teachers

Guido: To my family . . . Malgranda paŝo en la paca progreso de la homaro

Preface

The recent trend of humanoid robot development calls for an equivalent advancement of appropriate motion control schemes, as opposed to the kinematic motion control methods inherited from ‘dangerous’ industrial manipulators. This is an important prerequisite for roboticists working in the areas of human–robot interaction and social robotics, where robots are physically close to people. It has been proposed that an appropriate scheme would emulate the typical motions of a person, to permit both an increase in the confidence of an interacting human and also allowing the robot to exploit the configuration of its body. In addition, interaction of humans and robots requires physical safety (e.g. compliance), which again can be enabled by suitable controlled motion and sensing mechanisms within a humanoid robot. Such considerations encompass the industrial/manufacturing field of robotics in addition to service applications.

Driven by our interests, and the increasing need for such methods, we have written this book to share our biomechanically inspired solutions to the problem of motion and force control of humanoid robot arms. The authors are to a strong extent roboticists, with a deep-rooted spirit for advanced control. Notwithstanding, this book has been written for the general and often highly interdisciplinary robotics community. Thus, the book should be in large part accessible by post-graduate roboticists with some training in the fields of dynamics, control and mechatronics. An interest of the reader in biologically inspired engineering will be beneficial, while a basic understanding of machine learning/neural networks will be useful for the later chapters. In many ways, we have attempted to provide motivations, research reviews, and sufficient detail/explanations to suit a control engineer working in robotics or a roboticist trying to gain access to the field of control.

In this book, a biologically inspired method of robot arm control is presented and developed with the objective of dynamically synthesising human-like motion. This is an alternative to the kinematics-driven methods typically employed in various robot manipulators. We use nonlinear, robust and adaptive control techniques to permit direct application to practical humanoid robot systems (the *Elumotion* BERUL anthropomorphic arms and BERT humanoid torsos, located at the Bristol

Robotics Laboratory (BRL) in Bristol, UK). Inspiration for these schemes has been based on the wealth of biological motion literature that has indicated the drivers of motion to be dynamic, model based and optimal in nature. Thus, the literature on biological human motion and synthetic motion control builds the motivation for the main part of the book.

The operational space method of robot control has been used as a basis for this research due to a number of attractive and relevant features, such as the option for minimising a cost function to create optimal posture motion, based on biomechanically founded concepts. However, the shortcomings of the 'pure' technique are quickly encountered during practical implementations. Issues regarding robustness have been tackled using sliding mode control techniques. These have been applied to both task motion and posture control. Posture motion in particular has been enabled by a more robust and simplified method for instant minimisation of an 'effort' cost function, leading to a novel optimal sliding mode control scheme. Potential field theory has also been implemented to integrate *discomfort*-inspired 'smooth' joint limits into the effort function, while maintaining simplicity. These techniques have been tested using both simulated and practical robot systems.

A demonstration of the posture controller method's versatility has been shown when used within an active compliance control scheme for physically safe human-robot interaction, where task control is enabled via adaptive techniques. This adaptive controller also incorporates anti-windup methods to overcome actuator saturation, a feature often observed with adaptive controllers. The presented adaptive and sliding mode techniques avoid the need for accurate model parameter knowledge for a practical robot, as used in this work. Such knowledge is often unobtainable and subject to change.

Human motion capture techniques have also been employed in the presented work, for testing theories of human motion and acquiring example movement data for the testing and training of control schemes. These experiments led to the development of a novel method of learning by observation using neural networks. The final scheme therefore presents a robust and biologically inspired controller that simplifies existing work to permit ease of practical implementation with improved robot performance.

Considering the whole body of work of this monograph, the presented methods can serve as an inspiration to all readers wishing to control the motion of humanoid robots. Though our schemes focus on arm motions, they may be ported to other problems, platforms and applications and combined with other techniques. The resulting new methods may, for instance, consider control of the robot's hand or a more versatile set of sensors and actuators.

