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Human-Robot Interaction: Successes, Hurdles, and Remaining Challenges

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The past decades have seen an increasing number of robots deployed in the vicinity of humans, from vacuum cleaners roaming in our living rooms, drones flying over our heads, to prostheses attached to our bodies. Today, global efforts are focused on designing the next generation of robots, which will be employed and function in close or direct interactions with lay users. We are no longer in the realm of factory robots used by well-trained practitioners. It is, hence, not conceivable that these robots can be programmed without a deep understanding of the social, ethical, and cultural rules that underpin human environments. Developing robots that are cognizant of the world that surrounds them has led to a wide range of efforts worldwide, all of which fall under the general field of human-robot interaction (HRI).

We advocate for a research roadmap for HRI over the next two decades towards the development of robot **systems** capable of interacting with humans in a pertinent and helpful manner in any kind of environment.

HRI in a nutshell

The scope of HRI spans from developing algorithms and interfaces to facilitate seamless interaction between humans and robots to conducting observations and experimental evaluations of how stakeholders utilize robots in various contexts. The field addresses both non-physical interaction—such as multimodal communication based on verbal instructions and gestures—and physical interaction—where robots and humans are either in contact, as in prostheses, or in indirect contact, as when they jointly carry an object. Originally an offspring of Human-Computer Interaction, HRI established itself as a research field of its own in the mid-1990s, gaining traction over the following

three decades. It established itself with the launch of the IEEE-ACM International Conference on HRI in 2005 and subsequently of a few dedicated journals. HRI is inherently an interdisciplinary field of research, and requires close collaboration between roboticists and social scientists, cognitive scientists, psychologists, economists, and philosophers. The collaborative expertise is crucial to model human behavior and develop robots capable of interpreting and predicting the actions of the humans they interact with. It is also crucial to make sure that robots behave and speak in ways that are socially adequate and effective when communicating and collaborating with humans.

