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Claudio Pacchierotti

Cutaneous Haptic Feedback in Robotic Teleoperation

Springer

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Al mi' babbo e alla mi' mamma

Series Editors' Foreword

This is the 12th volume of the "Springer Series on Touch and Haptic Systems," which is published in collaboration between **Springer** and the **EuroHaptics Society**.

Cutaneous Haptic Feedback in Robotic Teleoperation is focused on analyzing haptic feedback by considering tactile and kinesthetic components. A new approach named "sensory subtraction," which represents a transformation of the interaction forces before being reflected on a user, is described and validated in telemanipulation scenarios, such as telesurgery and industrial robotics. Feedback of cutaneous interaction is a strong challenge in telerobotics since it is related to soft object deformations that can easily provoke unstable bilateral systems. Examples of how to solve these problems are provided by common telesurgery tasks such as needle teleoperation. In this book, engineering and perception issues are considered in order to properly display interaction forces during telemanipulation tasks on a user. This book is organized into two parts and six chapters. The first part is focused on cutaneous cues feedback and the second part is concerned with the integration of cutaneous and kinesthetic cues.

Dr. Claudio Pacchierotti has received the EuroHaptics 2014 Ph.D. award. In recognition of this award, he was invited to publish his work in the Springer Series on Touch and Haptic Systems. Pacchierotti's thesis was selected in an international competition from a large number of excellent theses all focused on the sense of touch that were defended in 2014. This volume of the "Springer Series on Touch and Haptic Systems" provides a state of the art on how to properly reflect telemanipulation forces.

September 2015

Manuel Ferre
Marc O. Ernst
Alan Wing

Foreword

Cutaneous deformation feedback is generated by haptic devices designed to deform the skin through some kind of mobile platform, and they are intended to provide no kinesthetic stimuli. Such type of feedback can simulate very well the shape and softness of virtual and remote objects. The information conveyed by this type of cutaneous feedback is very rich and, at the same time, it does not affect the stability of teleoperation systems. Moreover, the deformation provided is very close to the one experienced during direct interaction with real objects. In fact, the cutaneous deformation provided approximates the initial deformation of the skin during the interaction with an object, leaving out the subsequent kinestethic part. This is the intrinsic nature of the cutaneous feedback considered in the book of Claudio Pacchierotti.

The application of cutaneous feedback to robotic teleoperation is a natural consequence of the richness of information this type of feedback conveys and of the intrinsic stability it guarantees thanks to the low energy involved in the stimuli and the design of our cutaneous devices. The application of cutaneous feedback to teleoperation was so natural that Claudio and I chose to refer to this approach not as another sensory substitution technique but as a novel sensory subtraction method. In fact, haptic feedback can be considered to be provided to the human operator through a combination of cutaneous and kinaesthetic stimuli. For this reason, providing cutaneous stimuli only can be also seen as “subtracting” kinaesthetic feedback from the full haptic interaction. With the term “sensory subtraction” we want therefore to highlight the fact that we are removing the part of the interaction that can affect the stability and safety of our systems, i.e., kinesthetic feedback, leaving only the cutaneous cues. However, we had a lot of concerns about the use of the term “subtraction”, which might give the impression of somehow degrading the feedback information. Nonetheless, in the end, the algebraic interpretation of the term subtraction—cutaneous is equal to haptic minus kinesthetic—won. We hope that the reader will understand our choice and appreciate this naming as much as we do.

The first part of the book elegantly introduces the sensory subtraction idea and its application in a 2 needle insertion experiment, a peg-in-a-hole task, and a robot-assisted surgical scenario. From this first part we also understand another interesting feature of cutaneous haptic feedback: devices providing only cutaneous stimuli can be significantly smaller and less bulky than their kinesthetic counterparts, enabling us to easily integrate them in complex existing systems, such as the da Vinci Surgical System, where the sensory subtraction idea takes the shape of a thimble directly attached on the master console. The second part of the book explains how the synergistic exploitation of both cutaneous and kinesthetic feedbacks improves the performance of teleoperation systems with force reflection while guaranteeing their stability and safety.

Dr. Pacchierotti's admirable book establishes the foundations of cutaneous haptic feedback in robotic teleoperation and wonderfully addresses its applications in both surgical and industrial robotics. The book provides a comprehensive experimental evaluation of cutaneous haptic feedback in various teleoperation scenarios, proving that cutaneous feedback can truly be a viable and effective approach to force feedback in robotic teleoperation.

