Limits to Compliance and the Role of Tactile Sensing in Grasping

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***Abstract*— Grasping and manipulation in unstructured environments must handle a wide range of object properties and significant sensing errors. Underactuation and compliance have been shown to be an effective way to improve grasping performance under such uncertainty, but the degree of compliance plays an important role in both gently adapting to sensing errors and maintaining stable grasps of heavy objects. These demands limit the range of objects that can be grasped. We consider the role and required characteristics of tactile sensing as a compensation method when compliance alone is insufficient. By strategic use of contact sensing, it is possible to expand the capabilities of a hand to grasp effectively under a wide range of positioning errors using simple position-driven motors and low-cost hardware.**

I. INTRODUCTION

Grasping in unstructured environments promises to enable a wide range of important real-world applications, including aiding disaster response, performing household chores, and assisting the elderly and infirm. There has been considerable progress towards this goal of late, particularly using underactuated hands [1], [2], [4]. These end effectors are simpler than anthropomorphic hands, more capable than parallel jaw grippers, and aim for good performance at moderate cost. "Underactuated" implies the use of fewer motors than degrees of freedom (DOF), but the key feature is that the unactuated DOF are coupled so that the hand mechanism adapts to object geometry and task constraints using passive mechanics rather than active control [5], as required with high-DOF anthropomorphic hands [6]–[8]. In many underactuated hands, the unactuated DOF are constrained by compliance such as that imparted by flexure joints [2], [4]. During grasping, the deflection of these compliant joints is determined by the contact constraints, actuator motions, and joint stiffness.

Hands using this approach have demonstrated good ability to grasp unknown objects despite the sensing errors inherent in unstructured environments. Designs of such hands have been based on intuition, kinematic optimization [9], [10], and task analysis [4]. There has, however, been a limited understanding of the role of compliance in real grasping tasks using multifingered hands, including its relationship to object and task properties. Such an understanding maybe expected to improve hand design and enable the creation of more effective grasping controllers.

In this paper we examine the limitations of compliance as a means to enable effective grasping of the diverse objects encountered in unstructured environments. In general, when any coupled joints are not constrained by the geometry of the grasped object (for example, during fingertip grasps), compliance must be set to accommodate the heaviest objects (or highest forces) that will be encountered in order to maintain stable control of the position of the object. This means that for lighter objects, the benefits of compliance (i.e. low forces in response to sensing and control errors) are obviated, and target objects may be dislodged or damaged in the grasp acquisition process.

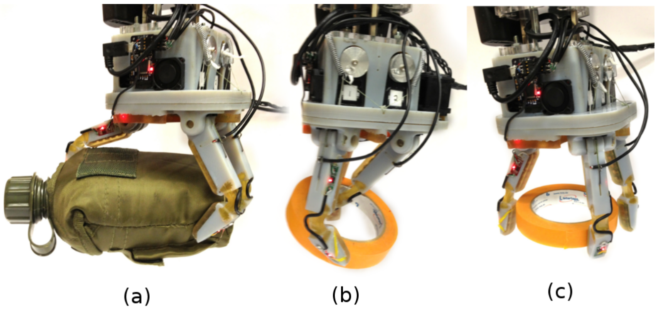

Fig. 1. Compliant underactuation allows hands to passively adapt to variations in object geometry and position to provide stable grasps (a). However, grasping too hard can cause undesirable joint motion and eject the object (b). Registering control actions against the object surface with tactile contact sensing results in better grasps using simple hardware (c).

We then consider the role and required characteristics of tactile sensing as a compensation method when compliance does not help. In this situation, simple methods are effective, particularly using the point of contact with objects as a reference point for subsequent compliant motion. This is compatible with low-cost, simple hardware and results in better compensation for positioning errors.

In this paper, we present an analysis of the limits of fingertip compliance to both maintain firm grasps and gently compensate for positioning errors, followed by an approach to use tactile sensing to compensate for these limitations using contact-relative motion. Experiments are presented that demonstrate the advantages of contact-relative motion to improve the tolerated positioning error and reduce grasp force. Finally, these results are analyzed in the context of the goal to create low-cost hands that function reliably in real-world settings.

