NRI: Design and Fabrication of Robot Hands for Dexterous Tasks

1 Introduction

Robot dexterity is critically important for robots working alongside people and for robots working in human spaces. Robots must be able to manipulate human objects and use tools made for people in order to assist people in performing tasks from mission critical to everyday.

Unfortunately, despite decades of development of high degree-of-freedom dexterous robot hands since the 80's, dexterous manipulation has remained elusive. Dexterity is a Grand Challenge level goal. In fact, the 2013 Robotics Roadmap [REFERENCE THIS PROPERLY] states:

> *Robot arms and hands will eventually out-perform human hands. This is already true in terms of speed and strength. However, human hands still out-perform their robotic counterparts in tasks requiring dexterous manipulation. This is due to gaps in key technology areas, especially perception, robust high fidelity sensing, and planning and control. The roadmap for human-like dexterous manipulation consists of the following milestones:*
>
> - *5 years: Low-complexity hands with small numbers of independent joints will be capable of robust whole-hand grasp acquisition.*
> - *10 years: Medium-complexity hands with ten or more independent joints and novel mechanisms and actuators will be capable of whole-hand grasp acquisition and limited dexterous manipulation.*
> - *15 years: High-complexity hands with tactile array densities, approaching that of humans and with superior dynamic performance, will be capable of robust whole-hand grasp acquisition and dexterous manipulation of objects found in manufacturing environments used by human workers.*

These goals are echoed in the NIST publication "A Roadmap to Progress Measurement Science in Robot Dexterity and Manipulation" [REF]. In this set of milestones, dexterous manipulation is not mentioned at all for the 5 year mark. Dexterity is expected in limited form at 10 years, and we are expected to achieve dexterous manipulation in robot hands in 15 years time.

We propose to enable considerable dexterity at the 5 year mark through task directed design with focus on joint limits and compliance.

There are many very excellent research groups working on the critical areas sensing, planning, and control. Our approach is orthogonal and complementary to these efforts. We aim to reduce the load on sensing, planning and control by designing the mechanism – the robot hand – to be as favorable to the intended task set as possible, i.e., by developing new analysis and design tools for crafting the robot hand mechanism to make dexterous manipulation easier from the start.

Our approach centers around several elements:

- **Develop a "Grasp Net" Benchmark.** We have observed from human studies that there are a relatively small number of grasping tasks and manipulation actions that are used over and over, and that common and useful grasp families are connected to one another with frequently used manipulation actions. We propose to create grasp net benchmark consisting of grasp families and manipulations to move between them. Mechanisms will be designed specifically to accomplish this grasp net.

- **Design Towards Specific Tasks.** We propose to design hands from the ground up with the specific goal of performing these grasping and manipulation tasks robustly. Even while we may

Figure 1: This trivial Grasp Net nonetheless captures two important grasps and a dexterous motion to move between them.

ultimately want a general purpose hand, evaluating a design vs. a comprehensive set of representative grasps and manipulation actions allows us to align our evaluation of suggested hands with useful tasks in the real world.

- **Strategically Place Actuators, Joint Limits, and Compliance.** Actuators of many types: tendon, linkage, flexible. Plus new analysis tools revolving around joint limits... Plus better understanding of design space for compliant joints and other components.... [FLESH OUT]

Why us? Synergistic combination of experience in grasp analysis and experience with robot hands and manipulation with expertise in mechanism design and construction. It is a great opportunity to develop the tools and make use of them to design robot hands to perform exactly the interactions that are needed for scenarios where humans and robots live and work together.

2 A Simple Example

In this section, we work out a simple example for purposes of illustrating our proposed approach.

Consider the trivial Grasp Net show in Figure 1. This figure shows two grasps. Grasp A is a pinch grasp, typical for lifting objects from a surface, placing them down, performing certain dexterous actions such as using tweezers, and as a staging point for moving to other grasps (e.g., consider lifting a wrench and then maneuvering it to enclose it within the palm). Forces in the pinch grasp oppose one another along the local y-axis. Objects may be of varying width, and grasp force may vary, creating a family of pinch grasps we would like the robot to be able to achieve.

Grasp B is a lateral grasp, often called the key pinch grasp, useful for comfortably and securely holding objects, for certain assembly operations (e.g., put a key or a card into a slot), and for offering an object to a person (or another robot). Forces for the lateral grasp in this example oppose one another along the x-axis. We consider the same object set, but rotated 90 degrees. Greater forces may be desired for this grasp. As with all grasps, we specify an exact set of relative contact locations and forces that defines our grasp.

Manipulation 1 is used to move between the two grasps. In this case we can imagine the "thumb" pivoting around the "index finger," although in our final design, the motion may be generated by either or both fingers. The variation in object widths creates a family of curves describing motion of the thumb relative to the finger. The object is specified to slide on the finger so that the thumb contact remains nearly constant.

Forces in this example do little more than guarantee that the object remains secured while performing the manipulation. The manipulation is assumed to be quasistatic.

A successful design must be able to move all of the benchmark objects from Grasp A to Grasp B using Manipulation 1.

Suppose that a mechanism designer has specified the following design constraints and suggestions:

- Actuators apply unidirectional linear force in the finger coordinate frame (e.g., tendons acting through the finger center of mass).
- Fingers can be made to be passively compliant using a linear stiffness model. [STELIAN GIVE ME A BETTER STIFFNESS MODEL.]
- At any time instant, at least one force must be active.
- Force directions during static grasping may be good directions in which to actuate a finger.
- Force directions during static grasping may be good directions in which to craft joint limits.