September 2015 Prof. Domenico Prattichizzo

Acknowledgments

First and foremost I would like to express my sincere gratitude to my Ph.D. advisor, Prof. Domenico Prattichizzo, for the continuous support of my study and research, for his motivation and contagious enthusiasm through all these years. His guidance helped me to grow both as a research scientist and a man, from the very first project together (when I was still a freshman!) to my Ph.D. thesis.

I wish to thank my fellow labmates for helping me during these years of hard work and for being such good friends, inside and outside the lab. I wish them all the best as they finish their own degrees and head out into the world.

I am extremely grateful to Prof. Katherine J. Kuchenbecker, for her hospitality, help, and support during my visit to her lab. She has contributed invaluably to my research and personal growth. I could have not invested better my months abroad, both from a personal and professional point of view. Together with her, I wish to thank my labmates at Penn, who made me feel immediately part of their group. My experience in Philadelphia has been made great also by the extraordinary people I met at the International House, who significantly contributed to my happiness and positive state of mind.

I am grateful to Prof. Giulio Rosati and Prof. Sarthak Misra for their hospitality and help during my visits in Padova and Enschede, respectively. The interdisciplinary nature of our projects broaden my view on the topics of haptic, robotics, and rehabilitation.

I would also like to thank all the developers around the world who gave their time to provide me and the community with incredible free software tools, such as GCC, ROS, GNOME, Linux, Inkscape, and OpenShot. Without these tools my work would have never been possible.

My parents, Gabriella and Giampiero, receive my deepest gratitude and love for their dedication and the many years of support during my studies.

Finally, I wish to thank all my good friends in Siena, who have never stopped cheering me up since high school times.

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Contents

About the Author

Claudio Pacchierotti received the B.S., M.S., and Ph.D. degrees from the University of Siena, Italy in 2009, 2011, and 2014, respectively. He was an exchange student at the Karlstad University, Sweden in 2010. He spent the first seven months of 2014 visiting the Penn Haptics Group at the University of Pennsylvania, Philadelphia, USA, which is part of the General Robotics, Automation, Sensing, and Perception (GRASP) Laboratory. He also visited the Department of Innovation in Mechanics and Management of the University of Padua and the Institute for Biomedical Technology and Technical Medicine (MIRA) of the University of Twente in 2013 and 2014, respectively. He received the 2014 EuroHaptics Best Ph.D. Thesis Award for the best doctoral thesis in the field of haptics. He is currently a postdoctoral researcher at the Department of Advanced Robotics of the Italian Institute of Technology, Genova, Italy. His research deals with robotics and haptics, focusing on cutaneous force feedback techniques, wearable devices, and haptics for robotic surgery.

Introduction

> ἐν μὲν γὰρ ταῖς ἄλλαις λείπεται πολλῶν τῶν ξῴων, κατὰ δὲ τὴν ἁφὴν πολλῷ τῶν ἄλλων διαφερόντως ἀκριβοῖ. διὸ καὶ φρονιμώτατόν ἐστι τῶν ξῴων. σημεῖον δὲ τὸ καὶ ἐν τῷ γένει τῶν ἀνθρώπων παρὰ τὸ αἰσθητήριον τοῦτο εἶναι εὐφυεῖς και ἀφυεῖς, παρ᾽ ἄλλο δὲ μηδέν· οἱ μὲν γὰρ σκληρόσαρκοι ἀφυεῖς τὴν διάνοιαν, οι δὲ μαλακόσαρκοι εὐφυεῖς.
>
> Ἀριστοτέλης, Περὶ Ψυχῆς

> *In the other senses man is inferior to many of the animals, but in the sense of touch he is far superior to the rest. And to this he owes his superior intelligence. This may be seen from the fact that it is this organ of sense and nothing else which makes all the difference in the human race between the natural endowment of man and man. Hard-skinned men are naturally deprived of intelligence, but the soft-skinned ones are naturally gifted with it.*
>
> Aristotle, *De Anima*

Aristotle in his *De anima* defines the sense of touch as the most precise sense of the human race, the one that makes humans the most intelligent animals among all the others living on Earth. He also asserts that humans with a more developed sense of touch are the ones naturally gifted with the most intelligence. In 1960, Frank Geldard advocated that the sense of touch was a "neglected sense of communication," observing that, while visual and auditory sensing systems were respectively superior at spatial and temporal discrimination, the somatosensory system was capable of both [1, 2]. More recently, science journalist Natalie Angier wrote in the New York Times that "Biologically, chronologically, allegorically and delusionally, touch is the mother of all sensory systems. It is an ancient sense in evolution: even the simplest single-celled organisms can feel when something brushes up against them and will respond by nudging closer or pulling away [3]."