II. GRASP CONTROL

A grasp control system maps information about a target object to actuator commands that result in a stable grasp. There is no definitive architecture for such control, and

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boundaries between perception, grasp planning, and grasp execution are mingled in the literature to various degrees depending on the goal. We are concerned with the near-term development of systems that can reliably grasp objects in real-world setting using inexpensive, low-complexity hardware. In this context, the primary challenge is overcoming large variability and uncertainty in object properties (geometry, pose, mass, etc.); sensing limitations (noise, occlusions, etc.); and robot behavior (friction, backlash, etc.).

To do so, simplicity and error-tolerance are important – motors are a major cost and complexity driver so fewer are better, acquiring extensive information about a target object in unstructured clutter is expensive, and adapting parameter-sensitive controllers to match a wide range of objects is time-consuming.

A. Limits to Compliance

The limitations on the useful range of compliance can be illustrated with a simplified model of the grasping process that shows the factors which determine performance for both the heaviest and lightest objects to be grasped. Figure 2 shows the hand idealized as a pair of fingers grasping heavy and light objects, with equivalent lateral finger tip stiffness k. For the heaviest anticipated object, with mass m_{max}, finger stiffness must be set high enough to limit unintended motion of the fingers and object during manipulation. One force that will be encountered in many tasks is gravity, so the object weight $m_{max}g$ can be applied in various directions during translation and rotation of the hand. The resulting displacement of the object within the hand is then

$$\Delta x_{max} = \frac{m_{max}g}{2k} \tag{1}$$

In the design process, the stiffness could be set using this relationship based on the maximum displacement that can be tolerated for the heaviest anticipated object.

For the lightest object with mass m_{min}, the performance limit for the grasping task occurs if one finger makes contact with the object before the other. Continued closing of the finger then compresses the finger tip spring and applies an unbalanced force on the object. This can make the object slide out of the graspable range or cause it to fall. If the distance between the opposite side of the object and the other finger is Δx_{min}, then the force developed before the second finger makes contact and applies a stabilizing force is $k\Delta x_{min}$. Using a simple Coulomb friction model with coefficient of friction μ, this will cause sliding if the applied force is

$$\mu m_{min} g = k\Delta x_{min} \tag{2}$$

We can calculate a mass dynamic range by looking at the ratio of the masses for these limiting cases

$$\frac{m_{max}}{m_{min}} = \frac{2\mu\Delta x_{max}}{\Delta x_{min}} \tag{3}$$

The hand system might be expected to successfully grasp and move objects whose mass falls within this range. For real systems, however, this range is limited. The maximum displacements that might be tolerated during transport of heavy objects are at most 1-2 cm, in order to avoid shifts in position that can cause twisting or sliding of the object within the fingers. For light objects, vision and range sensor systems cannot be expected to localize object surfaces to better than several mm accuracy. The coefficient of friction is often between 0.2 and 0.5 for many common objects. The overall the mass dynamic range is thus roughly an order of magnitude in size. While several measures can help increase this range (e.g. power grasp configuration, “caging” to prevent light objects from falling, etc.), useful hands need to grasp objects that span about three orders of magnitude in mass, from a few grams (e.g. a pencil) to a kilogram (a one liter bottle) or more. This suggests that a fixed finger stiffness is inadequate for the entire range.

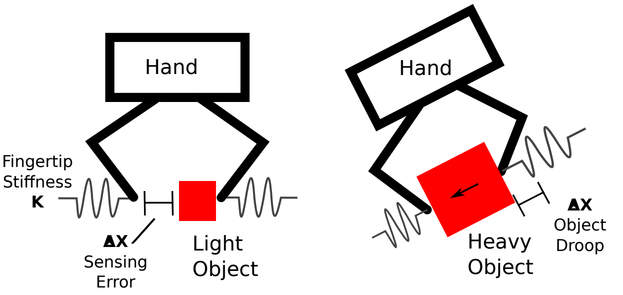


Fig. 2. Compliant underactuation allows a hand to compensate for positioning errors while exerting low forces. However, compliance is also responsible for maintaining the stability of heavier objects. This limits the range of objects that can be grasped.

