Human-Inspired Robotic Grasp Control with Tactile Sensing

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Penn
UNIVERSITY of PENNSYLVANIA


Haptic Slip Glove
144 TOWNE
Mechanical Engineering & Applied Mechanics
Haptics Group – GRASP Lab
Katherine J. Kuchenbecker
Skirkanich Assistant Professor
Haptics

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

Remote

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

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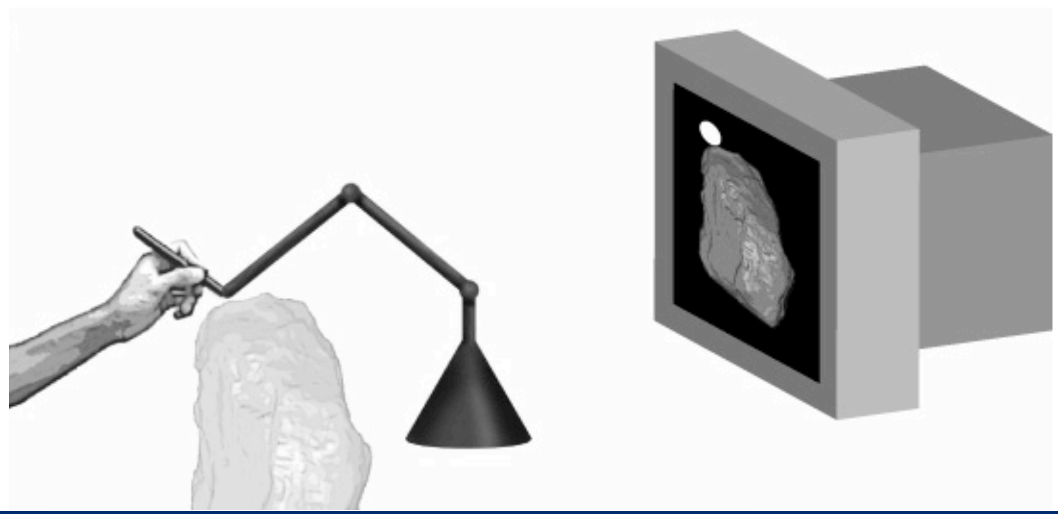
Virtual

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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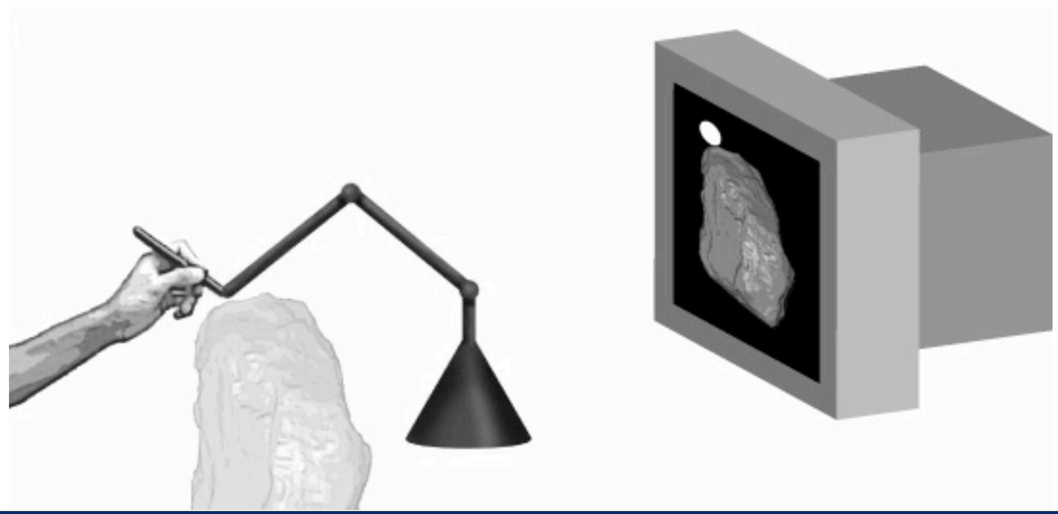

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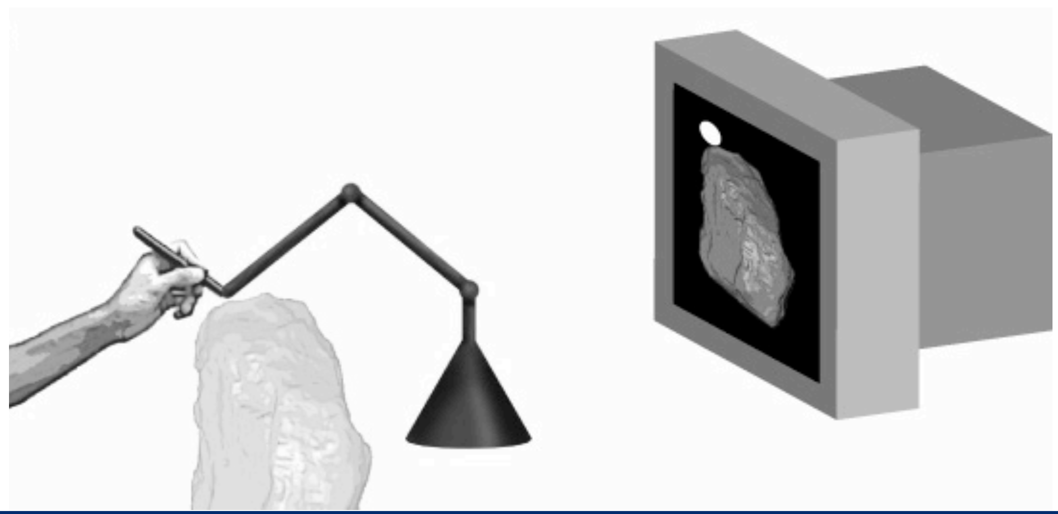