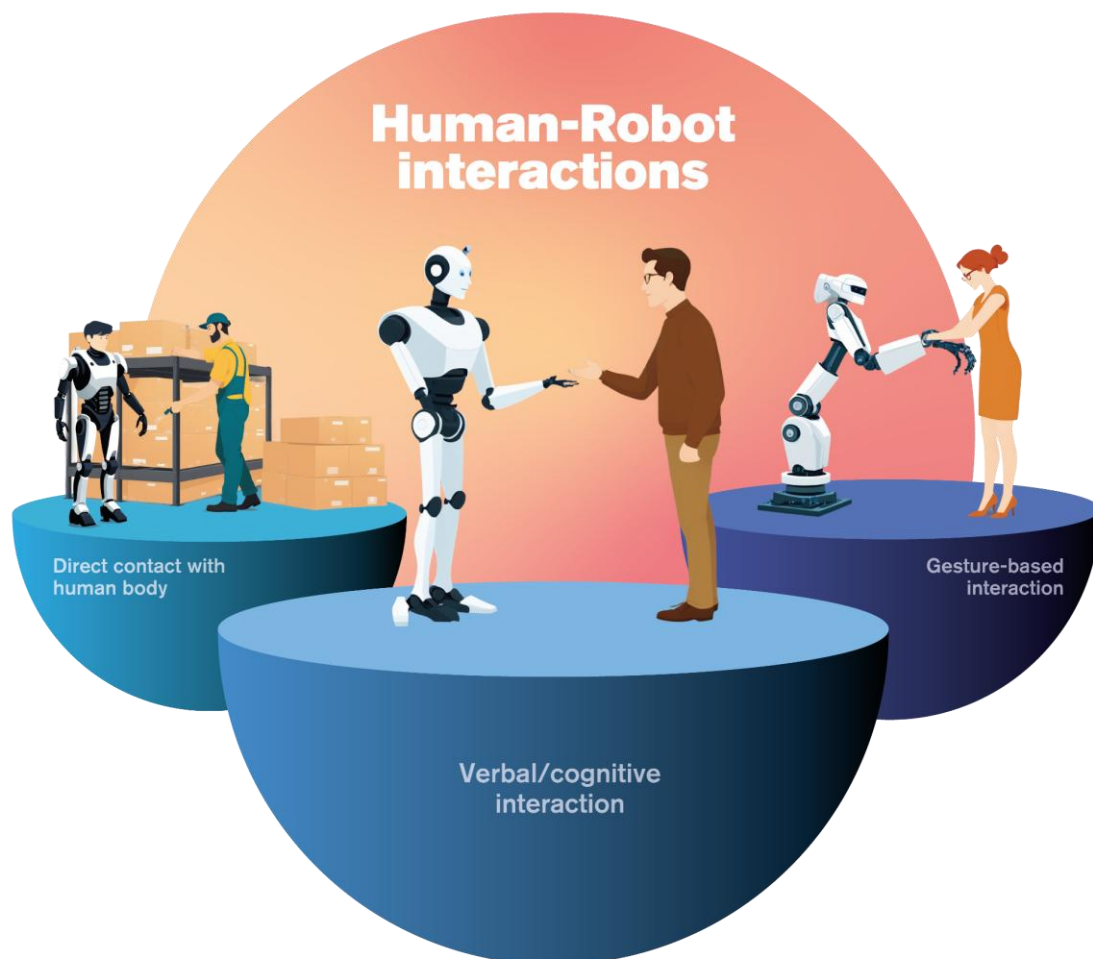


Figure 1: *Different types of human-robot interaction*

Human-robot interaction can be either haptic/physical, when humans and robots get into actual contact with each other, or non-physical (see Figure 1). Physical human-robot interaction is being used extensively for teleoperation or for teaching robots to perform tasks through what is known as programming – learning - from demonstration. Non-physical interaction can be both verbal, when humans talk to give order to a robot, and non-verbal, for instance by using the robot's eye gaze to augment verbal communication, convey the robot's internal state or gather the attention of the human, possibly directing it toward an object involved in a joint task. In physical human-robot interaction, the transition from rigid robots to those safely interacting with humans was enabled by compliant control strategies, which regulate interaction forces and system impedance rather than

following predetermined position trajectories. This approach, implemented through advanced force/torque sensing and tactile feedback from artificial skin technologies, fundamentally alters robot behavior from position-controlled to force-controlled operation, ensuring intrinsic safety during human-robot physical contact. In verbal, and more generally, in non-physical human-robot interaction, the improvement of computer vision algorithms, both traditional ones and those based on machine learning techniques, has contributed significantly to improving navigation in various environments, to detect humans, predict their intentions, and behave appropriately.

HRI has gained increasing attention as researchers started to conceive robots that could move outside of the confined industrial environment, where they used to work in cages or surrounded by fences to avoid any contact with humans. Human-robot interaction is now especially relevant for collaborative robots for the industry and the medical sector, wearable robots and exoskeletons, robots and drones for the inspection of remote locations and for search and rescue operations in collaboration with humans, mobile robots capable of navigating in crowded spaces, such as hospitals, airports, restaurants, and robots for social companionship.

During the last two decades, the type and complexity of both physical and non-physical HRI has changed largely due to introduction of new materials, new sensors such as artificial skins¹ and haptic interfaces that have enhanced the capabilities of robots to register and interpret physical contacts with humans the design of more realistic human-like bodies (androids, human-like avatars) that allow HRI to reproduce some forms of human-human interaction and more recently to large improvement in verbal interaction enabling more complex dialog thanks to speech recognition and Large Language Models (LLMs).

Another major advance in HRI is wearable robotics, especially exoskeletons. Made possible by lightweight, durable materials like titanium, they assist both physically impaired individuals and workers in demanding tasks, lowering social labor costs. Going further, anthropomorphic robots with human-aware control can communicate, express emotions, recognize, and adapt to human behavior. Such robots have shown promising results in rehabilitation and companionship (see Figure 2).