Finally, we would like to acknowledge the CHRIS project (Cooperative Human Robot Interaction Systems, FP7 215805, www.chrisfp7.eu), its project coordinator, Professor Chris Melhuish, BRL, and Professor Anthony Pipe, BRL, CHRIS project lead for work on Safety for Interaction. The humanoid robotic systems, BERT2 and BERUL2, and the doctoral studies of Dr S.G. Khan have been funded through CHRIS, while Dr Adam Spiers was sponsored for his PhD through an EPSRC

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New Haven, USA — Adam Spiers
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January, 2016

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Nomenclature

$(\cdot)^{-1}$	Matrix inverse
$(\cdot)^T$	Transpose of a matrix
α_i	Dynamically changing forgetting factor
$\bar{J}$	Inertia weighted pseudo Jacobian inverse
$\bar{J}$	Pseudo inverse of Jacobian
β_i	Adaptive learning gain
$\ddot{q}$	Joint acceleration vector
$\ddot{X}$	Task acceleration vector
$\ddot{X}_d^*$	Modified demand acceleration
δ	A positive design constant
$\dot{q}$	Joint velocity vector
$\dot{U}(q)$	Derivative of effort function
$\dot{X}$	Cartesian velocity vector
$\dot{X}_d^*$	Modified demand velocity
$\dot{X}_{y0}$	Target velocity
ℓ	Actuator amplitude limit
Γ	Vector of joints torque
γ	Forgetting factor
$\Gamma_0(s)$	Combined low frequency component of the combined task and posture torque
Γ_p	Posture torque
Γ_t	Task torque
Γ_{ext}	External torques
$\hat{.}$	Denotes estimate (model based or through adaptation)
$\hat{\Gamma}_G$	Gravity torque estimates
$\hat{\Lambda}$	Estimate of inertia matrix in Cartesian coordinates
$\hat{\phi}_n$	Parameter estimate
$\hat{B}$ and $\hat{K}$	Indirect estimate of Coriolis/centripetal forces
$\hat{p}$	Estimate of Cartesian coordinates gravity vector
$\lambda(\cdot)$	Eigenvalues of a square real matrix
$\Lambda(q)$	Cartesian form of inertia matrix

$\lambda_{max}(\cdot)$	Largest eigenvalue of a matrix
$\lambda_{min}(\cdot)$	Smallest eigenvalue of a matrix
$\mu(q, \dot{q})$	Cartesian Coriolis and Centrifugal forces vector
$\\|\cdot\\|$	Euclidean Norm of a vector
ϕ	Parameter matrix
$\varepsilon(\dot{q}, q)$	Un-modelled dynamics
ξ	Uncertainties
A	Mass / inertia matrix of the system
AW	Anti-windup
b	Vector of Coriolis and centrifugal terms
c	Coulomb friction
$c(\cdot)$	Smooth scheduling element switching function (AW compensator)
$c(q_n)$	Abbreviation $cos(q_n)$
c_i	Coefficients of a polynomial
c_{Lyap}	A positive scalar constant
C_{ref}	Damping matrix in the impedance Reference Model
DH	Denavit–Hartenberg
DOF	Degree of freedom
Dz	Dead zone function
f	Cartesian end effector forces vector
f_m	Friction forces
F_{ext}	External force on the end effector while physically interacting with its environment
g	Gravity vector
g_c	Acceleration due to gravity
I	Identity matrix
J	Jacobian (matrix)
J^{-1}	Jacobian Inverse
J^T	Jacobian transpose
J_{SVD}^{-1}	Singular value decomposition (SVD) based Jacobian inverse
K_a	Activation matrix or muscle matrix
K_d	Derivative gain
K_p	Proportional gain
K_v	Derivative gain in task space control
K_x	Proportional gain in task space control
K_{α_i}	Modified dynamically changing forgetting factors
K_f	The artificial limit, imposed on the control signal
K_{ref}	Stiffness matrix in the impedance Reference Model
K_s	Positive-definite diagonal matrix
$K_{vn}\dot{q}$	Viscous friction
L_1	Length of link 1
L_2	Length of link 2
L_3	Length of link 3
L_4	Length of link 4
M_1	Mass of link 1

