Human-Inspired Robotic Grasp Control with Tactile Sensing

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MEAM Department, SEAS, University of Pennsylvania

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Haptics
the scientific study of touch-based interaction between an agent and its environment
Remote Teleoperation: extends the reach of the human hand to remote, hazardous, unreachable environments
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**Remote**

*Teleoperation:* extends the reach of the human hand to remote, hazardous, unreachable environments

**Virtual**

*Simulation:* enables humans to touch geometric and dynamic computer-based data and models
Remote

**Teleoperation:** extends the reach of the human hand to remote, hazardous, unreachable environments

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Ph.D. Student
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Human-Inspired Robotic Grasp Control with Tactile Sensing

Joseph M. Romano, Student Member, IEEE, Kaijen Hsiao, Member, IEEE, Gunter Niemeyer, Member, IEEE, Sachin Chitta, Member, IEEE, and Katherine J. Kuchenbecker, Member, IEEE

Abstract—We present a novel robotic grasp controller that allows a sensorized parallel jaw gripper to gently pick up and set down unknown objects once a grasp location has been selected. Our approach is inspired by the control scheme that humans employ for such actions, which is known to centrally depend on tactile sensation rather than vision or proprioception. Our controller processes measurements from the gripper’s fingertip pressure arrays and hand-mounted accelerometer in real time to generate robotic tactile signals that are designed to mimic human SA-I, FA-I, and FA-II channels. These signals are combined into tactile event cues that drive the transitions between six discrete states in the grasp controller: Close, Load, Lift and Hold, Replace, Unload, and Open. The controller selects an appropriate initial grasping force, detects when an object is slipping from the grasp, increases the grasp force as needed, and judges when to release an object to set it down. We demonstrate the promise of our approach through implementation on the PR2 robotic platform, including grasp testing on a large number of real-world objects.

Index Terms—robot grasping, tactile sensing

I. INTRODUCTION

As robots move into human environments, they will need to know how to grasp and manipulate a very wide variety of objects [1]. For example, some items may be soft and light, such as a stuffed animal or an empty cardboard box, while others may be hard and dense, such as a glass bottle or an apple. After deciding where such objects should be grasped (finger placement), the robot must also have a concept of how to execute the grasp (finger forces and reactions to changes in grasp state). A robot that operates in the real world must be able to quickly grasp a wide variety of objects firmly, without dropping them, and delicately, without crushing them (Fig. 1). Non-contact sensors such as cameras and laser scanners are essential for robots to recognize objects and plan where to grasp them, e.g., [2], [3]. Recognition and planning may also instruct the grasping action, for example providing an object’s expected stiffness, weight, frictional properties, or simply the required grasp forces. But to safely handle unknown objects as well as to remain robust to inevitable uncertainties, any such a priori information must be complemented by real-time tactile sensing and observations. Indeed tactile sensors are superior to other modalities at perceiving interactive events, such as the slip of an object held in the fingers, a glancing collision between the object and an unseen obstacle, or the deliberate contact when placing the object. Understanding contact using tactile information and reacting in real time will be critical skills for robots to successfully interact with real-world objects, just as they are for humans.

A. Human Grasping

Neuroscientists have thoroughly studied the human talent for grasping and manipulating objects. As recently reviewed by Johansson and Flanagan [4], human manipulation makes great use of tactile signals from several different types of mechanoreceptors in the glabrous (non-hairy) skin of the hand, with vision and proprioception providing information that is less essential. Table I provides a list of the four types of mechanoreceptors in human glabrous skin. Johansson and Flanagan divide the seemingly effortless action of picking up an object and setting it back down into seven distinct states: reach, load, lift, hold, replace, unload, and release. In the first phase, humans close their grasp to establish finger contact with the object. Specifically, the transition from reach to load is known to be detected through the FA-I (Meissner) and FA-II (Pacinian) afferents, which are stimulated by the initial fingertip contact. FA signifies that these mechanoreceptors are fast-adapting; they respond primarily to changes in mechanical stimuli, with FA-I and FA-II having small and large receptive
How can we increase the PR2’s tactile intelligence?
Parallel jaw gripper
Parallel jaw gripper

High mechanical impedance
Parallel jaw gripper

High mechanical impedance

Naive control (100% motor effort)
How can we increase the PR2’s tactile intelligence?
How can we increase the PR2's tactile intelligence?

 GCC Gracefully pick up, transport, and set down a wide variety of everyday objects
Encoder & Motor Current Sensor
1000 Hz
Three-axis accelerometer

Encoder & Motor Current Sensor
1000 Hz

Three-axis accelerometer
3000 Hz
Two elements on each side

One element at the tip of the back

5x3 array of elements on the front

Three-axis accelerometer

3000 Hz

Encoder & Motor Current Sensor

1000 Hz

Two elements at the tip

24.4 Hz

Three-axis accelerometer

3000 Hz

5x3 array of elements on the front

Two elements on each side

One element at the tip of the back

24.4 Hz

Two elements at the tip
Coding and use of tactile signals from the fingertips in object manipulation tasks

Roland S. Johansson* and J. Randall Flanagan*

Abstract | During object manipulation tasks, the brain selects and implements action-phase controllers that use sensory predictions and afferent signals to tailor motor output to the physical properties of the objects involved. Analysis of signals in tactile afferent neurons and central processes in humans reveals how contact events are encoded and used to monitor and update task performance.

Tactile afferents
Fast conducting myelinated afferent neurons that convey signals to the brain from low-threshold mechanoreceptors in body areas that actively contact objects—that is, the inside of the hand, the sole of the foot, the lips, the tongue and the oral mucosa.

Proprioceptive afferents
Fast conducting myelinated afferents that provide information about joint configurations and muscle states. These include mechanoreceptive afferents from the hairy skin, muscles, joints and connective tissues.

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Correspondence to R.J. (email: roland.johansson@biol.umu.se or randall.flanagan@gmail.com)
Published online 8 April 2009
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| SA-I (slowly-adapting type I) Merkel endings | Weak pointed touch | 70 |
| • Sensitive to low-frequency dynamic skin deformations (<~5 Hz)  
• Sensitive to static force  
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| FA-II (fast-adapting type II) Pacini ending | Light tapping | 0 |
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In eBox Action-phase controllers (action phases) vertical movement

Load force Grip force

Load force

0.2s Vertical position

Mismatches trigger corrective actions

Comparison

Task subgoals (control points)

Action-phase controllers (action phases)

Vertical movement

Load force Grip force

Ensembles of tactile afferents encode:

Contact responses
- Contact timing
- Contact sites on digit
- Direction of contact force
- Friction information
- Local shape at grasp sites

Transient mechanical events
- Making and breaking contact between hand-held objects and other objects
- Weight information (indirect at lift-off)

Release responses
- Breaking contact between digit and object

Robotic Tactile Signals
Robotic Tactile Signals
Gripper Position and Force Controllers
Robotic Tactile Signals
Gripper Position and Force Controllers
Action-Phase Grasp Controller
Robotic Tactile Signals

Gripper Position and Force Controllers

Action-Phase Grasp Controller
# Robotic Tactile Signals

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<td><strong>FA-II (fast-adapting type II)</strong> Pacini ending</td>
<td></td>
<td></td>
</tr>
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<tr>
<td>• Respond to distant events acting on hand-held objects</td>
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<td><strong>SA-II (slowly-adapting type II)</strong> Ruffini-like endings</td>
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<td>Touch or skin stretch</td>
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\[
F_{gl} = \sum_{i=1}^{3} \sum_{j=1}^{5} f_{l(i,j)}
\]
## Robotic Tactile Signals

