
Figure 1: We propose to develop the underlying analysis techniques and mechanism optimization approaches to enable us (and others) to design robot hands from the ground up to perform robustly dexterous manipulation tasks such as these.

# 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, dexterous manipulation has remained elusive. Robot hands cannot lift a wrench in a pinch grasp and slide it into a secure grasp for use with ease. Robot hands cannot handle a pair of pliers with competence. Even the simple task of grasping and turning a lever or knob can be a challenge; compare to the variety of modes of the "twist" action shown in Figure 8. Our view is that robots fail in these tasks in large part because no one has designed a robot hand from the ground up to be robustly competent at exactly these kinds of manipulations.

The 2013 Robotics Roadmap [17] 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.*

Dexterous manipulation is not mentioned for the 5 year milestone. Dexterity is expected in limited form at 10 years, and approaching human levels in 15 years.

*We propose to enable dexterity at the 5 year mark by designing robot hands from the ground up to do the kinds of dexterous manipulation tasks we see in Figure 1.* This figure shows several examples of dexterously acquiring objects into the hand, as well as a collection of manipulation actions to move between four different grasps. Later figures have other examples.

There are many very excellent research groups working on the critical areas of 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 to be as favorable to the intended

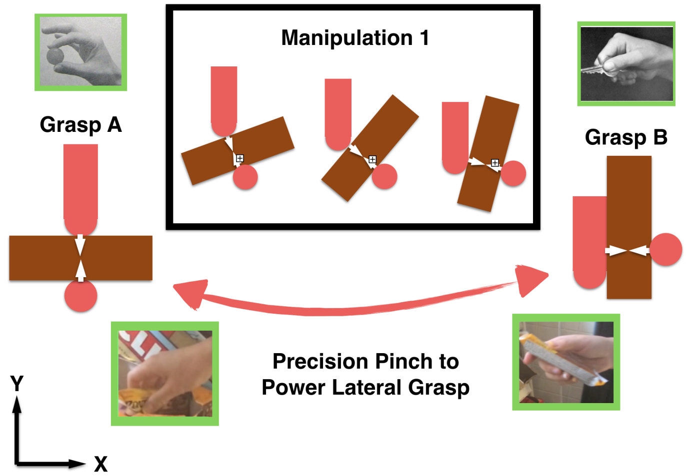



Figure 2: This trivial Grasp Net nonetheless captures two important grasps and a dexterous motion to move between them.

task set as possible by developing new analysis and design tools for optimizing the robot hand to make dexterous manipulation easier from the start.

This is a **high risk / high reward proposal**. The risk derives from the fact that dexterous manipulation is indeed complex. However, we observe commonalities in how people perform manipulation tasks that indicate sufficient structure to make design optimization feasible. For the reward, consider the change that can be effected by a robot hand that can manipulate the same objects and tools as its human counterpart in a cooperative task and carry out dexterous actions easily because it was designed to do just that.

Our approach centers around several elements: **"Grasp Net" benchmarks** to explore manipulation at its full complexity (Section 7), **Mechanism design** focused on manipulation tasks (Section 5), Strategic Placement of **Actuators, Joint Limits, and Compliance** (Section 3), and later in the project Strategic consideration of **Sensing** (Section 6).

Figure 3 shows a very simple robot hand which we developed to illustrate the potential. Through our design optimization process, we went from a manually designed version that was fiddly and difficult to coordinate to one where the manipulation almost does itself. A hand designed to do the manipulation tasks in Figure 1 as robustly as possible will change the landscape in terms of potential robot applications, especially in real-world co-robot applications where humans and robots work together and cooperate to accomplish a goal.

## 2 A Simple Example

Consider the trivial Grasp Net shown in Figure 2. This figure shows two grasps. Grasp A (Left) is a precision 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 (Right) 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.

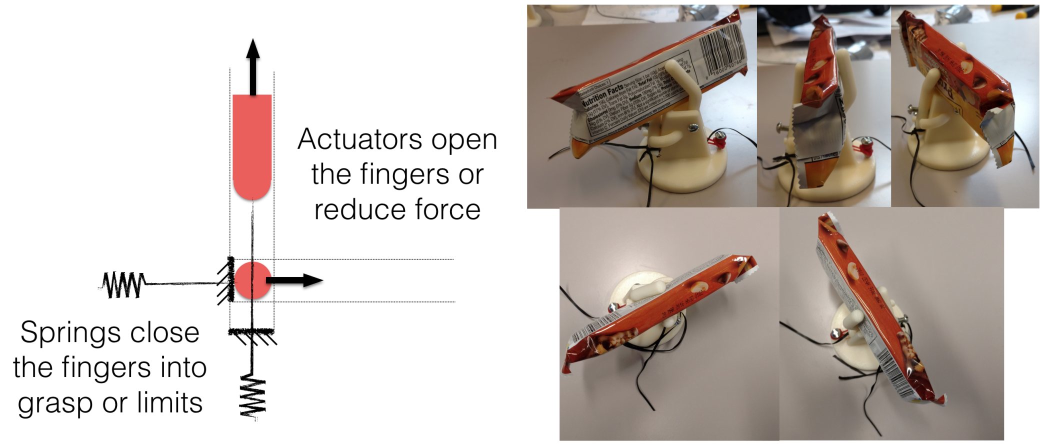



Figure 3: (Left) One final solution. (Right) A physical implementation that approximates this design with 3D printed base and fingers.

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. There is a collection of benchmark objects of varying width, required grasp force, and other physical properties. 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 accomplish Grasp A, Grasp B, and Manipulation 1 easily / robustly / reliably in the presence of uncertainties.

Figure 2 shows one solution that was derived based on the goal of minimizing the total number of actuators and the number of actuators per finger while ensuring that the mechanism could accomplish the task. This design relies on spring forces to close the fingers at both Grasp A and Grasp B, while using actuators to open the fingers. If both actuators are engaged briefly in a coordinated way, the grasp can be shifted from A to B or from B to A, performing Manipulation 1 in both directions. The coordination could be done mechanically for some range of objects, leading to a one actuator system. Such a system would be reminiscent of a body-powered prosthesis with a voluntary-opening end effector [78]. However, instead of a single available grasp, we have been able to accomplish two different grasps and a dexterous manipulation between them. A physical instantiation of this solution is shown in Figure 3. It was 3D printed and assembled in a matter of hours.