B. Contact-Relative Motion

An alternative to passive compliance is to augment the system with active sensing and control at low force levels. This allows the generalization of of grasp control across variations such as positioning error [11], and support surface and object height [12]. Directly closing the loop around sensor readings creates a number of challenges for low-cost hardware however. Measuring low forces through intrinsic sensing (e.g. cable tension, motor torque) requires a clean transmission with little backlash or friction that is costly to build. Strain gauges are likewise expensive and usually fragile. On the other hand, surface sensors such as tactile arrays have deadzones in areas such as joints; if a contact starts moving towards a deadzone, the reduced readings may cause the controller to push the object farther into it (a phenomena we have observed in our experiments). In both cases, achieving sufficient controller bandwidth to ensure stability can also be challenging.

Using sensors to detect discrete events such as contact, on the other hand, does not require high accuracy to maintain position or force. Guarded moves have been used to compensate for errors in perception and positioning, e.g. [13], [14].

The contact-relative control method presented here works as follows: the hand is positioned over an object and the

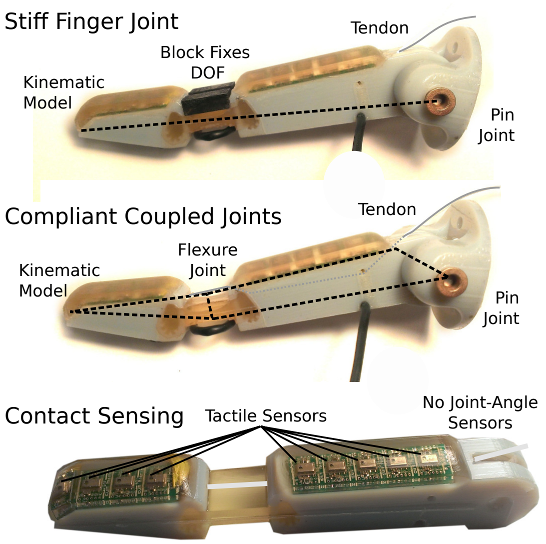


Fig. 3. Experimental conditions. In the control group (top), each finger is restricted to a single DOF by inserting a stiff plastic block over the flexure joint. In the compliant experimental group (middle), the distal flexure forms a coupled, spring-loaded linkage with the proximal pin joint through the tendon as shown. In the sensorized experimental group (bottom), nine tactile sensors are used to measure contact relative to tendon position.

fingers are closed around the expected object position. Each finger moves independently, stopping when it contacts an object. Once all fingers are in contact or have moved beyond the other fingers by a maximum threshold, the tendons are tightened by a fixed amount sufficient to grasp typical objects securely. The compliant underactuated joints of the hand then control and balance the internal forces and compensate for variations in object geometry. By referencing the motion of the actuators to the surface of the object, excessive force that might cause the links to eject the object are avoided.

Note this takes advantage of two additional observations. First, by indexing directly from the actuator position, the controller does not require accurate proprioceptive sensing, e.g. sensing of finger joint angles and a kinematic model of the hand. Second, because the motion of the finger is driven by only a single motor, the impact of messy mechanics such backlash and and friction can be sidestepped completely provided the direction of motion remains consistent.

This registration creates a larger "region of attraction" within which an object will be successfully grasped.

III. EXPERIMENTS

A. *Materials and Methods*

It is challenging to characterize performance in unstructured environments, because they inherently include great variability in objects, tasks, and environment properties. We have devoted extensive experimental effort to examining the grasping behavior of one such end effector, the i-HY Hand [4]. This is a compliant, underactuated hand with three fingers developed in collaboration between Harvard University, iRobot, and Yale University with the goal of performing tasks robustly under unstructured conditions. The present study uses a 3D printed version with 4 motors as shown in Fig. 4. Each finger has a proximal pin joint and a distal flexure joint, with a single tendon spanning past both as shown in Fig. 3. Previous work has shown that iHY hand is capable of grasping a large range of objects. The fingers and palm are embedded with strips of tactile sensors [15] (TakkTile LLC, Cambridge, MA) for contact detection. The contact threshold is set to approximately 40mN. The motors (Dynamixel RX-28, Robotis, South Korea) are driven by a torque-limited proportional-derivative position control loop.

