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Surprisingly Robust In-Hand Manipulation: An Empirical Study

Supplementary Material

Paper Presented at RSS 2021

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A. Detailed Description of the Spin and Shift Keyframes

We provide verbal descriptions of all seven *spin* keyframes and all six *shift* keyframes depicted in Figure 5 and analyzed in Section IV of the paper.

The *spin* movement:

- **KF1**: The tip of the little finger and the palm are inflated to move the object into the area spanned by the middle and ring fingers. In addition, the thumb tip and the distal bellow are inflated to move the thumb behind the object.
- **KF2**: The ring and middle tips as well as the proximal and middle below are inflated to clamp the object.
- **KF3**: The thumb tip is deflated to establish contact with the object. At the same time, the ring tip and the middle base are inflated to prepare the spin movement.
- **KF4**: The distal bellow and thumb tip are deflated while the ring tip is inflated to trigger the rotation.
- **KF5**: The middle bellow is inflated to prevent the object from falling out of the hand. This motion is executed fast compared to the other interpolations.
- **KF6**: Thumb tip and distal bellow are inflated to align the object with the ring finger.
- **KF7**: The ring base is inflated while the ring tip and the thumb tip as well as all bellows are deflated to ensure a proper transition to the shift movement.

The *shift* movement:

- **KF1**: The ring base is deflated again while the ring and little tips are inflated to form two walls against which the object is to be pressed. At the same time, the proximal and middle bellow are inflated to position the thumb for this push.
- **KF2**: The distal bellow is inflated to the press the object against the walls formed by the little and ring finger.
- **KF3**: Next, the thumb tip is inflated to press even stronger. The little base is inflated to prepare for the gait.
- **KF4**: The ring tip is deflated to remove the wall it formed. As a result, it slips down along the side of the object and slides underneath it to form a floor. This plays out as a finger-gaiting of the object to the sole remaining wall formed by the little finger.
- **KF5**: The distal bellow is deflated and the proximal and middle bellow are inflated to move the object towards the middle-ring area.
- **KF6**: The little base as well as the proximal bellow, the middle bellow and the thumb tip are deflated to release the contacts between hand and object. In addition, the palm bellow is inflated to place the object safely at the center of the palm.

B. The Control Program of the Twist + Pivot + MR-Gait + Shift Skill

The underlying air-mass control signal for the combined *twist* + *pivot* skill is depicted in Figure 11 while the respective air-mass signal for the *MR-gait* + *shift* is shown in Figure 12. In the following, we describe some interesting transitions in more detail.

Pivot: In the second keyframe-transition (5.8s – 6.0s, see Figure 11), the tip compartment of the index finger is inflated rapidly to pivot the object around the grasp-axis. In the subsequent keyframe-transition, the system is held constant for 2.5 seconds except for slight inflations of the thumb tip as well as the index base (6.0s – 8.5s). Throughout this transition, the index finger pushes against the object to induce the pivot-rotation, in case this does not happen immediately upon the index finger impacting the object. This is especially helpful for large objects that are slower to budge. Afterwards, a sudden inflation of the palm bellow strengthens the grip between thumb and middle/ring finger again (8.5s – 8.6s).

MR-Gait: In the second keyframe-transition (1.1s – 1.2s, see Figure 12), the middle finger's base and tip compartments are deflated, as fast as possible, to gait the object towards the ring finger. This movement unfolds near-instantaneously, catching the object between the thumb and ring finger before it has a chance to fall downwards to the palm.

Shift: Compared to the *shift* skill first depicted in Figure 5 and used for the *spin* + *shift* experiments in Sections III and IV, we performed three major updates. First, we added one keyframe-transition to the beginning, in order to position the thumb more effectively on the side of the object for the subsequent push (3.6s – 4.6s, see Figure 12). Second, we increased the deflation speed of the ring tip, to prevent the ring finger from dragging the object down (6.7s – 6.9s). Third, we added an additional keyframe at the end, involving an

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inflation of the palm bellow and the distal bellow, as well as the little finger's base and tip. This movement translates the object while keeping it slightly raised in the air, to prevent it from getting stuck in the crevice between the middle and ring fingers, and also to align the object with the little finger.

