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Exploring Dexterous Manipulation Workspaces with the iHY Hand

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1. Introduction

In the past several years, standards in experimental robotics have risen significantly. Robots are increasingly expected to be mobile, self-contained, and robust to the accidental collisions that inevitably accompany work in the real world. These requirements have placed particularly harsh constraints on robot hands. Fingers are also among the smallest and most fragile articulated links in a robot, as well as those most likely to make contact with the environment. In an effort to improve the capabilities of practical hands for experimentation, the authors have developed the iRobot-Harvard-Yale (iHY) hand in collaboration with iRobot Corporation and the Harvard BioRobotics Laboratory [1]. Aside from good grasping performance, which is present in a number of simplified or underactuated hands [2]～[7], one key design goal of the iHY Hand was to enable dexterous, within-hand manipulation of grasped objects. In this paper, we demonstrate some of this functionality, and in particular present experimental results characterizing the space of object configurations that can be reached by varying the hand's flexor tendon excursion from an initial tripod grasp, and without the need for sensory-intensive feedback control.

The iHY Hand, shown in **Fig. 1**, is a three-fingered hand with five actuators. Each finger is capable of rotating about the proximal pin joint, which is connected to a spring that returns the finger to a fully open configuration when unactuated. The distal joint of each finger is a compliant bending beam that principally moves in flexion, but also admits somewhat stiffer motion in twisting and out-of-plane bending. These added three-

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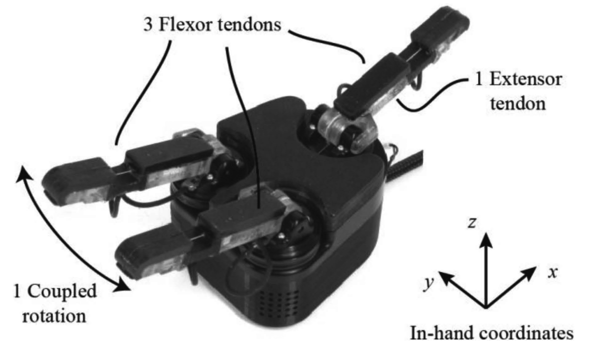

Fig. 1 The iRobot-Harvard-Yale Hand is a durable, self-contained hand that can be used to perform medium-complexity grasping and manipulation tasks. The coordinate axes shown denote the in-hand coordinate system used in this paper

dimensional deformational modes are useful for impact resistance, and for conforming to the surface of objects that are misaligned with the contact surfaces of the fingertip. Each finger has a single non-backdriveable flexor tendon that is inserted distally, so that both joints are actuated when the tendon is contracted. The fourth actuator rotates two fingers symmetrically on the palm, which enables a transition between a cylindrical wrap grasp, a tripod or spherical configuration, and a directly opposed configuration. Finally, a fifth degree of freedom allows the antagonistic actuation of the non-rotating finger, so that the distal and proximal thumb links can be independently moved (Fig. 1). For the experiments in this paper, only the flexor tendons were used to pinch the object. The finger rotation was held fixed in the spherical configuration illustrated in **Fig. 2**, and the antagonistic tendon was left slack.

2. Measuring Tripod Pinch Manipulation

When the iHY Hand acquires a three-finger pinch on an object, the hand and object form a parallel structure that can be manipulated like a platform, as seen in Fig. 2. It is difficult to exactly model the kine-

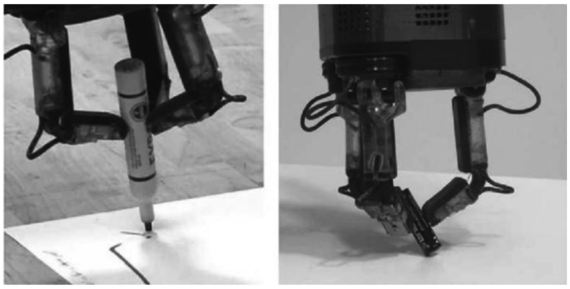

Fig. 2 From a tripod pinch grasp, the tendons can be moved to adjust the position and attitude of a grasped object while remaining passively stable due to the compliant adaptive finger design

