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Benchmarking Planar Rotation Capabilities of Robot Hands with Fingers

John Morrow, Joshua Campbell, Ravi Balasubramanian, and Cindy Grimm

Abstract— **Rotation manipulation tasks are a fundamental component of manipulation, however few benchmarks directly measure the limits of a hand's ability to rotate objects. This paper presents two benchmarks for quantitatively measuring the rotation manipulation capabilities of two-fingered hands. These benchmarks exists to augment the Asterisk Test to consider rotation manipulation ability. We propose two benchmarks: the first assesses a hand's limits to rotate objects clockwise and counterclockwise with minimal translation, and the second assesses how rotation manipulation impacts a hand's in-hand translation performance. We demonstrate the utility of these rotation benchmarks using three generic robot hand designs: 1) an asymmetrical two-linked versus one-linked gripper (2v1), 2) a symmetrical two-linked gripper (2v2), and 3) a symmetrical three-linked gripper (3v3). We conclude with a brief comparison between the hand designs and a observations about contact point selection for manipulation tasks, informed from our benchmark results.**

I. Introduction

When designing robot manipulators, systems which consist of an arm and a hand, it is important to consider how well the arm and the hand synergize. Not knowing what a hand is capable of makes it unclear whether a hand can compensate for the arm in difficult scenarios, such as in constrained environments [1].

Rotating an object in place is perhaps the most difficult movement for an arm to accomplish in constrained environments because it could require coordinated movements at multiple joints (see Figure 1). Therefore, knowing how well a hand can rotate objects is necessary for creating effective manipulator systems, however there are no existing methods for characterizing a hand's ability to rotate objects.

Specifically, current benchmarks measure performance on a task which has inherent rotation requirements (consider [2], [3], [4], [5]) and primarily focus on characterizing high-level aspects of that task. These task-based benchmarks do not directly characterize the limits of a robot hand's capabilities, and so it is difficult to compare one hand's *overall* ability to rotate with another hand's ability. This makes it difficult to compare results between hands because it provides a limited understanding of what aspects of a hand make it better than another.

In contrast, object-centric benchmarks [6], [3], [7], [8], [9], [10], avoid including the hand in the characterization. By measuring the movement of an object in the hand — rather than how the hand itself is moving — these benchmarks

All Authors are with the Collaborative Robotics and Intelligent Systems (CoRIS) Institute, Oregon State University, Corvallis, Oregon 97331 [morrowjo, campjos, balasubr, grimmc]@oregonstate.edu

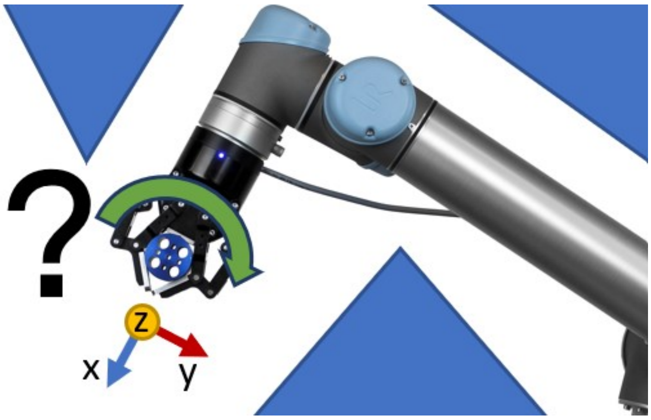

Fig. 1: *The Problem:* Robot arm cannot rotate object in place around Z on its own without coordinated arm movements that may be impossible to perform in constrained environments (such as human homes). Lacking a direct characterization of a hand's ability to rotate objects in-hand hampers efforts to design and understand hands synergize effectively with robot arms.

capture the effective combination of actuation and kinematics for a single motion without re-grasping. These simple benchmark motions could be strung together to evaluate the feasibility of more complex in-hand motions.

This work proposes object-centric benchmarks to *directly* measure a hand's ability to rotate an object— measuring (1) a hand's ability to rotate an object in place (Figure 2) and (2) how actively rotating objects impacts its ability to subsequently translate the rotated object within its workspace without regrasping (Figure 3).

We accomplish (2) by combining our rotation characterization with an existing object-centric benchmark for in-hand translation called the Asterisk Test [6]. Studying rotation+translation ability enables the study of tasks which combine rotation and translation in constrained environments, for example, picking a small fruit in bushes or apples in trees ([11]), which requires a twist (rotation) and then a shearing motion (translation) to pluck correctly.