¹ G. Cheng et al. (2019) A Comprehensive Realization of Robot Skin: Sensors, Sensing, Control, and Applications," in Proceedings of the IEEE, vol. 107, no. 10, doi: [10.1109/JPROC.2019.2933348](https://doi.org/10.1109/JPROC.2019.2933348)



Figure 2: Examples of successful development of robots for human-robot interaction: (Top left) Collaborative robot (cobot) can support users in industrial tasks; (Bottom left) the Sony AIBO dog capable of learning users' preference through reinforcement learning driven by the user's pat on its head. (Middle top) Androids push the frontiers of how human appearance can be; (Middle bottom and far right) toy robots can be programmed to support rehabilitation programs, such as Robota (EPFL) for children with autism spectrum disorders, or the Paro seal robot used with the elderly suffering from dementia. (Middle right) Humanoid robots such as Pepper can serve as guides in museums or order and serve dishes in fast food.

All together, these achievements have led to robots that are designed and programmed to be intrinsically safe for humans and thus can work in their proximity, even without being cognitively aware of humans or making interaction appealing. Prominent examples of this are the commercial deployment of collaborative robots (cobots) that can operate in the manufacturing industry outside of confined spaces. Robots that navigate and share space safely with humans are deployed in factories and warehouses², but their interaction with human workers is still carefully structured. Domestic robots performing household tasks, such as vacuum cleaners, are produced by the million. Mobile robots work quite well in sufficiently large environments, public spaces such as hospitals and airports. Robots have also been deployed in restaurants to serve people, where they can navigate without ground signaling, finding their way among customers and servers.

What next? A roadmap to address short-term and long-term challenges

In these first three decades, research on human-robot interaction has achieved important results, bringing robots to interact with humans in different contexts. However, achieving the goal of developing fully autonomous robots capable of interacting usefully and pertinently with humans is still quite far away and will require a continuum of significant technological advancements across multiple disciplines to address both short-term and long-term challenges (see Figure 3).

² <https://www.robust.ai/blog> (Retrieved 10/07/2024)

