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The Baxter Easyhand: A Robot Hand That Costs $150 US in Parts

Giulia Franchi, Andreas ten Pas, Robert Platt and Stefano Panzieri

Abstract— **This paper introduces and characterizes the Baxter Easyhand, a new 3D printed hand derived from the Yale T42 hand [5], [10], but designed specifically to be mounted on the Baxter robot from Rethink robotics. Because this hand is designed specifically for Baxter, we are able to make some important simplifications in the design relative to other 3D printed hands. In particular, the Easyhand is smaller than most other 3D printed hands and it is powered by the native Baxter gripper actuator. As a result, our hand is cheaper, lighter, and easier to interface with than other robot hands available for Baxter. This paper details the design of the hand and its mechanical characteristics and reports results from experiments that characterize its grasping performance.**

I. Introduction

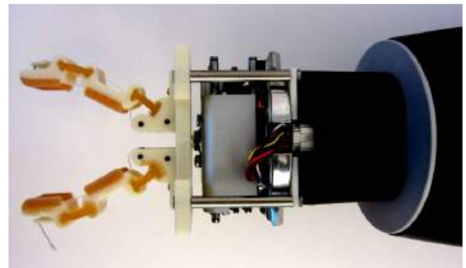
Underactuated robot hands produced using 3D printing have recently become a viable alternative to conventional commercially available robot hands. One of the key motivations for using a 3D printed hand rather than a commercial alternative is cost: 3D printed hands can typically be manufactured in a research lab for less than $1000 US dollars. In particular, the Yale OpenHand project makes available drawings, parts lists, and assembly instructions for a series of 3D printed hands [5], [10]. This is important because it gives many more researchers access to relatively sophisticated robot hands. The alternative is to spend tens of thousands of dollars to purchase a robot hand from a vendor such as Schunk, Barrett Technology, Robotiq, *etc.* Moreover, the compliant and underactuated nature of compliant 3D printed hands makes them suitable for a variety of robust grasping scenarios.

In this paper, we present and make available a new underactuated robot hand specifically designed for use with the Baxter robot from Rethink Robotics. Our goal is to provide researchers who use the Baxter robot with an inexpensive robot hand that is more flexible and robust than the native Baxter gripper. Easyhand assembly instructions are available at the following URL: http://www.ccs.neu.edu/research/helpinghands/easyhand/easyhand_assy_instructions.html.

Our design is derived from the T42 hand (one of the Yale OpenHand hands [10]), but differs from the T42 hand in important ways:

- it is cheaper to build (approximately $150US in parts);
- it is lighter;
- it is smaller and therefore better suited to typical Baxter grasping scenarios;
- it is easier to use and control because it uses the native Baxter gripper actuator and drivers.

To our knowledge, the Baxter Easyhand is currently the most inexpensive "research-grade" robot hand available.



(a)

(b)

Fig. 1: The Baxter Easyhand.

The key feature of the Baxter Easyhand relative to other 3D printed hands is that the fingers are actuated using the native Baxter gripper actuator rather than a Dynamixel servo. This results in the advantages cited above. It reduces the weight of the hand since it is no longer necessary to lift the additional servos. It makes the hand easier to use because we use the native Baxter gripper ROS driver. This driver already incorporates all the relevant hand speed/force settings. Finally, the Easyhand is smaller than most other 3D printed hands. This is important because, with a maximum payload of five pounds, the Baxter arm is essentially designed to lift small light objects. The smaller size of the Easyhand makes it more compatible with Baxter manipulation scenarios.

Compared to the native Baxter parallel jaw gripper, the Easyhand has one additional critical advantage: it can grasp any object that fits within the 8 cm aperture between the fingers. Each finger on the native Baxter parallel jaw gripper can only translate a maximum of 2 cm. As a result, it is impossible to grasp objects larger than 4 cm in diameter without manually removing the fingers and re-attaching them to the hand in a configuration where they are further apart. However, if one does this, then the fingers will no longer touch when they are closed fully. In contrast, the Easyhand fingers will close from a 8 cm aperture all the way to a fully closed configuration. We have designed the tendon arrangement so that the maximum travel of the underlying native Baxter gripper corresponds roughly with the maximum travel of the Easyhand fingers.

