Not Twisting Your Arm: Combining Grasping and Rotation in a Single Robot Hand Mechanism

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Abstract*—Object reorientation plays a vital role in dexterous robot manipulation tasks such as turning doorknobs or aligning a key. For robotic systems, this is most often done with a simple gripper attached to a 3-DOF wrist. But wrists are mechanically-complex, and the wrist axes are often far from the grasped object, resulting in parasitic translations and awkward whole-arm motions. We present the Sphinx robot hand that can both grasp and then rotate a wide range of objects in all three axes about a known fixed point within the hand and close to the object, replicating much of the function of traditional wrists. The mechanism of the hand is such that all the fingers' revolute axes intersect at a common point (independent of object shape, pose, or grasp), and all manipulated poses of objects are at a fixed distance from this point. We detail the spherical parallel design and workspace model of the wrist-like hand, validate its performance especially for lower-DOF robot arms without traditional wrists and show that it can accurately rotate objects over large angles with open-loop control. The Sphinx hand will be made available as open-source hardware through the Yale OpenHand project and experimental results can be seen in the video at: `https://youtu.be/EPUDe4hbHBk`.

I. Introduction

DEVELOPING robot hands that can perform tasks in unstructured human environments remains a key challenge in robotics. For industrial applications, such as on assembly lines, specially designed single-purpose grippers ensure certainty in the end-effector's interactions with objects in the surroundings. However, for the goal of robots robustly performing tasks in unstructured human environments, such as our homes, they need to be equipped with more general-purpose hands that can predictably manipulate a wide variety of objects [1].

Traditionally, robot manipulation is done first by grasping an object using a robot gripper or hand, with subsequent object motions brought about by the robot's arm, not by the hand itself. In many applications, grasped objects need to be reoriented along multiple rotation axes. For this purpose, robot arms usually rely on whole-arm motions to change the object orientation, typically with active wrist joints. Dexterous wrists, in particular, can be very useful and can significantly improve the overall manipulation capabilities of the arm/hand system [2].

Generally, wrist joints are expected to orient grasped objects about all three rotation axes with minimal coupled translations that would need to be compensated with proximal arm motions. This 3 degrees-of-freedom (DOF) manipulation carried out by robotic wrists is achieved through some common design objectives [2]. To achieve pure spherical rotations, wrist joints should be located as distally close to the grasped object as possible, with the axes of the wrist joints intersecting at a single point in space. These design objectives along with the need to route electronic cables through the middle for grippers or other terminal devices make the wrist one of the most mechanically-complex components of robotic arms.

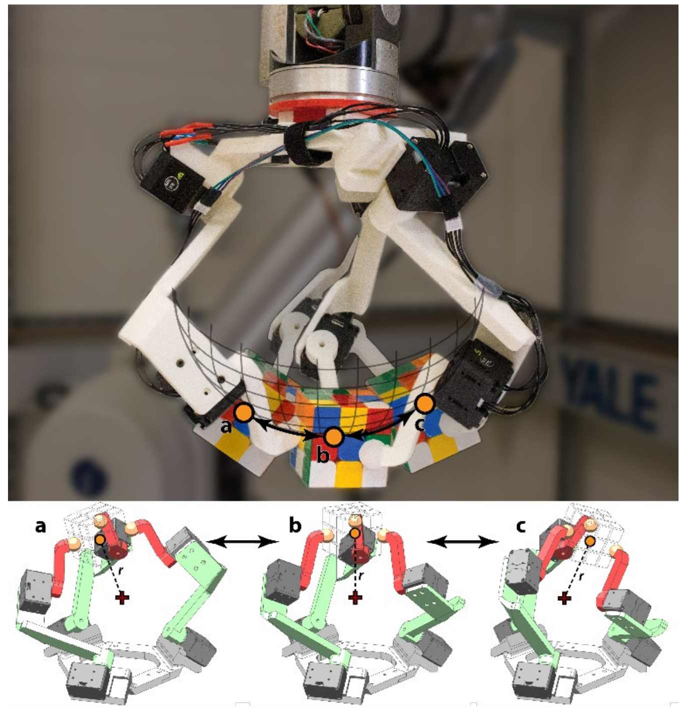

Fig. 1. Sphinx hand can rotate a variety of grasped objects on known spheres about a fixed center marked by the red cross. A sample manipulation sequence on one of the YCB objects along with a schematic from a different view of the hand is shown below.