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<tr>
<td>FA-I (fast-adapting type I) Meissner endings</td>
<td><img src="image" alt="Weak pointed touch" /></td>
<td>140</td>
</tr>
<tr>
<td>• Sensitive to dynamic skin deformation of relatively high frequency (~5–50 Hz)</td>
<td><img src="image" alt="Weak pointed touch" /></td>
<td>70</td>
</tr>
<tr>
<td>• Insensitive to static force</td>
<td><img src="image" alt="Weak pointed touch" /></td>
<td>0</td>
</tr>
<tr>
<td>• Transmit enhanced representations of local spatial discontinuities (e.g., edge contours and Braille-like stimuli)</td>
<td><img src="image" alt="Weak pointed touch" /></td>
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</tbody>
</table>

| SA-I (slowly-adapting type I) Merkel endings | ![Weak pointed touch](image) | \[ F_{gl} = \sum_{i=1}^{3} \sum_{j=1}^{5} f_l(i,j) \] |
| • Sensitive to low-frequency dynamic skin deformations (<5 Hz) | ![Weak pointed touch](image) |  |
| • Sensitive to static force | ![Weak pointed touch](image) |  |
| • Transmit enhanced representations of local spatial discontinuities | ![Weak pointed touch](image) | |

| FA-II (fast-adapting type II) Pacini ending | ![Light tapping](image) | |
| • Extremely sensitive to mechanical transients and high-frequency vibrations (~40–400 Hz) propagating through tissues | ![Light tapping](image) | |
| • Insensitive to static force | ![Light tapping](image) | |
| • Respond to distant events acting on hand-held objects | ![Light tapping](image) | |

| SA-II (slowly-adapting type II) Ruffini-like endings | ![Touch or skin stretch](image) | |
| • Low dynamic sensitivity | ![Touch or skin stretch](image) | |
| • Sensitive to static force | ![Touch or skin stretch](image) | |
| • Sense tension in dermal and subcutaneous collagenous fibre strands | ![Touch or skin stretch](image) | |
| • Can fire in the absence of externally applied stimulation and respond to remotely applied stretching of the skin | ![Touch or skin stretch](image) | |

## Robotic Tactile Signals

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<td>FA-I (fast-adapting type I) Meissner endings</td>
<td><img src="image1.png" alt="FA-I receptive field" /></td>
<td><img src="image2.png" alt="FA-I density" /></td>
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<td>• Sensitive to dynamic skin deformation of relatively high frequency (~5–50 Hz)</td>
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<tr>
<td>SA-I (slowly-adapting type I) Merkel endings</td>
<td><img src="image3.png" alt="SA-I receptive field" /></td>
<td><img src="image4.png" alt="SA-I density" /></td>
</tr>
<tr>
<td>• Sensitive to low-frequency dynamic skin deformations (&lt;~5 Hz)</td>
<td></td>
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</tr>
<tr>
<td>• Sensitive to static force</td>
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<td>Weak pointed touch</td>
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</tr>
<tr>
<td>FA-II (fast-adapting type II) Pacini ending</td>
<td><img src="image5.png" alt="FA-II receptive field" /></td>
<td><img src="image6.png" alt="FA-II density" /></td>
</tr>
<tr>
<td>• Extremely sensitive to mechanical transients and high-frequency vibrations (~40–400 Hz) propagating through tissues</td>
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<td>Light tapping</td>
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</tr>
<tr>
<td>SA-II (slowly-adapting type II) Ruffini-like endings</td>
<td><img src="image7.png" alt="SA-II receptive field" /></td>
<td><img src="image8.png" alt="SA-II density" /></td>
</tr>
<tr>
<td>• Low dynamic sensitivity</td>
<td></td>
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<td></td>
<td>Touch or skin stretch</td>
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\[
\tilde{F}_{gl}(z) = \sum_{i=1}^{3} \sum_{j=1}^{5} H_{F}(z) f_{l(i,j)}(z)
\]

5 Hz high-pass

\[
F_{gl} = \sum_{i=1}^{3} \sum_{j=1}^{5} f_{l(i,j)}
\]

Robotic Tactile Signals

### Afferent type (and response properties) | Receptive field (and probe) | Density (afferents per cm²) | Mathematical Models
--- | --- | --- | ---
FA-I (fast-adapting type I) Meissner endings  
- Sensitive to dynamic skin deformation of relatively high frequency (~5–50 Hz)  
- Insensitive to static force  
- Transmit enhanced representations of local spatial discontinuities (e.g., edge contours and Braille-like stimuli)  
Weak pointed touch  
![5x3 array of elements on the front](image)
| $\tilde{F}_{gl}(z) = \sum_{i=1}^{3} \sum_{j=1}^{5} H_F(z)f_l(i,j)(z)$  
5 Hz high-pass |
|---|---|---|---
FA-II (fast-adapting type II) Pacini ending  
- Extremely sensitive to mechanical transients and high-frequency vibrations (~40–400 Hz) propagating through tissues  
- Insensitive to static force  
- Respond to distant events acting on hand-held objects  
Light tapping  
![5x3 array of elements on the front](image)
| $F_{gl} = \sum_{i=1}^{3} \sum_{j=1}^{5} f_l(i,j)$ |
|---|---|---|---
SA-I (slowly-adapting type I) Merkel endings  
- Sensitive to low-frequency dynamic skin deformations (<5 Hz)  
- Sensitive to static force  
- Transmit enhanced representations of local spatial discontinuities  
Weak pointed touch  
![5x3 array of elements on the front](image)
|---|---|---|---
SA-II (slowly-adapting type II) Ruffini-like endings  
- Low dynamic sensitivity  
- Sensitive to static force  
- Sense tension in dermal and subcutaneous collagenous fibre strands  
- Can fire in the absence of externally applied stimulation and respond to remotely applied stretching of the skin  
Touch or skin stretch  
![5x3 array of elements on the front](image)

### Robotic Tactile Signals

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<tr>
<td><strong>FA-I (fast-adapting type I)</strong>&lt;br&gt;Meissner endings&lt;br&gt;- Sensitive to dynamic skin deformation of relatively high frequency (~5–50 Hz)&lt;br&gt;- Insensitive to static force&lt;br&gt;- Transmit enhanced representations of local spatial discontinuities (e.g., edge contours and Braille-like stimuli)&lt;br&gt;<strong>Weak pointed touch</strong></td>
<td><img src="image1.png" alt="5x3 array of elements on the front" /></td>
<td><img src="image2.png" alt="Summation of Fg(z)" /> = \sum_{i=1}^{3} \sum_{j=1}^{5} H_F(z) f_l(i,j)(z) <img src="image3.png" alt="5 Hz high-pass" /></td>
</tr>
<tr>
<td><strong>SA-I (slowly-adapting type I)</strong>&lt;br&gt;Merkel endings&lt;br&gt;- Sensitive to low-frequency dynamic skin deformations (&lt;~5 Hz)&lt;br&gt;- Sensitive to static force&lt;br&gt;- Transmit enhanced representations of local spatial discontinuities&lt;br&gt;<strong>Weak pointed touch</strong></td>
<td><img src="image4.png" alt="5x3 array of elements on the front" /></td>
<td><img src="image5.png" alt="Summation of Fg(z)" /> = \sum_{i=1}^{3} \sum_{j=1}^{5} f_l(i,j) <img src="image6.png" alt="50 Hz high-pass" /></td>
</tr>
<tr>
<td><strong>FA-II (fast-adapting type II)</strong>&lt;br&gt;Pacini ending&lt;br&gt;- Extremely sensitive to mechanical transients and high-frequency vibrations (~40–400 Hz) propagating through tissues&lt;br&gt;- Insensitive to static force&lt;br&gt;- Respond to distant events acting on hand-held objects&lt;br&gt;<strong>Light tapping</strong></td>
<td><img src="image7.png" alt="5x3 array of elements on the front" /></td>
<td><img src="image8.png" alt="Summation of a_h(z)" /> = \sqrt{(H_a(z)a_{h,x})^2 + (H_a(z)a_{h,y})^2 + (H_a(z)a_{h,z})^2}</td>
</tr>
<tr>
<td><strong>SA-II (slowly-adapting type II)</strong>&lt;br&gt;Ruffini-like endings&lt;br&gt;- Low dynamic sensitivity&lt;br&gt;- Sensitive to static force&lt;br&gt;- Sense tension in dermal and subcutaneous collagenous fibre strands&lt;br&gt;- Can fire in the absence of externally applied stimulation and respond to remotely applied stretching of the skin&lt;br&gt;<strong>Touch or skin stretch</strong></td>
<td><img src="image9.png" alt="5x3 array of elements on the front" /></td>
<td><img src="image10.png" alt="Summation of a_h(z)" /> = \sqrt{(H_a(z)a_{h,x})^2 + (H_a(z)a_{h,y})^2 + (H_a(z)a_{h,z})^2}</td>
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Robotic Tactile Signals