Suppose further that the designer's goals, in order of priority, are:

1. Grasp and manipulate all benchmark objects as specified in the Grasp Net.
2. Minimize the total number of actuators.
3. Minimize the number of actuators per finger.
4. Minimize the sum of forces that are actively applied (i.e., joint limits and passive forces due to compliance are "free")

For Goal 2, a test of rank on relative positions will determine that the minimum number of actuators is two.

For Goal 3, a tree search will find we can split these actuators between the fingers, so that each has one degree of freedom.

Now, we are left with 8 choices, as the thumb can be actuated in any of the four coordinate axis directions, and in each case there would be two choices of direction in which to actuate the index finger (specifically [x, y], [x, -y], [-x, y], [-x, -y], [y, x], [y, -x], [-y, x], [-y, -x]).

Figure 2 shows one final solution, where the thumb is actuated along the negative x-axis and the index finger is actuated along the negative y-axis. This is perhaps the most humanlike example and most resembles hands which actuate the grasping forces and use return springs to bring the fingers back to a fully open pose.

[SAY SOMETHING ABOUT JOINT LIMITS AND SPRINGS.]

[EXPLORATION: (1) THUMB GETS Y .. ANY DIFFERENCE? (2) VALUE OF 4 ACTUATORS?]

We can compare work done in the various cases, including without compliance.

Figure 2: Final solution.

3 Dexterous Manipulation Analysis with Joint Limits and Compliance

(requirements and objectives .. what makes for a good quality measure)

Here are some thoughts:

- Junggon's paper shows that we must consider the effects of physics and uncertainty.
- It seems likely that we can tweak our design to improve robustness.
- Sources of uncertainty (ideally to get from data)
  - Object uncertainty is clear .. size, shape, friction, initial configuration (possibly large)
  - Relative contact configuration is uncertain
  - Actuator force direction and magnitude are uncertain.
- Rollouts may be the place to start.
  - Randomize all uncertain parameters and simulate.
  - Histogram all unique event sequences.
  - Build event tree.
  - Record success.
  - What can we detect / sense to distinguish expected success from possible failure?
  - We have a quick way to gauge when we are outside the space of the example (2004 paper)
- The toy example is instructive. One actuator should be better than two, because an additional actuator introduces additional error (two ships passing). Giving the two actuators an offset that is not 90 degrees should improve robustness. We would end up tuning Grasp A to push the thumb into its joint limit corner. A change in shape would help avoid sliding problems with the other grasp (angle of surface results in force that pushes the index finger into its corner under low friction).
- The choice of active vs. passive clearly matters, as in the first item above, and it would be good to show quantitatively.

4 Dexterous Hand Design / Optimization

How we will create the form to follow the function!

Some random thoughts

- Good simulations of the mechanisms that are being proposed are key and are very hard. Can we get good material models? Can we construct good models of uncertainties so that our simulation rollouts match our experiments?
- Can we create a setup that allows lots of randomized tests for this purpose? Making simulations match reality appears to be hot right now.

5 The Grasp Net Benchmark

At least motivate how this might be possible. Show preliminary capture data.

6 Evaluations

- Generality. If we design for a specific task list, who is to say it is broad enough to do everything we would like to do? We can test generality with leave one out tests. That would be an interesting result to have no matter which way it comes out.
- Comparison to existing robot hands. Is it possible for existing robot hands to accomplish all grasps and manipulations within the grasp net? If not, what fraction can they achieve, based on kinematic structure and load capabilities alone? We can obtain experimental comparisons of our new hands vs. the Shadow and Barrett Hands available to us at CMU. Our hypothesis is that we will be able to exceed capability and robustness of existing hands in traversing the Grasp Net Benchmark with fewer actuated degrees of freedom and lower cost. We anticipate that the result may look quite different from the typical dexterous hand existing today.

7 Comparison to Related Work

Researchers have thought a lot about how to evaluate grasps, plan grasps

but design of a mechanism for a specific suite of grasp and manipulation actions that is meant to be general is less well considered.

Ciocarlie Frank Hammond III

Trinkle lever-up long train of Bicchi analysis papers

Many dexterous robot hand designs attempt to be as capable as possible – e.g., max manipulability.

In a way, we take the opposite approach – as capable as it needs to be and no more. Because limits help us.

8 Broader Impact

9 Results from Prior NSF Support

10 Timeline

11 Punch List

- Yong-Lae's student working on wrap-around sensors
- Scott Hudson re same sensors
- 3D print "fingers" with different elasticities / structures
- 3D print something to show Dexterous Motion 1
- letter of collaboration Paul Kry (do we want any others?)
- biosketches
- summary
- human subjects protection document
- data management plan
- facilities and equipment
- budget (DDH)
- current and pending (DDH)

Proposals involving human subjects should include a supplementary document of no more than two pages in length summarizing potential risks to human subjects; plans for recruitment and informed consent; inclusion of women, minorities, and children; and planned procedures to protect against or minimize potential risks.

Data Management Plan. All proposals must include a supplementary document no more than two pages in length describing plans for data management and sharing of the products of research, which may include (see sections II.D and VI.A):

The types of data, samples, physical collections, software, curriculum materials, and other materials to be produced in the course of the project;

The standards to be used for data and metadata format and content (where existing standards are absent or deemed inadequate, this should be documented along with any proposed solutions or remedies);

Policies for access and sharing including provisions for appropriate protection of privacy, confidentiality, security, intellectual property, or other rights or requirements;

A dissemination plan for using and sharing software and the robotics operating system, with appropriate timelines, must be included; and

Sustainability plan beyond the term of the award.