## 3 Dexterous Manipulation with Joint Limits and Compliance

One keystone of our approach is strategic consideration of joint limits and compliance. We illustrate the importance of these elements for the simple example. Specifically, we show that (1) Careful design of compliance can reduce the number of actuators and actuator load, and (2) Joint limits are important for robust performance. Following this discussion, we present an approach to analyze grasps and manipulations to consider joint limits (Section 4) and approaches for design optimization to handle much more complex Grasp Nets to accomplish tasks such as those shown in Figure 1 (Section 5).

**(1) Compliance matters.** Table 4 shows parameters for four tendon driven designs, which were optimized to perform Grasp A, Grasp B, and Manipulation 1 for objects having widths from 1 to 4 finger radii. Quasistatic analysis was performed for each design, with actuators for the thumb moving in the

| Design | x0 | y0 | kx | ky | cost | actuated x range | actuated y range |
|---|---|---|---|---|---|---|---|
| (A) 4 tendons, no compliance | - | - | - | - | 1600 | (-4, 0) | (-4, 0) |
| (B) 4 tendons, compliance | -1.887 | -2.58 | 0.54 | 0.43 | **107.65** | (-1.36, 1.02) | (-1.61, 1.11) |
| (C) 2 tendons, spring open | 7 | 7 | min | min | 1600 | (-4, 0) | (-4, 0) |
| (D) 2 tendons, spring closed | -5.883 | -4.998 | 0.45 | 0.5 | **445.3** | (0, 2.65) | (0, 2.49) |

Figure 4: Optimal parameters, cost, and actuator range for several mechanism designs to perform Grasp A, Grasp B, and Manipulation 1.

X direction, and actuators for the finger moving in the Y direction. The quasistatic analysis ensured that forces required for Grasp A, Grasp B, and Manipulation 1 could be generated by the mechanism. Each design was optimized using CMA [42] to require the minimum total actuation force, expressed as squared actuated forces summed over actuators, objects, and time samples. Where compliance was considered, linear springs were assumed, with zero point and stiffness given as parameters to the optimizer. Optimal parameters, cost, and range of actuated forces are shown in the Figure.

Design (A) contains 4 tendons, which give active control in the negative and positive X directions for the thumb and the negative and positive Y directions for the finger. This design considers no passive compliance. Design (B) contains the same 4 tendons, but it also includes linear springs. Note that the cost of forces provided by the actuators is less than 7 percent that of Design (A). Design (C) has two tendons which act to close the hand, with elastic return springs to open the hand. The presence of the spring elements reduces the total number of actuators, but does not reduce the cost of the design. Design (D) also has two tendons, which act to open the fingers. In Design (D), the spring elements close the hand and provide grip force. The cost of Design (D) is 28 percent of that of Design (A), and the design achieves this result with half the number of actuators. Clearly, compliance matters. If we are able to maintain 4 actuators, compliance allows us to reduce forces to a small fraction of their magnitude, even while handling a variety of object sizes. Adding compliant elements makes it possible to reduce the number of actuators to two and *also* reduce forces to a fraction of their original value. Fortunately, it has become increasingly easy to incorporate compliant elements into a design using 3D printing and other technologies, such that we can consider this just one more design element available to optimize.

**(2) Joint Limits matter.** We observe that joint limits are not avoided in human motion. In contrast, in the human system, joint limits and singularities are 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. In a lateral grasp (which motivated Grasp B), the moderately flexed fingers can passively support large forces, even though the force that can be actively generated by the fingers in that grasp is small, coming from small intrinsic muscles in the hand, such as the interossei [4]. The large grasp forces are available because the fingers are operating near their joint limits in this direction. As another example, 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 also exploits joint limits.

In this Section, we show one simple example that joint limits can make a practical difference. We explored the ability to learn robust open loop control for Manipulation 1. Motor velocities for the thumb and finger were represented as linear functions of time, with three velocity control points per finger, resulting in a search space of six parameters. CMA was used to optimize these parameters. Box2D [7] was used to simulate the manipulation for any given parameter set. The cost at the end of each simulation was the difference between the final object state and that desired for Grasp B. Once an optimal open loop motion had been identified by the optimizer, it was evaluated on a series of 5 test sets, each involving 100 simulations having perturbations in the direction of motion of the finger. Finger motion direction was perturbed about its intended direction using a normal distribution with

| Test Case | Errors at Gaussian perturbation (radians) | | | | |
|---|---|---|---|---|---|
| | None | 0.1 | 0.2 | 0.3 | 0.4 |
| (A) Joint limits, learn with perfect mechanism | **0.01** | 0.90 | 1.63 | 2.32 | 3.61 |
| (B) Joint limits, learn with perturbation | **0.04** | **0.05** | **0.08** | **0.21** | 1.42 |
| (C) No joint limits, learn with perfect mechanism | **0.01** | 1.05 | 2.13 | 2.84 | 4.06 |
| (D) No joint limits, learn with perturbation | **0.03** | **0.06** | 1.43 | 4.38 | 5.75 |

Figure 5: This exploration shows the value of joint limits. Mean error of an optimized manipulation is shown as perturbations to the perfect mechanism grow in magnitude. Standard deviation is in parentheses. The test having joint limits and optimized with perturbations is able to handle perturbations three time the size of any other situation tested.

standard deviation of 0, 0.1, 0.2, 0.3, and 0.4 radians. The motivation for this choice is that in a more complex hand, it is often difficult to know exactly where the fingers are relative to one another, and this variation can affect ability to manipulate robustly. When a test used joint limits, the limits for the thumb were placed in the X direction, both at the thumb's origin in Grasp A and at a wide open position that gave clearance twice the width of the largest object. Joint limits for the finger, when used, were placed in the Y direction, both at its destination in Grasp B and in a wide open position that gave clearance twice the width of the largest object.