M_2	Mass of link 2
M_3	Mass of link 3
M_4	Mass of link 4
M_{ref}	Mass matrix in the impedance Reference Model
$MRAC$	Model reference adaptive control
P	Muscle tension when length is constant
$p(q)$	Cartesian gravity forces vector
p_u	Minimal achievable cost
PD	Proportional derivative controller
q	Vector of joint positions
q_L	Joint limit
R	Orientation of the end effector
r_1	Radius of link 1
r_2	Radius of link 2
r_3	Radius of link 3
r_4	Radius of link 4
$Re(\cdot)$	Real part of a complex number
$s(e,\dot{e})$	Sliding surface
$s(q_n)$	Abbreviation $sin(q_n)$
$Sat(\cdot)$	Saturation function defined by the amplitude limits of the actuators
T	Transformation Matrix
T_D	Actual duration of the recorded human motion
T_s	Chosen normalization time
t_s	Time constant
u	Control input
U_p	Effort function
U_{lim}	Joint limit function
u_{sl}	Sliding mode control signal
V	Lyapunov function
v	Velocity of contraction
V_s	Lyapunov candidate for the sliding function $\tilde{s}$
W	Regressor function vector
X	Vector of task co-ordinates
X_e	Cartesian position error
X_t	A polynomial of time, t
X_x, X_y, X_z	Cartesian positions
X_y	Cartesian y coordinate, the height of the end effector
X_{y0}	Desired position of the end effector
X_{yd}	Original, unfiltered demand signal
X_{ye}	Steady state error

Chapter 1
Introduction

1.1 Prologue

Interest in humanoid robots has increased significantly in recent years. Improved core technologies have led to the construction of such systems becoming increasingly feasible for more reasonable costs. As a result, various research laboratories and other organisations have developed custom humanoid systems (e.g. Sakagami et al. 2002; Sandini et al. 2007; Elumotion 2010; Guizzo 2010; Park et al. 2006; Kaneko et al. 2008; Willow Garage 2009; Nelson et al. 2012; Dynamics 2010). Such is the progression of the core technologies (e.g. actuators, power supplies, sensors and processors) that fully programmable and reconfigurable miniature humanoid robots are commercially available within the budget of at-home hobbyists (Hitec 2010; Robotis 2010). High-profile international events such as the DARPA Robotics Challenge (DARPA 2015; Guizzo and Ackerman 2015), and competitions held at robotics conferences, provide an illustration of the complexity and diversity of cutting-edge humanoid robotics research at the present moment.

The goal of humanoid robots is multifaceted and different researchers have different objectives. On the one hand, a true humanoid robot is the perfect universal tool, being able to utilise equipment designed for its human counterparts and inherently suited to the human environments. Such an ideal system would also be able to withstand extreme conditions (e.g. heat, lack of oxygen or radiation) in which humans would perform inefficiently or perish. Such robots could therefore be ideal systems for hazardous work or exploration. Alternatively, humanoid robots may be regarded as extensions of industrial robots, performing menial tasks in the workplace or domestic environment. An inherent feature of this later concept is the potential interaction that such robots may have with humans. The human form immediately gives a machine personality and context, making it a more engaging working companion.