matics of the hand's constrained motion, because the three-dimensional deformation of the flexure joints and the rolling contact at the fingertips both add significant modeling complexity, including nonlinear large-deformation elasticity and stick-slip frictional contact. Furthermore, the rolling contact between the fingertips and the grasped object will introduce non-holonomic constraints to the mechanism, as seen in Ref. [8] [9], so that even a perfect model will produce path-dependent results rather than a closed-form function capable of describing clear limits to the object's motion. However, many practical manipulation problems involve only short, point-to-point repositioning operations, such as the task of picking up a peg and reorienting it to insert into a hole. In these cases, the path-dependent effects that scale with the time or path length of the object will be relatively small. One could therefore characterize the feasible workspace of configurations that can be reached starting from some initial symmetric pinch grasp along a short path (thereby disallowing configurations that might be reached by very long rolling motions).

In order to characterize this feasible workspace, an iHY Hand was attached to a frame above a fixture holding the test object, as shown in **Fig. 3**. The test object, a 60 [mm] ABS sphere weighing 23 [g], was grasped by the hand from the fixture, and brought to a central pinched configuration, where its position and attitude were measured by an Ascension TrakStar magnetic tracking sensor embedded in the center of the sphere. The hand and object were then commanded to move in a straight line to a pre-set location in the tendon excursion space, where the object position and attitude were again measured. The object configuration relative to the initial pinch was recorded as a point in the

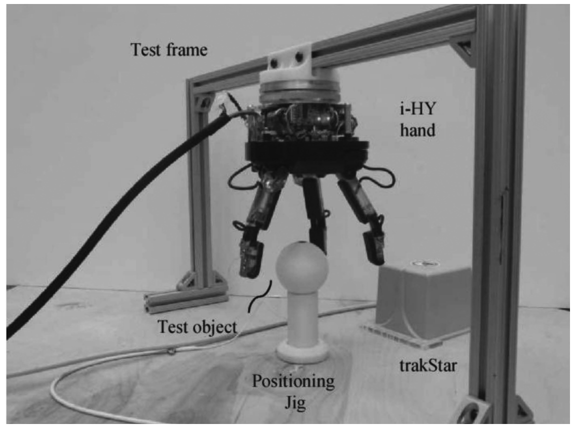

Fig. 3 The space of manipulable object configurations was measured by holding a spherical object in a tripod pinch grasp, then adjusting the tendon excursions to reposition and reorient the object. Measurements were performed with an Ascension Technology TrakStar system. After each manipulation operation, the object was released and regrasped from a fixture to ensure a repeatable measurement

workspace. Rather than moving the object from point to point, which might incur errors due to the violation of the short-path assumption, the object was moved back to the central pinch configuration and released after every measurement. This return to home before release also enabled the measurement of the slippage and rolling of the object. The cyclic displacement was also used as a test to determine whether the object had been dropped during manipulation, so that the measurement process could be automated to some degree. If the round-trip positional error was greater than 25 [mm], or the round-trip angular error was greater than 0.25 [rad], the point was removed from the workspace. The three-dimensional grid of tendon excursions explored in this manner was set in increments of 1.57 [mm].

3. Results

Figures 4 and **5** depict the short-path reachable workspace, as three-dimensional scatter plots in positional and attitude coordinates. The positional coordinates (Fig. 4), expressed in the coordinate system shown in Fig. 1, measure the displacement of the sphere's center from the initially pinched configuration. The x-y projection of the Cartesian workspace is approximately a circle of 20 [cm] diameter. Approximately 40 [mm] of motion is possible in the z direction (normal to the palm). Some asymmetry is observed in the Cartesian workspace; this is most likely due to asymmetric fric-

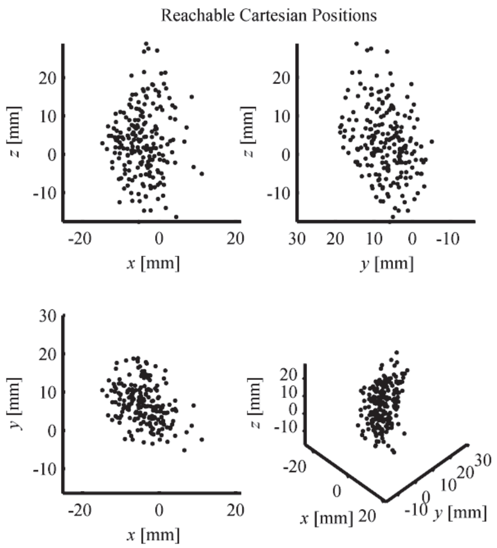

Fig. 4 The measured Cartesian workspace, as measured by the center of a grasped spherical object