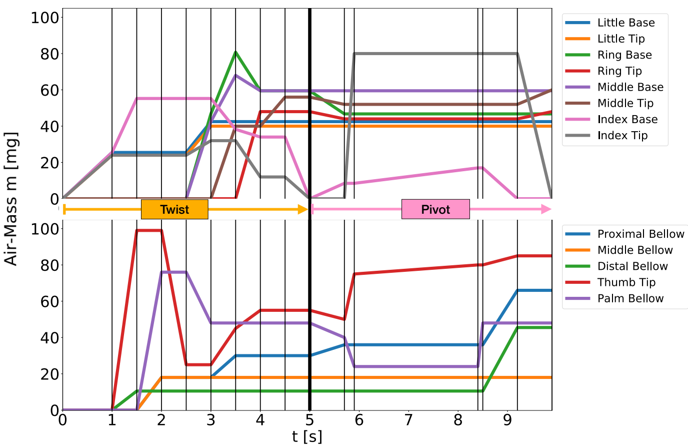

Fig. 11. **Air-mass actuation signal for the combined *twist* + *pivot* skill.** Each vertical line corresponds to an intermediate keyframe.

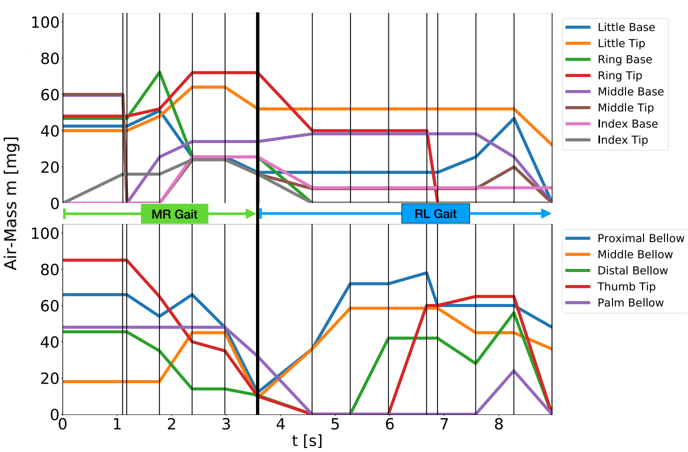

Fig. 12. **Air-mass actuation signal for the combined *MR-gait* + *shift* skill.** Each vertical line corresponds to an intermediate keyframe. The initial air-mass values at time 0s correspond to the last keyframe of the *pivot* skill shown in Figure 11.

C. Spelling Demo: Technical Description

In this section, we describe the technical setup for the spelling demo referenced in Section VI-C. The goal of this exercise was to demonstrate the ability to robustly execute long (and completely open-loop) dexterous manipulation sequences (video: https://youtu.be/tnq0xXMUbhc).

In this demo, the robot picks up, one by one, 5 cuboidal objects with different letters on their faces (see description of objects below), rotates them inside the hand, and places them back on the table to spell the word "FUNNEL".

Each of these five objects has a fixed initial position and orientation. We used yellow tape on the table as a reference for ourselves, so that we could quickly set up the scene. To be able to execute pick-and-place operations, we mounted the RBO Hand 3 onto the flange of the Panda arm. In addition to slightly updated versions of the skills presented in section II, we designed new skills to pick-up and place-down objects.
During **Pick-Up**, the hand moves to the position of the respective object. Afterwards, a *grasp* skill is executed (see Figure 13). With the object held in hand, the hand moves away from the table, and the wrist rotates to make the palm face upwards. Finally, the *lower* skill (see Figure 13) gently opens the fingers to place the grasped object onto the palm.
During **Place-Down**, the object is brought into a precision grasp via the *raise* skill (see Figure 14) which involves the thumb, middle and ring finger. While holding the object, the hand rotates and moves towards the table. Finally, the *release* skill (see Figure 14) opens the fingers to place the object safely back to its original position. The arm's movements are handcrafted for every object location on table, while the air-mass commands are the same for every object. The demo contains the following The open-loop manipulation sequence executed in the spelling demonstration is the following:

- **Cube (4.5cm)**: Pick-Up, Spin + Shift, Twist + Pivot + MR-Gait + Shift, Place-Down
- **Cuboid (6 x 4.5 x 4.5cm)**: Pick-Up, Spin + Shift, Place-Down
- **Rounded Cube (4.7cm)**: Pick-Up, Spin + Shift, Twist + Pivot + MR-Gait + Shift, Spin + Shift, Place-Down
- **Rubik's Cube (5.5cm)**: Pick-Up, Twist + Pivot + MR-Gait + Shift, Spin + Shift, Spin + Shift, Spin + Shift, Place-Down
- **Cube (4.5cm)**: Pick-Up, Spin + Shift, Spin + Shift, Spin + Shift, Twist + Pivot + MR-Gait + Shift, Place-Down

In between skills that are separated by a comma, all compartments of the RBO Hand 3 are deflated to rule out any drift in the low-level air-mass controller.

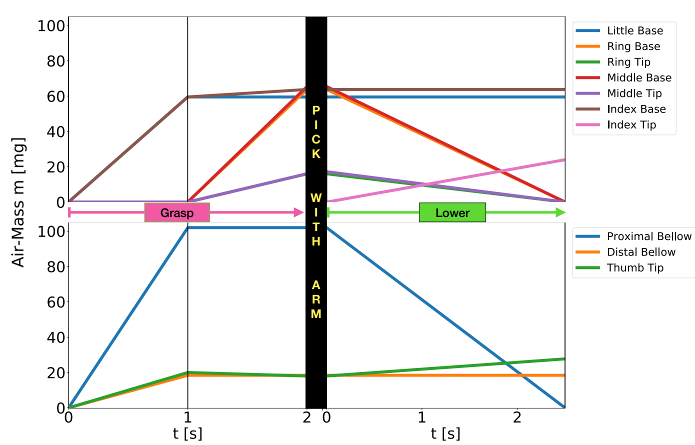

Fig. 13. **Air-mass actuation signal for the combined *grasp* + *lower* skill.** Each vertical line corresponds to an intermediate keyframe. In between those two skills the Panda is moving towards the respective pick-up location.

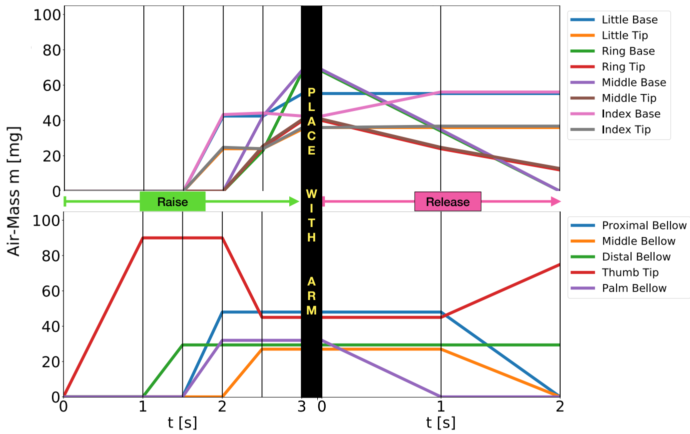

Fig. 14. **Air-mass actuation signal for the combined *raise* + *release* skill.** Each vertical line corresponds to an intermediate keyframe. In between those two skills the Panda is moving towards the respective place-down location.

D. Replacing Actuators and Influence of Frictional Properties

Between our experiments, we replaced actuators several times. Due to manufacturing differences, the properties of these actuators were slightly different each time. Therefore, we had to calibrate the maximum air-mass that corresponds to full inflation to achieve comparable inflation behavior. Since this behavior is highly nonlinear, we sometimes even had to adjust keyframes. This is currently done manually. In the future, we will work on an automatic calibration procedure.

During the course of our experiments, we observed that the frictional properties of the finger pulps are crucial for manipulation success, especially for movements that require sliding. With the first pulps we tried (made of *Ecoflex-30* silicone) the friction was too high. To reduce this friction, we massaged the hand with baby powder (brand name: *Penaten Puder*). In later pulp versions, we used a combination of *Slide STD/1 Surface Tension Diffuser* and *Ecoflex-30* for lower friction pulps to match our task requirements on the hardware-side.

This example illustrates nicely the possibilities emerging from the fact that the hardware is considered an integral aspect of the behavior generation process. The high-friction pulp setup could possibly be handled by a more complex control strategy. But by changing the frictional properties, we were able to come up with simple actuation commands that can make use of sliding.