A. Related Work

The design and manufacture of robot hands appropriate for industrial and research applications remains an important challenge. A number of robot hands are currently available commercially including the Barrett Hand [3], the Robotiq Adaptive Gripper [1], the Shunk hand [4], the Shadow Dexterous hand [11], and the Ottobock hand [2]. However, all these hands are relatively expensive (tens of thousands of US dollars) and several of them are heavy and large. Because many robot hands are significantly larger than human size, they typically have a hard time grasping many of the smaller objects that humans grasp easily (pens, credit cards, *etc.*). The Baxter robot comes equipped with a two-finger parallel jaw gripper that is light and easy to control. However, this gripper has a very limited stroke: each finger can only translate two cm.

Recently, there has been interest in underactuated 3D printed hands that can be produced using shape deposition manufacturing (SDM). The first robot hand to use SDM was the Harvard SDM hand [6]. The iRobot-Harvard Hand [7] from RightHand Robotics is a commercial hand based on SDM that was used in the DARPA Robotics Challenge. Recently, the Yale OpenHand Project [10] has made 3D printed hands based on SDM available to the wider public. Perhaps the most important feature of hands manufactured using SDM is that they can be extremely inexpensive to produce (assuming you have access to a 3D printer). All of the hands in the Yale OpenHand Project (model T, T42, O, and M2) can be built with a 3D printer, hardware costing approximately \$150 – \$200 US, and a set of Dynamixel actuators costing approximately \$400– \$800 US. These underactuated hands are able to grasp a variety of object shapes and sizes by passive adaptation of the finger conforming to the geometry of the object.

II. Design

The main distinguishing characteristic of the Baxter Easyhand is that is it driven using the same actuator that is used by the native Baxter gripper. Other 3D printed hands such as the Yale T42 hand are driven by Dynamixel servos. Although the Dynamixel is a great actuator, it is costly, heavy, and requires using a separate ROS driver. In contrast, most Baxter users already own the native Baxter gripper. The gripper is fast and can be controlled in a precise way using a ROS node pre-installed on the Baxter. However, each jaw of the Baxter gripper has a maximum of only 2 cm travel (Figure 2 (c)). If the user wishes to grasp objects more than 4 cm in diameter, then it is necessary to unscrew the parallel jaws from the sliders and manually mount them in a wider configuration. One way to view the Easyhand is as a way of replacing the parallel jaws with something that can grasp a wider variety of objects. The Easyhand can grasp any object up to 8 cm in diameter. Moreover, we have empirically observed that the Easyhand produces secure grasps and that it shares many of the compliance, flexibility, and robustness characteristics of the Yale OpenHand series [10] or the Harvard SDM hand [6].