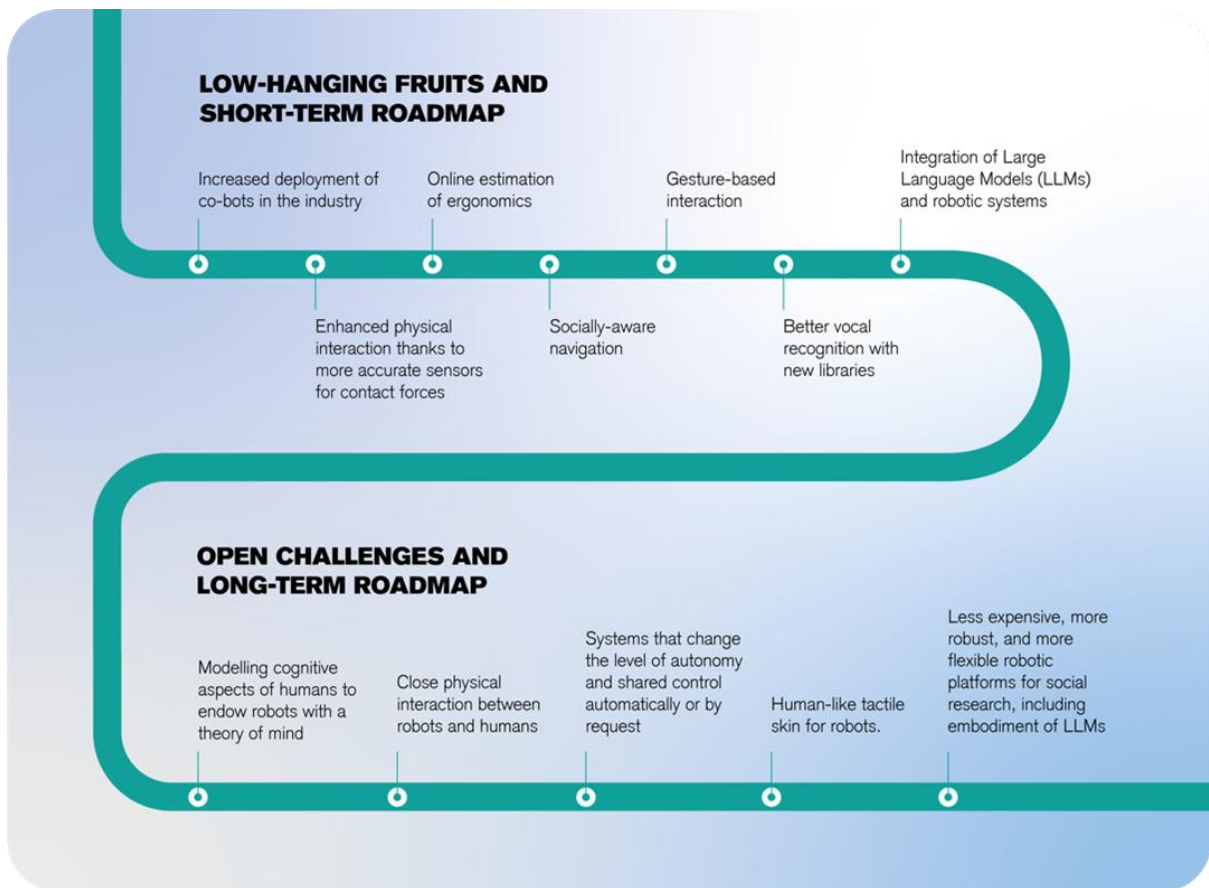


Figure 3: Short-term and long-term roadmap to large-scale human-robot interaction deployment

Short-term goals and challenges:

The market for collaborative robots in the industry has been growing substantially in the last ten years. Yet, collaborative robots still represent only 5 to 8% of the robots sold to industries. For their presence in manufacturing and logistics to increase, it will depend on these robots becoming more robust and capable of performing highly dynamic motions similar to what humans do, while remaining safe³. Many technologies could hence provide safety beyond traditional force/torque sensing. Safety when performing dexterous manipulation tasks involving multiple robot arms or more complex hand grippers in close contact with humans can be achieved with greater use of artificial skin. Current commercial versions mainly cover flat areas, avoiding joints like elbows and knuckles due to limitations in flexible electronics. Coverage is typically limited to key areas like fingertips, but full-body coverage is now possible, as demonstrated by a full-sized humanoid prototype⁴. But collaborative robots need to be more than safe. They should be aware of human ergonomics, e.g. by improving the intuitiveness of evaluation and visualization tools based on digital human models to facilitate their adoption by industrial operators⁵. These technologies could be employed in devices that alert workers performing

³ M. Grebenstein, et al., "The DLR hand arm system," in *Proceedings of the 2011 IEEE International Conference on Robotics and Automation* (2011).

⁴ S. Groß et al. *2023 IEEE International Conference on Robotics and Automation (ICRA)*, 12507-12513, DOI: [10.1109/ICRA48891.2023.10161344](https://doi.org/10.1109/ICRA48891.2023.10161344).

⁵ L. Vianello et al. *Sensors* **22**(11), 3981(2022). DOI: [10.3390/s22113981](https://doi.org/10.3390/s22113981)

heavy tasks about damaging postures to prevent musculoskeletal disorders and enhance safety in the workplace.

To increase trust and reduce risks when deploying robots in such close vicinity to humans, robots must become cognizant of their environment and socially aware. This includes providing robots with social compliance, which relates to the capacity of a system to conform to social norms and expectations⁶. Socially-aware navigation is now within reach, with significant progress made lately, especially in Europe⁷. In the coming years, robots may navigate among humans by not only keeping a distance but also recognizing confused behavior, leveraging improved algorithms for human detection and short-term motion prediction, balancing safety and utility. Socially-aware navigation would also greatly benefit from a better understanding of the interaction between naive users and robots in unstructured settings. This is particularly crucial for delivery robots and autonomous wheelchairs that share the sidewalk with humans.⁸

Interaction with gestures is quite mature now, and only small developments are required to guarantee they work seamlessly even when users do not act as expected, or with large occlusions and disturbances. Vocal and audio recognition is also mature, supported by strong libraries. Deployment is more challenging than gesture recognition due to speech variability and application-specific vocabularies. However, advanced signal processing tools can denoise audio, even isolating speech from noisy sources like drone microphones.

