REVIEW

ROBOTICS

Trends and challenges in robot manipulation

Aude Billard[1]* and Danica Kragic[2]

Dexterous manipulation is one of the primary goals in robotics. Robots with this capability could sort and package objects, chop vegetables, and fold clothes. As robots come to work side by side with humans, they must also become human-aware. Over the past decade, research has made strides toward these goals. Progress has come from advances in visual and haptic perception and in mechanics in the form of soft actuators that offer a natural compliance. Most notably, immense progress in machine learning has been leveraged to encapsulate models of uncertainty and to support improvements in adaptive and robust control. Open questions remain in terms of how to enable robots to deal with the most unpredictable agent of all, the human.

Have you ever found yourself busy foraging in your bag in search of a set of keys? If so, you may recall that it took only a few seconds to find them among the disparate contents of the bag. For certain, you did not reflect on your abilities and may have carried on this display of unique dexterity through a swift in-hand manipulation, taking out the correct key and inserting it into the lock even though the corridor lights had gone out. All day long, our fingers grasp, move, and transform objects and interact with objects in various media such as air, water, and oil. We do not spend time thinking about what our hands and fingers are doing or how the continuous integration of various sensory modalities—such as vision, touch, proprioception, and hearing—help us outperform any other biological system in the breadth of the interaction tasks we can execute. Largely overlooked, and perhaps most fascinating, is the ease with which we perform these interactions, resulting in a belief that they are also easy to accomplish in artificial systems such as robots.

Manipulating objects is such a ubiquitous activity that we forget how difficult it was to acquire this competence as a child. Children are born with simple grasp reflexes. It takes them 3 years to develop an individuated control of each finger and another 6 years to display an adult-equivalent ability for making smooth contact and for planning sequences of manipulation skills (*1*). Even for humans, some dexterous activities may pose a challenge. For example, tying shoes may be done in various ways, and there may be several valid models of how to execute such an activity. In addition, we can visually demonstrate how to do something and what the expected result may be, but we cannot easily communicate the magnitude of the applied forces and torques or the size of the friction coefficient necessary to satisfy stability conditions. Still, we find ways of achieving manipulation goals through training and exploration even if the end result is not always optimally performed. We may also adapt as circumstances dictate (e.g., tying shoes with an excess of free shoelace or when the ends are quite short), forcing us to deviate from our normal methods. Thus, the context in which interactions are performed affects various parameters of the execution.

Although robotics has made vast progress in mechanical design, perception, and robust control targeted to grasping and handling objects, robotic manipulation is still a poor proxy for human dexterity. To date, no robots can easily handwash dishes, button a shirt, or peel a potato.

What can robots do today?

Robots are skilled at picking up and manipulating objects in repetitive and familiar settings such as industrial assembly setups. In such settings, the geometry, material properties, and weight of the objects are commonly known. Robots can handle some variation in routine movements in terms of adapting to small differences in the object properties, but the whole process is typically optimized to a limited set of expected variations. In early factory settings, robot arms followed predetermined trajectories and assumed that objects would always appear at the same place. Today, robots can adapt their trajectory to retrieve objects at different locations, making it possible for objects to be placed by humans or simply dropped on a conveyer belt instead of being deposited at exact positions by other machines. The classical assembly lines in which robots were bolted into the floor and placed one after another, typical for the automobile industry, can now be made more flexible. Objects moving on conveyers can be detected fairly easily by cameras and picked up if fully visible. However, detection of transparent objects or objects partially hidden (e.g., when stacked on top of one another) remains difficult.

With the need to frequently change the type of goods produced, the robotics industry strives for multipurpose object grasping and handling solutions. One step toward this objective is to provide robots with a choice of grippers varying in size and strength and to enable robots with tool-changing mechanisms so that they can select the correct tool. To determine which tool to use for a given task, a robot must have knowledge of an object's properties, such as shape, weight, material, and so forth. This information is readily available in factories where all objects are known. However, this requirement presents a limitation for robots in other settings, where the set of objects to be manipulated may not be known beforehand.

What can robots not do today?

Although robots are adept at handling rigid objects, they still struggle with flexible materials—such as fruits and vegetables or clothing items—that differ in size, weight, and surface properties. Manipulations that produce a deformation (e.g., inserting, cutting, or bending) are particularly difficult, as accurate models of the deformations are needed. Industrial grippers often use pneumatic vacuum pumps to pick up objects by sucking. This technique is unbeatable when it comes to grasping an object but is much less useful for object manipulation (e.g., reorienting the object and placing it in a confined space). One step to address this challenge is to provide robots with more dexterous hands. Yet creating hands as dexterous as human hands is difficult, owing to a lack of sensors and actuators equivalent in size, precision, and efficiency to our skin and muscles.

Improvements in robots' dexterity are not limited to the engineering of more-capable hands. Advanced software programs are required to analyze in real time the large flux of visual, tactile, and force information and to relate these different senses to recognize objects and model their transformations. Additionally, robots need advanced cognitive capabilities to predict where, how, and why to manipulate objects. The rest of this Review describes why overcoming these challenges is difficult and where the field of robotics stands today.

Why is designing robotic hands difficult?