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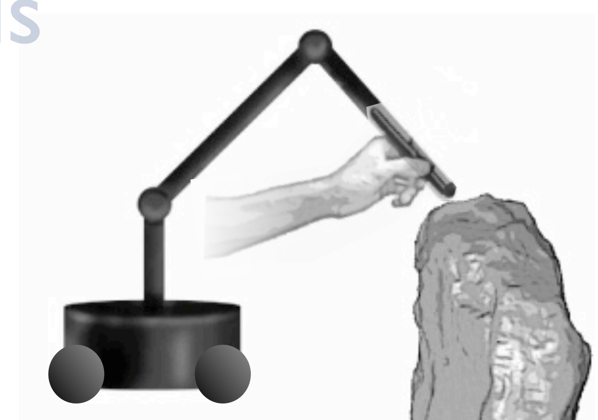

Real

Autonomous Robot: independently explores and manipulates real objects to accomplish tasks

Joe Romano
Ph.D. Student

Joe Romano
Ph.D. Student

Willow Garage

Joe Romano
Ph.D. Student

Kaijen Hsiao, Ph.D.
Willow Garage Researcher

Günter Niemeyer, Ph.D.
Willow Garage Researcher

Sachin Chitta, Ph.D.
Willow Garage Researcher

Human-Inspired Robotic Grasp Control with Tactile Sensing

Joseph M. Romano, *Student Member, IEEE,* Kaijen Hsiao, *Member, IEEE,* Günter 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**

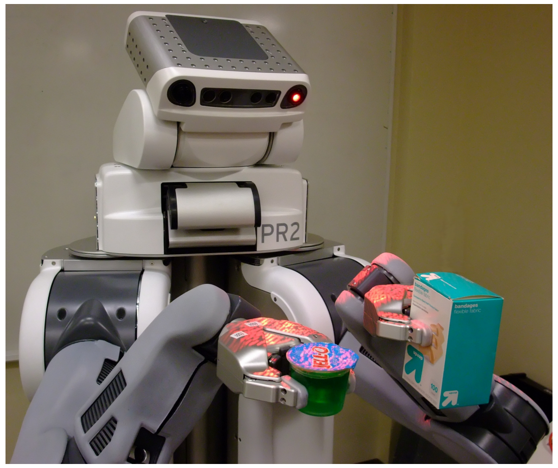

Fig. 1. The Willow Garage PR2 robot using our grasp controller to carefully handle two sensitive everyday objects.

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 grip 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

