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 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.*

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 focused on realistic everyday manipulation at its full complexity.** 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 benchmarks consisting of grasp families and manipulations to move between them. Mechanisms will be designed specifically to accomplish these grasp nets.

- **Design to optimally accomplish specific collections of manipulation tasks.** We propose to design hands from the ground up with the goal of performing a specific set of grasping and manipulation tasks robustly. From the beginning, these sets of tasks will include families of

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

objects for generality. They will reflect real-world manipulations from the Grasp Net in their full complexity. But they will be concrete lists of benchmarks that the hand must accomplish, facilitating rapid evaluation and design exploration. The goal is to pursue generality while rooting our evaluation of suggested hands solidly in useful tasks in the real world.

- **Strategically Place Actuators, Joint Limits, and Compliance.** We believe that the keys to robustness of hand designs will be selection and placement of actuators, generous use of joint limits, and strategic use of built-in compliance. We will explore a variety of actuator designs and mechanisms to add limits and passive compliance. Theoretical contributions to grasp analysis and optimization will be bolstered and improved with experimental data collected from many design iterations, component testing, and system testing.

PI Pollard brings decades of experience in grasping and manipulation analysis and experience working with various robotic hands and systems. PI Coros brings experience in design of creative, complex mechanisms to accomplish user specified tasks, as well as 10 years of experience in control algorithms for complex tasks. This combination of skills is critical for designing robot hands with the capability and skills to perform robustly exactly the interactions that are needed for scenarios where humans and robots live and work together.

2 A Simple Example

Consider the trivial Grasp Net shown 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. We observe that many objects are initially acquired from a surface in a pinch grasp and then moved to a final grasp that is more useful, comfortable, or powerful. Forces in the pinch grasp oppose one another along the local y-axis.

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. Greater forces may be desired for this 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 manipulation is specified to utilize sliding contact on the finger and rolling frictional contact with the thumb, such that the point of contact between object and thumb remains nearly constant. Forces are specified in this example to do little more than guarantee that the object remains secured while performing the manipulation; the manipulation is assumed to be quasistatic.

There are N benchmark objects of varying width and required grasp force. The design problem is to choose degrees of freedom, place actuators and joint limits, and select passive compliance for the mechanism. 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 for this toy example:

- Actuators will create linear motion in the x-y plane.
- Fingers are passively compliant using a linear 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 suggest a need for two actuators. Goal 3 will split these actuators between the fingers, so that each has one degree of freedom. Figure 2 shows one final solution. [EXPLAIN]

[TODO: INVESTIGATIONS]

- Minimize work. Without compliance. With compliance. With four instead of two actuators. Leave one out tests. Goals: show compliance matters, show some generality can be obtained.
- Maximize robustness. Allow shape changes. Test with and without joint limits. Goals: show joint limits and compliance both affect robustness.
- Simplify control. Optimize for robust performance with a simple control motion. Show that if we consider control in the design, it can be made very simple and we don’t sacrifice robustness. Can we get away with a single motor and drive the system in both directions?

Figure 2: One final solution.

3 Dexterous Manipulation Analysis with Joint Limits and Compliance

Traditional grasp and manipulation analysis assumes we operate the hand far from singularities and joint limits. In such a case, the dynamics of the system may be linearized and used to estimate our ability to control an object and apply and resist forces within a local configuration space [refs]. Such estimates may be used as a basis for hand design [ref].

However, such analyses are limited when it comes to understanding the broad spectrum of capabilities of a proposed robot hand, and designers have formed other tests, such as workspace analyses [Feix comparing to human hand] and heuristics such as ability to oppose the thumb to each of the fingers.

We propose to broaden such tests and make them focused on a broad spectrum of real-world grasping and manipulation actions that are observed to be of great use in everyday goal-directed activities. We advocate working from a specific set of well-defined target grasps and manipulations. We suggest that libraries of such specific tests be added to the benchmarking metrics that are under development. Our philosophy is first make a hand that is able to perform these manipulations in exactly the manner described and then we can be creative about how to achieve the same goals more effectively.

[Get in the idea here of needing to examine a sufficiently complex system to fully understand it.]

We observe that joint limits are not avoided in human motion. In contrast, in the human system, joint limits and singularities are often exploited. The limit at our knee that facilitates straight leg walking is a well known example, but there are many examples in grasping and manipulation as well. [FIGURE?] In a lateral grasp, the moderately flexed fingers can passively support large lateral forces. Large forces can be transmitted through our palm all the way up to our strong shoulder muscles, or even through to the ground in some cases. Pressing hard with a fingertip will also exploit joint limits.

New tools are needed to work with joint limits and compliance as first level design tools on par with selection of actuators and location of degrees of freedom. In addition, we need standard processes for evaluating robustness in performing complex manipulation actions, not only in maintaining a single grasp. We propose to address these gaps.

Specific problems that we will address include:

- Fast algorithms to prune subsets of the design space that are not feasible.
- Fast algorithms to determine feasibility (e.g., ensure required task forces can be actively applied over an entire manipulation trajectory).

- Efficient closure tests in the presence of joint limits.
- Fast algorithms to estimate robustness of a manipulation.

3.1 Example: Force Closure with Joint Limits

Force closure tests and many grasp quality measures examine whether it is possible to resist disturbances and apply task forces given the locations and friction properties at contacts. However, this approach does not in general differentiate between forces which must be actively applied to the object and those which can be passively resisted. Joint limits will prevent motion in a given direction and can allow the hand to resist large forces in that direction, but the joint limit may be an intended as an approximately frictionless surface, and care should be taken in expressing ability of a contact to resist forces tangent to that limit direction.

[Work out a first pass at equations here.]

Ideally, good things should happen if we just squeeze, as in the Trinkle 1990 paper. Otherwise, we want simple control algorithms where the hand can respond to local variations at each contact – e.g., reactions to roll, slide, or load imbalance.

3.2 Sensing

The promise is radically more competent hand designs given our current level of sensing capabilities and guidelines for sensing requirements that will most quickly increase capabilities.

3.3 Random thoughts that will either be incorporated or go away

Here are some thoughts:

- Junggon's paper shows that we must consider the effects of physics and uncertainty.
- Gravity is another tool and we should design our manipulations where possible to take advantage of gravity.
- 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.