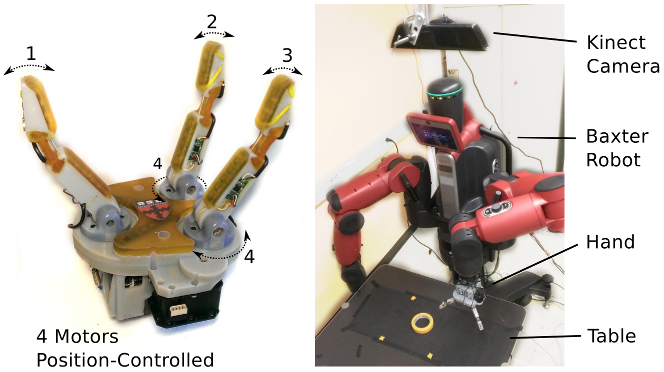


Fig. 4. Experiments were performed with a hand based on the i-HY hand [4]. It is driven by four position-controlled servos running three compliant underactuated fingers and one preshaping DOF. A Kinect Camera measures object centroid and major axis, a Baxter robot places the hand.

The hand is mounted on a 7dof arm on a Baxter Robot (Rethink Robotics, Boston, MA). The motors in Baxter's arms are serial elastic motors, which allows Baxter to be inherently compliant; at the current version of the control code, this also results in positioning errors of several cm under load (especially in the z-direction). Localizing the objects is accomplished by an overhead Kinect camera. A 2D image is acquired, and the major axis and centroid of the object is determined by segmenting the object with a binary threshold and fitting an ellipse to this contour. The Z-height of the object position is set separately for a each object. To evaluate the methods proposed, we performed the following series of experiments to show the advantage and limits of compliance and contact-relative motion on this hardware. The objects chosen are typical, selected to show behavior we have observed in many manipulation experiments.

B. *Experiment 1 - Compliance*

The first experiment compares hands with stiff and compliant fingers in handling large heavy objects, such as a bottle filled with water (mass approximately 1.5kg). Geometric variation is introduced to the grasp by rotating the hand away from the ideal grasping axis. The best grasp aligns the hand and water bottle axes so that the fingers wrap around the body of the bottle in the center, so that the weight of the bottle can be symmetrically distribution in the hand. To test the robustness of this grasp to positioning errors, the hand was rotated in 30 degrees increments around the vertical axis and 3 rounds of open-loop power grasps were executed using both the compliant fingers with flexure joints, and stiff fingers where the compliance is removed by the addition of rigid block across the distal join as shown in Fig. 3.

C. *Experiment 2 - Light Object*

In the second experiment, the effects of compliance and sensing on a light object were studied. The light object (a roll of masking tape, part number 76265A11, McMaster-Carr, Newark, NJ) is grasped under three conditions: no contact sensing with stiff fingers, no contact sensing with compliant fingers, and compliant fingers with contact sensing.

To test adaptation to variations in geometry, we tested against a range of position errors, systematically offsetting the hand position from the actual object location in 2cm increments in both x and y direction until the edges of the graspable region were discovered. In the control group of no sensing and no compliance, compliance is again removed by adding a block across the distal joint as shown in Fig. 3 to prevent it bending. In the first experimental group the distal joint is left compliant to adapt to object shape. In the second experimental group, the following contact-referenced control is used: each finger closes independently until contact is detected (or a tendon travel limit beyond fingers in contact is exceeded). Then all fingers are tightened by 4mm additional tendon travel (set to exert sufficient force to grasp typical objects).

D. *Experiment 3 - Controlling Gentle Contacts*

To demonstrate the effect of blind spots on the ability to compensate for position offset, several different controllers were tested as follows. The hand was mounted on a linear stage and and commanded to close on a cylinder (diameter 107mm) mounted on a force-torque sensor. The disturbance forces measured during this process were compared for compliant fingers driven directly by servomotors (controlled with a torque-limited proportional-derivative controller), compliant fingers with a closed control loop wrapped around the contact forces measured by the tactile sensors (in this case a simple hysteresis controller), and compliant fingers driven with a contact-relative controller tuned to match the force applied by the closed-loop controller.

