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Editorial

Special Issue on Autonomous Physical Human–Robot Interaction

The challenge of creating robots intended to operate in close proximity to humans and directly interact with them in an intuitive and safe manner has been intensively studied under numerous perspectives in robotics: design, control, motion planning, and to some extent task planning. As a major real-world milestone, recent applications involving *physical human–robot interaction* (pHRI) have even made their first steps into factory floors. Nonetheless, despite the great progress over recent years, several major issues remain open. The autonomous execution of complex physical interaction tasks is still a rather unsolved problem today. Indeed, it requires the systematic combination of higher-level cognitive perception–action loops with the underlying low-level control behavior. At the same time, robot design undergoes a fundamental paradigm shift: intrinsically compliant actuation has drawn large attention in the robotics community, and led to new and challenging interaction and motion control problems. Also, mainly due to the increasing desire to apply pHRI solutions in real-world industrial and domestic environments, human safety has taken a predominant role in pHRI research.

This special issue (SI) of *The International Journal of Robotics Research* (IJRR) is devoted to physical interaction between robots and humans with a particular focus on how robots are designed and controlled to safely act in human spaces. The idea for this SI originated from the workshop *Towards Autonomous Physical Human–Robot Interaction* held at ICRA 2011 in Shanghai. In total 8 manuscripts out of 31 submissions were accepted for the SI, including submissions of workshop participants.

Overview of the papers in this issue

Robustness is one of the major challenges when designing robots that are supposed to physically interact with their environments. In the work of Grebenstein, Chalon, Friedl, Haddadin, Wimböck, Hirzinger and Siegwart, this challenge is addressed by designing a robotic hand that can store energy in elastic elements. Variable stiffness actuators not only low-pass filter impacts, but also allow adjusting the finger stiffness depending on the requirements of the task. The proposed tendon-driven hand design comes close to the human ideal in terms of size, weight, grasping performance, robustness and dynamics. The article reports about all development stages focusing specifically on the mechanical design and control of the new robot hand.

While variable stiffness actuators exhibit a series of advantages in terms of robustness, they also come along with a number of new challenges in terms of control. In the paper by Flacco, De Luca, Sardellitti and Tsagarakis, the authors address the question of how to best estimate the varying, not directly measurable, robot joint stiffness without using additional joint torque sensors. They present an approach that combines a residual-based estimator of the torque at the flexible transmission with a recursive least-squares stiffness estimator. Extensive simulations for variable stiffness actuators in antagonistic or serial configuration were performed to test their proposed approach, while selected experiments on a real robotic platform show its validity.

Making robots act safely is certainly a fundamental requirement in pHRI. Apart from designing human-friendly robots that show very safe intrinsic behavior during unwanted collisions, robot control plays the key role in ensuring that a robot cannot cause harm during unwanted collisions. In this sense, Haddadin, Haddadin, Khoury, Rokahr, Parusel, Burgkart, Bicchi and Albu-Schäffer lay the foundations for the basic understanding of soft-tissue injury as a function of robot impact characteristics. They propose an algorithm to generate inherently human-safe robot velocities. Such basic data and treatment of injury relations in control could, e.g., serve as input into new standards for pHRI.

The work of Woodman, Winfield, Harper and Fraser proposes a framework for a safety-driven control system based on functional hazard analysis and safety improving processes. The resulting Safety Protection System can be used to verify procedures in the robot design process and to prevent the execution of unsafe actions during runtime. Furthermore, as such an overview was missing in the literature up to now, the developed hazard analysis check list will be helpful for systematic hazard identification. It may be completed over time and with emerging novel applications.

Silvera Tawil, Rye and Velonaki present a novel skin sensor based on electrical impedance tomography. The development of reliable skins that provide rich haptic information is one of the major open issues in pHRI. Such a device could have strong implications on robot design, sensor interpretation and control, as a new quality of contact signals would be provided. The authors showed that with their prototype they are able to discriminate the modality of touch with similar accuracy to humans. In particular, features based on intensity and duration are prime for this result.

The paper from Ajoudani, Tsagarakis and Bicchi introduces the novel concept of 'tele-impedance' as a way for transferring manipulation skills from a human user to a remotely controlled robot manipulator arm. The key idea is to let the robot manipulator replicate not only human arm motion, but also its current impedance level. This concept aims at obtaining human-like interaction performance with partially unstructured or uncertain environments. In the reported experiments, the human arm position is tracked by external sensing, while its stiffness is estimated by processing online electromyography (EMG) readings from muscles. The robot clearly shows better performance when its stiffness is actively regulated by tracking human stiffness measurements.

One of the main challenges in enabling physical interaction between a human and an assistive robot is the appropriate allocation of roles in cooperative manipulation tasks. The paper by Mörtl, Lawitzky, Kucukyilmaz, Sezgin, Basdogan and Hirche addresses this challenge by analytically investigating how to design effort sharing policies between a human and an assistive robot during the joint transportation of a table in a planar environment. Constant and dynamic role allocation policies are experimentally compared by means of quantitative and subjective measures, allowing a number of interesting conclusions to be drawn on how to optimally shape the interaction in such cooperative tasks.

Finally, the work of Garrell and Sanfeliu studies how multiple robots that share the same workspace with humans can guide people and keep them in a formation by applying virtual pushing and dragging forces. The authors propose a prediction and anticipation model that determines the position of the group, as well as the likelihood of people straying from it. This information is used to position the robots subject to a minimum robot work criterion and to determine their interaction behavior. Simulations were carried out to illustrate the resulting robot behavior for a series of situations, while real-life experiments were performed to provide evidence for the possibility to induce virtual pushing and dragging forces using robots.

Looking ahead

Clearly, pHRI has made vast progress over the recent decade and enriched robotics in several disciplines such as human-friendly design, interaction control, planning and safety. We are glad that the selected papers show the strong evolution in the field as advanced approaches are increasingly employed in real-world applications. At the same time, it becomes evident that several technologies and algorithms, still missing or not yet market ready, will contribute to the increase in pace that this field is experiencing. At the level of sensing, haptic skins that reliably provide contact location and intensity information in adequate resolution and sensitivity would certainly have a large impact. Such advancement would also enable multi-point contact treatment in interaction control, which has been theoretically analyzed for quite some time and offers new solutions for the redundancy problem related to sensing. Tight loop closing between control, perception and planning in terms of a unified framework would finally bridge the gap between the different communities. Furthermore, it is clear that the need for regulations and protocols for certification is urgently needed, such that the legal basis for robots in human environments can be laid. Finally, a key enabler for bringing robot technologies into everybody's life is low cost. Commercializing robots that are capable of direct and safe interaction with humans for an affordable price would probably be one of the most important milestones in robotics history so far. In summary, challenging and exciting advancements were made in pHRI, but even more challenging and exciting ones are still ahead of us.

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