HUMAN-ROBOT INTERACTION

Effective and natural human-robot interaction requires multidisciplinary research

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There are many physical tasks that cannot be handled by a human alone; these tasks can require assistance from another human, animal, or a machine. We have interacted with other humans and animals for millennia, and more recently, we have learned to interact with digital environments in computers. Intelligent robots are now starting to appear in everyday situations, and our interaction with them is an active area of research (*1*). Human-robot interaction includes both a social component, inspired by the perceived agency of the robot that naturally evokes expectations on its behavior, and a physical component, when the contact forces and perception of a robot need to be coordinated. We expect that robots will enter our daily lives, eventually. This is certainly the case for science fiction; in this issue, Murphy reviews *Klara and the Sun* by Kazuo Ishiguro—a story about and told from the perspective of a companion robot called Klara. In reality, and now in the time of a pandemic, it is hoped that robots may be deployed for disinfection, delivering medications and food, measuring vital signs, and providing advanced assistance (*2*).

There is a growing need to establish how robots should be developed to ensure natural, safe, and relevant interaction. This can only be achieved by taking an interdisciplinary approach. Robotic systems need to be able to understand the nuances of human behavior. This poses not only a perceptual challenge but also a challenge in modeling human behavior, expressions of internal states, and signaling of current goals. The opposite is equally important—the users need to have a detailed awareness of the robot's abilities, and its goals and internal states need to be communicated in a clear and timely way. Thus, robot systems need to be studied and developed from various perspectives. We need a better understanding of how humans interact and how these interactions are different from human-machine interactions, and if we want individualizable and adaptable robots, we need to figure out how to build systems that can perceive and react intelligently (*3*). Human-robot interaction (HRI) will also require that systems adhere to social, ethical, and moral norms. One can hope that the large-scale introduction of interactive machines in the society will enable a wider discussion around norms, maybe ultimately resulting in "norm normalization" in human-human interaction.

This special issue reflects the interdisciplinary nature of the research we conduct toward the development of robotic systems that take initiative. Topics covered range from basic research on development of methods for studying human behavior to experimental research considering specific scenarios and context of HRI.

How a robot looks and how a robot looks at you are important considerations in HRI. When a human and a robot interact in a shared workspace, a natural question to ask is whether the robot's behavior should mimic typical characteristics of human behavior. Belkaid *et al.* investigate how a robot's gaze—a strong cue in human-human collaboration—influences the person's reasoning in a decision-making context. The robot's gaze, either following or averting the human's actions, was taken by the human as a strong social signal, modulating the response times, decision threshold, neural synchronization, choice strategies, and sensitivity to outcomes. A literature overview study by Roesler *et al.* quantifies more generally whether and under which circumstances anthropomorphic features of robots facilitate HRI. This paper not only provides insights into design features that can improve the quality of HRI but also points out that more research is needed in the area of anthropomorphic robot design.

One crucial parameter of collaboration is timing. Cini *et al.* studied the role of timing of feedback, which can be detrimental for the task behavior if provided in the wrong moment. Asking to pass the object in the beginning of a reaching movement slowed down the arm movement, degraded the smoothness of transfer, and increased the number of errors. On the other side of a human-robot dyad, Abadía *et al.* investigate how a compliant robot can be controlled with long nondeterministic latencies in feedback, typical challenge for natural human interactions. DeWolf provides commentary to the work by Abadía *et al.*

One anthropomorphic aspect, to which humans seem to react differently in robots than in fellow humans, is authority. Contrary to expectation from human-human interaction, robots in a peer role are shown to be more persuasive than those in a role with formal or actual authority (controlling a monetary reward) in the study of Saunderson and Nejat. See also commentary by Young.

The second group of articles in this issue studies a tighter interaction between humans and robots, which includes a physical contact in a prosthetic device. Plooij *et al*. found that stability and safety are crucial parameters when humans learn to use a prosthetic device. People seem to choose the feeling of safety over energy efficiency in the user study in neurorehabilitation. This has implications on decisions about mechanical parameters of the prosthesis. Poggensee and Collins furthermore underscore not only the importance of training when using prosthetic devices but also customization, which substantially reduces the training time. The importance of multimodal sensing for upper-limb prosthesis is studied by Marasco *et al*. Combining touch, grip kinesthesia, and motor control improves performance of skilled hand behaviors, enhances error correction, and promotes prosthetic ownership. Thus, the authors argue that bionic prostheses help to achieve more human-like function and effective sensory-motor restoration. Ortiz-Catalan provides commentary to the work by Marasco *et al.*

Finally, understanding human and animal behavior is key for future development of human-robot interaction. Silvernagel *et al*. present a platform that enables animal behavioral studies, simultaneously recording behavioral parameters and neuronal activity in a free movement setup. Lee *et al*. present a hand-motion tracking system that combines vision and inertial skeleton tracking and demonstrates potential for real-world monitoring of hand movements.

This special issue touches upon different aspects of human-robot interaction, highlighting the need for a research program that would bring all different aspects together: study of human behavior and a better understanding of the social and physical interaction rules with other humans and robots, as well as the development of required sensorial and motor systems that can provide the robot with an adequate understanding of the interactive situations and means to react to them. Innovative AI algorithms will be needed to address the perceptual and motor challenges of interaction at the required speed, precision, and expressiveness. A broad discussion of the rules of human-robot interaction and expectation management will also be needed.

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