The integration of LLMs and robotic control architectures represents a paradigm shift toward natural-language-driven robot instruction⁹. This integration enables robots to process high-level semantic instructions and generate executable action sequences, thus bridging the gap between human communication patterns and robot control primitives.

Yet for successful and large-scale deployment of these new human-robot interfaces, one needs to understand much more about the interaction of robots with multiple users, and beware of how discrimination and social exclusion arise and how biases in various robot components can affect the group members depending on their features. Examples of these so-called “embodied biases” are natural language understanding models and voice recognition models that are known to be better at

⁶ A. Billard, *Robotics and Autonomous Systems* **88**, 157-164 (2017). DOI: [10.1016/j.robot.2016.08.030](https://doi.org/10.1016/j.robot.2016.08.030)

⁷ P. T. Singamaneni et al. *The International Journal of Robotics Research*, 2024;0(0). DOI: [10.1177/02783649241230562](https://doi.org/10.1177/02783649241230562)

⁸ A. M. H. Abrams et al., “Field observation: Interactions between pedestrians and a delivery robot”, *29th IEEE International Conference on Robot & Human Interactive Communication*, https://crowdbot.eu/wp-content/uploads/2020/09/Short-Talk-1-Workshop_Abstract_Field-Observation_final.pdf (Retrieved 11/07/2024)

⁹ L. Bärmann et al. (2024) Incremental learning of humanoid robot behavior from natural interaction and large language models, *Frontiers in Robotics and AI*, <https://doi.org/10.3389/frobt.2024.1455375>

recognizing male voices than female ones, or image recognition models that are better with white people than with people of color. All these elements will be embedded in robotic platforms, and biases can arise in multiple ways¹⁰. Robots could be programmed to apologize when they discriminate, and to explain and adapt their controller and actions to help reintegrate trust with affected individuals.

Long-term challenges:

The long-term goal of HRI research should be to design robot systems and AI systems that explicitly consider humans in terms of their actions, their preferences, their mental state, and their goals, and therefore understand when they need to act or communicate. All these questions are far from being solved today.

An open challenge is that of modeling basic cognitive aspects of humans, to endow robots with a theory of mind that allows them to understand humans' expectations during a joint task and to engage in a negotiation that leads to a satisfactory result for the human¹¹. Robots should also be able to update these models as time passes by. To achieve human-centered robotics, researchers should strive to develop robots that are easy to interact with and do not overly constrain humans. In logistics, where robots are already deployed, this kind of problem has already arisen, leading to a high degree of turnover among human workers. These workers often feel replaceable as they work to complement robots. The development of future cobots should be centered around human workers to ensure they do not refrain from intervening with robots out of fear of the consequences this could have on their jobs. The robots of the future should be able to adapt, give latitude and priority to humans, and help them rather than impose their rhythm. It is thus crucial to involve experts from fields such as psychology, economics, philosophy, and cognitive science to understand thoroughly what it means to collaborate with humans¹². European institutions should weigh in with meaningful regulations to enforce the principle of human-centered robotics, as they have already done concerning the use and exploitation of personal data and the deployment of AI systems. Moreover, robots should be well integrated with existing infrastructures, also digital ones.

To fulfill this long-term vision, several more specific challenges should be addressed.

In physical human-robot interaction, a challenge will be that of designing systems that allow a change of the level of autonomy and shared control. This could happen automatically or by request, so that it fits exactly what the human wants and needs in terms of ergonomics, but especially what the human feels comfortable with. This would allow humans to preserve their own sense of agency and not feel completely dominated by the robot. Solving this challenge will be crucial for exoskeletons, especially

¹⁰ A. Rosenthal-von der Pütten and S. Schiffer *arXiv:2310.01574 [cs.ROJ]* (2023). DOI: [10.48550/arXiv.2310.01574](https://doi.org/10.48550/arXiv.2310.01574).