While simple grippers mounted on 6 or 7-DOF manipulators with active wrist joints may be able to reorient grasped objects, these robot arms may have offset wrist axes – which can be over 30 cm away from the object – and require inefficient and awkward whole-arm motions to achieve pure rotations of the object. It can be more desirable to carry out rotations *in-hand* i.e., change the object orientation with respect to the hand frame, which is generally also how humans do it, with a range of strategies [3]. Moreover, robot hands with the ability to rotate objects *in-hand* can be highly beneficial, particularly for lower-DOF wrist-less robot arms

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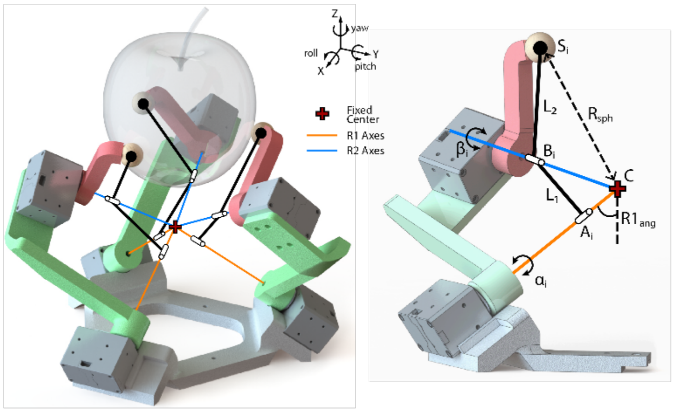


(a) (b)

Fig. 2. Sphinx hand topology and implementation. (a) A model of the hand illustrates the intersecting revolute axes of all 3 fingers. (b) The physical implementation of the Sphinx finger, and the design parameters pertinent to workspace modelling and optimization.

such as SCARA, Delta, Cartesian, and other 4-axis robots.

Although this type of *in-hand* manipulation is innate to how humans execute everyday tasks, it is significantly more challenging for traditional robot hands that are usually composed of serial, fully actuated fingers. If there is insufficient sensor information or too much actuation latency at any point, the object may be dropped. As a result, these hands are often limited to manipulation in controlled settings.

In this work, we present the Sphinx (Spherical Parallel Hand with INtersecting aXes) hand—inspired by a spherical parallel mechanism, this hand can stably grasp and perform wrist-like rotations predictably with unknown objects about a known center (Fig. 1). This center is fixed in the hand's frame at the intersection point of the fingers' revolute axes, and the motion of any grasped object is on a sphere with this point as its center. The Sphinx hand is tested through a series of experimental characterizations, and teleoperated and automated manipulation tasks. The teleoperator inputs ±2° rotation increments in the object frame (not joint space) about one of the 3 principal axes. We find that, even with a simple open-loop control, this hand can achieve accurate multi-DOF rotations over large workspaces for a variety of objects and can effectively combine the functions of both a gripper and a 3-DOF wrist. We also simulated feasible manipulation workspaces for the Sphinx topology with different objects and found an optimal set of design parameters for the hand.

II. The Sphinx Hand

The proposed Sphinx hand is a transformation of the 3-RRS spherical parallel mechanism (SPM) into a robot hand (Fig. 2) [4]. The kinematic properties of the SPM will then transfer to this hand and allow it to manipulate any object on a sphere, such that the sphere's center is at the intersection of the fingers' revolute axes. The two revolute joints in each leg or "finger" of the mechanism are transferred over as-is to the fingers of the hand. The revolute axis closest to the base is actuated in a 3-RRS mechanism, but in developing it into a hand, we add actuation to both the revolute axes on each finger. The spherical joint at each leg of the SPM is modelled as a point contact with friction at the fingertip since both have the same 3-DOF mobility and are kinematically equivalent [5].