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<th>Afferent type (and response properties)</th>
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<th>Mathematical Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FA-I (fast-adapting type I)</td>
<td>Meissner endings</td>
<td>5x3 array of elements on the front</td>
<td>[ F_{gl}^{'}(z) = \sum_{i=1}^{3} \sum_{j=1}^{5} H_{F}(z) f_{l(i,j)}(z) ] (5 Hz high-pass)</td>
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<tr>
<td>• Sensitive to dynamic skin deformation of relatively high frequency (¬5–50 Hz)</td>
<td></td>
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<tr>
<td>• Insensitive to static force</td>
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<td>• Transmit enhanced</td>
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<td>spatial discontinuities</td>
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<tr>
<td>(e.g., edge contours and Braille-like stimuli)</td>
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<td>SA-I (slowly-adapting type I)</td>
<td>Merkel endings</td>
<td>5x3 array of elements on the front</td>
<td>[ F_{gl} = \sum_{i=1}^{3} \sum_{j=1}^{5} f_{l(i,j)} ] (50 Hz high-pass)</td>
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<tr>
<td>• Sensitive to low-frequency dynamic skin deformations (¬5 Hz)</td>
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<tr>
<td>• Sensitive to static force</td>
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<td>spatial discontinuities</td>
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<td></td>
<td></td>
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<tr>
<td>FA-II (fast-adapting type II)</td>
<td>Pacini ending</td>
<td>One element at the tip of the back</td>
<td>[ \sim a_{h}(z) = \sqrt{(H_{a}(z)a_{h,x})^2 + (H_{a}(z)a_{h,y})^2 + (H_{a}(z)a_{h,z})^2} ]</td>
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<tr>
<td>• Extremely sensitive to</td>
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</tr>
<tr>
<td>mechanical transients and</td>
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<td>(¬40–400 Hz) propagating through tissues</td>
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<td>• Insensitive to static force</td>
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<td></td>
</tr>
<tr>
<td>• Respond to distant events</td>
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</tr>
<tr>
<td>acting on hand-held objects</td>
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<td>SA-II (slowly-adapting type II)</td>
<td>Ruffini-like endings</td>
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<tr>
<td>• Sense tension in dermal and</td>
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<tr>
<td>subcutaneous collagenous</td>
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<td></td>
</tr>
<tr>
<td>fibre strands</td>
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| **FA-I (fast-adapting type I)**
  Meissner endings
  - Sensitive to dynamic skin deformation of relatively high frequency (~5–50 Hz)
  - Insensitive to static force
  - Transmit enhanced representations of local spatial discontinuities (e.g., edge contours and Braille-like stimuli)
  Weak pointed touch
  5x3 array of elements on the front
  Two elements on each side
  One element at the tip of the back
  Two elements at the tip

\[ \tilde{F}_{gl}(z) = \sum_{i=1}^{3} \sum_{j=1}^{5} H_{F}(z) f_{l(i,j)}(z) \]
5 Hz high-pass

| **SA-I (slowly-adapting type I)**
  Merkel endings
  - Sensitive to low-frequency dynamic skin deformations (~<5 Hz)
  - Sensitive to static force
  - Transmit enhanced representations of local spatial discontinuities
  Weak pointed touch
  5x3 array of elements on the front
  Two elements on each side
  One element at the tip of the back
  Two elements at the tip

\[ F_{gl} = \sum_{i=1}^{3} \sum_{j=1}^{5} f_{l(i,j)} \]

| **FA-II (fast-adapting type II)**
  Pacini ending
  - Extremely sensitive to mechanical transients and high-frequency vibrations (~40–400 Hz) propagating through tissues
  - Insensitive to static force
  - Respond to distant events acting on hand-held objects
  Light tapping
  50 Hz high-pass

\[ \tilde{a}_{h}(z) = \sqrt{(H_{a}(z)a_{h,x})^2 + (H_{a}(z)a_{h,y})^2 + (H_{a}(z)a_{h,z})^2} \]

| **SA-II (slowly-adapting type II)**
  Ruffini-like endings
  - Low dynamic sensitivity
  - Sensitive to static force
  - Sense tension in dermal and subcutaneous collagenous fibre strands
  - Can fire in the absence of externally applied stimulation and respond to remotely applied stretching of the skin
  Touch or skin stretch

\[ \text{not possible on the PR2} \]

Robotic Tactile Signals
Gripper Position and Force Controllers
Action-Phase Grasp Controller
Robotic Tactile Signals
Gripper Position and Force Controllers
Action-Phase Grasp Controller
Gripper Position Controller
Gripper Position Controller

\[ E = KP \cdot (x_g - x_{g,des}) + KD \cdot (v_g - v_{g,des}) \]
Gripper Position Controller

\[ E = KP \cdot (x_g - x_{g,des}) + KD \cdot (v_g - v_{g,des}) \]

Gripper Force Controller
Gripper Position Controller

\[ E = KP \cdot (x_g - x_{g,\text{des}}) + KD \cdot (v_g - v_{g,\text{des}}) \]

Gripper Force Controller

\[ F_{g,\text{min}} = \min (F_{gl}, F_{gr}) \]
Gripper Position Controller

\[ E = KP \cdot (x_g - x_{g,des}) + KD \cdot (v_g - v_{g,des}) \]

Gripper Force Controller

\[ F_{g,\text{min}} = \min(F_{gl}, F_{gr}) \]

\[ v_{g,\text{des}} = KF \cdot (F_{g,\text{min}} - F_{g,\text{des}}) \]
Gripper Position Controller

\[ E = KP \cdot (x_g - x_{g,\text{des}}) + KD \cdot (v_g - v_{g,\text{des}}) \]

Gripper Force Controller

\[ F_{g,\text{min}} = \min(F_{gl}, F_{gr}) \]

\[ v_{g,\text{des}} = KF \cdot (F_{g,\text{min}} - F_{g,\text{des}}) \]

\[ KF = \begin{cases} 
    \text{KFCLOSE} & \text{if } F_{g,\text{min}} - F_{g,\text{des}} < 0, \\
    \text{KFOPEN} & \text{otherwise}
\end{cases} \]
Robotic Tactile Signals

Gripper Position and Force Controllers

Action-Phase Grasp Controller
Robotic Tactile Signals
Gripper Position and Force Controllers
Action-Phase Grasp Controller
- Close
- Load
- Lift & Hold
- Replace
-Unload
- Open