However, surprisingly, while evolution saw force senses in the limbs and skin of primitive animals long before the exteroceptors of light and sound developed, human technologies have developed in a reverse fashion [4]. First, in the second half of the nineteenth century, Thomas Edison claimed the invention of the phonograph. It recorded sound onto a tinfoil sheet phonograph cylinder and could both record and reproduce sounds. Then it was the time of moving images, reproduced along with sounds, which foreran modern television systems. Along with the rapid and widespread of audio and vision technologies, we also witnessed a drastic change in their form factor and target usage, from big and heavy machines to small and lightweight objects. Think, for instance, at the first hi-fi speakers, and compare them to the latest portable music players. The same applies to technologies made to reproduce video signals. From the first cathode ray tube televisions, nowadays companies are developing flexible organic light-emitting diode screens, which can be easily shipped in rolls.

What about the sense of touch?

What about devices able to reproduce the feeling of touching remote objects, similarly to how speakers and display screens reproduce remote sounds and videos?

Unlike speakers and display screens, artificial devices reproducing the feeling of touching remote objects have started to spread only recently. The science that took up this challenge is called *haptics*. As K.J. Kuchebecker pointed out [5], the adjective "haptic" is just a more formal synonym for the term "touch based," which origins from the Greek word ἁπτικός, meaning "able to touch or grasp." Etymology aside, A.M. Okamura links the word *haptics* to something more familiar to the layman and tells The Washington Post that "haptics is to touch as optics is to sight" [6]. The same expression stands also out in the home page of W. Provancher's haptics group at Utah [7], where I saw it for the first time. After years of vainly trying to explain to my family and friends what haptics is, this is now my opening line.

Haptics technology thus refers to our ability of designing artificial systems able to sense and transmit the several pieces of information we get from feeling the real world, similarly to how video cameras and display screens register information and feed them to our eyes, respectively. Haptics technology enabling humans to touch remote objects has typically been used in robotics for teleoperation. Telerobotic systems usually involve a slave robot, which interacts with the remote environment, and a master console, operated by a human operator. The slave robot reproduces the movements of the operator, who in turn needs to observe the remote environment with which the robot is interacting. The latter can be achieved by a combination of visual and haptic cues that flow from the environment to the operator. Visual feedback is already available in several popular telerobotic systems (e.g., the Intuitive Surgical da Vinci Si and the Space Shuttle Canadarm), but current teleoperated systems have very limited haptic feedback. This omission is related to many different factors. One of the most relevant is the negative effect that haptic feedback has on the stability of teleoperation systems. Haptic force feedback can in fact lead to undesired oscillations of the system, which interfere with the operation and may be dangerous for both the environment and the human operator [8, 9]. In this respect, cutaneous feedback has recently received great attention; delivering ungrounded sensory cues to the operator's skin conveys rich information and does not affect the stability of these teleoperation systems [8, 10, 11].

This book presents my contribution to the field of haptics and robotics, collecting all the work I have done toward my Ph.D. degree at the University of Siena and at the Italian Institute of Technology (January 2012–December 2014). It addresses the challenge of providing effective cutaneous feedback in robotic teleoperation, with the objective of achieving the highest degree of transparency while guaranteeing the stability, and thus the safety, of the considered systems. The book is divided in two main parts: cutaneous-only approaches (Part I) and mixed cutaneous–kinesthetic approaches (Part II).

Part I presents teleoperation systems that provide only cutaneous cues to the operator, thus guaranteeing the highest degree of safety. As mentioned before, in fact, cutaneous feedback does not affect the stability of teleoperation systems. We called this approach *sensory subtraction*, in contrast to sensory substitution, as it subtracts the kinesthetic part of the full haptic interaction to leave only the cutaneous cues. The sensory subtraction approach is best suitable for those scenarios where the safety of the system is paramount, e.g., robotic surgery. In this respect, Chap. 2 presents an application of the sensory subtraction idea in a 1 degree of freedom (DoF) simulated needle insertion task. Chap. 3 presents an application of the sensory subtraction idea in a more challenging remote peg-in-hole task, both in simulated and real environments. Finally, Chap. 4 presents an application of the sensory subtraction idea in a remote palpation task using the da Vinci Surgical System.

On the other hand, Part II presents teleoperation systems that provide mixed cutaneous and kinesthetic cues to the operator. In this respect, Chap. 5 presents a teleoperation system with haptic feedback wherein cutaneous cues are used to compensate for the temporary reduction of haptic feedback necessary to satisfy certain stability conditions. This mixed approach aims at improving the transparency of cutaneous-only systems described in Part I. Finally, Chap. 6 presents a teleoperation system where mixed kinesthetic and vibrotactile navigation feedback helps the operator in the steering of a bevel-tipped flexible needle in a tissue phantom.

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