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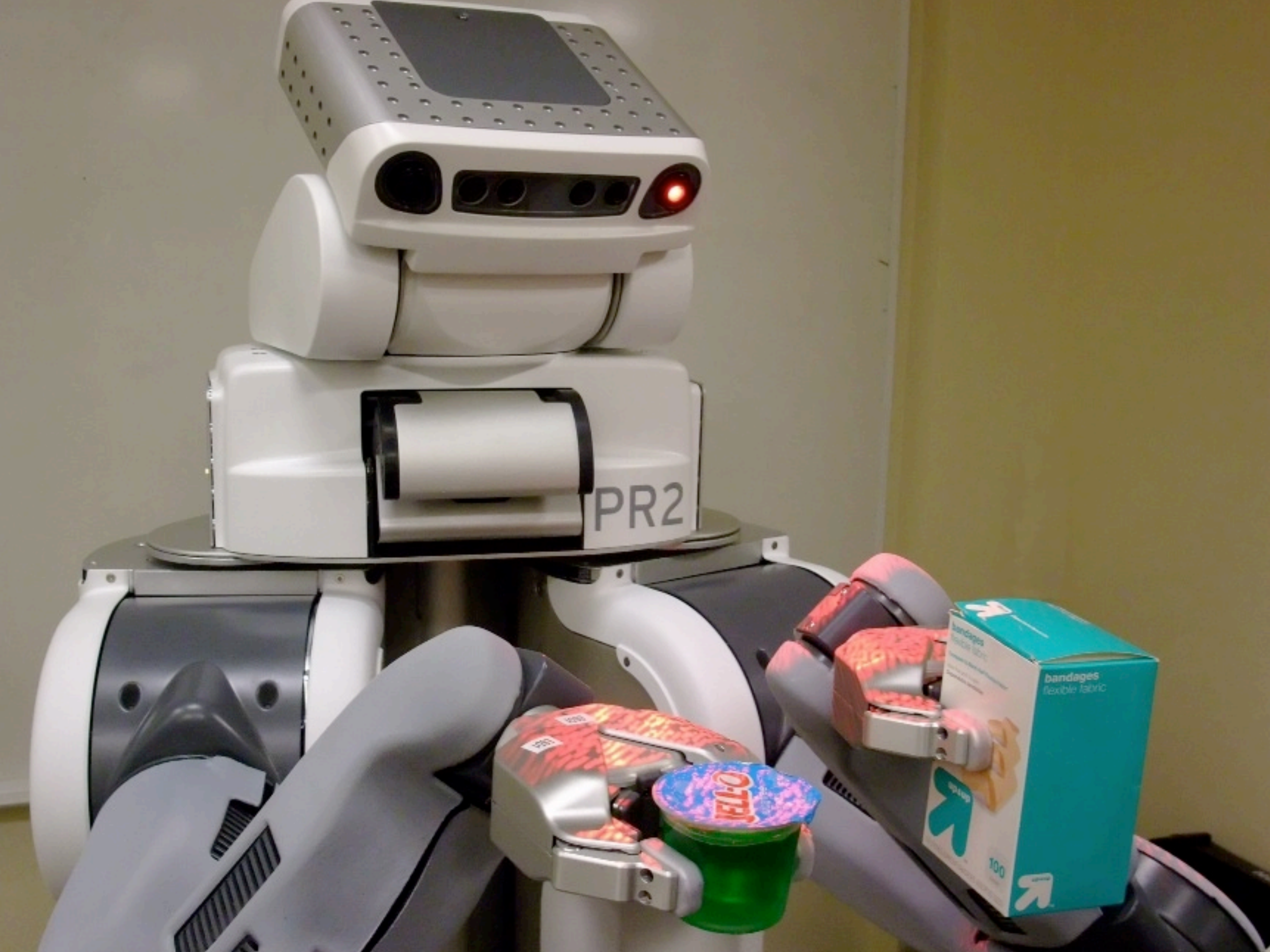
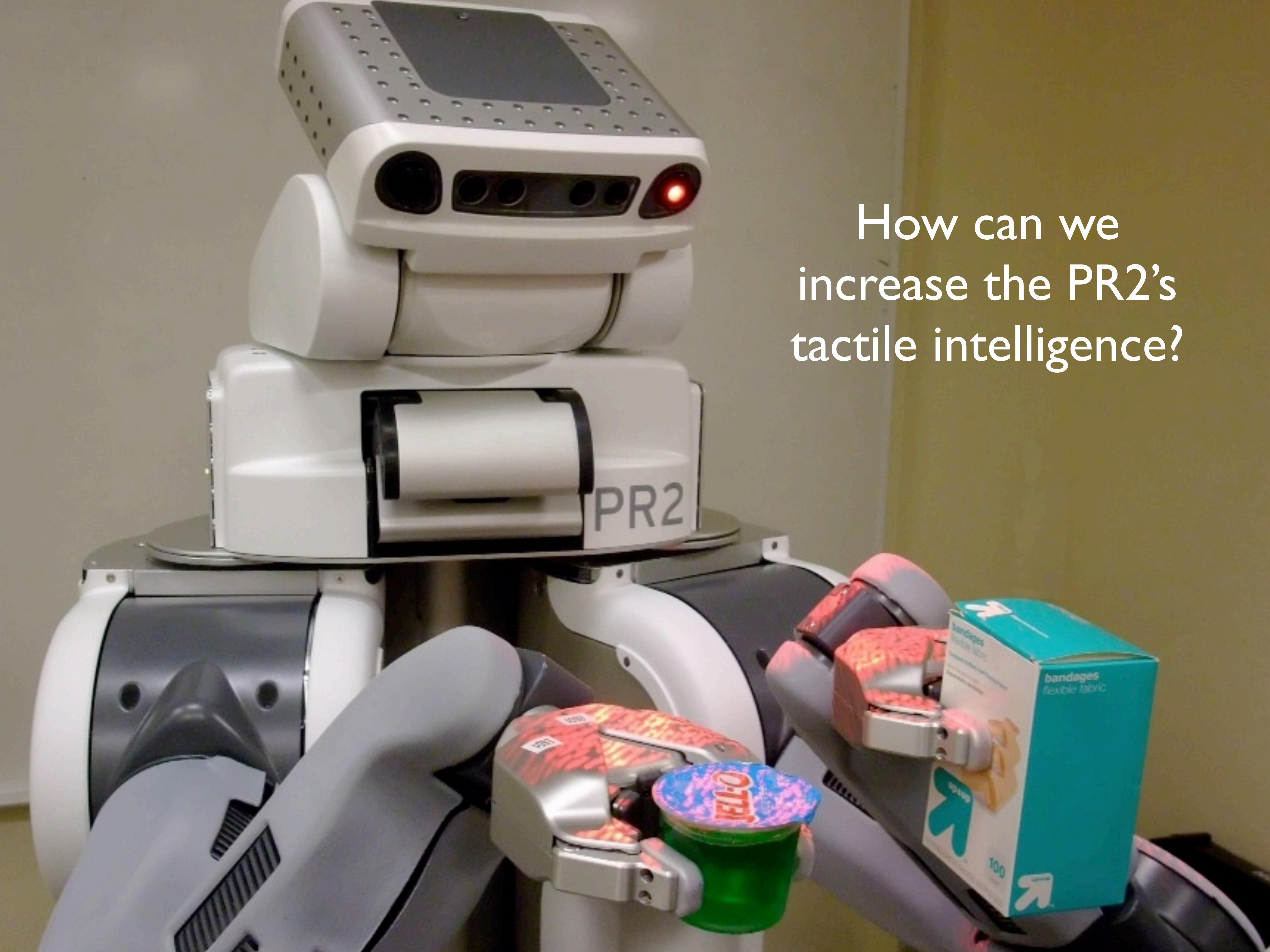
K. Hsiao, G. Niemeyer and S. Chitta are with Willow Garage, Menlo Park, CA, 94025 USA. e-mail: {hsiao, gunter, sachinc}@willowgarage.com


PR2
bandages
flexible fabric
100



How can we increase the PR2's tactile intelligence?