Four cases were considered (Figure 5). In Case (A), joint limits were included, and the manipulation action was optimized assuming a perfect mechanism. Case (B) is similar to Case (A), but included random perturbations during the learning phase, having a standard deviation of 0.2 radians. In cases (C) and (D), joint limits are not included. Figure 5 shows the results. Empirically, results with error less than 0.5 in our scale produced consistently good manipulations. These results show that when a task is optimized assuming a perfect mechanism, the effect of joint limits is not clear. However, when the optimization process has the opportunity to see perturbations, the optimizer learns to use the joint limits to create robust strategies. Case (B), including both joint limits and learning with perturbations, is able to handle three times the amount of disturbance of any other case. Clearly, joint limits matter. Intuitively, this is because driving a joint to its limit reduces uncertainty and reduces the need for control to be exact (i.e., many controls can drive the joint to its limit). Whenever such limits can be used, they offer great advantage. Fortunately, it is easy to build in joint limits as well, as part of shape optimization. For our physical instantiation of the Simple Example, we used geometric features to limit range of motion of the fingers.

In addition to joint limits and compliance, there are of course other things that matter. One design element is shape. Consider, for example, how people can make good use of our palm and its ability to conform. Another is surface properties. It may be beneficial to have some parts of the hand be slippery and others have high friction. For example, in the Simple Example we had the object slide on the finger and roll on the thumb. Another aspect is ability to sense unexpected slip, force, or motion. We propose to investigate these options in the context of the larger goal of optimizing a hand design to accomplish a family of manipulations (i.e., a Grasp Net).

# 4 Grasp and Manipulation Analysis with Joint Limits

One research challenge addressed in this proposal is to expand our analysis tools to deal well with joint limits. We illustrate the problem and sketch a solution through the simple example in Figure 6. Consider first Figure 6 A. The goal is to push into a surface, holding the object in the given grasp. There will be variation in the task, as the object may contact the surface at different points and with different surface contact normals, resulting in varying force directions and moment about the object center of mass. The Figure shows just a single example of task forces that could be encountered. Each finger has one tendon to actuate it, with directions of actuation shown. We assume the two fingers on the sides have considerable compliance in the horizontal direction. Actuating these fingers does not help, as this will only cause the fingers to slide along the object surface. With the design as shown in Figure 6 A, the grasp will only be able to apply a very small range of task related forces to the object.

We can examine the force balance equations. Because the fingers are very compliant, forces on the fingers must be balanced to prevent them from moving:

$$f_{s,i} + f_{a,i} + f_{JL,i} + f_{c,i} = 0 \tag{1}$$

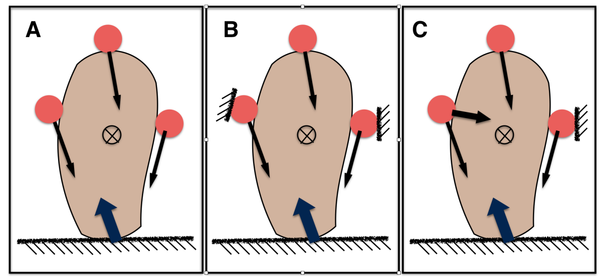



Figure 6: Several designs for a pushing task.

Parameter $f_{s,i}$ is the spring force, with a component due to deviation of the initial contact location $c_i$ from rest position $c_{i,0}$ and a second component due to object motion that results from unequalized forces $\Delta X_o$, which is intended to be small for a good grasp. Matrix $K_i$ encodes stiffness as seen at the fingertip and $G_i$ is the grasp matrix for finger i.

$$f_{s,i} = -K_i(c_i - c_{i,0}) - K_i G_i^T \Delta X_o \tag{2}$$

Parameter $f_{a,i} = D_i P_i A_i$ is force generated by the actuators as in [55], and is expressed using activation levels $A_i$, $0 \leq a_i \leq 1$, diagonal matrix $P_i$ of maximum actuator forces, and matrix $D_i$ of actuator directions.

Parameter $f_{JL,i}$ is the novel component compared to other treatments that consider grasp quality for compliant systems (e.g., [56]), and can be expressed for a frictionless joint limit surface as:

$$f_{JL,i} = -k_{JL} N_i S_i N_i^T G_i^T \Delta X_o \tag{3}$$

with joint limit normal matrix $N_i$ and (large) stiffness experienced at the limit of $k_{JL}$. Note the selector matrix $S_i$ which indicates which joint limits relevant to finger i are currently engaged by some external or active force.

Parameter $f_{c,i}$ is the contact force, which must be within the friction cone at the contact and contributes to balancing a desired external wrench $W_{ext}$ due to the pushing contact with the ground in this case:

$$-\sum_i G_i f_{c,i} = W_{ext} \tag{4}$$

For a given value of selector matrices $S_i$, we can solve the resulting linear system for actuator forces $A$ and object motion $\Delta X_o$. In a valid solution, $\Delta X_o$ must be consistent with selection matrix $S_i$ such that the object motion pushes the object into the limit to engage it. The system as a whole can be resolved through pivoting or other discrete search techniques.

A similar analysis gives guidance for design of joint limits. Following [55] we can identify the worst case task wrench. Knowing this wrench, we can attempt to place a joint limit to oppose it. To visualize this process, note that in two dimensions a task wrench is a line with direction and moment about the origin. We wish to identify the joint limit to supply the opposing wrench nearest to this line, with the added consideration that task wrenches or other actuators must engage this limit.

In the case shown in Figure 6, a search for optimal joint limits may result in Figure 6 B, having joint limits that oppose horizontal motion at the two side fingers. This solution is similar to using two fingers laterally as guides while pushing with a middle finger. Here, the range of task forces that can be applied is considerably greater. Torques due to ground contact forces at the object base engage one of the joint limits, allowing a force balance to be created.

A third option, shown in Figure 6 C, is to add an additional actuator that can actively engage the joint limit opposite to it. The result is a very strong grasp, reminiscent of human power lateral grasps, which can easily provide the task forces and many more. As a side benefit, the two previously useless actuators can now contribute to the task, sharing the load with the actuator of the top finger.

In each case, the force balance equation as shown here, along with a straightforward linear optimization, have made it possible to evaluate the effect of any new design element on the ability of the push grasp to achieve task forces. Extension to complex and redundant mechanisms is more complex but can follow the same line of reasoning. Developing and evaluating these analysis tools is one task of the proposed research.