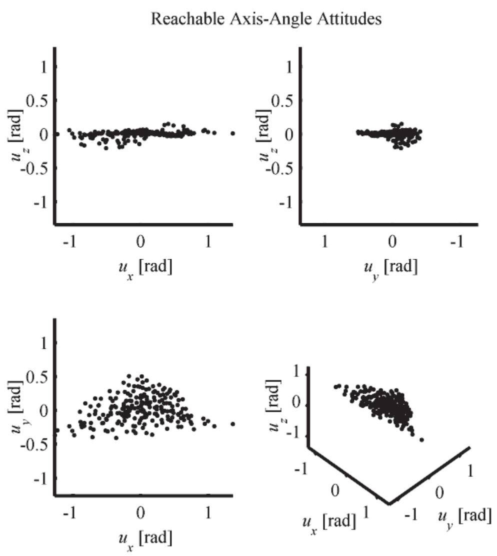

Fig. 5 The measured attitude workspace, plotted in Cayley-Rodriguez (exponential) coordinates. Here u_x, u_y, and u_z denote rotations about the x, y, and z axes as depicted in Fig. 1. Virtually all of the rotational workspace is comprised of rotations about axes parallel to the palm

tional conditions on the fingertips, and possibly a slight asymmetric misalignment of the rotating finger pair.

In many ways, the angular workspace achievable through in-hand manipulation is more important than the Cartesian workspace. A robot hand is typically mounted on an arm capable of providing fine adjustments to the wrist position. However, the ability to rotate a grasped object with a robot arm is often limited by the fact that an arm naturally produces rotations about its joint axes, located far from the object's center. As a consequence, achievable wrist attitudes are often more limited than achievable positions. The angular workspace of the iHY Hand for 60 [mm] spherical object is represented in Fig. 5 using Cayley-Rodriguez coordinates, that is, a vector u which is converted into a rotation matrix via the exponential map for so (3),

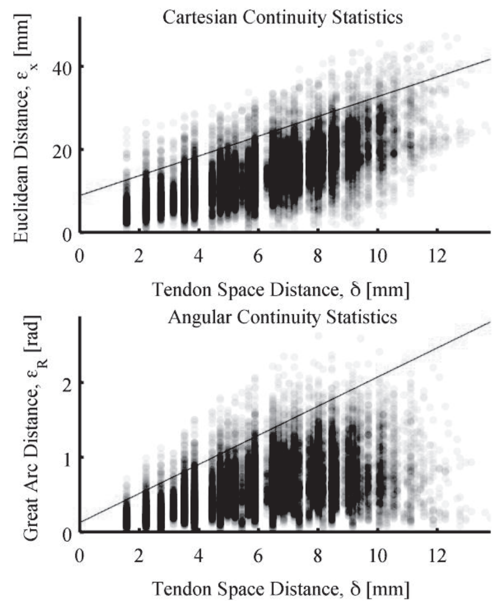

Fig. 6 The delta-epsilon continuity of the tendon-to-workspace mappings was tested by plotting the distance between all points in tendon space against the points in Cartesian and axis-angle coordinates. The solid line indicates the trend line fit to the 95th percentile in each column as the distance in tendon space becomes small (< 5 [mm]). These results indicate that the angular workspace is K-continuous to within 0.1 radians, and the Cartesian workspace is K-continuous to within 8.5 [mm]

$$R = \exp(\hat{u}) = I + \frac{\hat{u}}{|u|}\sin|u| + \frac{\hat{u}^2}{|u|^2}(1 - \cos|u|) \quad (1)$$

The direction of each point in the plot represents the principal axis of rotation for the object's attitude; the distance of the point from the origin represents the great-circle magnitude of the rotation in radians. The x-y projection of the attitude workspace in **Fig. 6** shows that arbitrary rotation of an object about an axis within the plane is possible at magnitudes up to 0.5 radians. However, the x-z and y-z projections indicate that rotation about the z direction is not possible. This is due in large part to the design choice not to include asymmetric adduction/abduction at the base of the fingers, as most robot wrists can provide motion about this axis.