雀巢
Confidence
可冲10杯
NESCAFÉ

Parallel jaw gripper

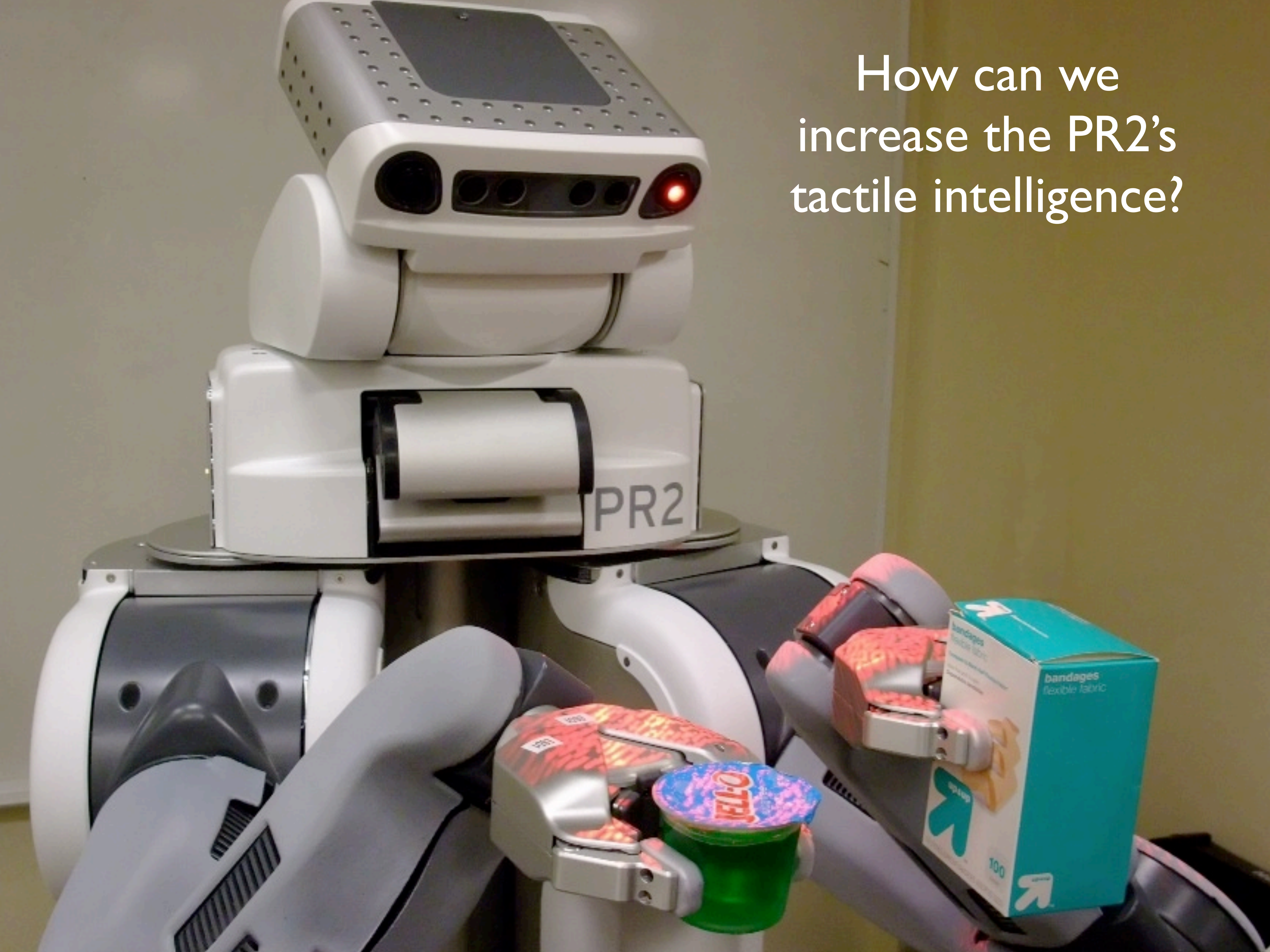
Parallel jaw gripper

High mechanical impedance

Parallel jaw gripper

High mechanical impedance