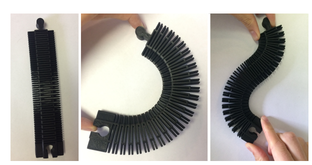
# 5 Dexterous Hand Design / Optimization

Recent work has shown that carefully engineered mechanical designs can prove crucial in improving the versatility of robotic manipulators for static grasping tasks [19]. The aim of our work is to generalize this concept in order to revolutionize dexterous manipulation in the same way. We therefore propose mathematical models and algorithmic approaches to co-design mechanical structures and control policies for robotic manipulation tasks. Our hypothesis is that by complementing each other and working in unison, control policies can be significantly simpler, and appropriate mechanical features – joint stops, compliance, etc. – can passively improve the robustness of the manipulation tasks while reducing sensing and actuation requirements.

## 5.1 Bottom-up Design

The design process will begin with a specific family of tasks (i.e., a Grasp Net). As described in Section 4, features such as compliance of passive structures or joint limits can be computed through numerical optimization. Our goal is to automatically translate these optimized features into mechanical structures that can be 3D printed. As a first step, we will investigate bottom-up approaches. For the physical prototype of the 1 degree-of-freedom manipulator shown in Figure 3, for example, we used a script to generate 3d printable geometry using constructive solid modeling. After fabrication, we used rubber bands to approximately match the optimized compliance of the passive features. The resulting mechanical setup was actuated manually. We view this first result as very encouraging because, with no sensing and very crude actuation, the simple robotic hand was able to reliably and repeatedly perform the manipulation task it was designed for.

Our future investigations will formalize the process we used to design and fabricate our first robotic hand. We will begin by building upon the mechanism design work led by PI Coros [27, 1] to automate the synthesis and optimization of assemblies based on trajectories of contact points. We will then extend these models to appropriately control the compliance of the mechanical structures. As illustrated in the inset figure, 3D printing is capable of fabricating objects



with complex geometric features, which, in turn, allows the compliance of manufactured parts to be modulated. PI Coros has already started to develop computational methods to explore the relationship between geometric shape, material parameters and deformation behavior [77, 65]. Briefly, we will model mechanical structures using a Finite Element Method (FEM) approach, where volumetric structures are discretized into a set of elementary shapes (e.g. tetrahedrons). Through a constitutive model, the deformations of the elementary shapes are mapped to elastic energy by integrating over the domain of each element. The global deformation energy $W$ is obtained by summing up elemental contributions, and internal forces are computed as $\mathbf{f}_{int} = -\frac{\partial W}{\partial \mathbf{x}}$, where $\mathbf{x}$ is an array concatenating the vertex coordinates for each element. Quasi-static configurations for the mechanical structures under load can be obtained by finding the deformed configuration $\mathbf{x}$ that leads to force equilibrium.

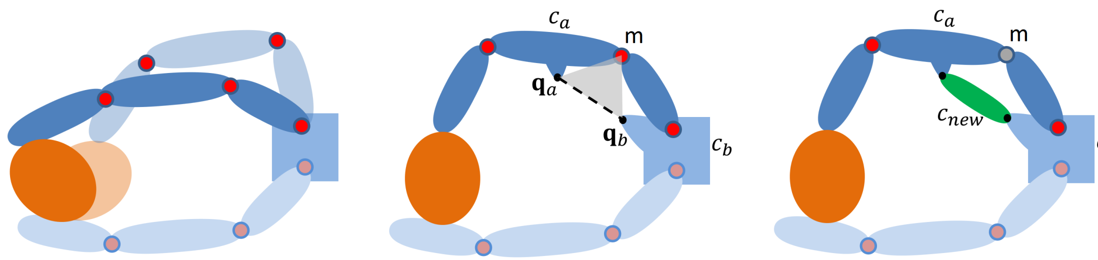



Figure 7: (Left) A conceptual, fully actuated hand design performing a dexterous manipulation task. Active motors are highlighted in red. (Middle) Given two components $c_a$ and $c_b$, we seek a pair of points $\mathbf{q}_a$ and $\mathbf{q}_b$ such that the distance between them varies least throughout the motion. To avoid singularities, the area of the highlighted triangle must remain positive throughout the entire motion. (Right) The hand design is simplified by removing motor $m$ and introducing a new passive link $c_{new}$.

Our mathematical models predict how these quasi-static configurations change with the shape of the mechanical parts and their material parameters [77]. We will leverage these models to optimize the internal forces generated when mechanical parts deform as the robot hand performs manipulation tasks. To increase the range of materials that can be used, we will experiment with both 3D printing and laser cutting technologies to manufacture the mechanical components.

## 5.2 Top-down Design

While bottom-up approaches aim to create a hand design from scratch, we will also investigate top-down approaches. The strategy here will be to begin with a conceptual design of a highly actuated robot hand design. For example, if a dexterous manipulation task was described through motion capture data, then the initial design would be given by an actuated articulated structure that matches the kinematics of the performer's hand. The underlying assumption is that, with perfect state knowledge and optimal controllers, this robot hand would be able to perform the desired dexterous manipulation tasks. Through an iterative process, the mathematical models we will develop will be used to replace active degrees of freedom with appropriate passive mechanical structures such that a balance between adaptability and simplicity is achieved.

Figure 7 illustrates a conceptual, fully actuated robot hand consisting of rigid links connected to virtual actuators that control their motions. In principle, physical actuators could be used to directly replace their virtual counterparts when fabricating this robot hand. However, this would come at an increased cost, a more complex mechanical design setup, and it would require sophisticated control policies to coordinate all the actuators. As an alternative, we propose an automated design process that iteratively replaces virtual actuators with new rigid or compliant links that appropriately couple the motion of different parts of the hand mechanism. The attachment locations, length and material properties of the new mechanical components will be optimized such that changes to the functionality of the input hand design are minimized.