We demonstrate both the rotation-only and rotation+translation tests on generic robot hand designs using Physical Human Interactive Guidance (PHIG), using a methodology similar to our previous work [12], [6]. Please note that using PHIG is not required for the asterisk test benchmark, but is used in this paper to gather data for multiple hand designs.

Contribution: We propose rotation-only and rotation plus

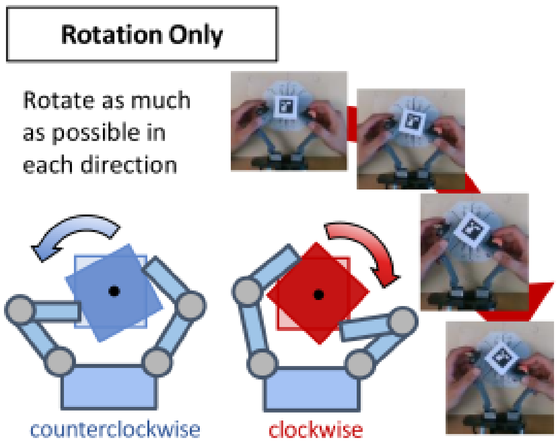

Fig. 2: We extend the Asterisk Test with two test sets which characterize a hand's ability to rotate objects. The first test (shown here) measures how well a hand can rotate an object in place without translation.

translation (R+T) tests to complement the translation tests in previous work (the Asterisk Test). We evaluate the benchmark by quantitatively assessing the rotation capabilities of three robot hand designs with increasing dexterity.

II. Related Works

Rotation is fundamental to manipulation and most methods indirectly measure a hand's rotational ability due to the necessity of in-hand rotation in the tasks they are measuring [2], [13]. For example, the box and block [4], rubik's cube [3], and NIST peg in hole [5] tests provide opportunities for robot hands to rotate objects, however rotational movement is not directly benchmarked. Another NIST benchmark considers rotation capabilities as part of a larger objective, such as characterizing a robot's ability to change an object's orientation [10]. In addition, co-design methods, which optimize both a hand's morphology and actuation scheme at the same time, benchmark complex manipulation trajectories which can include a combination of both object translation and rotation [14].

Other work has characterized rotational ability in ways unique to the robot hand being characterized. For example, the Model GR2 [15], Model Q [16], [17], and Model W [18] Yale OpenHand designs characterize their designed method of rotation outside of a manipulation scenario. Further, the Model Q [16] and Model W [18] characterizations include regrasping for rotation manipulation.

This work directly characterizes the *limits* a hand can rotate an object without regrasping. This includes a characterization of how well a hand can rotate an object (while penalizing translation, which differs from [15]) and how rotating an object can affect how well a hand translates an object. Similarly, it should be noted that this work differs from [10] because it characterizes rotational limits and not a hand's ability to reorient objects.

III. The Benchmark

We define two test sets for measuring a robot hand's ability to rotate an object in-hand without re-grasping, which test: 1) the performance limits a hand has on rotating objects in place (rotation-only, Sec III-A), and 2) discretely coupling rotation and translation movements to observe the effect that rotation has on translation performance (rotation+translation, Sec III-B).

We chose to couple rotation and translation in this order, out of the infinite ways they could be combined, due to practical concerns — most hands could not do the reverse combination (translation+rotation) well. We use a discrete combination because it enables an easy comparison to translation-only data from previous work [6].

We chose to use a square object for our tests because it has well-defined sides and enables easier sliding and rolling, particularly when grasping the corners. A cylinder is an obvious second choice, which would allow continuous rolling contact. We discuss further details of how to implement the Asterisk Test rotation tests in Section III-C.

A. *Rotation-Only Test*

In this test set, we separately test a hand's ability to rotate in both clockwise and counterclockwise manner, with no desired translation. The objective of the rotation-only test is to maximize rotation with as little translation as possible.

We require contact to stay on the side that the fingers originally contacted. Re-grasping an object is not allowed, however the *position* of the contact can still be changed (i.e. sliding or rolling) as long as it does not round a corner to another side (if there are defined sides on the object; ex: a cube).