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Though robotics has naturally progressed from single arm manipulators of limited DOF (degrees of freedom) to more complex anthropomorphic forms, the control methods that drive such systems have not always matched this physical development (Tellez et al. 2009) with many humanoids driven by the same inverse kinematics methods as their industrial counterparts. This choice of motion scheme, though efficient and relatively simple to implement, has primarily benefitted the speed, accuracy and repeatability demands of an industrial production line. Like most industrial manufacturing technology, which is inherently dangerous and not intended for use near humans, the safety of inverse kinematics can also be questioned. If one considers that the large majority of industrial robots are contained in some sort of barricaded work cell and automatically deactivated if approached by a human, then it is clear that deploying such a control scheme within a human environment is likely to result in catastrophe. By implementing a dynamics-based motion scheme, one has much more control over the robot system, with the ability to monitor and manipulate parameters relating to forces and torques acting on the robot. Once equipped with suitable sensors, this approach also allows for methods which permit to introduce physical safety of humans in the proximity of the robot.

It has been widely agreed that human motion patterns are the result of an optimisation of some quantity (Todorov 2004). Optimality is also a major branch of control system design. It is a logical step then to consider the use of non-linear and optimal control as a method of dynamically driving a robot for efficient task achievement while also striving for naturalistic motions (the benefits of which will be discussed in Chap. 3). However, such dynamics-based methods of control are obviously more involved than traditional kinematics schemes, as a multi-joint robot system is characterised by non-linear dynamics and so requires alternative techniques for generating desired motions.

In order to develop controllers that are dissimilar to industrial robot control, it is first necessary to be aware of what constitutes such control and why it is not suitable for humanoid robots.

1.1.1 Industrial Robots

The European Standard EN775 (European Committee for Standardization 1992) and ISO 8373 (International Organization for Standards 2012) define a robot as an 'automatically controlled, reprogrammable, multi-purpose, manipulative machine with several degrees of freedom, which may be either fixed in place or mobile for use in industrial automation applications'. Clearly this definition refers to industrial robots.

Typically industrial robots are contained in work cells and have little or no autonomy. They perform the same task endlessly throughout the working day with high precision and speed, often using only minimal sensors as part of a relatively

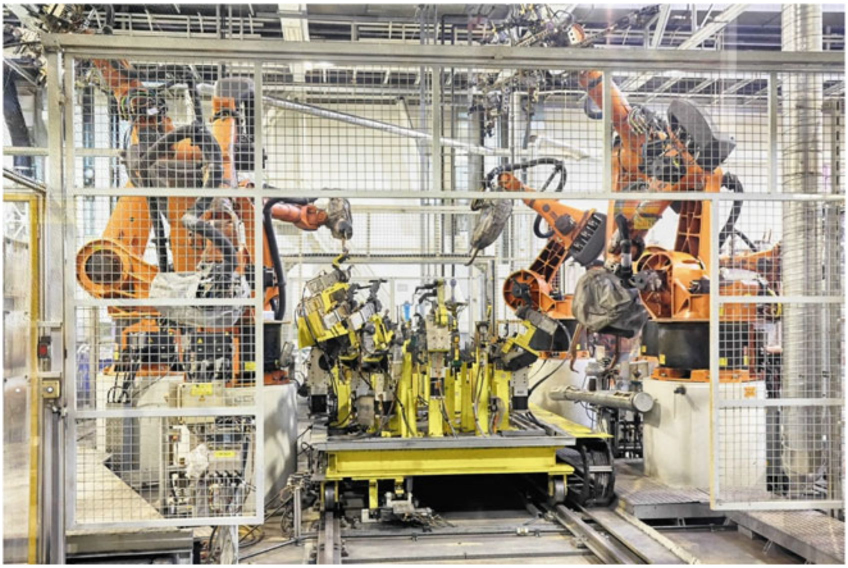

Fig. 1.1 Industrial robot work cell. The robots operate inside a safety cage that prevents interaction with human workers. The robots utilise only simple sensors to trigger a state machine of events

simple state machine. Industrial robots are considered highly dangerous due to their high speed and strength coupled with rigid joint-level control schemes. Normally, such robots are placed in safety cages or are otherwise isolated from human workers. If the cage is entered or a light curtain is broken, then the robot deactivates.