The starting point for our investigations is a method recently developed by PI Coros and his colleagues. This method is used to design complex linkage structures that generate a desired motion trajectory [79]. The concept behind this method, which we will extend as part of our proposal, is based on a simple observation. Removing a motor and adding a new rigid link preserves the invariant that there are always as many constraints as degrees of freedom in the hand's mechanism: eliminating a motor removes one constraint, adding the (planar) link introduces three degrees of freedom, and two pin joints used to connect the new link to the existing structure result in four additional constraints. The motion of each mechanical component is thus either directly driven by a motor, or is mechanically coupled to that of other components.

To determine which motor should be replaced, and how to optimally insert a new mechanical component, we developed a mathematical model based on the following observation: if the distance $d$ between two points on a pair of existing components does not change as the hand performs a manipulation task, then these components can be connected through pin joints to a new rigid link of length $d$. Although the resulting mechanism would technically be over-constrained, the new link and its pin joints would be completely redundant. Removing a motor along the kinematic chain between the two components would resolve this redundancy while perfectly preserving the original motion. In general, there are no guarantees that such pairs of points always exist. Therefore, given two components, $c_a$ and $c_b$, we seek to find a pair of points $\mathbf{q}_a$ and $\mathbf{q}_b$ whose world-space distance varies least throughout the motion. The mean squared world-space distance between these two points is given by $l_{ab} = \frac{1}{n_s} \sum_i^{n_s} ||\mathbf{q}_a(t_i) - \mathbf{q}_b(t_i)||^2$, where $n_s$ is a number of discrete time samples that span the entire motion, and the variance of this quantity is $E_{\text{variance}} = \frac{1}{n_s} \sum_i^{n_s} (||\mathbf{q}_a(t_i) - \mathbf{q}_b(t_i)||^2 - l_{ab})^2$. When searching for the pair of points that minimize this variance term, it is critical that singular configurations are avoided at all times. As illustrated in Figure 7, when the selected motor ($m$) is removed, the new link ($c_{new}$) becomes responsible for driving the motion of component $c_a$ by direct coupling to component $c_b$. To ensure that the effective moment arm remains sufficiently large at all times, the area of the shaded triangle needs to always remain a safe distance away from zero. This can be accomplished through a log barrier term $E_{\text{area}} = -\log \sum_i^{n_s} \text{area}\left(\mathbf{q}_b(t_i), \mathbf{m}(t_i), \mathbf{q}_a(t_i)\right)^2$, where $\mathbf{m}(t_i)$ denotes the world-space position for the motor $m$.

Given two components $c_a$ and $c_b$, which are selected in an outer loop, our mathematical model minimizes a weighted combination of the terms $E_{\text{variance}}$ and $E_{\text{area}}$. With gradients and hessians for these objectives readily available, a Newton-Raphson scheme efficiently solves the resulting optimization problem. Once points $\mathbf{q}_a$ and $\mathbf{q}_b$ are found, they define a candidate rigid link to be added to the hand mechanism. Our design system then individually removes each motor on the kinematic chain between $c_a$ and $c_b$ and further optimizes the motion of the resulting assembly using our recently developed method [1]. Importantly, this optimization step not only adapts the kinematic parameters of the design, but also the actuator signals that control the motion of the hand mechanism. As a measure of the success of each potential replacement operation, we evaluate the difference in motion between the initial hand design and the optimized mechanism with fewer active degrees of freedom. If the resulting mechanisms deviate too much from the hand's initial motion, a new set of components will be selected and the process repeats. Otherwise, the replacement operation is finalized.

To improve the reliability of the designs generated with our mathematical models, we will develop additional optimization objectives based on the linear robustness analysis introduced by PI Pollard [66, 68, 69]. Further, we will improve their adaptability by exploiting compliance. More specifically, rather than coupling different parts of a mechanical design with rigid components, flexible structures, such as those seen in the inset figure of the previous subsection, can be used instead. Consequently, the simplified robot hands designed with our models will aim to not only duplicate motion trajectories, but also the contact forces required to manipulate objects.

At a high level, the research challenge we propose to address is the following: given a collection of parameterized components – rigid and flexible links, different types of actuators, different types of compliant structures, etc., how should they best be combined to generate the required set of contacts and forces needed for robust, dexterous manipulation tasks? Although we highlighted two specific design methodologies here, the space to explore is very rich. For example, another design approach we will investigate will have us start with a (conceptual) soft robotic hand controlled with networks of hundreds of tendons and soft actuators that are distributed throughout. Our goal will be to simplify such an initial design by optimizing, with a sparse regularizer, the placement and routing of all these structures. The key idea will be to express manipulation tasks as a decomposition of deformation modes that are in some sense orthogonal to each other, and determine the minimum actuation required to activate each deformation mode.

## 6 Research Tasks and Questions

Primary tasks and research questions for this project follow.

**(1) Extend Quasistatic Grasp and Manipulation Analysis approaches to consider Compliance and Joint Limits.** Building on the simple example of Section 4, develop mathematical tools for quasistatic grasp and manipulation analysis in the presence of joint limits. Extensions include multiple degree of freedom fingers, redundant mechanisms, actuators and links of various types including compliant links, and different varieties of joint limit surfaces. Our goal is to quickly evaluate the effect of any design change so that alternative designs can be explored and the hand can be optimized in a very fast search loop.

**(2) Fast techniques for Evaluating Robustness.** Quasistatic Grasp and Manipulation Analysis as discussed in (1) does not consider uncertainty, i.e., a test for feasibility will be carried out for one specific scenario. However, we care very much about robustness to uncertainty, even (especially!) in the mechanism design stage. In Section 3, we showed how robustness could be evaluated through rollouts of the manipulation under samples of a distribution of likely scenarios. Using rollouts to evaluate success is functional, but slow. Using simulation rollouts may not scale well to the breadth of situations we plan to address.

Previous research by PI Pollard has resulted in techniques that can use a simple and fast linear projection to analyze robustness to errors in placing the fingers on an object [68]. We have extended the process to evaluate robustness for manipulation tasks [66] and shown that the same approach can be used to express ability to grasp objects of different geometries [69] and to work with tendon driven systems [55].