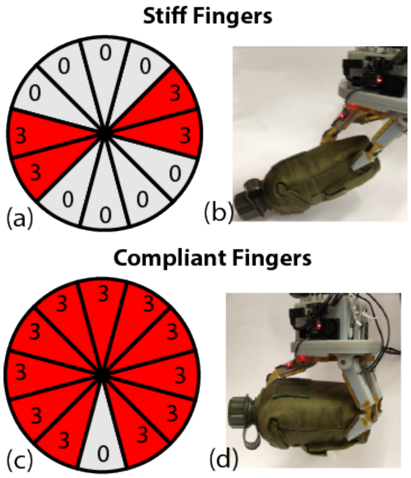
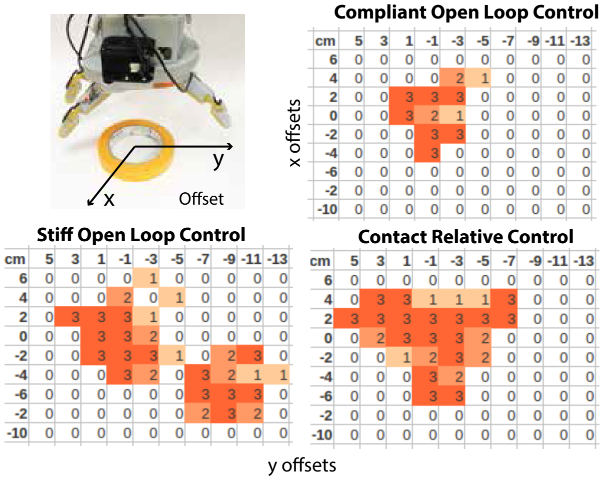


Fig. 5. Compliance helps considerably when grasping larger, heavier objects due to the creation of multiple contacts that can better resist gravitational loads. A water bottle was grasped at 30^{o}increments around the vertical axis with stiff fingers (top) and compliant fingers (bottom).



Compliant Open Loop Control

cm	5	3	1	-1	-3	-5	-7	-9	-11	-13
6	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	2	1	0	0	0	0
2	0	0	3	3	3	0	0	0	0	0
0	0	0	3	2	1	0	0	0	0	0
-2	0	0	0	3	3	0	0	0	0	0
-4	0	0	0	3	0	0	0	0	0	0
-6	0	0	0	0	0	0	0	0	0	0
-2	0	0	0	0	0	0	0	0	0	0
-10	0	0	0	0	0	0	0	0	0	0

Stiff Open Loop Control

cm	5	3	1	-1	-3	-5	-7	-9	-11	-13
6	0	0	0	0	1	0	0	0	0	0
4	0	0	0	2	0	1	0	0	0	0
2	0	3	3	3	1	0	0	0	0	0
0	0	0	3	3	2	0	0	0	0	0
-2	0	0	3	3	3	1	0	2	3	0
-4	0	0	0	3	2	0	3	2	1	1
-6	0	0	0	0	0	0	3	3	3	0
-2	0	0	0	0	0	0	2	3	2	0
-10	0	0	0	0	0	0	0	0	0	0

Contact Relative Control

cm	5	3	1	-1	-3	-5	-7	-9	-11	-13
6	0	0	0	0	0	0	0	0	0	0
4	0	3	3	1	1	1	3	0	0	0
2	3	3	3	3	3	3	3	0	0	0
0	0	2	3	3	3	2	0	0	0	0
-2	0	0	1	2	3	2	0	0	0	0
-4	0	0	0	3	2	0	0	0	0	0
-6	0	0	0	3	3	0	0	0	0	0
-2	0	0	0	0	0	0	0	0	0	0
-10	0	0	0	0	0	0	0	0	0	0

Fig. 6. For small objects, contact-relative control is better at compensating for position alignment than compliance alone, which actually performs worse than stiff fingers.