Figure 1.1 shows a typical robot work cell implementation. Here, the robots facilitate the assembly of automotive parts. It is evident that a situation where a human is in the proximity of these robots would be dangerous to the human. At most, a human could only participate in the production process outside the work cell, for instance, loading or unloading parts.

The HSE robot safety guidance document, HSG43 (Health and Safety Executive 2000), is a comprehensive 50-page document that covers such manufacturing tasks as palletising and machine unloading. The guidance on the entry of a human into a work cell (i.e. the workspace of the robot) is defined as follows:

> . . . for situations where whole-body access to the robot cell is required. . . it may be better to use a gate-locking key-exchange system. . . Again, the robot benefits from a controlled shutdown and the power is also removed before access can be gained.

A 'gate-locking key-exchange system' means that a human in the vicinity of a robot holds a device that prevents power being applied to the robot by any other operator or automatic process. Clearly, such a set of constraints cannot be applied to humanoids that are designed to exist in the human environment and actively partake in physical human–robot interaction, such as the passing of objects.

1.1.2 Humanoid Robots

Currently, most advanced humanoid robots only operate in research laboratories, competition scenarios (as discussed in Sect. 1.1) or at the public relation events of their manufacturers. Conceptually, however, humanoid robots should be able to operate in the majority of environments in which humans can function, with the addition of hazardous environments, such as radioactive areas (Nagatani et al. 2013), space (Bluethmann et al. 2003) or in the presence of dangerous chemicals (Nelson et al. 2012).

Ideally, humanoid robots will also perform useful tasks in environments alongside humans and will be capable of performing physical human–robot interaction (HRI) to a level that is comparable to functional human–human relationships (e.g. Sakagami et al. 2002). Such a scenario is illustrated in Fig. 1.2, in which the BERT2 robot of the Bristol Robotics Laboratory is physically interacting with a human in a task with mild risk, the handing over of a cup. Such task could be conducted in a hospital, where the patient is given medication or the cup is to be discarded. If one considers allowing a young child to carry out this same task, then it becomes apparent why such robot systems should inspire confidence in their human

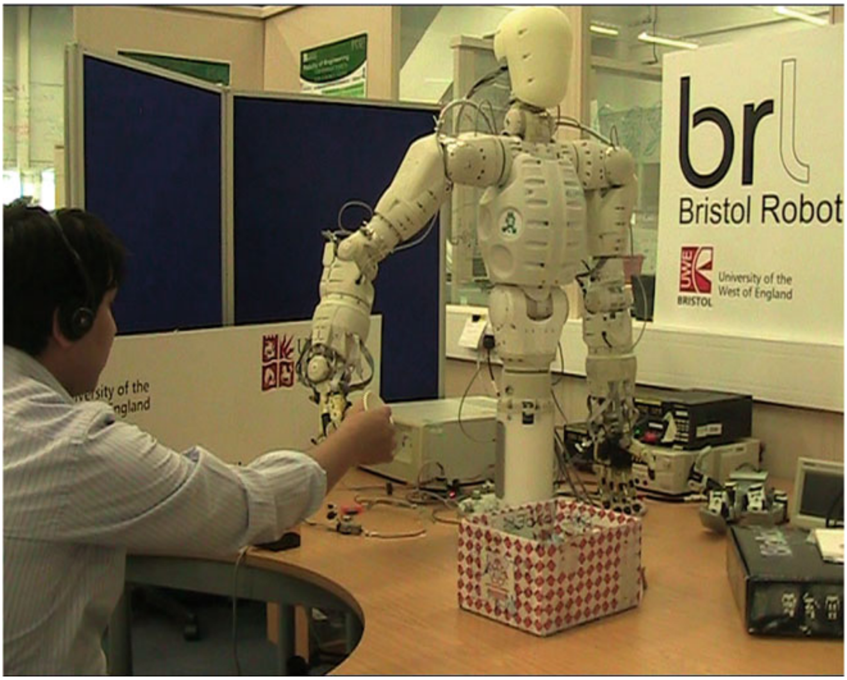

Fig. 1.2 An ideal social application of a humanoid robot, manipulating objects and physically interacting with a human. See Chap. 8, the relevant video in Appendix D and Khan et al. (2010, 2014) for further details

counterparts. The person receiving a cup is unlikely to value the service of a robot if they fear it to be dangerous or incapable of performing tasks which adult humans achieve with ease. Further discussion on potential applications of humanoid robots will be given in Sect. 2.1.