Action-Phase Grasp Controller

Grasp()

set $t = 0$

Close

position

$x_{g, \text{des}} = x(0) - \text{VCLOSE} \cdot t$

$v_{g, \text{des}} = -\text{VCLOSE}$

LeftContact &&

RightContact

set $x_c = x$, $t_c = t$

Load

position

$x_{g, \text{des}} = x_c$

$v_{g, \text{des}} = 0$

$t - t_c > \text{TSETTLE}$

set $F_c = \max_t (F_g) \cdot \frac{\text{KHARDNESS}}{\text{VCLOSE}}$

Unload

force

$F_{g, \text{des}} = F_c$

Open

position

$x_{g, \text{des}} = x_u + \text{VOPEN} \cdot (t - t_u)$

$F_{g, \text{des}} = 0$

$Lift and Hold$

force

$F_{g, \text{des}} = F_c$

$F_c = F_c \cdot \text{KSLIP}$

Replace

force

$F_{g, \text{des}} = F_c$

Place()

Slip ||

Vibration

set $t_s = t$

Unload

force

$F_{g, \text{des}} = F_c - F_c \cdot \frac{t - t_s}{\text{TUNLOAD}}$

Open

$F_{g, \text{des}} = F_c - F_c \cdot \frac{t - t_s}{\text{TUNLOAD}}$

$F_{g, \text{des}} = 0$

$F_{g, \text{des}} = 0$

$F_{g, \text{des}} = 0$
Action-Phase Grasp Controller

**Grasp()**
- set $t = 0$

**Close**
- position
  - $x_{g,\text{des}} = x(0) - V\text{CLOSE} \cdot t$
  - $v_{g,\text{des}} = -V\text{CLOSE}$
- LeftContact & RightContact
  - set $x_c = x$, $t_c = t$

**Lift and Hold**
- force
  - $F_{g,\text{des}} = F_c$
  - Slip
    - set $F_c = F_c \cdot K\text{SLIP}$

**Replace**
- force
  - $F_{g,\text{des}} = F_c$
- Slip || Vibration
  - set $t_s = t$

**Stable**
Action-Phase Grasp Controller

LeftContact = $(F_{gl} > \text{FLIMIT}) \lor (\tilde{F}_{gl} > \text{DLIMIT})$

RightContact = $(F_{gr} > \text{FLIMIT}) \lor (\tilde{F}_{gr} > \text{DLIMIT})$
Action-Phase Grasp Controller

**Grasp**

- Set $t = 0$

**Close**

- Position
  
  $x_{g, des} = x(0) - V_{CLOSE} \cdot t$
  
  $v_{g, des} = -V_{CLOSE}$

- LeftContact & RightContact
  
  Set $x_c = x$, $t_c = t$

**Lift and Hold**

- Force
  
  $F_{g, des} = F_c$

**Replace**

- Force
  
  $F_{g, des} = F_c$

**Stable**

- Slip || Vibration
  
  Set $t_s = t$
The state diagram for our robotic grasp controller. State transitions occur only after specific tactile events are detected. The details of this controller are presented in Sections IV and V.

Inspired by the fluidity of human grasp control, this article describes a high-level robotic grasp controller that emulates human control responses. The controller is centered on mechanical events that mark holding phases when the tactile feedback does not match the existing knowledge about the object and tactile information. The load is expected to be increased to avoid slip [1], thereby achieving the dual goals of safety and efficiency.

In our approach, the tactile sensors and corrective reactions are again important during unload to properly set the object down before full release. The load is known to respond to tangential loading such as skin stretch. The load is also slowly adapting with small receptive fields.

The tactile sensing capabilities and corrective reactions must be detected to successfully transition to unloading. The tactile feedback does not match the load, and the critical importance for rejecting disturbances in the lifting and transport it to a new location. Corrective actions typically apply a grip force that is only slightly more than the minimum amount needed to avoid slip [1], thereby achieving the dual goals of safety and efficiency.

Humans typically increase their grasp force to the target level, using their existing knowledge about the object and tactile information. Indeed, humans typically cannot measure such signals; though our approach could be expanded to include them if they were available.

We omit this channel because our current experimental system cannot measure such signals, though our approach could be expanded to include them if they were available. The tactile input from said devices is critical, and the low-level position and force control are described in Section VI. We validated our methods through a high-level robotic grasp controller that emulates human control responses. The control responses are nearly identical for the hand. Each state is purposefully mirroring those of human grasping: Lift and Hold, Replace, Unload, and Open.
**Action-Phase Grasp Controller**

\[
\text{StableContact} = \left( |F_{g,\text{min}} - F_{g,\text{des}}| < F_{\text{THRESH}} \right) \\
\land \left( |v_g| < V_{\text{THRESH}} \right)
\]

---

**Load**

- **position**: \(x_{g,\text{des}} = x_c, \quad v_{g,\text{des}} = 0\)
- \(t - t_c > T_{\text{SETTLE}}\)
- set \(F_c = \max_t (F_g) \cdot \frac{K_{\text{HARDNESS}}}{V_{\text{CLOSE}}}\)
- force \(F_{g,\text{des}} = F_c\)

---

**Unload**

- force \(F_{g,\text{des}} = F_c - F_c \frac{t - t_s}{T_{\text{UNLOAD}}}\)
- \(F_{g,\text{des}} = 0\)
- set \(x_u = x, \quad t_u = t\)

---

**Open**

- position \(x_{g,\text{des}} = x_u + V_{\text{OPEN}} \cdot (t - t_u)\)
- \(v_{g,\text{des}} = V_{\text{OPEN}}\)

---
Action-Phase Grasp Controller

- **StableContact**
  - \( x_{g,des} = x_c \)
  - \( v_{g,des} = 0 \)

- **Load**
  - \( t - t_c > \text{TSETTLE} \)
  - \[ F_c = \max_t (F_g) \cdot \frac{\text{KHARDNESS}}{\text{VCLOSE}} \]
  - \( F_{g,des} = F_c \)

- **Unload**
  - \( F_{g,des} = F_c - F_c \cdot \frac{t - t_s}{\text{TUNLOAD}} \)
  - \( F_{g,des} = 0 \)
  - \( x_{u} = x \)
  - \( v_{g,des} = VOPEN \)

- **Open**
  - \( x_{g,des} = x_u + VOPEN \cdot (t - t_u) \)
  - \( v_{g,des} = \text{VOPEN} \)
Action-Phase Grasp Controller

Grasp()

\[
\begin{align*}
\text{set } t &= 0 \\
x_{g,\text{des}} &= x(0) - \text{VCLOSE} \cdot t \\
v_{g,\text{des}} &= -\text{VCLOSE}
\end{align*}
\]

Lift and Hold

force

\[F_{g,\text{des}} = F_c\]

set \[F_c = F_c \cdot \text{KSLIP}\]

Replace

Place()

force

\[F_{g,\text{des}} = F_c\]

set \[x_c = x(0)\]

set \[t_c = t\]
Slip = \left( \left| \tilde{F}_g \right| > F_g \cdot \text{SLIPTHRESH} \right) \\
& \& \left( F_g^{BP} < \text{FBPTHRESH} \right)
We assume that fingertip presents a set of methods that enable a robot to delicately grasp real-world objects. We define constant valued parameters such as VLOS, such as VLOS, are defined in Table II and firmly grasp real-world objects. Indeed, humans typically apply a grip force that is only 1–2% more than the minimum amount needed to avoid slip [1], thereby achieving the dual goals of safety and efficiency.

When it comes time to place the item back on the table, contact between the object and the table must be detected to successfully transition to unloading. The holding phases when the tactile feedback does not match the expected data, increase their grasp force to the target level, using both previously gathered during the interaction. This loading process is regulated largely by the response of the S–I, II, and V–II mechanoreceptors.

Inspired by the fluidity of human grasp control, this article focuses on robotic grasp control. We implemented our methods on the PRfi's high-impedance gripper, which is centered on mechanical events that mark transitions between consecutive action phases that represent the robot's interaction with its environment. These states purposefully mirror those of human grasping, including Grasp, Lift and Hold, Replace, Unload, and Open.