Naive control
(100% motor effort)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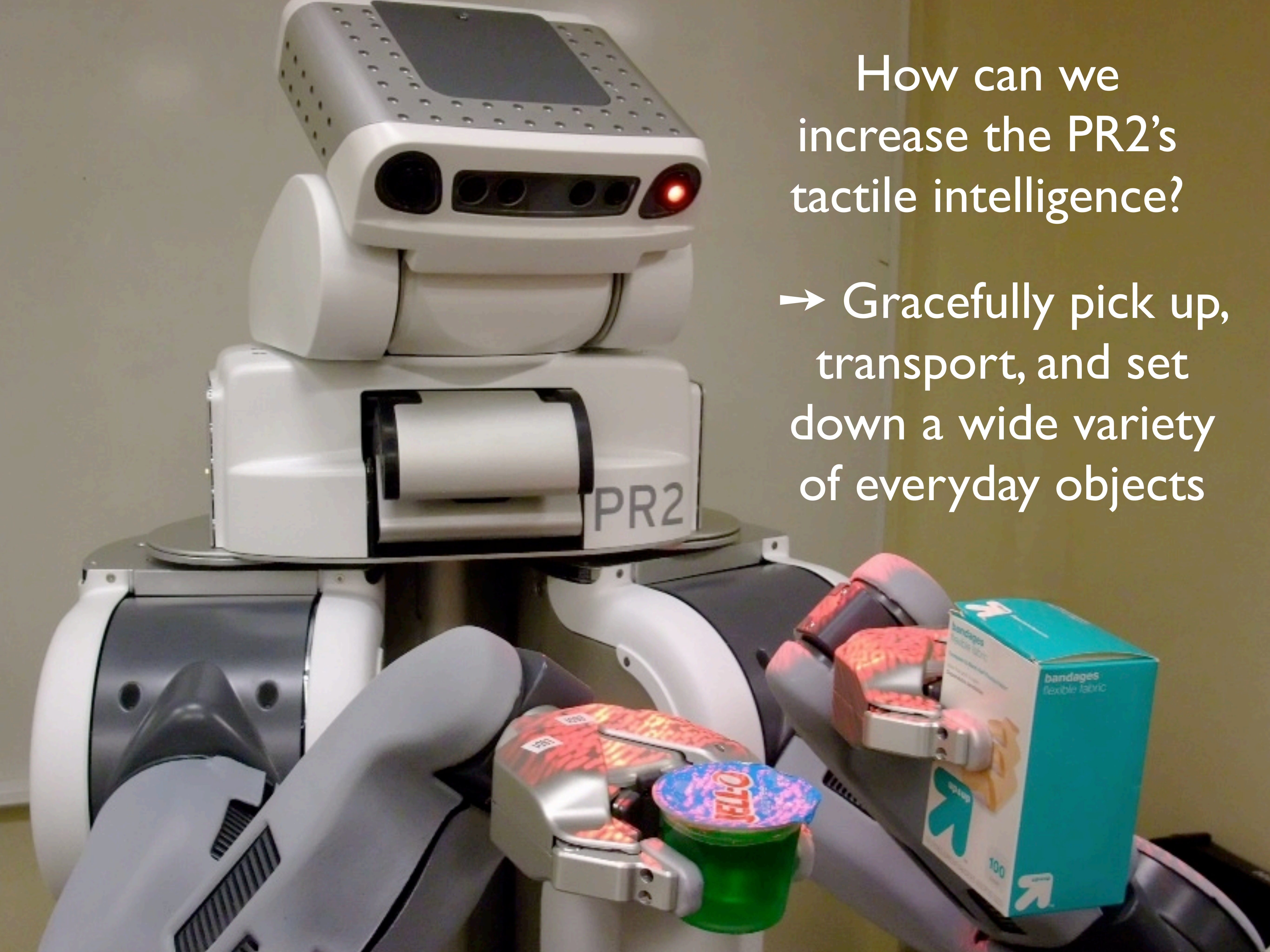
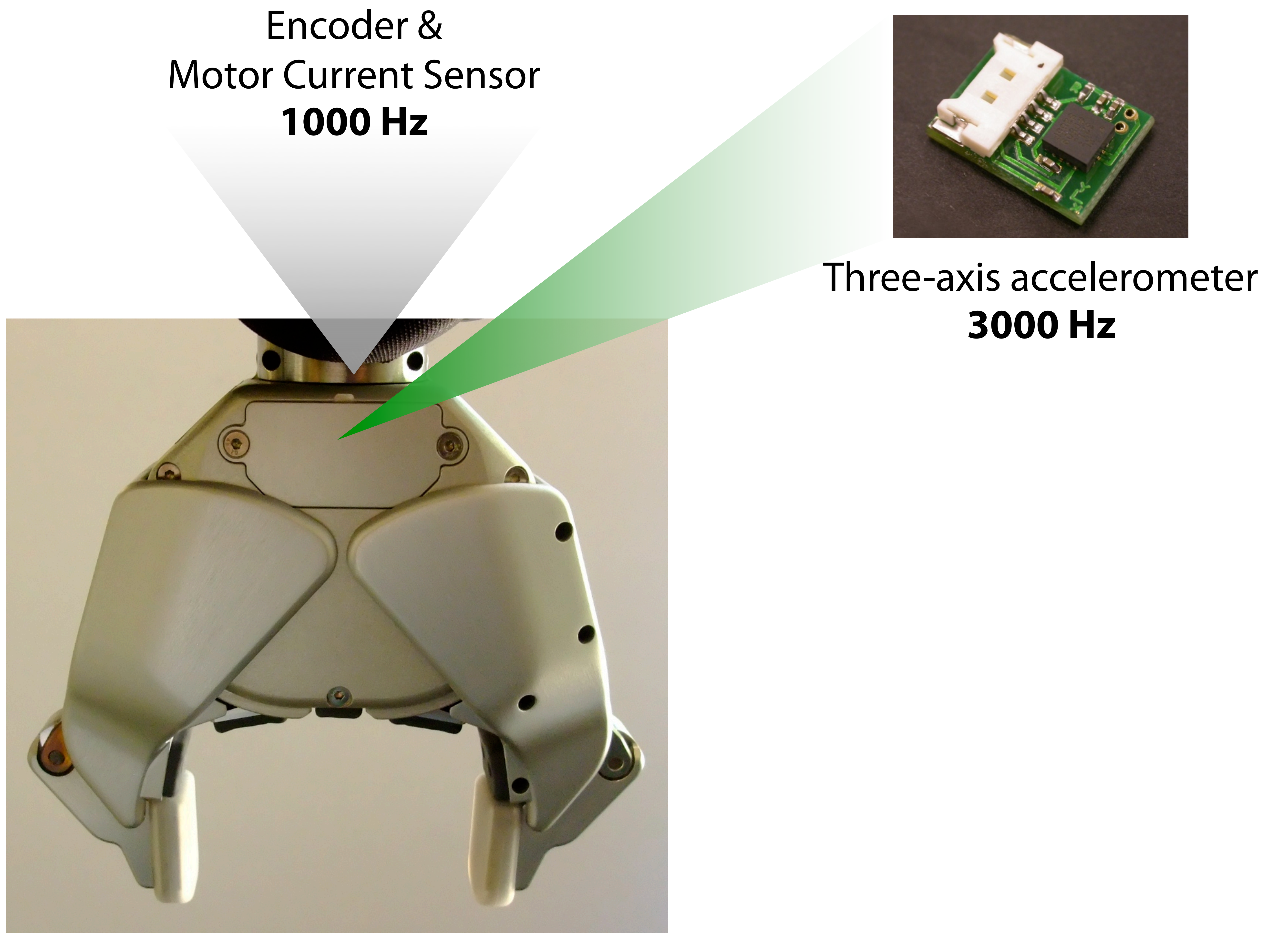