1.1.3 The Importance of Human-Like Motion

Human motion follows typical paths and constraints (Lacquaniti and Soechting 1982; De Sapio et al. 2006). This is something that we are all subtly aware of, as it is obvious when somebody is moving in an unnatural way. If we see persons walking with their arms in the air, we assume they have assumed that pose for a reason, not simply because their body has naturally gravitated towards that position.

Though the form of a humanoid robot potentially offers vast benefits of tool handling and physical interaction, a roughly humanoid appearance also facilitates natural interaction and communication with people (Matsui et al. 2005). In the same publication, which deals with a robot with a realistic appearance, the authors state that 'If human-like appearance causes us to evaluate an android's behaviour from a human standard, we are more likely to be cognizant of deviations from human norms'. This is similar to the view of Breazeal (2004), who has highlighted the potential for mismatched expectations from human-like robots, i.e. when human-like attributes automatically assigned to the robot by virtue of its human form are not fulfilled due to limited capabilities, such as moving unnaturally.

It has been suggested that humanoid robots designed around a 'pleasing mirror' will be successful in eliciting interaction by engaging the mental resources that lead to social interaction in human–human interactions (Kemp et al. 2008). In terms of appearance alone, neural centres of the human brain have been identified specifically for detection of regions of the human form (Farah et al. 2000).

In addition, if 'the perceived intelligence of a robot is a subjective phenomenon that emerges during human–robot interaction' (Minato et al. 2004), then it is probable that confidence and other attributes will also emerge based on the behaviour of a robot during such encounters. Logically then if a humanoid robot has motion that is human-like, it is more likely to succeed in engaging a human in confident, physical interaction (Bicchi et al. 2008).

In terms of expectations, it has also been stated that 'the lay view of a robot is a mechanical human, and thus robotics has always been inspired by attempts to emulate biology' (Arbib et al. 2008). Such a biologically inspired approach should not be limited only to emulation of form and appearance but also the underlying control mechanisms of a natural human. As it has been theorised that human motion is rooted in anatomy and physiology (De Sapio et al. 2005), this book hopes to base its motion controller (at least in part) on biomechanic concepts, from which human-like motion should then emerge.

Human-like motion may also lead to the development or understanding of higher level human-like abilities in robotic systems. In Hersch and Billard (2006), it was suggested that 'a robot with human-like control may be given the ability to interpret human actions in terms of its own actions and thus better "understand" them'. This has been suggested in the context of primates being able to imitate the motions of others with a similar body form. The authors also state that 'Conversely, humans are likely to better enjoy interactions with robots that seem "natural" to them'. In a similar vein, the iCub (Metta et al. 2008) has been developed around the concept of tangible manipulation being a key to human-like cognitive development (Sandini et al. 2007).

1.1.4 Biologically Inspired Design

The forms and functions of natural systems are a great stimulus for engineering design, and the imitation of a biological control scheme should, in theory, lead to a similarly efficient and effective robotic control scheme. However, the results of evolution are not often bound by the same limits as artificial systems. This means that more appropriate solutions (in terms of robustness, complexity, etc.) to many problems (e.g. flight) can often be found by biological inspiration (e.g. fixed wings), rather than direct imitation (e.g. flapping wings). In this vein, one must also recall that perhaps the most rewarding engineering achievement of mankind, the wheel, has only been identified in nature at a microscopic level (Macnab 1999), illustrating that nature is perhaps not always a flawless teacher. Considering these points, the control schemes presented here are based on biological ideas but with appropriate modifications for practical application on a robotic system.