Although research on robot hands has been ongoing for more than five decades (*2*–*4*), the most common hand used in many applications to date is still a parallel jaw gripper, usually without any extra sensing. Picking up objects with a gripper devoid of sensing is akin to grasping with the tip of your thumb and index finger when both are numb! This tool may suffice for simple pick-and-place actions, but not for more-complex motions such as shuffling keys. Because the human hand performs intricate movements with

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BACKGROUND: Humans have a fantastic ability to manipulate objects of various shapes, sizes, and materials and can control the objects' position in confined spaces with the advanced dexterity capabilities of our hands. Building machines inspired by human hands, with the functionality to autonomously pick up and manipulate objects, has always been an essential component of robotics. The first robot manipulators date back to the 1960s and are some of the first robotic devices ever constructed. In these early days, robotic manipulation consisted of carefully prescribed movement sequences that a robot would execute with no ability to adapt to a changing environment. As time passed, robots gradually gained the ability to automatically generate movement sequences, drawing on artificial intelligence and automated reasoning. Robots would stack boxes according to size, weight, and so forth, extending beyond geometric reasoning. This task also required robots to handle errors and uncertainty in sensing at run time, given that the slightest imprecision in the position and orientation of stacked boxes might cause the entire tower to topple. Methods from control theory also became instrumental for enabling robots to comply with the environment's natural uncertainty by empowering them to adapt exerted forces upon contact. The ability to stably vary forces upon contact expanded robots' manipulation repertoire to more-complex tasks, such as inserting pegs in holes or hammering. However, none of these actions truly demonstrated fine or in-hand manipulation capabilities, and they were commonly performed using simple two-fingered grippers. To enable multipurpose fine manipulation, roboticists focused their efforts on designing humanlike hands capable of using tools. Wielding a tool in-hand became a problem of its own, and a variety of advanced algorithms were developed to facilitate stable holding of objects and provide optimality guarantees. Because optimality was difficult to achieve in a stochastic environment, from the 1990s onward researchers aimed to increase the robustness of object manipulation at all levels. These efforts initiated the design of sensors and hardware for improved control of hand–object contacts. Studies that followed were focused on robust perception for coping with object occlusion and noisy measurements, as well as on adaptive control approaches to infer an object's physical properties, so as to handle objects whose properties are unknown or change as a result of manipulation.

ADVANCES: Roboticists are still working to develop robots capable of sorting and packaging objects, chopping vegetables, and folding clothes in unstructured and dynamic environments. Robots used for modern manufacturing have accomplished some of these tasks in structured settings that still require fences between the robots and human operators to ensure safety. Ideally, robots should be able to work side by side with humans, offering their strength to carry heavy loads while presenting no danger. Over the past decade, robots have gained new levels of dexterity. This enhancement is due to breakthroughs in mechanics with sensors for perceiving touch along a robot's body and new mechanics for soft actuation to offer natural compliance. Most notably, this development leverages the immense progress in machine

Holding two objects in one hand requires dexterity. Whereas a human can grab multiple objects at the same time (top), a robot (bottom) cannot yet achieve such dexterity. In this example, a human has placed the objects in the robot's hand.

PHOTOS: LEARNING ALGORITHMS AND SYSTEMS LABORATORY, EPFL

world settings is costly in terms of both time and hardware. To further elaborate on data-driven methods but avoid generating examples with real, physical systems, many researchers use simulation environments. Still, grasping and dexterous manipulation require a level of reality that existing simulators are not yet able to deliver—for example, in the case of modeling contacts for soft and deformable objects. Two roads are hence pursued: The first draws inspiration from the way humans acquire interaction skills and prompts robots to learn skills from observing humans performing complex manipulation. This allows robots to acquire manipulation capabilities in only a few trials. However, generalizing the acquired knowledge to apply to actions that differ from those previously demonstrated remains difficult. The second road constructs databases of real object manipulation, with the goal to better inform the simulators and generate examples that are as realistic as possible. Yet achieving realistic simulation of friction, material deformation, and other physical properties may not be possible anytime soon, and real experimental evaluation will be unavoidable for learning to manipulate highly deformable objects.

OUTLOOK: Despite many years of software and hardware development, achieving dexterous manipulation capabilities in robots remains an open problem—albeit an interesting one, given that it necessitates improved understanding of human grasping and manipulation techniques. We build robots to automate tasks but also to provide tools for humans to easily perform repetitive and dangerous tasks while avoiding harm. Achieving robust and flexible collaboration between humans and robots is hence the next major challenge. Fences that currently separate humans from robots will gradually disappear, and robots will start manipulating objects jointly with humans. To achieve this objective, robots must become smooth and trustable partners that interpret humans' intentions and respond accordingly. Furthermore, robots must acquire a better understanding of how humans interact and must attain real-time adaptation capabilities. There is also a need to develop robots that are safe by design, with an emphasis on soft and lightweight structures as well as control and planning methodologies based on multisensory feedback. ■

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Read the full article at http://dx.doi.org/10.1126/science.aat8414

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Cite this article as A. Billard, D. Kragic, *Science* **364**, eaat8414 (2019). DOI: 10.1126/science.aat8414