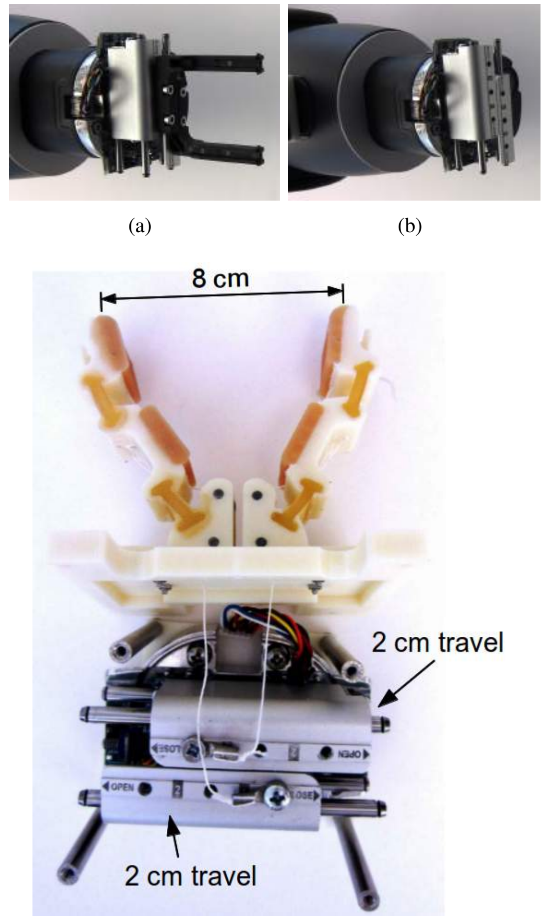


Fig. 2: (a) native Baxter gripper; (b) sliding bars to which the gripper fingers are mounted; (c) tendon attachment to the sliders.

A. Actuation

The native Baxter gripper is driven by a single motor that actuates two sliders in opposite directions via a wormgear (Figure 2 (a) and (b)). Each slider has approximately 2 cm of translational travel as shown at the bottom of Figure 2 (c). The speed and maximum force of the actuator can be controlled by interfacing with a ROS node that runs on the Baxter robot itself. Each finger of the Easyhand is actuated by one tendon that flexes (closes) the finger. Each tendon is connected to one of the sliders via a wire ring terminal crimped onto the tendon and the wire terminal is screwed into the slider (Figure 2 (c)).

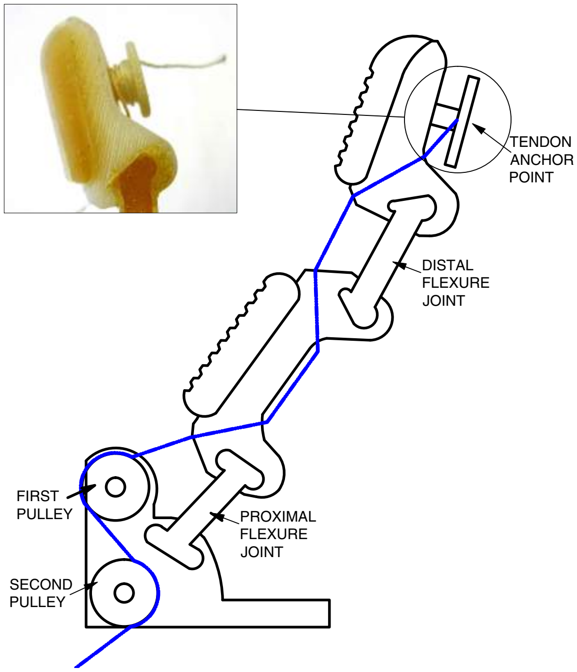
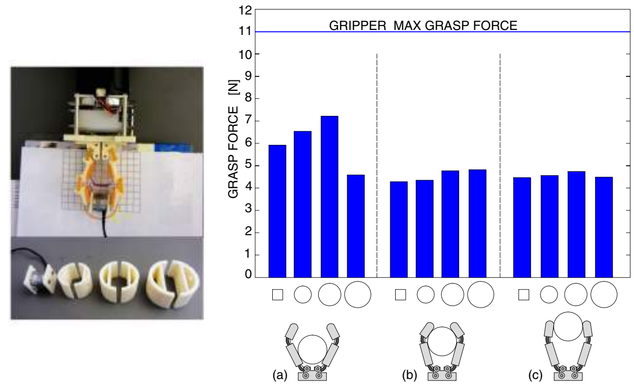


Fig. 3: Details of finger design and parts including a description of tendon routing path and a zoom on the tendon terminator.



(a) (b)

Fig. 4: (a) apparatus for measuring the Easyhand squeezing force; (b) squeeze force profile for four different objects in three different positions. All results are averages over ten trials.