1.1.5 Physical Safety and Active Compliance for Safety

Though we have listed the benefits of biologically similar motion during human–robot interaction, it is clear also that physical safety is of paramount importance in such interactions. One method of achieving physical safety in such interactions is via active compliance, the control of forces acting on the robot during possible collisions.

Most initial work in the area of force control or its variants (i.e. 1970s and 1980s) was aimed at solving shop floor industrial problems such as polishing/grinding surfaces or assembly operations such as inserting one part into another. Active compliance schemes and hybrid force/position control schemes were investigated for stiff and rigid industrial robots. In the 1990s and onwards, the focus shifted to intrinsic or passive compliance capabilities of robots. In the last decade or so, the interest in compliance control and passively compliant robots and structures became the centre of interest to overcome safety issues in the interaction of robots with humans. A new generation of passive actuators, such as artificial muscles and cable-driven mechanisms, are now gaining popularity. There is no doubt that passively compliant robot arms are much safer than rigid ones. However, they are generally mechanically complex and difficult to design and manufacture without other compromises. A robot arm with too much passive compliance might lose the capability to properly manipulate objects. Such robots may not be suitable for tasks where position accuracy and effort are required. Deeper discussions of a compliant control scheme in combination with the biomechanically inspired motion control component are provided in Chap. 8.

1.1.6 Robust and Adaptive Control

Any dynamic model of a robotic manipulator will be subject to model uncertainty. Minor changes to the robot due to component wear or environmental changes (such as ambient temperature) can lead to possibly unwanted variations within the robot, causing deviations in the parameters of existing models. Additionally, it is practically difficult to determine physical dynamic properties, such as the precise inertial model of a link, meaning the model of a robot is unlikely to precisely match the physical robot. These factors introduce problems of reliability in control schemes, which are designed using fixed mathematical models. A solution to this is the use of practically applied non-linear control schemes that are robust or adaptive. Thus, this book advocates the use of both. Sliding mode control is a robust control scheme which is presented here to overcome friction in joints and parameter changes within the manipulators (Chaps. 5, 6 and 7). Adaptive methods can be very powerful when used in combination with sliding mode control, which will be further discussed for application of compliance control in Chap. 8.

1.2 Objective of the Book

The objective of this book is to provide the necessary technical details, guidance and foundational knowledge to allow readers to become familiar with an ‘alternative’ branch of robot motion techniques. These techniques borrow various aspects from the study of biological motion generation, in order to better suit the requirements of humanoid robots, which are robotic systems that physically emulate the human form. The techniques are implemented via a series of non-linear, dynamics-based controllers that also consider practical application on physical robots. As such, in addition to generating human-like robot arm motion, the controllers also generate this motion in real time while simultaneously dealing with the uncertainty of physical systems. These properties make the control schemes attractive for use in real-life dynamic environments, where the predetermined motion trajectories synonymous with industrial robots are likely to fail. Furthermore, novel control methods are presented later in the book, to enable adaptive compliance control (for safe human–robot interaction) and a method for a robot to generate new motion paths, based on examples observed from human volunteers (learning by observation).

To achieve the proposed goal, we take inspiration from the drivers of human motion (which are non-linear, dynamic, optimal, etc.) and fit these into the framework of robot control. Essentially, once these features are established (via robotics and biomechanics literature, in the early stages of the book), a controller is selected and developed to meet these requirements. This development is discussed in detail and provided gradually, with most chapters building on their predecessors. Overall, a route to learning and familiarisation is defined, with all stages verified experimentally.

Beyond the development of motion controllers, the book also addresses the motivations and applications of humanoid robots and human-like motion, additionally providing a foundation in biological motion and motion capture technologies. Much further reading material is referred to throughout the book, providing an excellent reference for further investigations into these fascinating areas of research.