In addition to creating this approach to robotic grasp control, we validated our methods through experiments on typical household objects at human-like speeds, without the need to carefully define each control rule and state transition. We validated our methods through experiments on typical household objects at human-like speeds, without the need to carefully define each control rule and state transition.
Grasp() set $t = 0$

**Close**

- Position:
  - $x_{g,des} = x(0) - V_{CLOSE} \cdot t$
  - $v_{g,des} = -V_{CLOSE}$

**LeftContact & RightContact**

- Set $x_c = x$
- $v_{g,des} = 0$
- $t_c = t$

**StableContact**

**Lift and Hold**

- Force:
  - $F_{g,des} = F_c$

  - Slip
  - Set $F_c = F_c \cdot K_{SLIP}$

**Replace**

- Force:
  - $F_{g,des} = F_c$

- Slip || Vibration
- Set $t_s = t$

**Unload**

- Force:
  - $F_{g,des} = F_c - F_c \frac{t}{T_{UNLOAD}}$
Vibration = (\(\tilde{a}_h > \text{ATHRESH}\))
Our Approach: Human-Inspired Robotic Grasp Control

We designed a high-impedance gripper robot to manipulate a variety of everyday objects at human-like speeds, without crushing or dropping them. We implemented our methods on the Willow Garage PRfi, a standardized hardware and software platform.

We validated our methods through experiments with the PRfi and a large collection of everyday objects under a variety of challenging test conditions. Our approach separates robotic grasping into six discrete states: Close, Lift and Hold, Replace, Unload, and Open, which are defined in Sections IV and V.

Mechanoreceptors and their responses are critical for successful robotic grasping. The S–vI afferents, which are slowly adapting with small receptive fields, are important during the lifting and transport of objects. The S–vII afferents are again important during unload to properly set the object down before full release.

In our approach, robotic grasping is controlled by a set of rules for each action phase. The close phase begins with the robot grasping an object and moving towards a set position. Once contact is detected, the robot lifts and holds the object. Corrective actions are typically needed to avoid slip, which are applied during the lifting and corrective actions are applied during the lifting and transport of objects.

The equation for the position of the gripper during the close phase is given by:

\[ x_{g,des} = x(0) - V_{CLOSE} \cdot t \]
\[ v_{g,des} = -V_{CLOSE} \]

where \( x(0) \) is the initial position, \( V_{CLOSE} \) is the velocity of closing, and \( t \) is time.

Once contact is detected, the robot lifts and holds the object. The force required to lift the object is determined by the response of the S–vI afferents, which are known to respond to tangential loading such as skin stretch. The initial force is applied to lift the object, and the load is gathered during the interaction. This loading process is regulated largely by the response of the S–vI afferents.

Once the object is securely grasped, the robot uses its arm muscles to lift up the object, hold it in the air, and possibly transport it to a new location. Corrective actions are typically applied during the lifting and transport of objects.

These tactile sensing capabilities and corrective reactions are expected results in human grasp control. Srinivasan et al. [2] showed that the S–vI afferents gather during the interaction and are important for rejecting disturbances in the lifting and transport of objects.

We validated our methods through experiments with the PRfi and a large collection of everyday objects under a variety of challenging test conditions. We carefully defined each control rule and state transition to achieve the dual goal of lifting and holding objects without crushing or dropping them.

In summary, our method for human-inspired robotic grasp control is designed to replicate the fluidity and adaptability of human grasp control. It enables a robot to delicately manipulate objects under a variety of challenging test conditions, thereby achieving the dual goal of lifting and holding objects without crushing or dropping them.
**Action-Phase Grasp Controller**

**Load**
- $t - t_c > T_{SETTLE}$
- set $F_c = \max_t (F_g) \cdot \frac{KHARDNESS}{VCLOSE}$

**StableContact**

**Replace**
- force $F_{g,des} = F_c$
- Slip $||$ Vibration
- set $t_s = t$

**Unload**
- force $F_{g,des} = F_c - F_c \frac{t - t_s}{TUNLOAD}$
- $F_{g,des} == 0$
- set $x_u = x$
- $t_u = t$

**Open**
- $x_{g,des} = x_{u} + v_{g,des}$
Our Approach: Human-Inspired Robotic Grasp Control

Inspired by the fluidity of human grasp control, this article focuses on developing a high-level robotic grasp controller that emulates human grasping. The controller is designed to mimic the important tactile signals provided by human mechanoreceptors.

### Control Diagram

![Action-Phase Grasp Controller Diagram]

1. **Load**
   - \( t - t_c > T_{SETTLE} \)
   - Set \( F_c = \max_t (F_g) \cdot \frac{K_{HARDNESS}}{V_{CLOSE}} \)

2. **Open**
   - \( F_{g,des} = 0 \)
   - Set \( x_{u,des} = x_u + V_{OPEN} \cdot (t - t_u) \)
   - \( v_{g,des} = V_{OPEN} \)

#### Equations

- \( F_{g,des} = \) desired grip force
- \( x_{g,des} = \) desired position
- \( v_{g,des} = \) desired velocity
- \( t \) is time
- \( F_c \) is critical force
- \( F_g \) is grip force
- \( t_c \) is critical time
- \( T_{SETTLE} \) is time to settle
- \( V_{CLOSE} \) is close velocity
- \( V_{OPEN} \) is open velocity
- \( K_{HARDNESS} \) is hardness

This controller is designed to handle various scenarios such as placing objects on a table, grasping and firmly grasping real-world objects, and transitioning between different grasping states.
Action-Phase Grasp Controller

**Close**
- **position**
  - \( x_{g,\text{des}} = x(0) - V\text{CLOSE} \cdot t \)
  - \( v_{g,\text{des}} = -V\text{CLOSE} \)
- **LeftContact \&\& RightContact**
- **set** \( x_c = x \), \( t_c = t \)

**Load**
- **position**
  - \( x_{g,\text{des}} = x_c \)
  - \( v_{g,\text{des}} = 0 \)
- **force**
  - \( F_{g,\text{des}} = F_c \)
- **set** \( t - t_c > T\text{SETTLE} \)
- \( F_c = \max_t (F_g) \cdot \frac{\text{KHARDNESS}}{V\text{CLOSE}} \)

**Unload**
- **force**
  - \( F_{g,\text{des}} = F_c - F_c \cdot \frac{t - t_s}{\text{TUNLOAD}} \)
- **set** \( t_u = t \)

**Open**
- **position**
  - \( x_{g,\text{des}} = x_u + V\text{OPEN} \cdot (t - t_u) \)
  - \( v_{g,\text{des}} = V\text{OPEN} \)

**Lift and Hold**
- **force**
  - \( F_{g,\text{des}} = F_c \)
- **Slip**
- **set** \( F_c = F_c \cdot \text{KSLIP} \)

**Replace**
- **force**
  - \( F_{g,\text{des}} = F_c \)
- **Slip || Vibration**
- **set** \( t_s = t \)

**Close**
- **Grasp()**
- **set** \( t = 0 \)

**StableContact**
Sample Grasp Execution
Sample Grasp Execution

![Graph showing various parameters during a grasp execution](image)

- $x_g$: Grip aperture (m)
- $F_{gl}$: Left gripper force (N)
- $F_{gr}$: Right gripper force (N)
- $\tilde{F}_{gl}$: Left gripper disturbance (N)
- $\tilde{F}_{gr}$: Right gripper disturbance (N)
- $\tilde{a}_h$: High-frequency gripper acceleration (m/s²)
- $E$: Gripper motor effort (%)