Briefly, the idea we have exploited in this previous research is to portion variations out to different parts of the mechanism (e.g., to each contact). As long as each contact is confronted with a situation within its portioned space of variations, we can guarantee that overall, the task can be completed at least X percent as efficiently as an example. Decreasing X gives more freedom, but less efficient results (e.g., for lower X we may need to reduce weight limits on manipulated objects). Unlike many other approaches, which scale exponentially with number of contacts, this approach scales linearly with number of contacts and works better and better as number of contacts increases; with large numbers of contacts comes great ability to adapt to uncertainties and variations. Many human manipulation tasks benefit from large numbers of contacts and we expect to exploit this property.

Use of this idea in a design process is as follows. Suppose a mechanism design for which we wish to test robustness. Given a solution to manipulate one object, we develop a test that utilizes a small number of linear projections to evaluate the expected success of any combination of uncertainties in mechanism and variations in object geometry, following the approach of apportioning out variation spaces to different parts of the mechanism as outlined above. These projections will be trivially fast and will not require analyzing details of each object or computing a mechanism trajectory.

Funding for this proposal will give us the opportunity to investigate this idea properly. The potential impact is large, both for manipulation planning and mechanism design, as having linear projections in the inner loop of a planning or optimization process as opposed to simulation rollouts to evaluate the same thing can speed these operations by orders of magnitude, allowing real-time planning and user-in-the-loop interactive design optimization.

**(3) Design and Optimization Tools for robotic manipulators.** The first two tasks will provide the means to plan and analyze dexterous manipulation actions when considering features such as joint limits and compliance. The goal of this task is to translate these features into functional robot hands. This proposal will allow us to develop mathematical models that automate the synthesis of optimized mechanisms, and to explore different computational approaches and digital fabrication techniques to create physical structures with precisely controlled deformation behaviors.

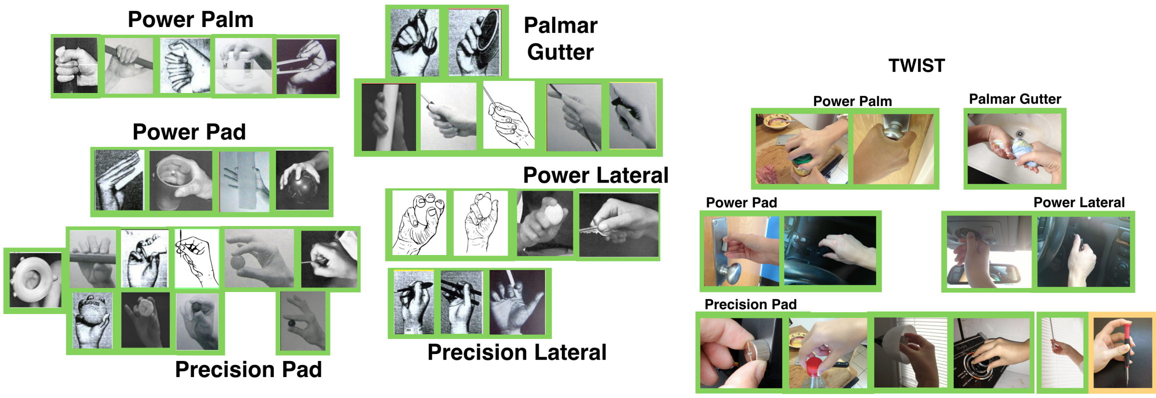



Figure 8: (Left) The 33 grasps of the Feix et al. taxonomy [31] can be grouped into six classes. (Right) Examples of 5 of these classes in use for the "twist" action.

**(4) Understanding the Delta Provided by different Sensing Approaches.** Sensor design will be considered in later stages of the project with the point of view of what type of sensor could most improve performance of the mechanism on its intended tasks (e.g., increase generality or robustness and/or eliminate catastrophic failure). We hypothesize that the best role for sensing in many manipulation actions is to identify when things are going very wrong and to make a straightforward adjustment to compensate. Reflexes are a good example, response to slipping of the grip, total loss of contact, or stopping of expected motion. One type of response may be to lift the object and move it aside to clear an obstacle. It is encouraging that in our human subjects studies we observe frequent failures such as collisions prior to reaching the intended destination, which are resolved (after a delay of approximately 100ms) with characteristic corrections. In fact, this happens so frequently that it is possible these "failures" are intentional, helping to localize the object with respect to the environment. Our first line of attack will be to enable similar behavior. The proposed research will assess sensors as any other design element in terms of their expected value in completing the intended manipulation tasks in a robust manner.

# 7 Grasp Net Benchmarks

To tackle dexterous manipulation head-on, we must consider grasping and manipulation in its full complexity. We take inspiration from human dexterity. Full scale humanlike dexterous manipulation may appear enormously complex. However, we have observed a relatively small number of grasping tasks and manipulations that are used over and over, with common actions linked to one another, forming what we call Grasp Nets. These Grasp Nets give us a way to proceed without oversimplifying. We propose to create Grasp Net benchmarks to cover expanding portions of the dexterous manipulation space. In tandem, we will develop evaluation procedures that test ability of a mechanism to accomplish Grasp Net tasks in the presence of uncertainty. One project goal is to create and debug these tests to contribute them to the Roadmap to Progress Measurement Science in Robot Dexterity and Manipulation [30] where evaluation metrics for dexterous manipulation are needed.

In this section, we provide some examples to illustrate the idea of a Grasp Net and some of the organizing principles we have observed through various human subject studies [57, 58, 12, 13, 59]. These observations are as yet unpublished.

Consider first the grasp taxonomy recently developed by Feix and colleagues [31], which pulls together the wealth of research on grasp classification over the last century. There are 33 grasps in this taxonomy. However, we find that they can be placed into six groups (Figure 8, Left). Variations within a group depend mostly on object geometry, and occasionally function (scissors, knife, chopsticks). Figure 8, Right shows examples of the "Twist" action, uncovered in one of our studies [59]. Twist actions are found for five of the six categories. Only the last, Precision Pad, requires intrinsic motions of the fingertips to achieve the twisting action. In the remaining cases, most of the motion is performed by the wrist and/or arm.