B. Tendon Arrangement

One disadvantage of using the native Baxter gripper actuator is the limited force that it can apply. Without any modification, we have found that the Baxter gripper can only squeeze an object with 11 Newtons of force (at the maximum gripper force setting in the driver). In the context of our design, this is a potential problem because tendons typically need to apply many times the force that the hand will ultimately be required to apply at the fingertip. Because of this, we have designed the tendon routing in order to maximize the ratio of the force applied by the finger with respect to the tendon tension (see Figure 3). In particular, the "first pulley" in Figure 3 routes the flexion cable such that the tendon pulls in a direction nearly parallel to the direction of finger closing. As a result, we obtain a nearly one-to-one ratio between finger-force and tendon tension for a contact near the tendon attachment point. As the point of contact moves up the finger, the finger force decreases linearly with distance from the proximal flexure joint.

We experimentally characterized the squeezing force that our hand can apply using the apparatus shown in Figure 4 (a). A Nano25 Force/Torque sensor from ATI Industrial Automation was placed between the fingers and used to measure hand squeezing force. We designed and printed four sets of shells (30 mm, 40 mm, 50 mm, and 60 mm in diameter) that we mounted to the rectangular force sensor plates in order to measure squeezing force when grasping objects of different sizes. For each object, we performed a grasp in three different positions: close to the proximal link (case a), just in the middle of the two links (case b), and close to the distal link (case c).

The results are shown in Figure 4 (b). Note that the maximum squeezing force is roughly half the maximum tendon tension force in the actuator: all finger squeezing forces are between 4 Newtons and 7.5 Newtons. As might be expected squeezing forces are largest when grasping close to the palm of the hand (the left side of Figure 4 (b)). Here, the object makes contact with the finger very close to the tendon attachment point and we therefore expect the highest squeeze force. As the contact moves away from the palm (the center and right side of Figure 4 (b)), squeezing force drops somewhat. These results illustrate the trade-off between squeeze force and swept volume of the fingers. Since we're using the Baxter gripper actuator, we have limited force and limited actuator travel. The Easyhand trades some of this force for additional finger travel – essentially doubling the swept volume of the fingers while cutting the squeezing force in half.

C. Tendon termination in the fingertip

Tendon termination and length adjustment is another important part of our design. It is common in robot hands to adjust tendon length at the point where the actuator attaches to the tendon. For example, in both the Robonaut 2 hand and the Yale OpenHand designs, tendon length is changed by adjusting the position at which the tendon is attached to the actuator [10], [12]. In contrast, we adjust tendon length at the tip of the finger, as illustrated in the insert of Figure 3. One end of the tendon is crimped to a wire ring terminator (Figure 2 (c)). The other end is pulled through the finger and terminated at the tendon anchor point on the back of the fingertip as shown in Figure 3. The tendon is wrapped around the anchor point several times and then tied off in a slot in the anchor point. The advantage of adjusting tendon length via a fingertip terminator is that it makes it relatively easy to adjust

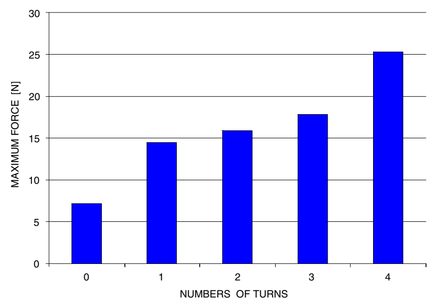
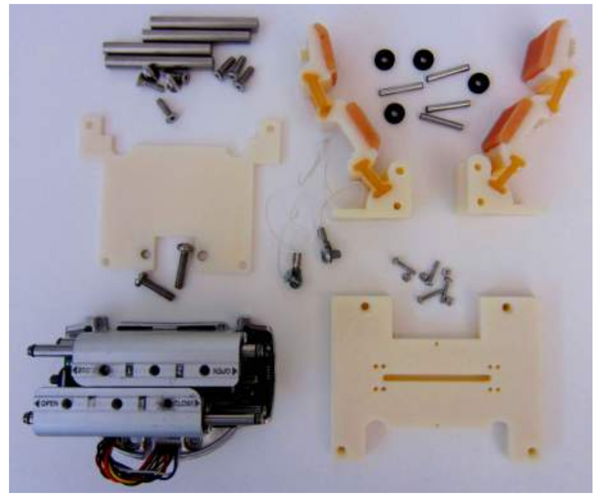
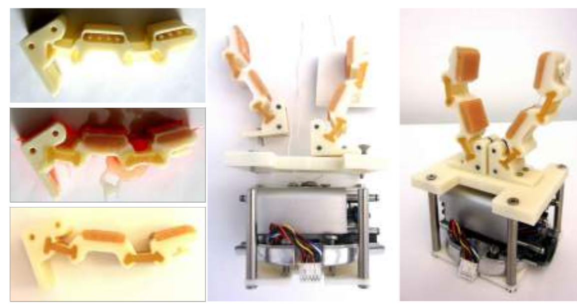