¹¹ S. Lemaignan et al. *Artificial Intelligence* **247**, 45-69 (2017). DOI: [10.1016/j.artint.2016.07.002](https://doi.org/10.1016/j.artint.2016.07.002)

¹² D. Kragic et al. *Science Robotics* **6**(58), eabl7022 (2021). DOI: [10.1126/scirobotics.abl7022](https://doi.org/10.1126/scirobotics.abl7022)

active ones, which will be more and more deployed in assisting humans in various tasks, such as lifting heavy payloads, and for manipulators on a mobile base in a factory.

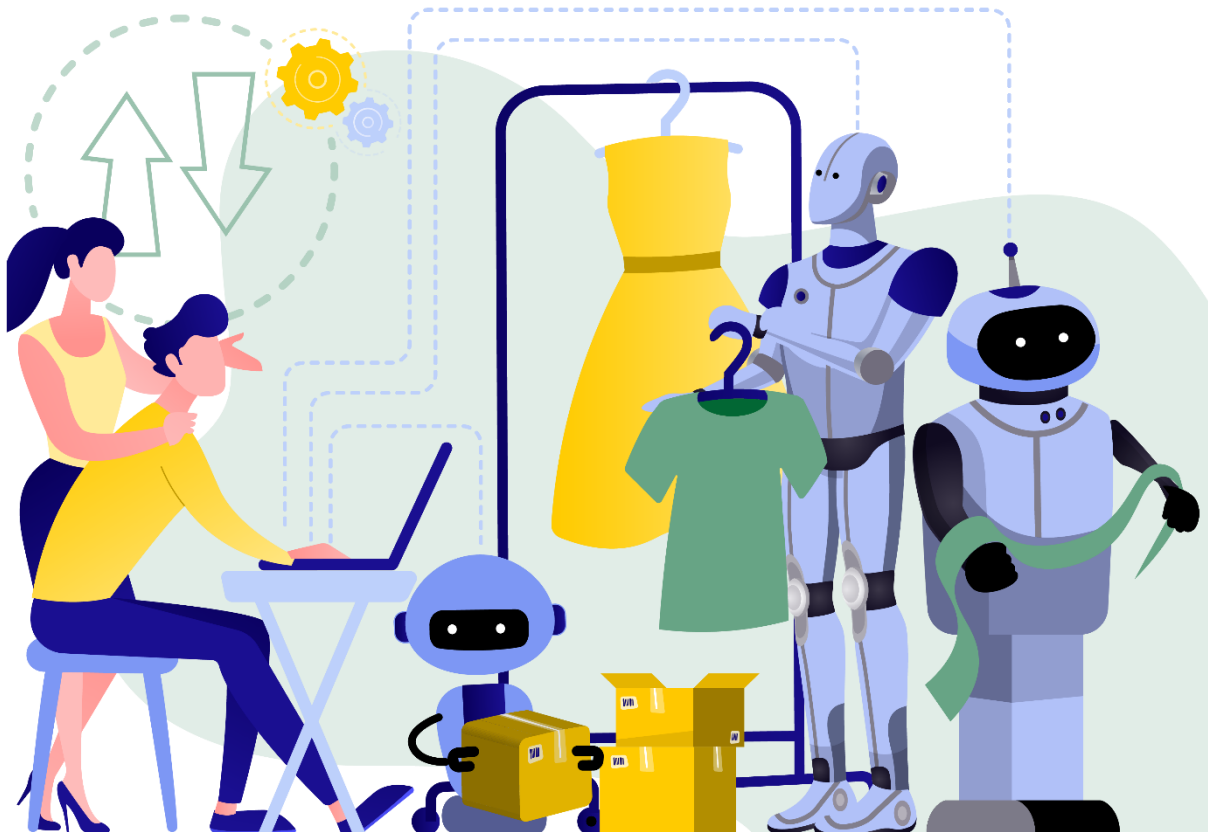


Figure 4: As robots, be it humanoid or other forms, may enter our homes, they will need to learn and adapt continuously to new demands to fulfill a variety of tasks required from them and personalize this to their user's preference.

