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ROBOTIC MANIPULATION

The unstable queen: Uncertainty, mechanics, and tactile feedback

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Tactile feedback is a natural pathway to robot dexterity in unstructured settings.

Uncertainty is at the core of robotic manipulation. Mason (*1*) recalled trying to program a robot to repeatedly pick up and put down a queen chess piece. When grasped from the top, the queen would end up falling after five or six pick-and-place cycles. The simple act of grasping and placing seemed to turn the queen "unstable." But this did not happen when the robot grasped the queen from the side.

Mason's insight was to consider uncertainty in the mechanics of contact and how the natural dynamics of physical interaction can be exploited to tame that uncertainty. This philosophy has motivated the development of many naturally stable manipulation strategies, for example, based on tray-tilting (*2*), squeeze-grasping (*3*), stable-pushing (*4*), or push-grasping (*5*) among many others. These strategies exploit natural invariances in the dynamics of manipulation, ensuring that they are used to reduce task errors. From a control perspective, we would say that in those strategies the dynamics of manipulation, without the need of sensing, define a negative passive feedback loop that regulates the task. In the case of the unstable queen, instead, the process of grasping and placing from the top defines a positive feedback loop that destabilizes the alignment of queen and gripper.

Using passive mechanical feedback, without sensors, is quite extended in industry. It makes sense; it leads to simple, efficient, elegant, and responsive solutions, by specializing to the task. Probably the most impactful and inspirational examples are the use of vibratory bowl feeders for automatic part orienting and the use of passive Remote Center of Compliance devices for automatic alignment in insertion tasks.

TACTILE FEEDBACK

Staying within the control perspective, sometimes it can be more effective to use a sensor-based feedback loop than a mechanical one—for example, using an optical encoder and a PID loop to control the speed of an engine or actuator instead of a mechanical governor. It is then natural to ask when it would be a good idea to use a sensor instead of mechanical feedback in manipulation control loops.

In a review on the state of the art on the use of tactile feedback, Lee (*6*) pointed out that, "There has been a longstanding and widely held expectation that tactile sensors would have a major impact on industrial robotics and automation. However, this promise has not been realized, and few, if any, tactile sensors can be found in factory-based applications." He goes on to justify that it is the structured nature of many industrial settings that reduces the potential benefits from the flexibility that tactile feedback provides. If sufficiently structured, highly engineered solutions will always win, so industrial settings that are structured or are susceptible to being structured might not be the most straightforward application for tactile feedback. The corollary is that, in unstructured settings, solutions that are designed to exploit the natural dynamics of manipulation will have a harder time.

The ability to deal with this type of unstructured uncertainty, such as when carefully reorienting an unknown grasped object or when controlling the forceful grasp on an oddly shaped handle, is key to building flexible manipulation systems. In these unstructured settings, with uncertain or unknown geometries, materials, and configurations, tactile feedback provides a natural means to regulate manipulation control loops. An emerging class of tactile sensors (*7*) collocated at the frictional contact surfaces of a robot (Fig. 1) provide accurate, dense, and timely feedback on the same variables that we use to model the mechanics of contact: spatial distributions of contact geometry and of contact forces, as well as the events captured by their derivatives, such as slip or making/breaking contact.

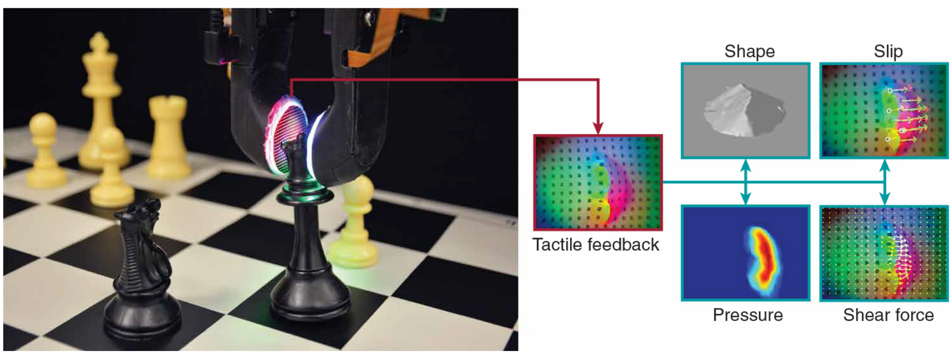

Fig. 1. Grasp of a queen chess piece making an edge contact with the board. Tactile sensors GelSlim (*7*) capture feedback of the physical interaction and estimate shape, slip, pressure, and shear force distributions.

BUT WHAT MANIPULATION CONTROL LOOPS DO WE NEED TO REGULATE?

The mechanics of frictional contact, even the approximations we commonly use in robotics, lead to complex dynamic systems that are underactuated and hybrid and consequently difficult to control. I believe a key role of tactile feedback, if not its key role, is to regulate manipulation around states that benefit from simpler dynamics.

Howe (*8*) writes in an early review on tactile sensing in robotic manipulation:

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"Human dexterity is a marvelous thing: People can grasp a wide variety of shapes and sizes, perform complex tasks, and switch between grasps in response to changing task requirements…in large measure, this control capability is founded on tactile and force sensing, especially the ability to sense conditions at the finger-object contact." These contact conditions that Howe refers to include contact modes such as making and breaking contact, rolling, or sliding.

I conjecture that regulating contact modes is one primary way by which tactile feedback control can simplify the dynamics of contact, for example, by enforcing that contacts are maintained/released or by preventing/regulating slip. The principle is to think of tactile feedback control loops as responsible for forcing contacts to behave more like the ideal models that we then use for simulation and planning. We have recently shown the use of regulated contact modes to facilitate dexterous manipulation of rigid and deformable objects with sticking (*9*) and sliding (*10*) contacts.

THREE TACTILE CONTROL PROBLEMS

Below I list three tactile-feedback control problems aimed at addressing the absence of accurate models of geometries, materials, or configurations:

1) Control of a single contact. Maintaining a contact mode (e.g., stick, slip, or desired pressure distribution) between a robot finger and its environment. The opportunity to observe the interaction firsthand through tactile feedback is matched with the challenge of adapting to an uncertain environment that can be fixed, or can be moving, or can be movable. This problem is related to skills like probing, contour following, or shared grasping.

2) Control of a multiple-contact configuration. Maintaining a contact mode in a multi-contact formation, for example, in the grasp of an uncertain or unknown object. Here the challenge is to regulate modes that involve the internal forces in a forceful stable grasp or modes involving the simultaneous sticking/sliding of contacts in fine object manipulation.

3) Control of an external contact. Maintaining a contact mode at the interaction between a grasped object and its environment—for example, the contact between the unstable queen and the chess board. The challenge now is in controlling an unsensed contact, indirectly through feedback at the sensed contacts at the grasp. This problem is related to skills like placing an object, guiding an insertion, or using a tool.

In summary, a key role of tactile feedback in manipulation is to simplify the dynamics of frictional contact. Robots can do this by regulating contact modes, for example, by enforcing that contacts slip or slide when they are supposed to. This improves our ability to simulate and plan complex dexterous manipulation. While the efficiency of mechanical feedback is desirable in many structured applications, the promise of robotics includes many unstructured settings such as agriculture, health care, or home service, where tactile feedback can help close the gap.

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