Once this overall architecture for the hand is established, a complete computational model of the Sphinx hand is built to simulate how the different design parameters affect its workspace for various object sizes. A design optimization study is then conducted with a quality metric that considers measures such as friction stability at the contacts and force transmissibility through the fingers during manipulation.

The performance of the optimized Sphinx hand is experimentally validated through a series of tests that begin with characterizing the actual workspace of the hand (Fig. 3). Then, the rotation capabilities of the hand are evaluated on a wide variety of everyday objects of different shapes, sizes, and weights. And finally, the hand is mounted on two different wrist-less robot arm configurations to carry out a range of automated and teleoperated manipulation tasks that mimic real-world applications. The videos of robot arm experiments can be found at: `https://youtu.be/EPUDe4hbHBk`.

References

[1] C. Piazza, et al., "A century of robotic hands," *Annual Review of Control, Rob., and Autonomous Systems*, pp: 1-32, 2019.

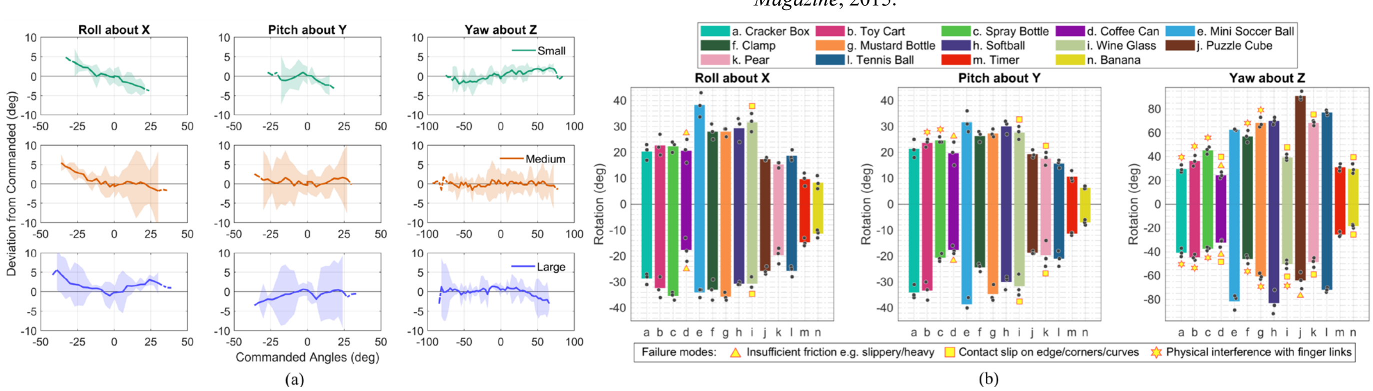
[2] N. M. Bajaj, et al., "State of the art in artificial wrists: A review of prosthetic and robotic wrist design," *IEEE Trans. on Rob.*, 2019.

[3] I. M. Bullock, et al. "A hand-centric classification of human and robot dexterous manipulation." *IEEE Trans. on Haptics*, 2012.

[4] R. Di Gregorio, "The 3-rrs wrist: a new, simple and non-overconstrained spherical parallel manipulator," *J. of Mechanical Design* 126, 850, 2004.

[5] N. Rojas, A. M. Dollar, "Classification and kinematic equivalents of contact types for fingertip-based robot hand manipulation," *J. of Mechanisms and Rob.*, 8, 2016.

[6] B. Calli, et al., "Benchmarking in manipulation research: Using the Yale-CMU-Berkeley object and model set," *IEEE Rob. & Autom. Magazine*, 2015.



(a) (b)

Fig. 3. Some of the experimental evaluations with the Sphinx hand. (a) Workspace characterization along the principal rotation axes for 3 test objects. (b) Evaluation with real-world objects from the YCB Object Set [6], and any observed failure modes for if the grasp on object is lost.