We observe common transitions between the six grasping categories shown in Figure 8, such that a brief motion causes a robust transition from one grasp to another. Figure 1, Right shows several examples, with the different colored arrows indicating some of the transition paths from one grasp to another. Beyond transitions between the six grasping categories, a Grasp Net must contain task related manipulations, such as the twist manipulations shown in Figure 8 and manipulations to acquire and release an object. One research challenge will be to map out benchmarks of GraspNet metrics of gradually increasing complexity, but such that each one provides full functionality for a set of tasks (e.g., the robot can get some family of objects into the hand, use them for their intended purpose, and put them back where it found them).

As preliminary work, we have collected detailed human motion data of a Grasp Net containing 21 grasps and more than 25 manipulations and have plans for several more such capture sessions. Our marker set includes 39 markers on the hand and three on the forearm. It is processed to a subject specific skeleton [9, 10, 11]. Object models are available and object motions are tracked to allow estimates of likely contacts. From these contacts, necessary, sufficient, and plausible families of contact forces can be estimated [55].

# 8 Evaluations

Each unit of research will of course be evaluated as we go. Two overall evaluations are:

**Generality.** If we design for specific task families, will the resulting robot hand be robust and capable enough to generalize beyond the specific given examples? Because we place such importance on robustness in the design process, we believe the answer will be yes. We will test generality with leave one out tests and by extent of ability to extrapolate beyond the bounds of the object set given in the Grasp Net.

**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, Barrett, Robotiq, Kinova, and other 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 relatively few actuated degrees of freedom and low cost. We anticipate that the result may look quite different from the typical dexterous hand existing today.

# 9 Comparison to Related Work

Design optimization for robot hands has been considered by a number of research groups, and just a few examples are mentioned here. Salisbury designed the Stanford/JPL hand to optimize ability to manipulate a small object held in the fingertips [75]. Dollar and his colleagues optimize hands to improve ability to capture the object in a grasp, to maximize workspace while holding a grasped object, and to consider the manipulation task of lifting an object from a table with a two actuator hand [3, 61, 64]. Ciocarlie and colleagues optimize a hand to grasp objects securely, whether they be small and flat or larger and round by keeping the distal links parallel until contact between hand and object[20]. Hammond III and colleagues consider which joint ranges of motion can be reduced (or even eliminated) while maintaining ability to achieve a fixed set of grasps [41]. Bicchi and his colleagues have explored the idea of adaptive synergies in the design of robot hands [6]. Birglen and Gosselin discuss optimization of underactuated hands in part to avoid the phenomenon of ejection [2]. We are inspired by these and other efforts in robot hand design optimization and wish to take the next leap to optimize for complex manipulation tasks observed to be critical for dexterity in human environments.

There have been many exciting highly dexterous hands designed, some with the explicit goal of duplicating or exceeding the capabilities of the human hand. Just a few examples are found in these references [45, 82, 21, 63, 60, 39, 84]. Perhaps in contrast with some of these works, we begin with the goal to achieve a given network of grasps and manipulation actions, with the approach to make the hand exactly as capable as it needs to be – not less and perhaps not more – because adding limits can help. Our hand may or may not look much like the human hand. How it comes out will depend on the design elements we provide and what is needed for it to do the required manipulations in a robust manner.

There has been a virtual explosion of ideas on how to use rapid prototyping techniques in robot design [29], in soft robot design [43, 28, 74, 83, 71], and design of compliant elements such as joints [53], making this a great time to be exploring the research problems of this proposal.

There has been much work on grasp and manipulation analysis that is also very inspiring [81, 73, 72, 56]. We especially appreciate the points of view that we can use "defective" mechanisms to our advantage, that local stiffness properties are important for computing quality metrics, and that we wish to configure the mechanism so that abstractly "if we just squeeze," good things will happen. We will build on and extend this research, which will become more and more valuable as we build robots which exploit limits, singularities, asymmetries, and highly coupled action as a matter of course.

The research of Abeel with Levine and colleagues [32, 52, 54] suggests that learning manipulations on real robots is possible with small numbers of iterations. We expect even faster learning and increased robustness if the mechanism is designed to simplify the manipulations being performed.

# 10 Broader Impact

The expected result of this proposal is robot hands that are robust, inexpensive, dexterous, and as simple as they can be to achieve their function. The long term promise is dexterous co-robots that can contribute in all corners of life, rendering competent assistance in manual tasks to improve our quality of life, our health, and our safety. Example application areas include manufacturing, rehabilitation and prosthetics, assembly / disassembly operations in space, and personal robots that are able to assist with shopping, cooking, maintenance, dressing, and feeding, allowing elderly or disabled individuals the dignity to live longer in their own homes.

**International Collaboration.** We are have active collaborations with ETH Zurich, we host students from the University of Karlsruhe in Germany, and we anticipate productive collaborations with Paul Kry's group at McGill University in Canada in connection with the proposed research (see letter).

**Graduate education.** This project will have a significant impact on graduate students. Students will be encouraged to work on the project directly, and to experience the research through course offerings at CMU, including 15869 Computational Aspects of Fabrication and 16899 Hands: Design and Control for Dexterous Manipulation.

**Undergraduate education.** We expect numerous undergraduates to be involved in this research as well. PI Pollard has advised more than 20 undergraduates, more than one third female, most involved in NSF supported research, and many who have gone on to graduate school. Both PIs offer advanced undergraduate courses that will expose undergraduates to the proposed research and encourage them to get involved themselves.

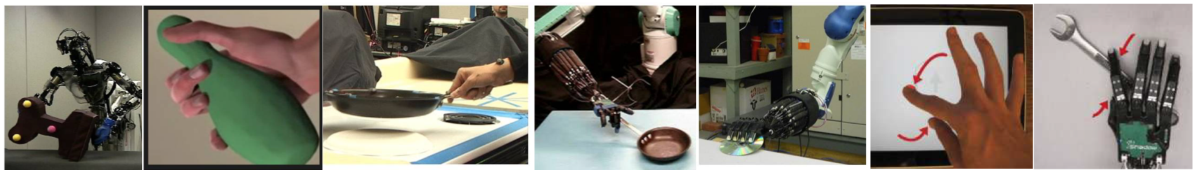


Figure 9: Examples show prior research of PI Pollard in transfer of grasp and manipulation tasks, grasp planning with preparatory manipulation, and teleManipulation.

