Human and robot hands: Sensorimotor Synergies to Bridge the Gap between Neuroscience and Robotics

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The human hand is our preeminent and most versatile tool to explore and modify the external environment. It represents both the cognitive organ of the sense of Touch and the most important end effector in object manipulation and grasping. Our brain can cope efficiently with high degree of complexity of the hand, which arises from the huge amount of actuators and sensors. This allow us to perform a large number of daily life tasks, from the simple ones, such as determining the ripeness of a fruit or drive a car, to the more complex ones, as for example performing surgical procedures, playing an instrument or painting. Not surprisingly, an intensive research effort has been devoted to (i) understand the neuroanatomical and physiological mechanisms underpinning the sensorimotor control of human hands and (ii) to attempt to reproduce such mechanisms in the artificial side. This book reports relevant issues in the robotics and neuroscience of the hand, which were investigated within the international cooperation project "THE Hand Embodies". The leading idea of THE project was the concept of synergies, intended as "a functional property of a multi-element system performing an action, whereby many elements of the system are or can be constrained to act as a unit through a few coordination patterns to execute a task" [Santello et al., 2013]. There is extensive evidence in neuroscience for the organization of the sensorimotor system in functional or structural synergies (see [Santello et al., 2013] for an exhaustive review). Accordingly, recent studies have demonstrated strong covariance patterns in the control of the hand, in both kinematics and force domains. At the same time, it has become popular in robotics the idea of exploiting these reduction mechanisms to better control and design robotic hands and haptic systems using a reduced num-

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ber of control inputs, with the goal of pushing their effectiveness close to the natural performance. Central to this point of view is the concept that merely mimicking the architecture of the hand is an unfeasible and daunting task: our belief is that the modelling of the synergistic organization and its translation into a mathematical language can represent an effective step forward to advance the state of art of artificial systems [Bicchi et al., 2011]. In this sense, neuroscience and robotics can "work together" and act as a "synergy". Research in neuroscience can provide the theoretical and experimental foundations to describe the hierarchical organization of the human hand. Then such foundations can be suitably translated into a language understandable by artificial systems and used to drive the design of more effective robotic devices. Analogously, robotic and technological systems can represent useful tools to perform neuroscientific investigations on the hand and to offer new insights to better deal with this topic. With this book, we propose to bridge the gap between neuroscience and robotics with the twofold goal of increase the comprehension of the functional and neuroanatomical organization of the human hand and to derive the guidelines for a more effective development of robotic and haptic devices. This book is organized into two parts to mirror this dual approach. Part I of the book deals with the functional and behavioural aspects of the sensorimotor control of the hand. In all chapters, the theoretical framework of synergies provides a coherent solution to reduce the degrees of freedom in motor control and to organize the rich sensory information provided by cutaneous touch. Chapter 1 analyse force synergies in unconstrained hand grasping, examining how humans stabilize an external object in response to external perturbations. Chapter 2 and 3 discuss the possible neural basis of synergies in subcortical and cortical structures. Specifically, Chapter 2 reviews recent findings from neurophysiology showing the synergistic organization of the subcortical circuitry. Synergies appear to be a natural solution due to the diverging organization of the nervous system, where each neuron is connected to multiple motor units. Chapter 3 proposes a functional Magnetic Resonance Imaging (fMRI) study where novel encoding techniques are employed to determine whether regional brain activity during grasping movements can be predicted by the kinematic combination of hand synergies. Chapter 4 models the control of the hand-arm system through building blocks consisting of neuronal populations. These blocks can be regarded as neuronal operation amplifiers (opamps) that implement an efficient adaptive feedback control that could be profitably applied in robotics for the identification of unknown sensors on-the-fly Chapter 5 evaluates the hypothesis that cutaneous touch from the interaction with external object provides information on the hand displacement. This cutaneous contact information is fused with classical proprioceptive cues from musculoskeletal system and skin stretch to produce a robust estimation of the displacement. The correlation between finger movements and skin deformation suggest the existence of sensorimotor synergies. Part II of the book focuses on the definition of the exploitable guidelines for the replication of the sensory and motor aspects of the human hand through robotic and haptic/sensing devices. These guidelines are devised from the neuroscientific results reported in Part I. At the same time, Part II describes tools and procedures that can be used to perform more effective behavioural investigations, even providing novel inspirations to better understand natural systems. Chapter 6 presents the Pisa/IIT SoftHand, a novel robot hand prototype designed with only one motor with the purpose of being robust and easy to control as an industrial gripper, while exhibiting high grasping versatility, inspired by the synergistic control of human hand along the first most common actuation pattern. Chapter 7 proposes a Learn by Demonstration approach to learn anthropomorphic robot motions for reach to grasp movements towards different positions and objects in 3D space. Exploiting principal component analysis to extract a lower dimensional manifold for humanlike robot data, Navigation Functions (NF) based models are defined, which operate in a synergistic manner. A methodology for robust grasping with tactile sensing is also used to relax uncertainties and increase robustness of the final grasp. Chapter 8 and 9 deal with electromyography (EMG) based synergistic control of robotic and prosthetic hands. Chapter 8 presents an overview of the teleimpedance control concept and provides two application examples. In this tele-impedance control the user postural and stiffness synergy references are tracked in real-time by using surface EMG signals acquired from one pair of antagonistic muscles on the forearm. In the first example, an electromyography based model is developed to estimate the operator's arm endpoint stiffness in real-time, while in the second example the teleimpedance concept is translated to control the Pisa/IIT SoftHand described in Chapter 6. Chapter 9 analyses synergistic muscle patterns for the control of a dexterous hand prosthesis and for the restoration of a missing hand function by introducing the concept of incremental learning as the main feature of modern machine learning for the amputees. Chapter 10 and 11 propose mathematical tools to model and analyse the grasp and control of under-actuated synergistic robotic hands. Chapter 10 identifies a mapping strategy to transfer human hand synergies onto robotic hands with dissimilar kinematics and presents a novel software tool "SynGrasp, which includes functions for the definition of hand kinematic structure, the coupling between joints induced by a synergistic control, compliance at the contact, joint and actuator levels and graphical functions. Chapter 11 describes new, general approaches for the analysis of grasps with synergistic underactuated robotic hands. Two different approaches to the analysis are presented, the first one is based on a systematic combination of the quasi-static equations, while the second one focuses on the strategies to determine the feasibility of the pre-defined tasks, operating a systematic decomposition of the solution space of the system. Chapter 12 describes how the concept of hand synergies, which has been used to control and design robotic hands with a reduced number of control inputs and actuators, can be exploited to optimize the performance of hand pose reconstruction systems in terms of estimation accuracy and optimal design. Finally, Chapter 13 presents a model of the human hand calculated from data obtained from a small number of sensors, which can be used for movement analysis in object exploration and contact point analysis.

References

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