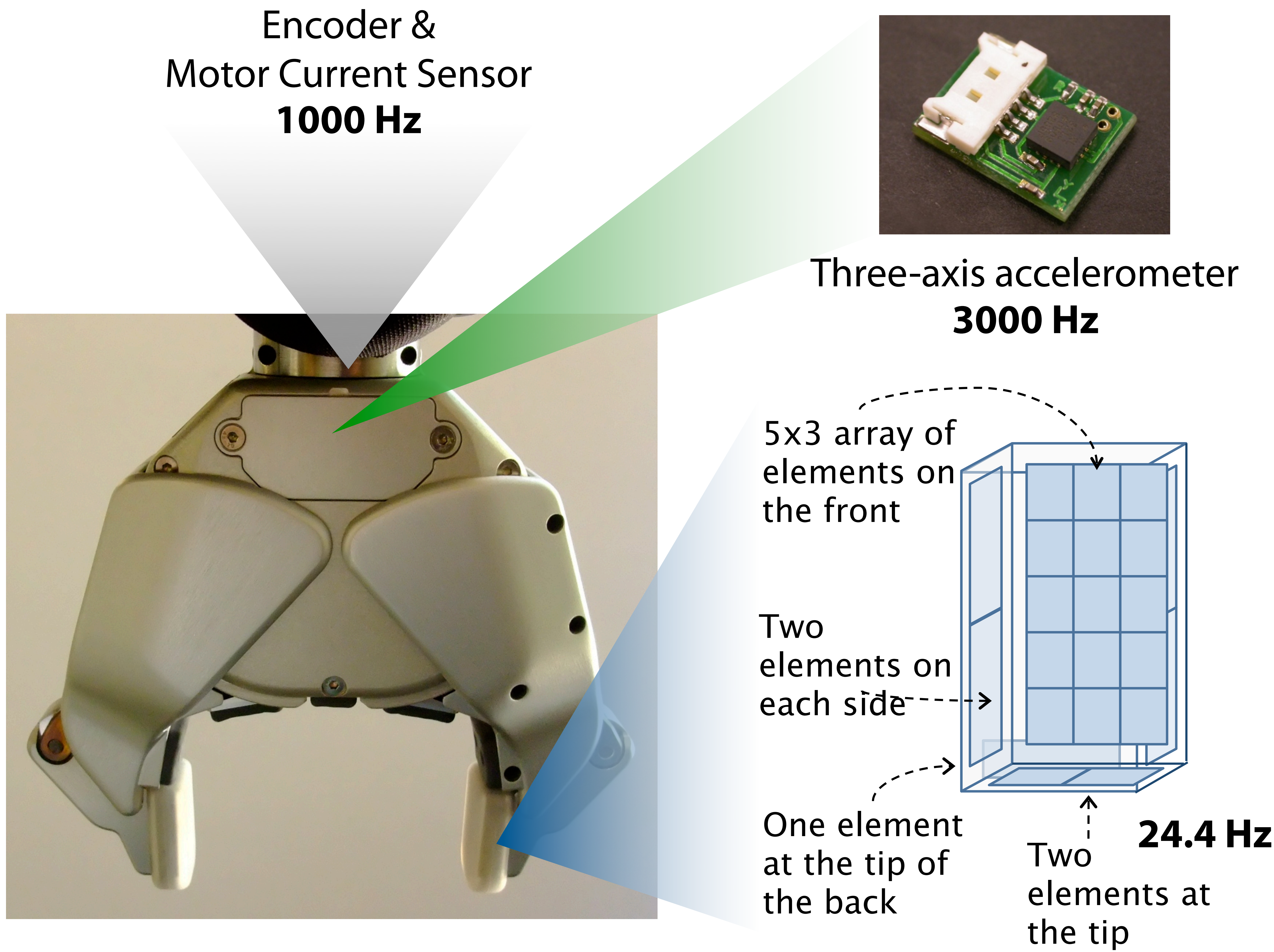
How can we increase the PR2's tactile intelligence?

→ Gracefully pick up, transport, and set down a wide variety of everyday objects

Encoder &
Motor Current Sensor
1000 Hz



Encoder &
Motor Current Sensor
1000 Hz
Three-axis accelerometer
3000 Hz



Encoder &
Motor Current Sensor
1000 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
Two elements at the tip
24.4 Hz

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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doi:10.1038/nrn2621
Published online 8 April 2009

The tactile afferents that innervate the inside of the hand signal the transformation of soft tissues that occurs when the hand interacts with objects and thus provide information about the physical properties of the object and the contact between the object and the hand. People with impaired tactile sensibility have difficulties with many everyday activities because the brain lacks the information about mechanical contact states that is needed to plan and control object manipulations. Vision provides only indirect information about such mechanical interactions, and proprioceptive afferents exhibit low sensitivity to mechanical fingertip events[1–4].

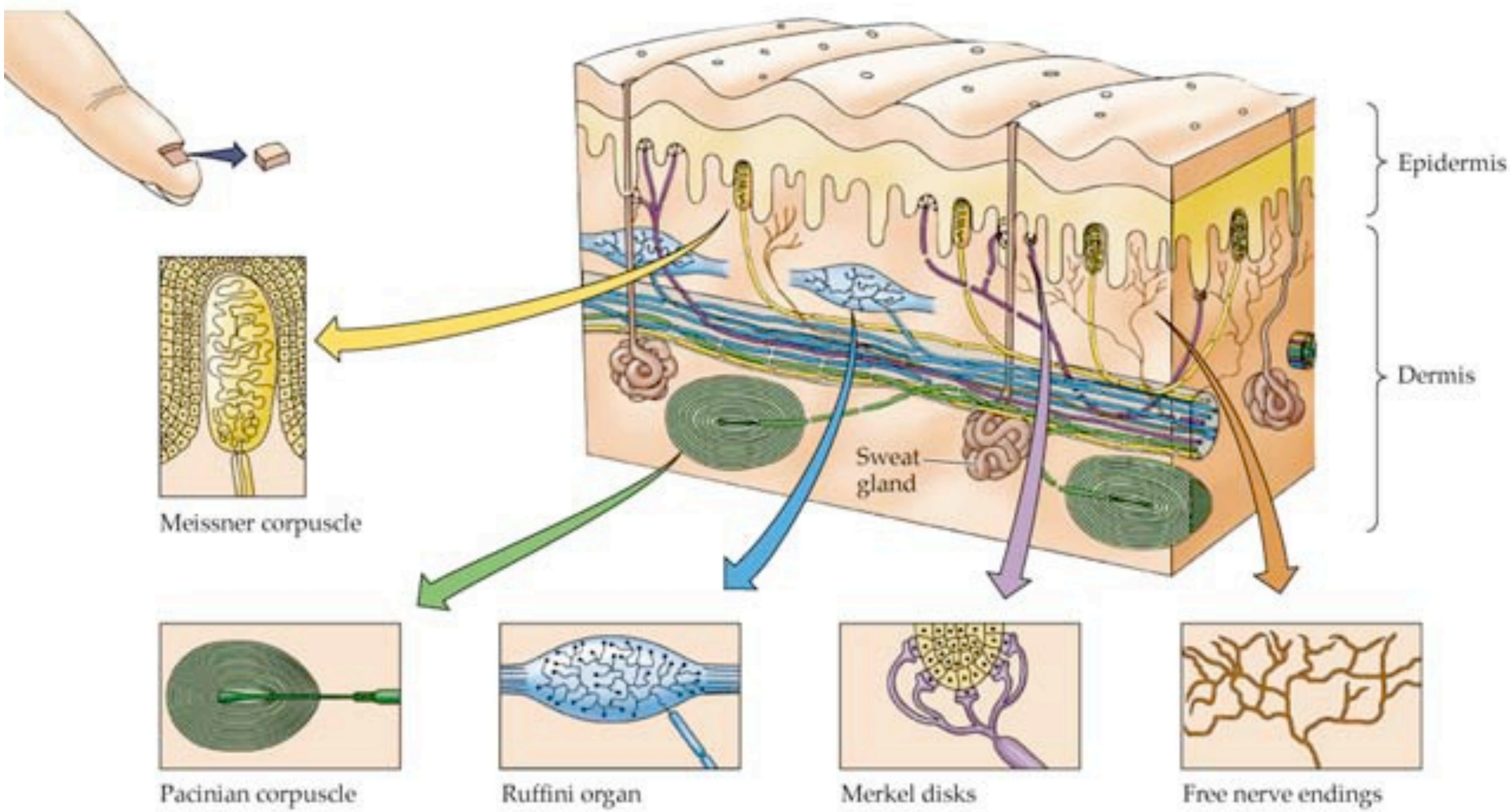
In this Review, we address emerging concepts regarding the use of tactile information by the brain in manipulation tasks. In doing so, we discuss the notion that the planning and control of manipulation tasks is centred on mechanical events that mark transitions between consecutive action phases and that represent subgoals of the overall task. We highlight recent findings that help explain the speed with which the brain detects and classifies tactile fingertip events in object manipulation. Finally, we discuss multisensory representation of action goals in object manipulation. Our account differs from a recent review of tactile signals in manipulation[5] by emphasizing the use of these signals in the control of manipulatory tasks, by considering how other sensory signals contribute to this control and by discussing the central neural mechanisms involved in manipulation tasks.