We capture the x, y, and θ coordinates of the object throughout each trial. A trial ends when the hand can no longer move the object in the testing direction. The maximum rotation values achieved in a trial are also recorded separately. We visualize this information in a custom donut chart, with the average translation shown in the center. We disallow trials with substantial translation (0.1 normalized distance, calculated from the hand's dimensions [19], [6]). Whether these trials are repeated until successful or labeled as a zero rotation is up to the trial coordinator, who is best able to determine if the trials are do-able without substantial translation.

B. *Rotation + Translation Task*

We test for the impact that rotation manipulation has on translation performance by discretely combining rotation and translation tasks.

Before translation can occur, we require an approximately 15° rotation to the object (trials are repeated for both clockwise and counterclockwise directions). We chose this limit empirically to allow as many hands as possible to be able to complete the test while still having a discernible rotation.

The translation component is the same as a normal translation Asterisk Test — moving the object in each direction

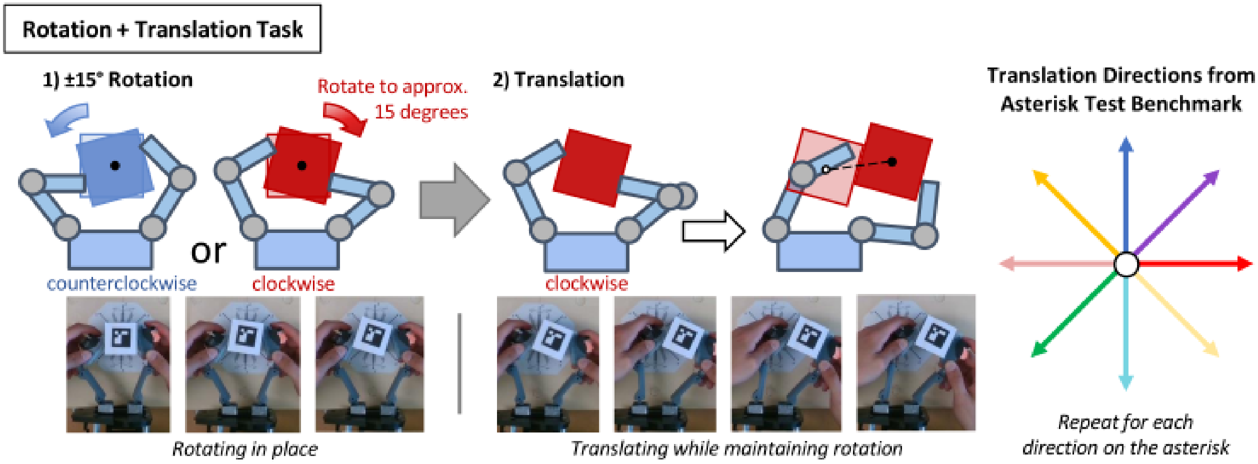

Fig. 3: The second test set focuses on combined rotation and translation tasks. This test separates both components discretely into two steps: 1) rotation in place to approximately 15 degrees (repeating for clockwise and counterclockwise rotation), and 2) translation in a direction of the asterisk. This test resembles picking small fruit.