**Participation of underrepresented groups.** Pollard has mentored four women through the CRA-W Distributed Research Experiences for Undergraduates (DREU) program, and has advised 7 female graduate students and 8 female undergraduates, three of whom have gone on to PhD studies at Stanford and CMU.

**Public and K-12 outreach** Pollard has been involved in discussing robotics and 3D printing of functional objects at local elementary schools to increase interest in STEM and Maker topics, especially with young girls. The proposed research offers a great opportunity for K-12 outreach, due to the hands-on nature of the robot hand prototypes which will be generated at many stages of the research project. We will introduce young students to these prototypes and to robotics in general, both through annual CMU outreach programs and through our own school visits and talks.

**Dissemination.** Dissemination will be primarily through publication in conferences and journals and participation in and organization or relevant workshops. Prototype designs will be made available in the form of design files and instructions to speed progress in this critical area. Human manipulation data collected as part of this project will be made available online. Grasp Net manipulation benchmarks will be provided as metrics for testing potential and actual hand designs for dexterity, contributing to the valuable efforts that have resulted in the NIST "Roadmap to Progress Measurement Science in Robot Dexterity and Manipulation" [30] and the YCB Object and Model Set benchmarks for manipulation research [5].

## 11 Results from Prior NSF Support

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 optimal 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 and creating robot hands with the capability and skills to grasp and manipulate robustly in complex, real-world scenarios where humans and robots live and work together.

**Pollard's prior work on physics-based grasping and manipulation.** PI Pollard has extensive experience in grasp and manipulation planning, transfer, and optimization (Figure 9). She has developed algorithms for grasping and manipulation that allow fast transfer of examples from human to robot and generalization to varying object geometries in a manner that is both fast and provides bounds on performance [68, 66, 70, 55]. She and her students have performed numerous human subjects studies to better understand the complex process of grasping in real-world situations [16, 8, 44, 59] and followed up with more highly capable robot planning algorithms and quality metrics that function well for robot grasping in the presence of uncertainties [14, 47, 50]. She has studied human-in-the-loop manipulation (teleManipulation) [80, 18, 48] and examined anatomical considerations of the human hand that may lead to better robot hand designs [67, 33, 11, 9, 10].

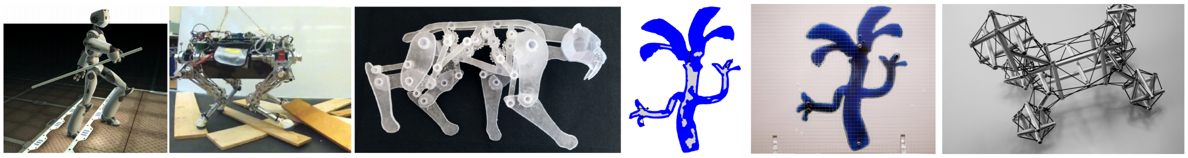


Figure 10: Examples show prior research conducted by PI Coros in control methods for locomotion and manipulation, computational design of complex mechanical structures and digital fabrication.

**Results from Prior NSF Support.** Pollard has been funded by NSF awards *CCF: Capturing and Animating the Human Hand: Robust Recovery of Hand-Object Interactions* NSF CCF0702443 (PI: Pollard 6/07 - 5/11, $325,000) and *CGV: Small: Simulation Motion Capture of Dexterous Manipulation* NSF IIS1218182 (PI: Pollard 8/12 - 7/16, $499,838). **Intellectual Merit:** Results include taxonomies of everyday grasps, manipulations, and manipulation actions prior to grasping, findings on rotation prior to grasping, a novel algorithm for planning robotic tasks with preparatory manipulation, quality metrics for grasping that reflect real-world uncertainties and physics, robust algorithms for capturing human hand skeletal structure, fast algorithms for simulation of deformable systems, a novel interactive system for guiding simulations, a system for robot teleManipulation using multitouch, and an investigation of new representations for motion that are meaningful across individuals and species (including robots). This award resulted in the following publications [59, 18, 57, 44, 50, 80, 13, 34, 47, 49, 48, 51, 8, 14, 46, 16, 11, 15]. **Broader Impact:** In addition to top venues in Robotics and Computer Graphics, results have been published in the Journal of Motor Behavior, the Journal of Biomechanics, the Journal of Theoretical Biology, and in the book "The Human Hand: A Source of Inspiration for Robotic Hands." These grants supported two female PhD students, Lillian Chang and Yuzuko Nakamura, whose dissertations contained many of the core research findings. They also provided partial support for four masters students (two female), three undergraduates (two female), and one postdoc.

**Coros's prior work on computational design and digital fabrication.** PI Coros has extensive experience in computer animation, robotics, computational design and digital fabrication, which are all areas of crucial importance for this proposal. Within the field of computer animation, the PI has developed physics-based methods that enable virtual actors to move autonomously using the same principles that underlie human and animal motions [85, 24, 22, 23, 25]. The PI extended these motor control models to apply them to *StarlETH*, a dog-sized quadrupedal robot [36, 37, 38]. In addition to this line of work, the PI is investigating mathematical models and computational approaches to significantly simplify challenging design tasks that traditionally require a great deal of domain-specific knowledge. For example, he has developed several computational design systems that allow casual users to quickly design 3D printable mechanical automata [27, 79, 62, 1]. Such complex mechanical assemblies combine geometric features, functionality and motion through a complex set of kinematic relationships and are notoriously difficult to design with traditional approaches. The PI's research has also ventured into the domain of multi-material 3D printing. For example, the goal of one of his recent projects was to automatically determine the distribution of rigid and soft materials within 3D printed objects such that the way in which they deform under the influence of external forces can be controlled [77]. This work complements other research efforts aimed at controlling the elastic properties of fabricated objects [35, 65] and builds on the soft body simulation models investigated by Coros and his colleagues [26, 40, 76]. Building on this body of work, this proposal will enable the design of a new class of robotic hands that are specifically designed for dexterous manipulation tasks.

**Results from Prior NSF Support.** PI Coros is an NSF beginning investigator with no prior support.

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