**Legend:**
- Close
- Lift and Hold
- Unload
- Load
- Grip aperture (m)
- Left gripper force (N)
- Right gripper force (N)
- Left and right gripper disturbance (N)
- High-frequency gripper acceleration (m/s²)
- Gripper motor effort (%)

**Events:**
- LeftContact & RightContact
- StableContact
- Slip
- Place()
- Slip
- Vibration
- $F_{g,des} = 0$
Robotic Tactile Signals
Gripper Position and Force Controllers
Action-Phase Grasp Controller
Robotic Tactile Signals
Gripper Position and Force Controllers
Action-Phase Grasp Controller
Does it work?
Control Parameter Tuning
Control Parameter Tuning
Control Parameter Tuning
Control Parameter Tuning

![Control Parameter Tuning Graph]

F O R M U L A S

\[ F_{\text{c}} = F_{\text{c}} - F_{\text{c}} T_{\text{u}} \]

\[ t_{\text{r}} = t_{\text{r}} - t_{\text{r}} s \]

\[ K_{\text{SLIP}} \] and \[ K_{\text{HARDNESS}} \]

These two parameters play a major role in the success of the manipulation. Section V is to select appropriate values for \[ K_{\text{SLIP}} \] and \[ K_{\text{HARDNESS}} \].

A. Parameter Tuning

Using a collection of fifty everyday household objects, we conducted a more general test of the PRfi’s capabilities and vibration signals during replace. To understand how our controller performs this unloading, we need to open the gripper. This movement is accomplished by gradually reducing the grip force from its maximum value.

Once the robot has released the object, it contacts the target surface. The goal of this phase is to ensure that the object is securely grasped before proceeding to open the gripper. This experiment helps show how these parameters affect grasp success.

The Unload phase is entered automatically after the held state is exited. Here, \[ v \] is a deformation of \[ z \] mm beyond the initial surface contact. We define crushing to be a deformation of 10 mm or rotation greater than 2 radians.

We define slippage in two forms: translation greater than 2 mm and rotation greater than 2 radians. High rates of object crushing or slippage are unacceptable. Very large value for \[ K_{\text{HARDNESS}} \] will cause the robot to overcompensate and crush the object. On the other hand, very small value result in a slip unacceptable amount. If \[ K_{\text{SLIP}} \] is increased, the robot tends to overcompensate and crush the object. If \[ K_{\text{HARDNESS}} \] is increased, the grip force is decreased away from the tuned value, objects tend to slip within the grasp.

We evaluated this technique during grasp testing on eight different objects: a paper cup, a raw meat canister, a plastic cylindrical-shaped object, a paperboard tea box, a ripe banana, an empty soda can, and a raw meat canister. These tests were done by placing each object in a known location and orientation on a table. The robot then lifts each object. These measurements of the minimum grip force necessary for the PRfi to successfully manipulate the object are recorded.

The five different values for \[ K_{\text{SLIP}} \] and \[ K_{\text{HARDNESS}} \] were selected such that they caused the controller response to vary between the two extremes of crushing and slipping. The results are presented in Fig. 2. Setting \[ K_{\text{SLIP}} \] and \[ K_{\text{HARDNESS}} \] to the central values, as listed in Table II, yields somewhat successful grasp behavior, but they typically deviate from the ideal parameter values.

These results are presented in Fig. 2. The effect of varying \[ K_{\text{SLIP}} \] and \[ K_{\text{HARDNESS}} \]. As \[ K_{\text{HARDNESS}} \] is increased, the robot tends to overcompensate and crush the object. If \[ K_{\text{SLIP}} \] is increased, the robot tends to overcompensate and crush the object. If \[ K_{\text{HARDNESS}} \] is increased, the grip force is decreased away from the tuned value, objects tend to slip within the grasp.

KH(RDNESS to the central values, as listed in Table II, yields somewhat successful grasp behavior, but they typically deviate from the ideal parameter values. These deviations from the ideal parameter values result in completely unsuccessful grasp results, as defined by our strict crushing and slipping metrics. Very large value for \[ K_{\text{HARDNESS}} \] does not respond strongly enough to slip events, and the object is allowed to slip an unacceptable amount. As \[ K_{\text{SLIP}} \] is increased, the robot tends to overcompensate and crush the object. If \[ K_{\text{HARDNESS}} \] is increased, the grip force is decreased away from the tuned value, objects tend to slip within the grasp.
Control Parameter Tuning

![Graph showing control parameter tuning with KSLIP on the y-axis and KHARDNESS on the x-axis. The graph has a blue circle labeled 'Slip' at the origin (0,0). The circle is labeled '100%'.]
We began the experiment by obtaining ground-truth measurements of the minimum grip force necessary for the PRfi to lift each object. These tests were done by placing each object in a known location and orientation on a table. The robot then monitored to detect crushing conditions before the task. During the task, the grasp aperture was continuously positioned around the object. Next, the Grasp command was sent to the robot to initiate the event-driven grasping approach. The robot lifted the object upward and rotated it. A canister was placed on a table in front of the robot, and the open robot gripper was used to avoid crushing the object. First, the canister was placed on the table, and its flexible body necessitated using a delicate grasp. 'Otte' Mate canister with a mass of 1.2 kg for our parameter tuning experiments proved successful. We chose a plastic cylindrical-shaped container as an alternative to the canister. Paperboard tea box, a ripe banana, an empty soda can, and a raw potato were selected for testing. Normalized by contact speed, we evaluated this technique for slip and deviation from the ideal parameter values. Very large values for KHARDNESS to the central values, as listed in Table II, yield somewhat successful grasp behavior but they typically result in crushing. Large deviations from the ideal parameter values result in completely unsuccessful grasp results, as defined by our strict crushing definition. Unsuccessful grasp results lead to object drops, or successful grasps result in objects being lifted away from the target surface. The goal of this phase is to select appropriate values for KSLIP and KHARDNESS. These two parameters play a major role in the successful manipulation of objects. Proper tuning will result in successful manipulation of objects, while improper tuning will result in objects being dropped. These results are presented in Fig. 2. Setting KSLIP and KHARDNESS to the central values, as listed in Table II, yields 100% success. For the PRfi robot, our parameter tuning experiments proved successful in delicate manipulation, while improper tuning will result in objects being dropped. We define crushing to include object drops, or successful manipulation of objects. Proper tuning will result in successful manipulation of objects, while improper tuning will result in objects being dropped. These results are presented in Fig. 2.

The Unload phase is entered automatically after the held object contacts the target surface. The goal of this phase is to remove the object from the robot. Once the robot has released the object on the surface, it proceeds to open the gripper. This movement is accomplished using a linearly reduced grip force, which represents the present time, and the desired grip force is gradually reduced away from the tuned value. Objects tend to slip within the grasp due to inadequate initial grip forces. As KSLIP is decreased, the robot does not respond strongly enough to slip events, and the object is allowed to slip. As KHARDNESS is increased, the grip force is overestimated, and crushing occurs. As KSLIP is decreased, objects tend to slip within the grasp due to inadequate initial grip forces. As KHARDNESS is increased, the grip force is overestimated, and crushing occurs. As KSLIP is decreased, objects tend to slip within the grasp due to inadequate initial grip forces. As KHARDNESS is increased, the grip force is overestimated, and crushing occurs. As KSLIP is decreased, objects tend to slip within the grasp due to inadequate initial grip forces. As KHARDNESS is increased, the grip force is overestimated, and crushing occurs. As KSLIP is decreased, objects tend to slip within the grasp due to inadequate initial grip forces. As KHARDNESS is increased, the grip force is overestimated, and crushing occurs.
A. Parameter Tuning

For the PRfi robot, our parameter tuning experiments proved successful manipulation of objects. One challenge in implementing the grasp controller of the PRfi robot is the parameter interaction as seen here. We defined slippage in two forms: translation greater than 2 mm, which represents a deformation of 0.1 mm beyond the initial surface contact, and rotation greater than 24.2 radians, which is a deformation of 0.001 mm beyond the initial surface contact.