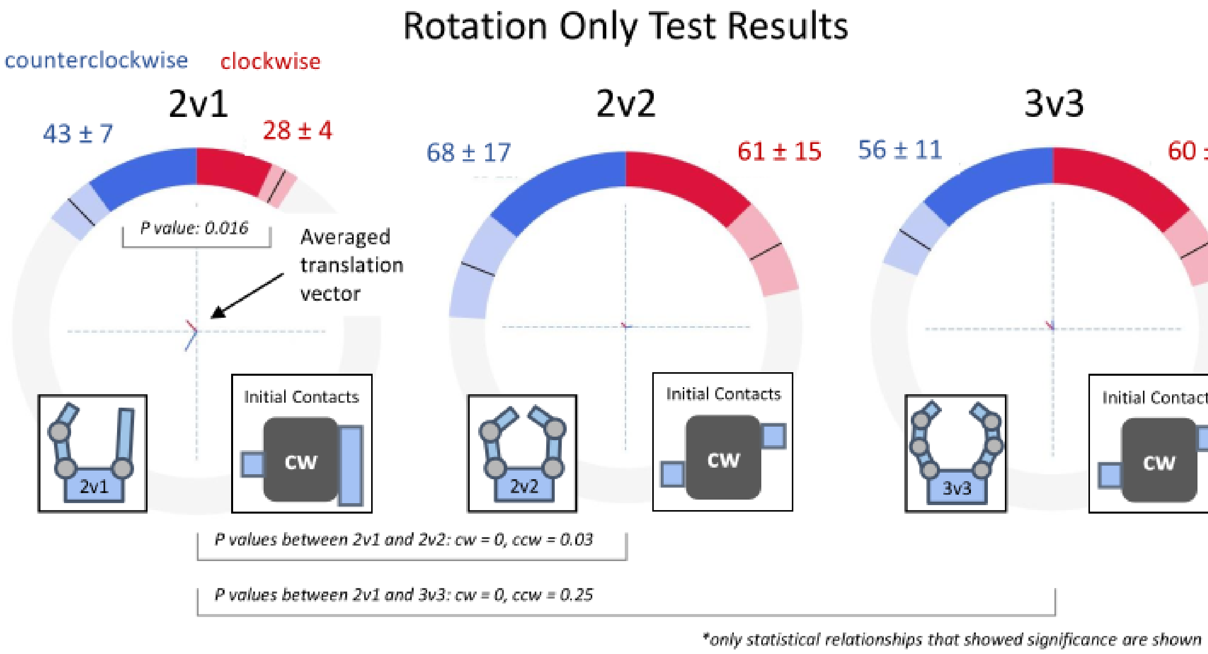

Fig. 4: Rotation-only results. Shows clockwise and counterclockwise rotational ability for 1v2, 2v2, and 3v3 hands. In the center of each circle is the average displacement that occurred during the rotation, which is normalized by the hand's size. Only statistical relationships with a significant difference are shown. Also shown are the most common initial contact positions for the clockwise rotation for each hand, in the bottom right of each plot.

of a 2d asterisk on a surface as far as possible and as close to the desired direction as possible with no re-grasping.

In summary, the R+T task is: 1) first the hand must rotate the object to $\pm 15^\circ$ in the center of the asterisk, then 2) the hand must translate the object in the direction of the trial, while maintaining the 15° rotation as best as possible. During the translation, we require the object to maintain that rotation to the end of the translation, $\pm 10^\circ$. The contact conditions are the same as in the rotation-only trials.

If more than 10% of a trial's translation takes the object outside of a $\pm 25^\circ$ zone around the desired direction then we also consider that trial a failure. As above, if the trial fails, it can either be re-done or considered a zero translation.

We capture the x, y, and θ coordinates of the object throughout each trial. We use the eight metrics used in previous work [6] to quantify performance; many of these contain a penalty for undesirable rotation. For simplicity in this paper we focus solely on the *Total Distance* metric. This is the distance the object travelled in the desired motion (translation). This is calculated as the projection of the