Other problems that need to be solved to have humanoid robots perform these tasks concern the ability to learn continuously and the ability to personalize behavior to different people (Fig. 4). Also, such robots need to be soft enough to absorb undesired contact and reduce risk of injury. A major development step is required also on all levels of hardware and control to enable close physical interaction, for tasks like feeding or undressing, washing, and dressing again a person, currently performed by caregivers. Humanoid robots can play multiple roles because they fit in the environments we have built for us humans, both in terms of shape and size. Moreover, getting assistance from a humanoid robot is more effective because humans know how to behave in such situations, e.g., they know they can put a hand on the shoulder or how to walk together (Fig. 5).

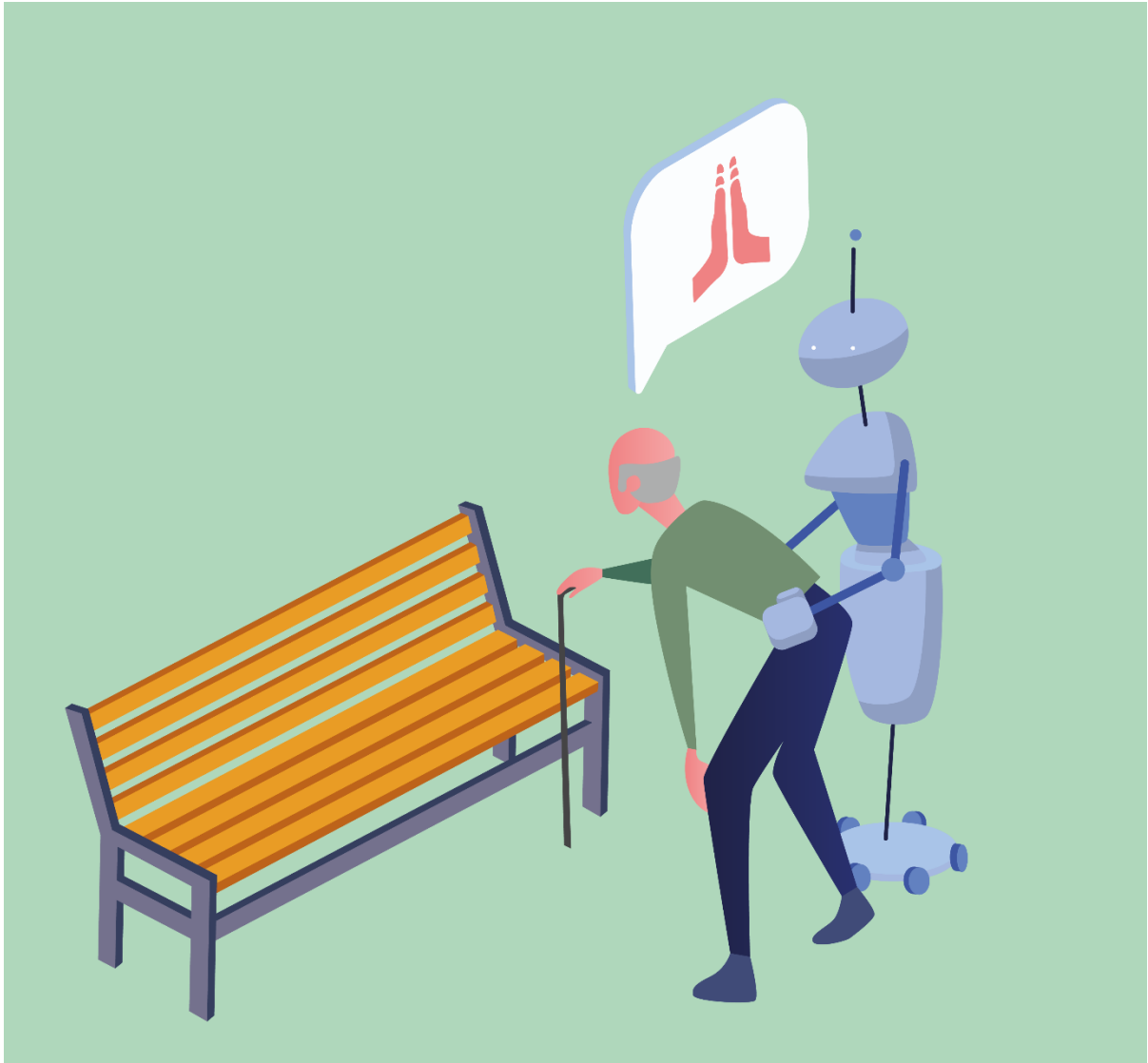


Figure 5: LLM can play a role in easing HRI as it can convey high-level instructions in human-intelligible languages. Yet, for robots providing physical support to humans, an understanding of body language conveyed through haptics (touch and proprioception) is crucial.

As the interaction between robots and humans becomes more unconstrained, more interdisciplinary research is needed, especially on managing humans' expectations of the robots' capabilities. To investigate the social aspects of human-robot interaction, cheaper, more robust, and more flexible robotic platforms are needed. Currently, the choice is between robot toys, which are very robust and very cheap but with a very specific application area that cannot be changed easily, and research platforms, which are instead quite expensive. In between, there are platforms developed by computer scientists and engineers that are often too complex to customize. As a result, the choice of platform is rather restricted. Today, a long-term study on social robots requires major investments. Real-world data on long-term interaction between robots and humans is not yet available.

AI and machine learning techniques, especially deep learning and LLMs, will play an important role in developing the robots of the future. The integration of LLMs into robotic systems could enable

individuals, irrespective of their technical knowledge, to interact with robots and direct their actions. The use of LLMs could prove highly effective in social science research. For example, studies on the impact of language tone in communication, both between humans and between robots and humans, are challenging to perform by asking humans to change their tone, whereas LLMs can do this very efficiently. However, attention must be paid to reproducibility, especially in long-term studies. Given that LLMs evolve rapidly due to the availability of new training data, their consistency throughout experiments or across experiments performed at different times should not be taken for granted.