We evaluated this technique by using a collection of fifty everyday household objects, including a chicken egg, a tennis ball, a glass bottle, and a full soda can. We chose a plastic cylindrical-shaped paperboard tea box, a ripe banana, an empty soda can, and a raw potato. We then conducted a more general test of the PRfi's capabilities to see how our approach compares to more simplistic grasping solutions.

The five different values for KSLIP and KHARDNESS were selected such that they caused the controller response to the Slip during Load and Hold, the effect of Slip on the controller, and the response to Slip during Lift and Hold. We then discussed experiments that test the performance of the novel control parameter tuning method.

These results are presented in Fig. 2, which shows the effect of varying KSLIP and KHARDNESS. The diagram illustrates the successful manipulation of objects, with Slip and Crush states on the graph. Setting KSLIP and KHARDNESS to appropriate values for our parameter tuning study helps show how these parameters affect grasp success.
experimenter measured the translation and rotation of the object during the task.

Monitoring was conducted to detect crushing conditions after the task. The grasp aperture was continuously adjusted as the robot lifted the object upward and rotated it. The sequence of actions continued until stable contact was achieved. Then, a command was sent to the robot to initiate an event-driven grasping sequence. The grasp command was positioned around the object. Next, the open robot gripper was manipulated to avoid crushing the object. First, the canister was placed on a table in front of the robot. Then, a plastic cylindrical-shaped canister with a mass of 1.2 kg was used as an example object. This object was selected for its heavy weight, which necessitates using a strong grasp to prevent object slip.

In our experiment, we performed tuning studies on a collection of fifty everyday household objects. The parameters were chosen based on the maximum force required to lift each object. These tests were done by placing each object on a table in a known location and orientation. The robot then lifted each object. These tests were conducted to understand how our controller interacts with the environment. The grip force chosen during load is linearly reduced to zero over a set period of time using a constant positive desired grip force. The desired grip force is gradually increased away from the tuned value to achieve the desired grip force. The state is exited when the object contacts the target surface. The goal of this phase is to select appropriate values for KSLIP and KHARDNESS, which affect grasp success.

In our experiment, we explored the parameter interaction as seen in Section V. The controller in the Load phase selects the target grip force based on the maximum force measured during loading. The parameter space was divided into five different values for KSLIP and KHARDNESS, for a total of 25 different parameter combinations. These results are presented in Fig. 2. Setting KSLIP and KHARDNESS to the central values, as listed in Table II, yields the tightest possible grasp. In practice, this parameter space will cause the robot to saturate its grip force, resulting in unsuccessful grasp results, as defined by our strict crushing and slipping metrics. Very large values for KHARDNESS will lead to completely unsuccessful grasps, while very small values will cause the robot to overcompensate and crush the object. Increasing KSLIP will lead to an increase in the likelihood for slip and crushing results. Large deviations from the ideal parameter values can often lead to unsuccessful grasp behavior. However, they typically yield somewhat successful grasp behavior. Large deviations away from the ideal parameter values can often lead to unsuccessful grasp behavior. However, they typically yield somewhat successful grasp behavior.

Fig. 2 shows the effect of varying KSLIP and KHARDNESS. As KHARDNESS increases, the grip force increases, while KSLIP decreases away from the tuned value. Objects tend to slip within the grasp if KSLIP is decreased away from the tuned value. If KSLIP is increased, the robot tends to overestimate the required grip force and crush the object. If KSLIP is decreased, the robot tends to underestimates the required grip force and object slip. If KHARDNESS is increased, the grip force increases, while KSLIP decreases away from the tuned value. Objects tend to slip within the grasp if KSLIP is decreased away from the tuned value. If KSLIP is increased, the robot tends to overestimate the required grip force and crush the object. If KSLIP is decreased, the robot tends to underestimates the required grip force and object slip.
Initial Grip Force Testing
C. Slip Response During Lift and Hold

It was observed that if the object was crushed, the robot's gripper would move upwards by 21 cm. If slip occurred during lifting, the trial was repeated with the grasp force incremented by 1.2 N. If the object did not slip, the desired grip force was recorded as the final grip force. This entire process was repeated with the grasp force incremented by 1.2 N. If slip occurred during lifting, the trial was repeated with the grasp force incremented by 1.2 N.

Lastly, we determined the force necessary to crush each object. The experiment was then repeated using the grasp controller instead of the force controller. We also conducted a separate experiment to test slip compensation.

Fig. 9 shows the results of the slip test for three different trials. The glass cup was repeatedly dropped an object without requiring unnecessarily high grasp forces. This test's ground truth data was obtained for each of the eight everyday objects. The gain K_HARDNESS was empirically tuned to yield a grip force that is consistently above the minimum grip force needed for lifting.

In all cases, operation damages the object. These crush force measurements appear as red X's with the other results in Fig. 8. In all cases, the operation damages the object. These crush force measurements appear as red X's with the other results in Fig. 8. These results indicate that this value increases up to an object weight of about 3.7 N. One can see its tendency to always choose a grip force value above the level needed to prevent slip. The variation between the three trials is primarily due to differences in how the experimenter shook the gripper; it watches for Slip events which it does not always chose a grip force value above the level needed to prevent slip. However, reliable grip force measurements were obtained for all objects except the egg, which needed to avoid slip. For crushable objects, it chose grip forces well below the crush limit for all objects except the egg, which needed to avoid slip. The controller always chose a grip force value above the level needed to prevent slip. The variation between the three trials is primarily due to differences in how the experimenter shook the gripper; it watches for Slip events which it does not always chose a grip force value above the level needed to prevent slip. However, reliable grip force measurements were obtained for all objects except the egg, which needed to avoid slip. For crushable objects, it chose grip forces well below the crush limit for all objects except the egg, which needed to avoid slip.
The robot monitors target grasp force and watches for slip events during the Lift and Hold phase. In Section V, we describe slip response during the Lift and Hold phase.

For crushable objects, it chose grip forces above the minimum level to prevent crushing. The controller chose a grip force value above the level needed to crush the object. These crush force measurements appear as red X's with other results in Figure 8. In all cases, the robot's operation damages the object. These crush force measurements were obtained by successively incrementing load phase for each of the eight test objects.

The desired loading force for each trial was the grip force needed to lift the object. This entire process was repeated with the grasp force incremented by 1.2 N. If slip occurred during lifting, the trial was repeated with the grasp force incremented by 2 N. If the gripper was closed on the object, the desired loading force was recorded as the minimum grip force needed for lifting. This calculation provides a good estimate for a large range of objects, but it can overestimate the force necessary to hold objects that are both hard and light. The red × symbol marks the crushing force for all objects.

Lastly, we determined the force necessary to crush each object. The experiment was then repeated using the grasp controller, and the desired loading force was recorded as calculated with ±2 N. The dark red "Grip Force" bars in Figure 8 show the mean and standard deviation of the minimum grip force needed to prevent slip. The variation between the three trials is primarily due to differences in how the experimenter shook the gripper. The variation always chose a grip force value above the level needed to hold the cup at each of the six weights. The controller's desired grip force was incremented by 1.2 N after six cup weights using the force controller of Section IV.