The angular workspace is also somewhat asymmetric.

As the object is rotated in the negative y direction, a larger range of x rotation is possible. This is not due to any error, but to the asymmetry of the palm. The pair of rotating fingers on the iHY Hand (shown left in Fig. 1) are opposed to the third, stationary finger. When the object is pressed against the stationary finger so that the fingertip can act as a pivot point, the two paired fingers can be moved in and out relative to the palm, producing larger x axis rotations. In this region, a 2 radian range of x rotation is possible.

4. Workspace Continuity

Many of the configurations included in the workspace shown in Fig. 4 and 5 were reached by slipping as well as rolling along the fingertips. While slippage is often thought of as undesirable, in many cases it is unavoidable, and can be usefully exploited to transition an object into a desired grasp, for example, from a pinch grasp to a power grasp [1]. In the context of dexterous manipulation, the most important question is not whether the object slips, but rather whether the workspace of the object remains continuous despite slippage. If this is the case, then many techniques for learning, estimation and adaptation should still be applicable despite inexact models. Given a grid of measured workspace points, continuity can be assessed by comparing pairwise distance between the i^{th} and j^{th} measurements in the input space of tendon excursions, δ_{ij}, to the distance between the i^{th} and j^{th} measurements in the positional and attitudinal workspaces, $\epsilon_{x,ij}$ and $\epsilon_{R,ij}$. By comparing the input-output distances, a linear bounding relationship can be established in the form:

$$\epsilon_{ij} < a \cdot \delta_{ij} + K \qquad (2)$$

If this is the case, then the mapping can be said to be uniformly K-continuous, that is, the rate of change between input and output distance is bounded, and some noise floor exists as represented by the offset, K. Each pair of measurements was processed to examine the workspace continuity. Pairwise distance in the tendon excursion space and the positional workspace were measured using a Euclidean norm, while the great arc distance between two attitudes ($\boldsymbol{R}_i$ and $\boldsymbol{R}_j$) was computed using the norm of the matrix log of the relative rotation between the pair:

$$\epsilon_{R,ij} = |\log(\boldsymbol{R}_i^{-1}\boldsymbol{R}_j)^{\vee}| \qquad (3)$$

The resulting distances were compared to each other in Fig. 6. These scatter plots show that despite the some noise, the vast majority of the sampled configurations exhibit noisy but K-continuous behavior. The pairwise tendon distances are arranged vertically in columns because the gridded tendon space produced discrete sets of pairwise distances. The lines drawn on Fig. 6 are fit to the 95th percentile values for each column of pairs having a distance in tendon space smaller than 5 [mm]. This means that the distance between 95 percent of closely neighboring configurations can be bounded from above by a line whose vertical intercept of the line indicates that the data has a noise/repeatability floor. In Cartesian space, the vertical intercept K_x is 8.5 [mm], and in attitude space, the vertical intercept K_R is 0.1 radians. Some of this is due to measurement error; the TrakStar sensors claim an accuracy of 2 [mm], and four measurements are stacked up to determine the distance (two in each of the points compared, because the workspace is a relative offset from the initial pinch grasp). Another source of possible error is the presence of metal components in the iHY hand, which can cause distortion. Despite the noise, these results are encouraging evidence that the workspace continuity is sufficient to apply manifold learning and adaptive control techniques for higher-level planning and control on top of these passively stable primitives.

5. Conclusion

These experiments performed on the iRobot-Harvard-Yale Hand demonstrate that three-dimensional, in-hand manipulation is possible with a simplified robot hand. More importantly, this manipulation capability requires no feedback control for stabilization, thanks to the intrinsic compliance of the fingers and the adaptive, underactuated design of the iHY Hand's tendon transmission. A number of future directions for work with the iHY Hand are clear from these results. First, while the exact kinematics of a real hand in contact with a real object are very difficult to predict from first principles, it may be possible to construct gray-box models of the hand having a relatively small parameter space, so that fast machine learning and adaptive control techniques can be used to infer the workspace of an unknown grasped object from a small set of measurements, rather than a systematic grid of data. Second, although they were not used in these experiments, the iHY Hand contains a large number of highly sensitive contact sensors, which can be used to actively inform kinematic models of manipulation. Finally, in the future, fully closed-loop manipulation can be implemented using vision and other advanced imaging modalities.

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