As in other robotics fields, human-robot interaction must intelligently combine model-based AI with deep learning to mitigate risks, particularly misinterpretation of human instructions. This requires establishing criteria for distinguishing between minimal risk situations and safety-critical scenarios requiring alternative control methods offering deterministic verification and guarantees. Current large language models, while powerful for natural interaction, cannot provide the reliability guarantees required for safety-critical tasks and must be augmented with verification and fail-safe mechanisms. Ultimately, the most challenging application is inside homes, which are among the most unstructured and unpredictable human behavior. Successful deployment of home robots demands robots with appropriate social behavior, a high level of adaptability to change, effective communication, and stringent privacy protection measures.

Data protection presents additional complexity in HRI systems, as robots continuously collect multimodal data about human behavior, preferences, and private spaces. Unlike traditional IoT devices, HRI systems often process biometric data, spatial mapping of private environments, and behavioral patterns that require enhanced privacy protection measures. Developing privacy-preserving machine learning techniques, such as federated learning and differential privacy, will be essential for maintaining user trust while enabling personalized robot behavior. The development of secure HRI systems requires establishing cybersecurity frameworks specifically designed for human-robot interaction contexts, including secure authentication protocols for human-robot communication and robust intrusion detection systems that can distinguish between normal operational variations and potential security threats.

The future of human-robot interaction holds significant promise for transforming how robots support human activities across diverse domains. However, realizing this potential requires careful attention to both technical and societal challenges. Successful large-scale deployment will depend on systematically addressing risks to human physical and psychological safety, establishing robust regulatory frameworks, and maintaining public trust through transparent development practices. The roadmap presented here provides a foundation for coordinated research efforts that balance technological advancement with responsible implementation.

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