SCIENCE ROBOTICS | FOCUS

ARTIFICIAL INTELLIGENCE

The future lies in a pair of tactile hands

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Advancing robot hand dexterity with optical tactile sensing raises questions about humanoid robotics.

Human-like robots are big business. This year, the company Figure AI raised $675 million to develop general-purpose humanoids. The company is currently valued at $2.6 billion. Tesla's Optimus robot handling an egg was front-page news around the world. According to Elon Musk, it has "the potential to be more significant than the vehicle business." Boston Dynamics was acquired by Hyundai for $1.1 billion. Its latest Atlas humanoid is scarily impressive, twisting its body like a contortionist. Musk responded by tweeting a photo of the twisted ghost from the Japanese horror film *The Ring*.

Investors are rushing in because they see humanoids as general-purpose robots that will serve humans to do our manual work. According to the mission statement of Figure AI, "our first applications will be in industries such as manufacturing, shipping and logistics, warehousing and retail, where labor shortages are the most severe." Human environments are designed for the human body, befitting a humanoid with legs, arms, torso, hands, feet, and a head. Mirroring humans in reality, our movies and media portray futuristic robots as humanoid in form, from C-3PO to the Terminator.

Henry Ford once said, "How come when I want a pair of hands, I get a human being as well?" Likewise, if the humanoid is intended for physical work, would not a pair of hands on any suitable robot be enough for most jobs? The rest of the humanoid just moves the hands to where they are needed. This question is important because in companies like Figure AI, Tesla, and Boston Dynamics, most of the money and effort goes into building and controlling the robot body. But if physical work is the aim, those resources would be better spent on building better hands co-designed with the AI to control them (*1*).

SIMPLE OBJECT HANDLING

The state of the art in using two robot hands to pick and place objects is demonstrated by Bauza and colleagues (*2*) in this issue of *Science Robotics* with their method SimPLE (Simulation to Pick Localize and placE). They consider precise pick and place: A jumble of known objects in unknown positions on a table must each be picked up, then placed in known locations with tight tolerances. For example, the objects could be variously sized bolts laid across a surface; the robot would pick up each in turn, reorient it, and place it in a specific socket that fits that bolt (Fig. 1A).

Sounds simple? Actually, it gives a nice example of Moravec's paradox that what is easy for humans is difficult for machines. The solution relies on combining three key technologies. Firstly, a pair of robotic grippers was installed on a bimanual robot such that a grasped object could be adjusted midtask by passing from hand to hand; for instance, a bolt lying on a table may only be graspable on its shaft but placing it in a socket requires grasping its head. Secondly, a three-dimensional computer model of each object was developed so that the grasps could be evaluated in simulation to plan where the robot will try to grasp the object. The position of a grasp determines whether the object is held stably, how it can be manipulated for placement, and which features are under the fingertips—all of these can be simulated and compared with a visual depth image from a camera placed above the scene. Thirdly, high-resolution tactile sensing improved the accuracy to reliably pick and place all objects that were tested.

Overall, visuotactile sensing together worked better than vision or touch alone. With just vision, the pick and place may still be possible, but the placement is more likely to fail; for example, inaccurate insertion of a rod into a tight holder may miss or clip the edge. These failures arise from the uncertainty in estimating the position and orientation of the held object relative to the fingertips (*3*), which determines how accurately the gripper can place the object. The object's pose can be measured from high-resolution tactile data by estimating indentation depth maps at each fingertip, then orienting the object model in simulation so that those indentations match on the object (*4*).

A RENAISSANCE IN ROBOT DEXTERITY

Tactile sensing helps by directly informing about how the robot's fingertips are contacting the object. However, a specific type of tactile sensor is needed: one that details the spatial geometry of the contact. The GelSlim sensor (*5*) used in SimPLE is a version of an optical tactile sensor relying on an internal camera, of which there are now many established designs, including the GelSight (*6*) and the TacTip family (*7*). Optical tactile sensing has taken off recently because digital cameras from mobile phones can fit comfortably within robot fingertips at a cost of just a few dollars.