E. *Results*

The results of these experiments show that both compliance and contact-relative motion improve performance under positioning errors, but that these benefits occur under different domains. For the water bottle, the ideal grasp for the bottle is placing the fingers at the 3 and 9 o'clock positions because the fingers are symmetrically distributed over the object balancing the force exerted. However, this is disturbed as the grasp is rotated around the vertical axis. Compliance improved the ability of a cylindrical power grasp primitive to compensate for variation in object orientation around the z-axis. In the control case with stiff fingers, the grasp was able to handle only $\pm 30^o$ of orientation error, wheras with compliance the grasp was able to handle all orientations except for one that placed the thumb directly over the bottle neck (the hand is not large enough in its span the reach the whole bottle lengthwise).

In the second set of experiments, the lighter roll of tape was grasped with a spherical fingertip grasp. In the control group, an open loop grasp with stiff fingers functioned well because the light object does not need multiple contacts from compliant fingers to resist gravitational loads, and when sufficiently aligned, caging [16] served to align the object. At larger offsets, however, the fingers pushed the object out of the way before a good grasp could be achieved as shown in Fig. 7. The disconnected region of success on the lower right is caused by the geometry of the object, which allows both an external grasp and an edge pinch. This region is asymmetric due to minor variations in the tendon length between the two fingers, which caused small

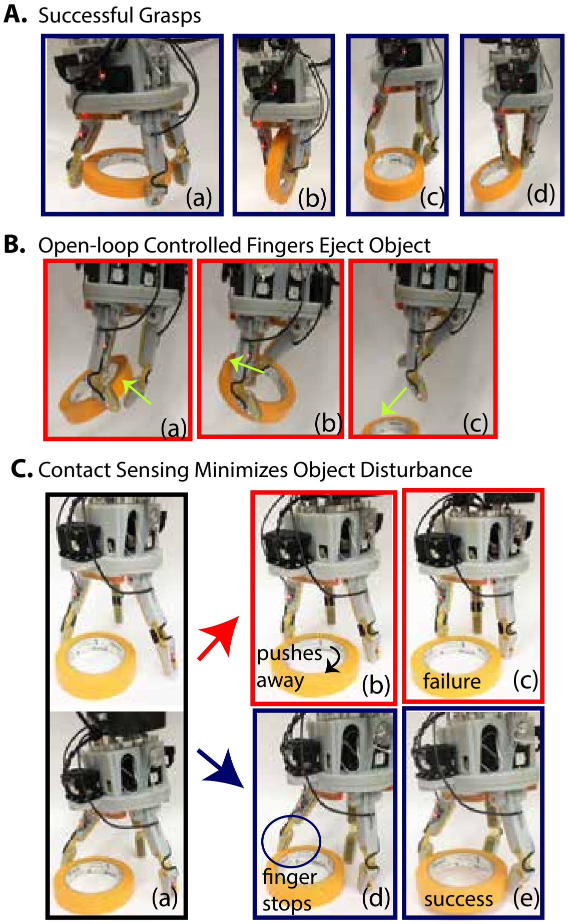


Fig. 7. Various successful grasps (top row), and typical error modes. Unconstrained compliant joints deflect and allow the object to be ejected (row 4, move to row 2). Stiff fingers push an offset object out of the way (row 3). Contact-referenced control results in a stable grasp under the same offset (row 2).

position differences that resulted in large force differences from the stiff fingers. The first experimental group shows that compliance alone was unable to compensate for positioning errors. In this case, the fingers are comparatively stiff with respect to the object mass, and tend to move the object before deflecting. Subsequent deformation of the flexures during the remainder of the grasp actually tended to eject the object.

The second experimental group tested contact-referenced control with compliance. The admissible offset in the primary grasp was larger than both open loop cases because the fingers stopped against the object rather than pushing it way. Moreover, although all grasps in this experiment were counted as "successful" for consistency if they withstood 3 seconds of shaking without dropping the object, some grasps were superior to others for subsequent operations such as placing the object as shown in the top row of Fig. 7. For the contact-reactive control, all grasps fell into modes described in Fig. 7 (a) or (c). The controller did not capture the region of edge-pinch grasps because a single finger contacting the object would stop and wait for other fingers to arrive, rather