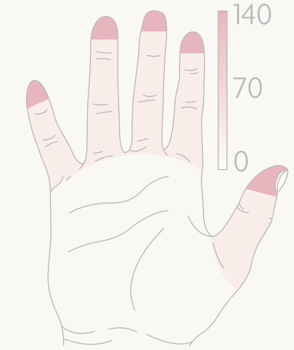
Tactile sensors encoding fingertip transformations

When humans manipulate objects, the brain uses tactile afferent information related to the time course, magnitude, direction and spatial distribution of contact forces, the shapes of contacted surfaces, and the friction between contacted surfaces and the digits. The inside of the human hand is equipped with four functionally distinct types of tactile afferents (TABLE 1; reviewed in more detail in REFS 5,6). FA-I (fast-adapting type I) and SA-I (slow-adapting type I) afferents terminate superficially in the skin, with a particularly high density in the fingertips. FA-Is exhibit sensitivity to dynamic skin deformations of relatively high frequency[7,8], whereas SA-Is are most easily excited by lower-frequency skin deformations[7,8] and can respond to sustained deformation. There are more FA-I afferents than SA-I afferents in the fingertips (TABLE 1), reflecting the importance of extracting spatial features of dynamic mechanical events, such as the skin forming and breaking contact with objects or scanning across a textured surface.

FA-II and SA-II afferents innervate the hand with a lower and roughly uniform density and terminate deeper in dermal and subdermal fibrous tissues. FA-II afferents are optimized for detecting transient mechanical events[7–10]. Hundreds of FA-II afferents, distributed throughout the hand, can be excited when hand-held objects contact or break contact with other objects[11]. SA-II afferents can respond to remotely applied lateral stretching of the skin[12,13] and can be sensitive to the tangential shear strain to the skin that occurs during object manipulation[2,11]. SA-II-like afferents are found in most fibrous tissues (such as muscle fascias and joint capsules and ligaments)[14] and there is evidence that they can act as proprioceptors (BOX 1).

Traditional studies on tactile sensing that examine correlations between afferent signals and perceptual (declarative) phenomena evoked by gently touching passive digits (for reviews see REFS 6,14–20) provide little information about the encoding and use of tactile information in object manipulation for several reasons: the control processes that are active in manipulation operate


Epidermis
Dermis
Sweat gland
Meissner corpuscle
Pacinian corpuscle
Ruffini organ
Merkel disks
Free nerve endings

Afferent type (and response properties)	Receptive field (and probe)	Density (afferents per cm²)
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	
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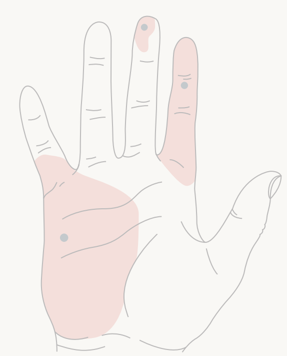
FA-II (fast-adapting type II) Pacini ending • Extremely sensitive to mechanical transients and high-frequency vibrations (~40–400 Hz) propagating through tissues • Insensitive to static force • Respond to distant events acting on hand-held objects	 Light tapping	
SA-II (slowly-adapting type II) Ruffini-like 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	