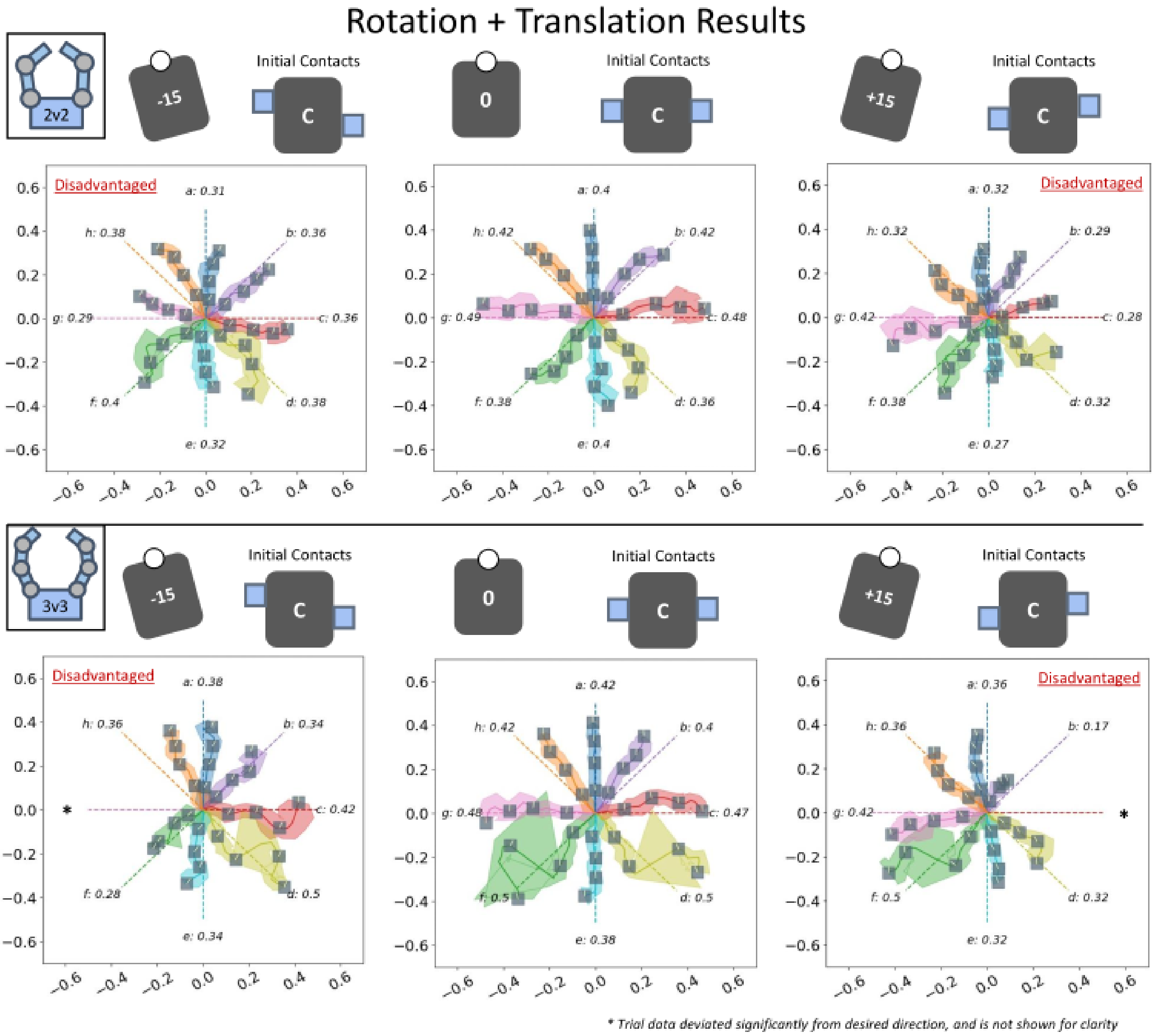

Fig. 5: Rotation+Translation results. Asterisk Test results for no rotation (center) and R+T for -15 (left) and +15 (right) degrees. Shaded regions are standard deviations for the translation. The Total Distance value for the averaged line is given at the end of each direction. Trials without a total distance value did not have sufficient translation to be counted. The square dials show the average rotation of the object. Also shown are the most common initial contact positions for the right (C) direction in the upper right of each plot.

object's path onto the desired direction's vector.

C. Implementing the Benchmark

The Asterisk Test requires an object with an ARuCo tag [20] and an overhead camera with sufficient resolution to track it. The hands are fixed in place at the edge of the table.

In addition to choosing the robotic hand to measure, there are three more experimental design variables a researcher needs to choose regarding the experimental setup: 1) the object's size relative to the hand, 2) the object's shape, and 3) the initial distance which the object is placed at the start of the interaction. These measurements require the hand to be measured according to [19] and [6].

In our work, we have used an Intel Realsense D415 placed approximately 70cm over the table top. We also used the following experimental settings: the square object (approx. 25% hand's max span) was placed about 75% of the hand's max depth from the palm. See [6] for more details.

To simplify the data collection process, we provide code which simplifies and manages data capture and data analysis — covering the entire pipeline from video capture (for all tests: translation-only, rotation-only, rotation+translation) to generating results figures (such as those seen in Fig 4 and 5). The code is provided on github [21].