The glass cup was repeatedly shaken for two seconds after each batch of marbles was added to the cup at intervals of three seconds. The gripper was lightly shaken for two seconds after each batch of marbles was added, during which time the controller reacted to any detected slip. Marbles were then added to the cup at intervals of three seconds. Five batches of fifteen marbles (about 1.8 N per batch) were then added to the cup. The weight of the cup was measured to be 1.8 N, and it was oriented vertically. The experimenter began a trial by activating the Lift controller with an initial desired grip force of 7 N. The cylindrical section of a glass cup was placed in the robot gripper, as seen in the inset of Figure 9. The weight of the cup was measured to be 1.8 N, and it was oriented vertically. The experimenter began a trial by activating the Lift controller with an initial desired grip force of 7 N. The cylindrical section of a glass cup was placed in the robot gripper, as seen in the inset of Figure 9.
Slip Reaction Testing
Slip Reaction Testing

Grip Force (N) vs. Object Weight (N) diagram.
Slip Reaction Testing

We sought to understand our system's slip response by testing it with a variety of objects and conditions. The graph shows the results of slip testing for three different trials. The solid lines represent the actual grip forces measured during each trial, while the dashed line indicates the minimum grip force needed to prevent slip. The red circles mark the crushing force for all objects.

The experiment was designed to test the system's ability to maintain grip force and prevent slip across a range of object weights and conditions. The controller's desired grip force was adjusted based on the observed slip behavior, as shown in the graph. The results indicate that the system is able to adapt to different objects and conditions, maintaining grip force and preventing slip even under challenging conditions.

In software before the experimenter added another batch of marbles, the gripper was lightly shaken for two seconds after each batch of marbles was added to the cup at intervals of three seconds. The gripper was then firmly grasped by the robot gripper, as seen in the inset of Fig. 9. The weight of the cup was measured to be 1.8 N, and it was oriented vertically. The experimenter began a trial by activating the Lift and Hold controller with an initial desired grip force of 7 N. For each trial, the desired loading force of the object was set to a small value, starting between 1.7 N and 8 N, depending on the object. The robot then used its arm joints to move the gripper up by 21 cm if the object was not crushed in three of the eight trials. For crushable objects, it chose grip forces above the minimum level needed to avoid slip.

The variation between the three trials is primarily due to differences in how the experimenter shook the gripper; stronger external disturbances cause more corrective actions. The final selected grip force value was recorded during arm motion if slip occurred during lifting. The trial was repeated using the grasp controller if slip occurred during the Load phase for each of the eight test objects.

The blue "Minimum Force" bars in Fig. 8 show the mean and standard deviation of the eight everyday objects. The gain K_HARDNESS was empirically tuned to have the gripper hold objects that are both hard and light with a good estimate for a large range of objects. However, one can see its tendency to overestimate the force necessary to hold objects.

The system's behavior is designed to grasp objects more tightly when it detects slip. This behavior reduces the likelihood of slip and allows the system to maintain grip force under varying conditions. The results shown in the graph demonstrate the system's effectiveness in maintaining grip force and preventing slip across a range of objects and conditions.
50 Object Marathon
50 Object Marathon
<table>
<thead>
<tr>
<th></th>
<th>100% Motor Effort</th>
<th>Our Methods</th>
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<tr>
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<td>Rotated Within Grasp</td>
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**OUTCOMES OF GRASP TESTING WITH EVERYDAY OBJECTS.**

![A variety of everyday objects including marbles, a robotic arm, and various household items.](image-url)
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<th>100% Motor Effort</th>
<th>Our Methods</th>
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**Outcomes of Grasp Testing with Everyday Objects.**

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Contact Sensing During Replace
Contact Sensing During Replace
Contact Sensing During Replace

Standard Controller
Contact Sensing During Replace

Standard Controller

Our Controller
Contact Sensing During Replace

The first test consisted of 14 trials using the standard non-contact sensing approach to object placement. The second set of 14 trials used our contact sensing approach to replace the object once the slip or vibration signal was detected. The resulting pressure-sensitive sensing strategy is more efficient than the naive controller which always uses contact between the held object and the table surface during object replacement.

Qualitative inspection of the resulting films suggests that the sensors could detect contact with the tables a total of 3 out of the 14 trials, which both contain errors that lead to forceful impacts. Our approach indicates regions of higher pressure than the standard approach, which assumes perfect knowledge of the table position and object position within the grasp.

This article introduced a set of sensory signals and control approaches that attempt to mimic the human reliance on cutaneous sensations during grasping tasks. We presented a number of objects ranging from soft to hard, such as the foam ball and the %id box with zero motor effort, to the wood plank, the duct tape roll, and the sunglasses case, all had an average motor effort of fizzx and the full beer bottle all had an average motor effort of f2x7zz to f27vzzz Ny. The objects with the highest initial grasp force were the large plastic bowl, the stress ball, and the coffee mate, in ascending order. From this we observe that soft objects generally receive lower initial grip forces than hard objects, as one would expect from the design of our controller.

The objects with the lowest initial grasp force were the towel, the coffee mate, in descending order. These values range from 1x4 N to 16x4 N with most objects below 6x4 Nx. The objects with the highest initial grasp force were the towel, the coffee mate, and the wood plank, in ascending order.

E. Contact Sensing During Replace

In contrast, our contact sensing controller uses the tactile sensor data to detect contact between the held object and the table surface during object replacement. This allows the robot to contact the object down into the table very firmly because the visually estimated target location was beneath the surface of the actual object. This results in gentler placements than those caused by the object to drop onto the table in the remaining 1fix trials with the standard controller. The robot pressed the object down into the table with greater torque after the initial contact, pushing the object down into the table.

Lastly, we carried out a set of tests to evaluate the effectiveness of the Slip and Vibration signals used to detect contact with the tables. This was done by comparing the number of drops caused by the object to drop onto the table with the standard controller to the number of drops caused by the object to drop onto the table with our contact sensing controller. The standard approach released the object when table contact was detected, yielding gentler placements. The vibration approach also released the object when table contact was detected, yielding gentler placements. The vibration approach also released the object when table contact was detected, yielding gentler placements.
Robotic SA-I, FA-I, and FA-II tactile signals from fingertip pressure cells and a palmar accelerometer
Robotic SA-I, FA-I, and FA-II tactile signals from fingertip pressure cells and a palmar accelerometer

Low-level position and force controllers
Robotic SA-I, FA-I, and FA-II tactile signals from fingertip pressure cells and a palmar accelerometer

Low-level position and force controllers

Human-inspired action-phase grasp controller with tactile events
Robotic SA-I, FA-I, and FA-II tactile signals from fingertip pressure cells and a palmar accelerometer

Low-level position and force controllers

Human-inspired action-phase grasp controller with tactile events

Robust performance in picking up, transporting, and setting down common objects
Another Kind of Tactile Intelligence
Another Kind of Tactile Intelligence
Demo at Google I/O on Wednesday, May 11
Hi Katherine,
FYI
High-five code was demonstrated live onstage at the big google yearly conference Google I/O (youtube link below), and as a live demo during the conference (attached video). I thought that was neat.

-Joe

------------- Forwarded message -----------
From: Ken Conley <kwc@willowgarage.com>
Date: Thu, May 12, 2011 at 2:29 PM
Subject: Re: google IO
To: Joe Romano <jrom@seas.upenn.edu>, Benjamin Cohen <bencohen2@gmail.com>
Cc: Brian Gerkey <gerkey@willowgarage.com>

Joe (adding Ben),

Shot this video for you -- thanks to your code, hundreds of Google I/O attendees got to experience the joy of fist-bumping a robot (plus the high-five at the start of the I/O talk).

We decided at the last minute to throw in pr2_props -- svn co, rosmake, followed the roswiki docs, and everything worked perfectly. Many, many thanks. There's now a demand for pr2_hugs :).

- Ken
Demo at Google I/O on Wednesday, May 11
Demo at Google I/O on Wednesday, May 11
Acknowledgments

Joe Romano  
Ph.D. Student

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Willow Garage Researcher

Sachin Chitta, Ph.D.  
Willow Garage Researcher
Thank You