**Elliott and Connolly Benchmark Protocol**

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| Reference No / Version | 1.0 |
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| Purpose | To evaluate the potential in-hand dexterity of a robot hand. We specify *potential* dexterity because this benchmark is only concerned with the capabilities of the robot hardware, regardless of whether these capabilities can be implemented in an autonomous system using current algorithms. |
| Task Description | This benchmark consists of 13 distinct in-hand manipulation patterns, defined in a classification by Elliott and Connolly\*:   1. Pinch (P) 2. Dynamic Tripod (DT) 3. Squeeze (S) 4. Twiddle (T) 5. Rock (R) 6. Rock II (RII) 7. Radial Roll (RR) 8. Index Roll (IR) 9. Full Roll (FR) 10. Rotary Step (RS) 11. Interdigital Step (IS) 12. Linear Step (LS) 13. Palmer Slide (PS)   \*Elliott, John M., and K. J. Connolly. "A classification of manipulative hand movements." *Developmental Medicine & Child Neurology* 26, no. 3 (1984): 283-296. |
| Setup Description | **List of objects and their descriptions:**  Objects from the YCB Object Set are used for all manipulation patterns except for Squeeze. The Squeeze pattern uses a 5 mL syringe, which can easily be purchased from commercial vendors, such as Amazon.com.   1. Pinch (Bolt and Nut) 2. Dynamic Tripod (Small Marker) 3. Squeeze (5 mL Syringe) 4. Twiddle (Bolt and Nut) 5. Rock (Cup – yellow) 6. Rock II (Small Marker) 7. Radial Roll (Marble – green) 8. Index Roll (Marble – green) 9. Full Roll (Wood Block) 10. Rotary Step (Cup – yellow) 11. Interdigital Step (Small Marker) 12. Linear Step (Large Marker) 13. Palmer Slide (Large Marker) |
| **Initial and target poses of the objects:**  There are no precisely “correct” initial or target poses for any of the manipulation patterns – rather, the experimenter is encouraged to refer to the descriptions and illustrations provided by Elliott and Connolly, as well as the accompanying video of the human hand baseline.  Since the dexterity of the robot is being evaluated in part based on the *Average Normalized Translation* or *Average Rotation* achieved for each manipulation pattern, experimenters are encouraged to select target poses which maximize these metrics, while still adhering to the provided criteria. |
| **Description of the manipulation environment:**  There are no specific requirements for the manipulation environment. |
| Robot/Hardware/Software/Subject Description | **Targeted robots/hardware/software:**  Any robot may be used to complete this benchmark. |
| **Initial state of the robot/hardware/subject with respect to the setup:**  No initial state is specified for this benchmark. |
| **Prior information provided to the robot:**  No prior information must be provided to the robot. |
| Procedure | Step 1: Measure the average finger length of the robot hand being used. This can be achieved by attaching threads to the fingertips of the robot and extending the threads towards the palm. The threads are then cut where they all intersect (defined as the center of the palm), and their resultant lengths are measured and averaged.  Step 2: Attach AprilTags to each object. In most cases, AprilTags can be attached to objects in a way that allows them to be manipulated without causing interference. The Marble is an exception. In order to attach AprilTags to this object without causing interference, attach a bolt (from YCB Object Set) to the marble and then attach the AprilTag to the end of the bolt. Another bolt is attached to the opposite side of the marble in order to balance the weight. In the case of the Rock II and Interdigital Step manipulation patterns, no AprilTag is needed since the tilt angle of the marker can be measured directly. Additionally, no AprilTag is required for Squeeze since linear displacement of the syringe plunger can be directly measured.  Step 3: Perform each manipulation pattern. Start with the robot configured in the desired initial pose and the object in the grasp of the robot. The manipulation begins as soon as the robot moves out of its initial pose, and lasts until the robot reaches its target pose. During each manipulation, a camera records the rotation and translation of the AprilTag (when applicable). The resultant data must then be analyzed in order to determine a value for rotation or translation about a particular hand coordinate axis. In some cases, a single pattern may involve both translation and rotation. Each manipulation must be repeated at least three times in order to calculate a mean and standard deviation from the data. Each manipulation pattern can be repeated as many times as necessary in order to achieve at least three successful trials - there is no need to record individual failed trials.  Step 4 (optional): Repeat Step 3 with a human hand. If attempted, it makes sense to complete this step *prior* to Step 3, since intuition gained from testing with the human hand can be applied when testing with the robot hand. |
| Execution Constraints | The experimenter is permitted to adjust initial contacts between the robot and the object prior to the execution of a manipulation pattern. However, no intervention from the experimenter is permitted during execution of a manipulation pattern. |