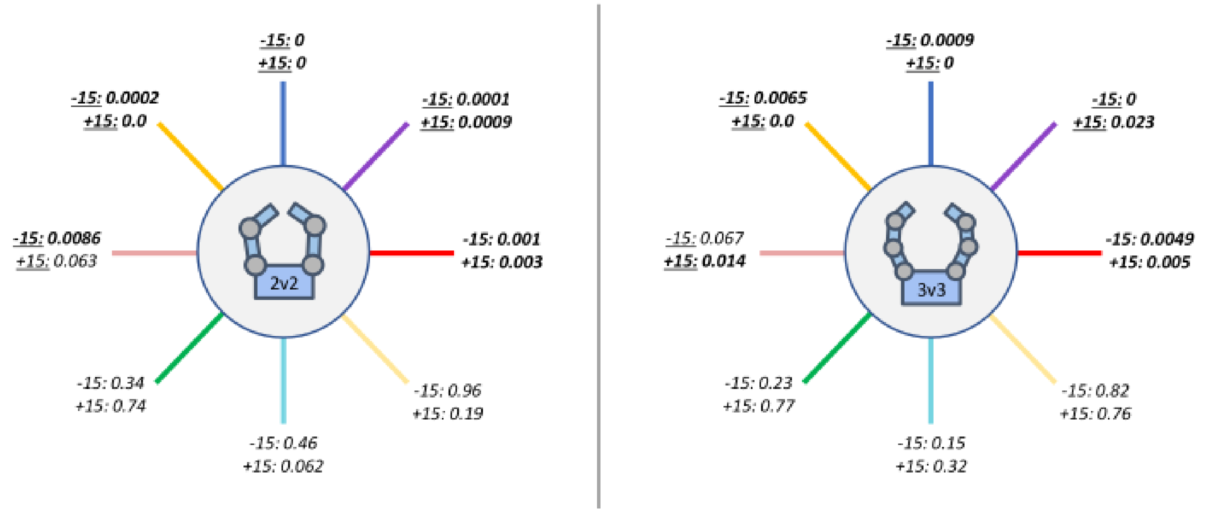

Fig. 6: Statistical differences when comparing the -15 and +15 trial results to the no-rotation results, using total distance values. Trials with a significant difference are bolded.

IV. Benchmark Evaluation Protocol

We demonstrate the rotation benchmarks using a human-study approach called Physical Human Interactive Guidance (PHIG) which uses human subjects to manually guide un-actuated robot hands through manipulation tasks [12], [6].

Please note that although we use a human subject approach to demonstrate this work, the Asterisk Test does not rely on it — it is agnostic to hand design, actuation strategy, and software control [6]. We use PHIG to focus primarily on the effect that a hand's design (kinematics) has on manipulation.

In our demonstration, we use three generic robot hand designs: 1) a symmetrical two-link fingered hand (2v2), 2) a symmetrical three-link fingered hand (3v3), and 3) an asymmetrical hand with a two-link finger opposite a one-link finger (2v1, inspired from the M2 OpenHand design [22]). All fingers used were the same total length, with equal ratios for link lengths.

These hands were made to reflect a fully-actuated version of each hand — they are un-actuated and have only mechanical joint limits according to their design. This results in few, or no restrictions, on how the human subjects can articulate the fingers. Before the formal trials, the participants were given as much time as needed to practice moving the object around. They were given explicit instructions about how to move the object and what would cause a trial failure [6].

In this work, we used three human subjects who performed five trials for the four test sets: a) clockwise rotation-only, b) counterclockwise rotation-only, c) 8 asterisk directions for -15 condition, d) 8 asterisk directions for +15 condition. Participants also performed the original asterisk benchmark (translation-only) on each hand to compare the R+T data to. For the convenience of the human subjects we printed the asterisk directions and markers for approximately 15° on the testing surface.

V. Benchmark Evaluation Results

We show the results of the rotation benchmarks using three generic robot hand designs: 2v1, 2v2, and 3v3. Rotation-Only results are shown in Fig 4. R+T results are shown in Fig 5, see Fig 6 for a statistical analysis of the R+T data.

A. *Rotation-Only Trial Results*

The benchmark found a significant difference between the 2v1 hand's clockwise and counterclockwise results (pvalue: 0.016). The 2v2 and 3v3 did not have a significant difference between their clockwise and counterclockwise results.

When comparing the 2v1 hand to the 2v2 and 3v3, the 2v1 hand had a significant difference in performance for both the clockwise (2v2, pvalue: < 0.01; 3v3, pvalue: < 0.01) and counterclockwise (2v2, pvalue: 0.03; 3v3, pvalue:0.25) directions.

Between the 2v2 and 3v3 hands we found no significant differences between their results. This suggests that from the strategies our human subjects found the 3v3 hand does not increase performance over the 2v2 hand despite the higher degrees of freedom (echoing [23] but in a 2d plane).