Optical tactile sensing is creating a renaissance in robot dexterity. Five years ago, OpenAI showed that it is possible to learn complex manipulation skills with a human-like robot hand by rotating a cube held in hand through a sequence of goal orientations (*8*). However, their setup—a "cage" holding 19 cameras—meant that their methods relied on huge amounts of visual data around the hand. Clearly, this does not scale easily to other dexterous skills, because it is impractical to install lots of cameras. It has taken several years for tactile sensing to catch up, but very recently, several labs have demonstrated in-hand rotation of objects using touch (*9–11*). All of these demonstrations relied on using multifingered hands fitted with optical tactile

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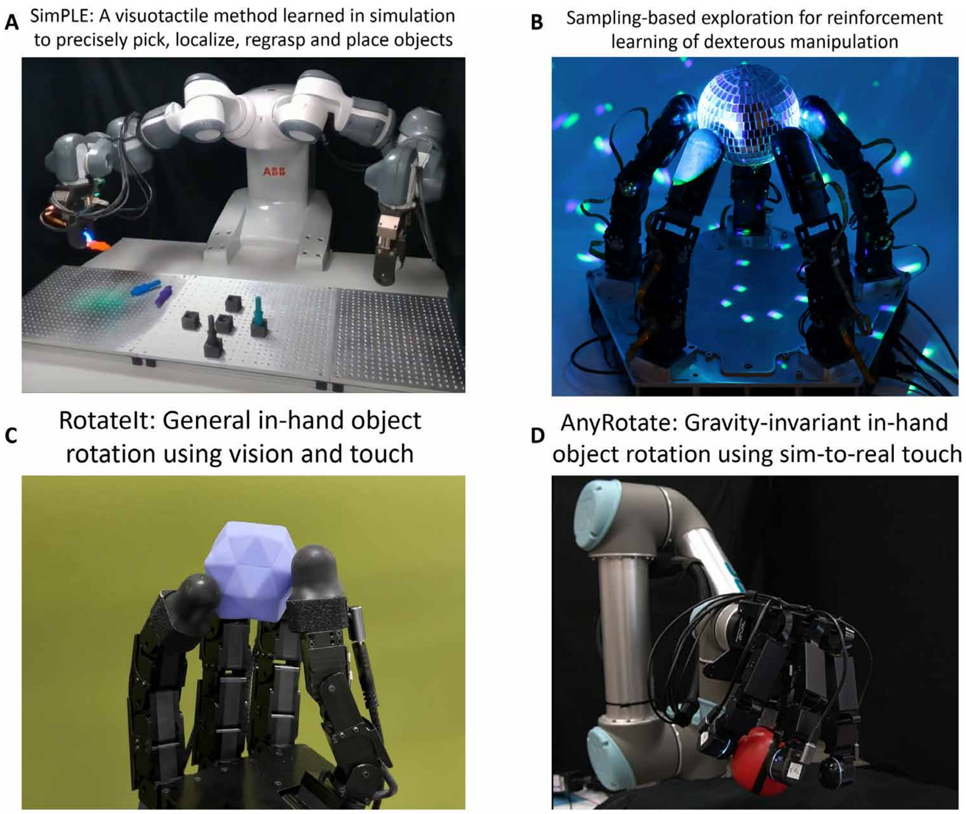

Fig. 1. State of the art in robot dexterity with optical tactile sensing. (**A**) SimPLE, with two high-resolution tactile fingertips on each of the two grippers of a bimanual robot (*2*). (**B**) Dexterous manipulation with optical tactile sensors on five fingers (*9*). (**C**) RotateIT, with four optical tactile fingertips on a robot hand (*10*). (**D**) AnyRotate, with four optical tactile fingertips on a robot hand-arm system (*11*).

sensors (Fig. 1, B to D). The cameras have found a home inside the fingertips.

Now, suppose the bimanual dexterity demonstrated by SimPLE is combined with the in-hand dexterity using multifingered tactile hands. The whole would be greater than the sum of the parts: Two hands could work flexibly together to impart greater dexterous control of held objects. At heart, the manipulation skills natural to humans are no more than a capability to precisely control the poses of held objects and the forces exerted, allowing us to handle a myriad of everyday items and tools from picking up a cup for a drink to checking a mobile phone for emails. Following this path, human-like manipulation may soon be within reach for robots. That future may lie within the grasp of a pair of tactile robot hands.

Supplementary Materials

The PDF file includes:

Legend for movie S1

Other Supplementary Material for this manuscript includes the following:

Movie S1

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