1.3 Guidance for the Reader

The book consists of three major parts. Part I provides background information related to humanoid robots (in Chap. 2) and human motion (in Chap. 3). Within Chap. 2, some general concepts of robotics are introduced, including the practical goals of humanoid robots and human-like motion. Additionally, an overview of typical robot motion control approaches is also provided, along with details of the specific robot hardware used as experimental platforms throughout this book. In Chap. 3, the focus turns to the biological aspects of human arm motion, as various observations and theories related to the structure and drivers of human motion are presented. This chapter also presents an overview of methods for observing human motion, as well as several common techniques for reproducing or synthesising human motion.

Equipped with the background knowledge of Part I, Part II deals with incrementally implementing practical human-like robot arm control methods. The first step towards this is achieved via the *Operational Space* control approach, pioneered by Prof. Oussama Khatib. This technique is introduced in Chap. 4, where it is applied to the control of a simplified humanoid arm, performing an overhead reaching task. The controller (a simplified version of that proposed in De Sapio et al. (2005)) provides a dynamic, model-based and optimal approach to synthesising naturalistic motion via decomposition of motion control into *task* and *posture* elements, which deal with end-effector and redundant elements of the robot, respectively. In Chap. 5, a shortcoming of the controller (poor end-effector positioning when implemented on physical robots) is addressed via a sliding mode task controller, which is able to manage model uncertainty. In Chap. 6 a novel method of implementing robot joint limits, without compromising human-like motion, is introduced. This modifies the existing cost function of the optimal posture controller to introduce regions of 'discomfort' into the robot's workspace. The posture controller is further modified in Chap. 7, via a novel sliding mode optimal controller which increases the robust performance of the posture controller.

Chapter 8, the final chapter of Part II, applies an adaptive compliance controller to task motion (i.e. motion of the end effector). The actively compliant task controller enables safe human–robot interaction, while the posture controller follows ideas developed in Chaps. 4 and 6. As is the case throughout Part II, task motion follows some given nominal linear dynamics, while posture follows a biomechanically inspired scheme.

Part III of the book deals with methods of dynamically generating task (end-effector) motion based on observations of human motion, made via an optical motion capture system. Chapter 9 provides an analysis of human reaching experiments captured from human volunteers. The objective of these experiments was to determine whether human motion is straight or curved and subject to a gravitational component. A method is also described of scaling the recorded motion from human to robot bodies. The outcomes are used in Chap. 10 in which a learning-by-observation technique is integrated into the prior operational space controller to permit new task trajectories to be generated based on previously learned example motions.

The appendices of the book, provide further background material. This comprises of a general overview of robot kinematics (Appendix A), the inverse kinematic solution of the BERUL2 robot arm in 4DOF configuration (Appendix B) and theoretical proofs of stability for the adaptive controller presented in Chap. 8 (Appendix C). A list of the online videos that support specific chapters of the book is also presented in Appendix D.

1.3.1 Recommended Reading Routes

A number of different routes for reading have been suggested in Fig. 1.3. First and foremost, it is clearly advisable to read the book from start to end (Route 1). However, some readers may have different objectives to others and/or may already possess a fair background in some of the introductory topics. Two alternative recommended routes are as follows:

- **Route 2 :** **Compliant arm motion** with reliable **human-like posture** motion
  This route will convey an understanding about the theory and use of practically validated compliant controllers in physical human–robot interaction. To achieve this, one may skip to Chap. 4 (for an understanding of operational space control), Chap. 5 (to enable implementation on physical systems via a robust addition), Chap. 6 (for joint-limit constrained biomechanically inspired posture motion) followed by Chap. 8 (for the design and testing of an adaptive compliant controller). Note that Chap. 5 may also be skipped, though the controller will then not function on a physical robot until the controller of Chap. 8 has been fully implemented.