B. *R+T Trial Results*

We observed that for both 2v2 and 3v3 the rotation+translation trials were 'skewed' compared to the no-rotation trial results (metric: Total Distance). The 2v1 results are not shown because of poor relative performance.

The skew we observed in the R+T trials was dictated by the direction the object was rotated. If the object was rotated clockwise then the translation to the right was affected, and vice-versa. We refer to this as the disadvantaged side.

We found that our human subjects used contact points that were optimized for the 15° rotation, but limited translation performance. This is especially true for the disadvantaged side of the asterisk. For the 3v3 hand, subjects had an especially difficult time at this — translations deviated significantly outside the allowed threshold in the disadvantaged side. Fig 5 shows only the non-deviated translations for clarity.

Subjects utilized two strategies for bottom right (D) and left (F) directions on the 3v3 hand. The first strategy was as expected, the object was moved along the ideal path. In the second, the object was moved in the motion of an arc and was able to get significantly farther than the first strategy (by approx. 200%), but with larger error. This resulted in the large standard deviations for those directions. The arc strategy was unable to be performed in the disadvantaged direction — another indicator of reduced control in that region.

Statistically, we found that the $15°$ rotation had a significant impact on the top half of the Asterisk Results, according to Total Distance. At the bottom, although there are visible differences in the path taken, Total Distance values showed no significant difference. We attribute this to the strategies used by the human subjects — we hypothesize that they were less impacted by the rotation-optimized contact points.

VI. Discussion

A. Assessing Rotation Results with the Asterisk Test

Our rotation benchmarks serve as a quick way to *quantitatively* measure differences between robot hands. By using the Asterisk Test with a PHIG study, a roboticist could use the human controller as a tool to approximate a high level of performance on a robot hand design (approaching a hand's optimal potential for manipulation) or to normalize control strategies across different hand designs. This enables hand designs (and perhaps actuation schemes) to be prototyped without completing a full robot hand system every iteration. This would make the hand design process simpler.

We highlight two performance comparisons attained with our benchmarks. First, we observed that the 3v3 hand did not do much better than the 2v2 hand, according to the Total Distance metric, on the rotation-only and rotation+translation tests. This could suggest that the 2v2 design matches well with PHIG and the strategies that our human subjects employed. However the 3v3 hand could also be more difficult to control for a human subject using PHIG.

We also observed that the 2v2 hand rotated objects more than a hand with one less degree of freedom (2v1). This could suggest that this missing degree of freedom is integral to a high level of rotation ability.

B. Assessing Contact Points

The Asterisk Test also can be a good evaluation metric for finding good contact points in manipulation tasks. This information would be useful for those designing manipulation controllers for robot hands.

In our study, we observed that the initial contact points varied both between our human subjects and per trial. Furthermore, the contact points changed in different ways (rolling, sliding) throughout each trial to maximize test performance. Despite the variation, there were still commonalities between the initial contact points and the shifting contact strategies — we show a small sample of the most common, initial contact points in both Figs 4 and 5 for their respective trials.

For rotations, subjects most often chose initial contacts at opposite corners, as shown in Fig 4. In contrast, contacts chosen for translating to the right (C direction) were symmetrical and in the center (Fig 5, center).

Contacts for rotation+translation tasks combined the two strategies, for example in +15 (clockwise) direction C (Fig 5) subjects most often chose more centered initial contacts that were still offset for rotation.

Subjects also made frequent use of sliding and rolling contacts to complete their tasks. Unfortunately, an in-depth analysis of contact points is outside of the scope of this paper. However, this data could be analyzed to inform an in-hand manipulation controller as to potentially good starting and sliding contacts (such as using [24], [25]).

VII. Conclusion

In this work we extend the Asterisk Test to include a characterization of a hand's ability to rotate objects. This includes tests to characterize the limits of a hand's rotational capabilities (rotation-only) and how rotating an object impacts a hand's ability to translate while maintaining the rotation (rotation+translation).

We demonstrated both test sets on three generic hand designs using a cube as a test object. In this demonstration, we used a human study approach called Physical Human Interactive Guidance (PHIG). Although separate from the Asterisk Test, when used together, it allowed us to investigate the effects of robot hand design and contact points on manipulation performance.

Acknowledgment

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