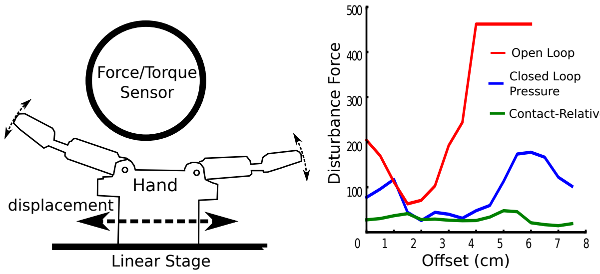


Fig. 8. Control comparison. A large cylinder was mounted on a force-torque sensor and grasped under a range of offsets to compare different controllers. For the same pad contact forces, contact-referenced control resulted in lower forces on the object due to better handling of blind spots and low-bandwidth control loops.

than pulling it towards the center as in the open loop stiff-finger case. This capability could be added programatically if desired, but the grasps that resulted from this edge case were generally the pathological successes (b) and (d).

The third experiment showed that comparing to open-loop power grasps, both closed-loop force control and contact-referenced control significantly reduce the disturbance force applied to the object. However, contact-referenced control exerts an even smaller force than force feedback control strategy.

IV. DISCUSSION

Robot hands are frequently designed intuitively, or for specific tasks, or by optimization of kinematics for a specific metric. Unfortunately, the mechanics of grasping is extremely complex, with highly nonlinear contacts at the ends of multiple serial kinematic chain fingers in parallel. This makes it difficult to effectively calculate or control contact forces. Recently, reduced-complexity underactuated hands have demonstrated good performance. There is an urgent need to explain this success, to enhance hand control, improve hand designs, and develop simple, inexpensive, and robust hands that enable real-world applications. This study aims to understand how compliance and simple tactile sensing contribute to grasping by underactuated hands by minimizing complexity and maximizing performance.

Compliance keeps forces low despite the wide object variability and uncertain sensing inherent in unstructured environments [17]. This is demonstrated in the first experiments where grasping a heavy water bottle resulted in low success rates with stiff fingers, but good grasping with compliant fingers. Hand stiffness values, however, must be specified to accommodate objects at the high end of the anticipated range of forces and object weights to enable good control of the object after it is grasped. This makes compliance less effective at low forces and with light objects, because the forces generated by positioning errors can dislodge objects before the fingers deflect. This is seen in the second set of experiments, where contact with one finger often moved the object out of grasp range before the other fingers could make contact.

One potential solution to this dilemma is using a variable stiffness actuator or structure such as [18]. While a number of interesting designs for variable impedance actuators and joints have appeared in the literature, both of these approaches greatly increase complexity and cost due to the sensing, motors, and mechanisms required. Use of a nonlinear stiffening structure avoids these complications, but it is challenging to define a fixed set of passive nonlinear stiffnesses that work across the range of objects and tasks in unstructured environments.

Tactile Sensing is a promising technology for enhancing robot grasping – and it has been promising for decades. While seemingly simple, implementation of effective tactile sensing has proved challenging. Low and inconsistent sensitivity, limited spatial coverage ("blind spots"), low durability, and difficulty in integrating sensors into the finger surface are some of the many problems encountered, and contact signals are inherently noisy due to the complex interaction dynamics of the hand and object. These issues makes real-world use of many tactile signal processing approaches in the literature problematic at present. As a result, grasp controllers that make simple use of tactile sensing are more likely to achieve satisfactory performance in real applications.

Contact-referenced control combines the strengths of both approaches, using low-threshold contact sensing to compensate for positioning errors, but using compliance to control and balance the internal forces on the object. This allows the use of simple position-controlled actuators, limited-bandwidth control loops (50Hz in this case), and results in gentler grasps under larger positioning errors. Such reductions in system cost drivers are an important step towards enabling better robot participation in solving real-world tasks.

V. CONCLUSIONS

This study addresses the problem of creating low cost and reliable grasping systems for unstructured environments. Attaining good performance for a wide range of object sizes and weights can be achieved with a combination of passive compliance tuned for heavy objects and tactile sensing to minimize disturbances for light objects. This approach requires only simple contact detection and localization from tactile sensing, which is consistent with the current state of this technology. In addition to enabling real-world applications, the methods advocated here can create working grasping testbeds, which permits incremental progress towards more sophisticated systems that use advanced sensing and control methods and more elaborate and capable hand mechanisms.

VI. ACKNOWLEDGMENTS

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