Fig. 5: Maximum tension reacted by the fingertip tendon terminator as a function of the number of times the tendon is wound around the terminator (results averaged over ten measurements).



(a)



(b)

Fig. 6: (a) Components used to create the Baxter Easyhand, (b) main steps of the building process: (left) pouring rubber for finger construction, (center) assembling fingers, tendons and bases, (right) fixing the tendon around the termination.

tendon length. Tendon length adjustment is the last step in finger assembly. It occurs after the fingers are assembled and the hand is mounted to the robot. If the tendon stretches or slips in the terminator, it is simple to unwrap the tendon on the fingertip terminator and adjust length. After length adjustment, it is only necessary to execute a standard Baxter gripper calibration sequence and the hand is ready to be used again. The entire process takes less than two minutes.

We performed experiments to quantify the load that our terminator could react. We mounted a Nano25 force/torque sensor from ATI Industrial Automation in series with the tendon and measured the amount of force we could apply until the tendon started to slip in the terminator. We repeated this experiment for different numbers of (zero to four) “wraps” of the tendon around the fingertip terminator. The results are shown in Figure 5. At four wraps, we were able to exert a maximum of 25 Newtons of force. Since this is well above the 11 Newton maximum force that can be applied by the Baxter gripper actuator, we used a four-wrap termination in all of our subsequent work.

D. Hand Fabrication

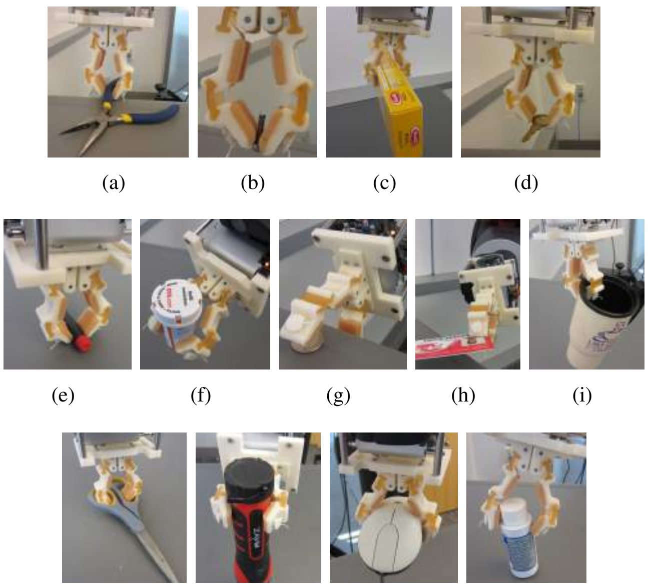
TABLE I: List of components used to build Easyhand

Part	Usage	Vendor
Power Pro Spectra	Tendon	Amazon
PMC-780 Urethane	Finger Joint	Smooth-On
Vytaflex 30 Urethanea	Finger Pad	Smooth-On
4 nylon pulley D3/8, Wd1/8	Tendon Routing	McMaster-Carr [3434T31]
4 Steel Dowel Pin D1/8, L13/16	for Pulley	McMaster-Carr [98381A173]
4 Round Head Screw 2-56 X 7/16”	for base-finger	McMaster-Carr [91772A080]
4 Hex Nut 2-56a	for base-finger	McMaster-Carr [91841A003]
4 Female Standoff OD1/4”, L2”, 6-32	for bases	McMaster-Carr [91125A250]
4 Flat Head Machine Screw 6-32 X 1/2”	for bases	McMaster-Carr [91500A148]

The Baxter Easyhand is simple to build. All that is required is access to a 3D printer and the ability to order approximately $150 worth of hardware from standard vendors. Figure 6 (a) illustrates all of the required parts. The fingers are similar to those in the Yale T42 hand. Essentially, the Easyhand fingers can be viewed as miniaturized versions of the T42 fingers with a slightly different tendon routing. As in the T42 hand, the fingers are manufactured using shape deposition manufacturing. Figure 6 (b) illustrates the main steps of the manufacture process. First, the fingers are printed using a fused deposition modeling 3D printer (in our case, the U-Print SE Plus [8]). The fingers are printed with cavities that function as molds for Polyurethane material is poured once printing is complete (0.7 mm thick shell). Two types of Polyurethane are used: a flexible type of material for the joint flexures and a gripping type for the finger pads. Once the Polyurethane is dry (almost 24 hours), the cavity shells are removed and finger assembly is completed by installing a pair of pins and pulleys into each finger. Then, tendons are routed and the fingers are mounted onto the palm plate. The palm plate is mounted to the arm via four screws that attach to four quarter-inch standoffs that mount onto another plate

(a) (b)

Fig. 7: (a) objects used in the teleoperation grasping; (b) objects used in autonomous grasping.



(a) (b) (c) (d) (e) (f) (g) (h) (i) (j) (k) (l) (m)

Fig. 8: Teleoperated grasps for each of the objects shown in Figure 7 (a).

mounted below the Baxter gripper actuator.

III. Grasping performance

We evaluated how well the Easyhand can grasp objects when under teleoperated control and autonomous control.

A. *Grasp performance under teleoperation*

In teleoperated grasping, the joints of the robot arm and hand are controlled directly by a human. Since autonomous robot grasping still cannot match the capabilities of a human operator, teleoperation can give us a sense for the best-case performance of the hand under the control of an "ideal state of art" controller. In our experiment, Baxter was placed a master-slave mode where one arm functioned as the master and the other as the slave (we used the "Puppet" example program that ships with Baxter). A human controller moved the master arm kinesthetically and this motion was reflected on a joint-by-joint basis to the slave arm. In addition, the human was able to open and close the hand by pressing a button on the side of the master arm. We were able to grasp each of the objects shown in Figure 7 (a) under teleoperation. Figure 8 shows the teleoperated grasps that we obtained. These grasps indicate that the Easyhand is capable of graping a variety of objects including keys and small screws as well as larger objects such as the flashlight or the computer mouse. The most difficult objects for the Easyhand to grasp were thin objects such as the student ID, the coin, or the key. The teleoperator was only able to grasp these objects by first sliding them to the edge of the table (see Figure 8 (g), for example), and then performing the grasp. This is a deficiency relative to other 3D printed hands (for example, the Harvard-iRobot hand [7]) which are equipped with "fingernails" that can "scoop up" small objects.

TABLE II: Results for the autonomous grasping experiments.

Object	Success Rate
Lint Roller	100%
Britannia Box	100%
Yarn Roll	83.33%
Computer Mouse	83.33%
Green Tape Roll	83.33%
Red Tape Roll	66.66%
Coffee Filters	83.33%
Vacuum Cleaner Part	66.66%
Coffee Bag	83.33%
Pepper Dispenser	100%
Average	85%

B. *Grasp performance under autonomous control*

The teleoperated grasping results described above characterize the potential of the Easyhand given a very intelligent control system (*i.e.* a human). However, we are also interested in understanding what kind of objects the Easyhand can be expected to grasp under autonomous control, given the algorithms currently available. In order to accomplish this, we used a grasp localization system developed in conjunction with our recent antipodal grasp prediction work [9]. Essentially, our system uses two RGBD cameras to create a point cloud that characterizes the scene in front of the robot. Our algorithm searches the point cloud for hand configurations where antipodal grasps are predicted to exist. Once a set of potential grasp configurations is obtained, the algorithm selects one based on manipulator kinematics, obstacle configuration, *etc.*. Here, we performed single-object tests where a single object was placed in front of the robot and our system performed a grasp. Our test set consisted of the ten objects shown in Figure 7 (b) (note the absence of hard-to-grasp items such as the key in Figure 7 (a)). We attempted to grasp each object in six different poses. A trial was considered a success only if the robot successfully localized, grasped, lifted, and transported the object to a container on the side of the robot where the object was dropped. During our experiments, the perceptual system sometimes found spurious grasp targets in the air or elsewhere caused by occlusions or noise in the point cloud. We eliminated this effect from our results by reporting on only those grasp trials when the robot hand actually made contact with the object.

The results of this experiment are shown in Table II. The robot was able to successfully grasp, transport, and drop into

(a) (b)

Fig. 9: Failure modes: (a) object rolls away when one finger pad is making contact with object surface, (b) unstable pinch grasp.

a box objects approximately 85% of the time (8 failures out of 60 attempts). Of the 8 failures, one was caused by dropping the object after an initially successful grasp, and another one was caused by one of the fingers colliding with the target while attempting the grasp and thus pushing the object out of range of the hand. The other 6 failures were due to perception: missing data in the RGBD images caused our algorithm to select non-existent grasps or to reach to configurations where the Easyhand did not fully envelop the object.

These results are particularly interesting when they are compared with the results of using the same grasping system with the native Baxter parallel jaw gripper as reported in [9]. There, we reported an 88% grasp success rate for a collection of 30 objects. Perhaps the main reason why the 85% success rate reported here is lower than the 88% success rate reported for the parallel jaw gripper is because the object set in this paper (Figure 7 (b)) has a wider variety of objects (including thin objects and deformable objects) relative to the 30-object test set used in [9]. The greater versatility of the Easyhand relative to the Baxter gripper enabled us to grasp these additional objects but our grasp success rate suffered somewhat. Tuning various system parameters could increase the success rate in the Easyhand scenario relative to the gripper scenario.

However, we also observed a couple of failure modes that are important to point out. First, we observed a rolling failure mode that occurred when attempting to grasp cylindrical objects presented horizontally. One finger would make contact with the surface of the object prior to the other. In some situations, the way that contacting finger complied with the object actually caused the object to roll out of the grasp (Figure 9 (a)). This failure did not occur with the parallel jaw gripper because the gripper did not comply with the object in the same way. Another failure mode occurs because the Easyhand grasps small-diameter objects with the fingertips (Figure 9 (b)). This is in contrast to the grasps generated by a parallel jaw gripper where the fingers are always parallel. Since Easyhand grasps small-diameter objects with the fingertips, these grasps are less stable than those generated by a gripper.

IV. Conclusions

In this paper we describe the Baxter Easyhand, a new 3D printed robot hand specifically designed for use with the Baxter robot. This is an underactuated, two finger, flexible joints, low cost robotic hand made through 3D printing and SDM that is derived from the Yale T42 hand [10]. Our goal is to provide those who use the Baxter robot with an inexpensive hand that is easy to build that is more robust and flexible than the native Baxter gripper. We demonstrate via teleoperated and autonomous grasping experiments that the Easyhand is an effective hand. Assembly instructions will soon be available online at http://www.ccs.neu.edu/research/helpinghands/easyhand /easyhand_assy_instructions.html.

V. Acknowledgement

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