Johansson and Flanagan, Nature Reviews Neuroscience, 2009

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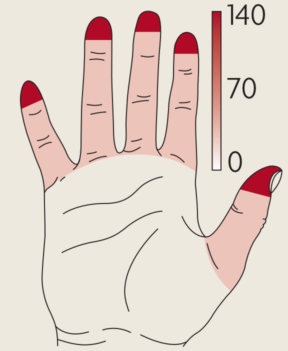
FA-I (fast-adapting type I) Meissner endings • Sensitive to dynamic skin deformation of relatively high frequency (~5–50 Hz) • Insensitive to static force • Transmit enhanced representations of local spatial discontinuities (e.g., edge contours and Braille-like stimuli)	 Weak pointed touch	
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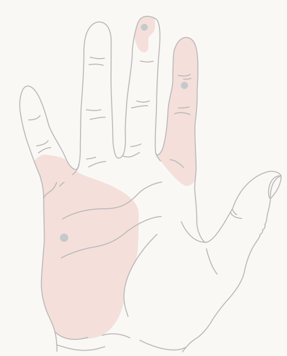
FA-II (fast-adapting type II) Pacini ending • Extremely sensitive to mechanical transients and high-frequency vibrations (~40–400 Hz) propagating through tissues • Insensitive to static force • Respond to distant events acting on hand-held objects	 Light tapping	
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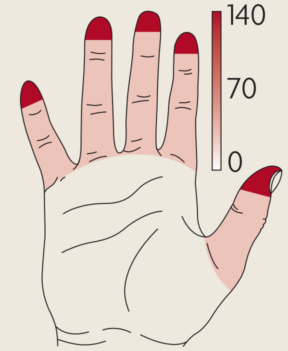
FA-I (fast-adapting type I) Meissner endings • Sensitive to dynamic skin deformation of relatively high frequency (~5–50 Hz) • Insensitive to static force • Transmit enhanced representations of local spatial discontinuities (e.g., edge contours and Braille-like stimuli)	 Weak pointed touch	 140 70 0
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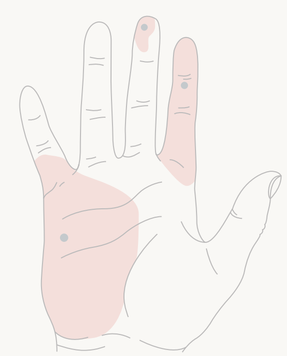
FA-II (fast-adapting type II) Pacini ending • Extremely sensitive to mechanical transients and high-frequency vibrations (~40–400 Hz) propagating through tissues • Insensitive to static force • Respond to distant events acting on hand-held objects	 Light tapping	
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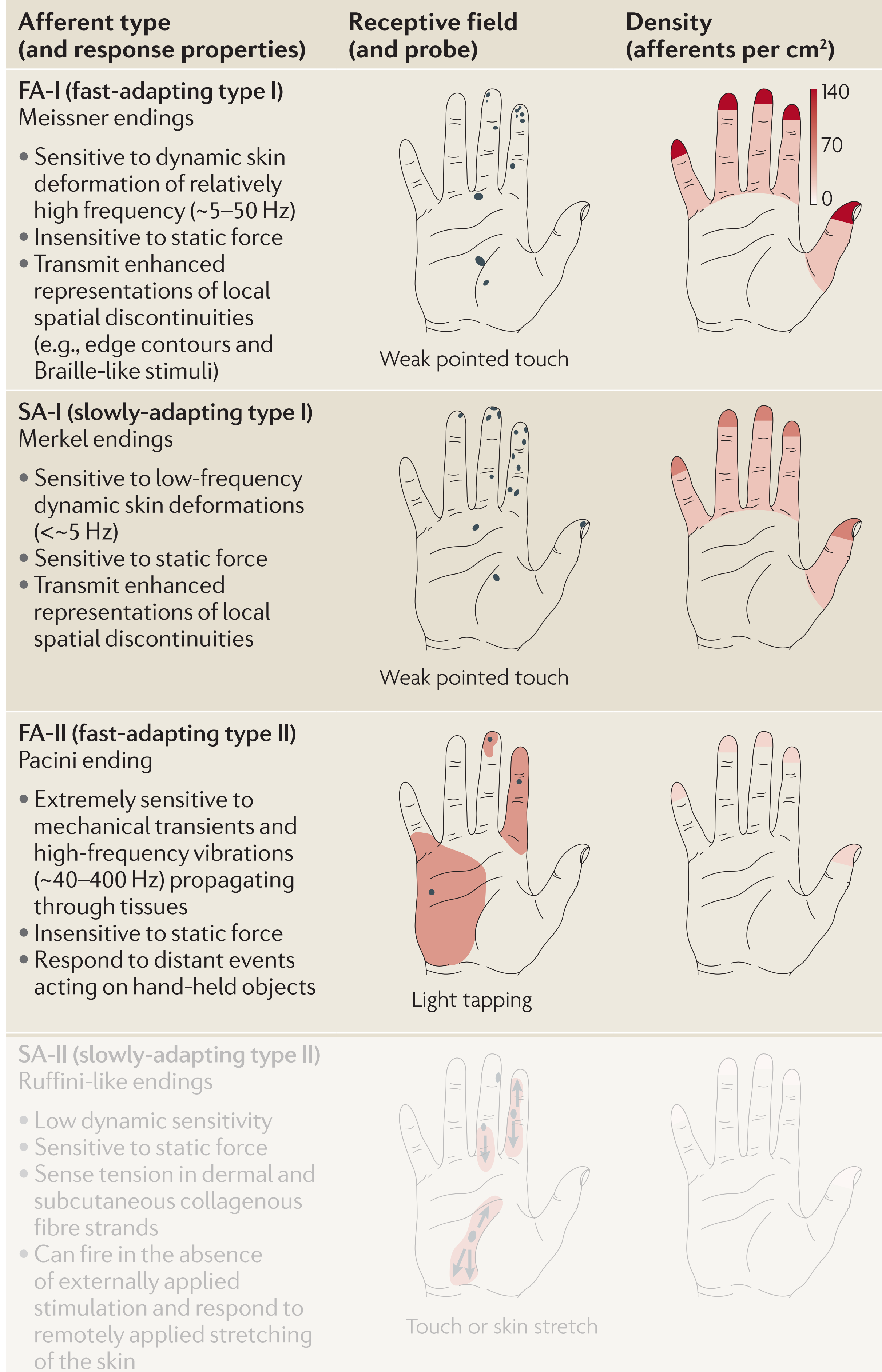

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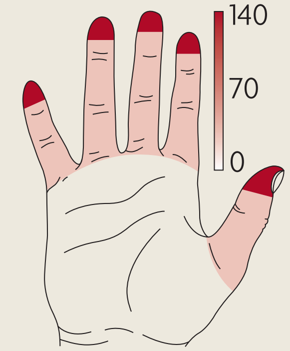
FA-I (fast-adapting type I) Meissner endings • Sensitive to dynamic skin deformation of relatively high frequency (~5–50 Hz) • Insensitive to static force • Transmit enhanced representations of local spatial discontinuities (e.g., edge contours and Braille-like stimuli)	 Weak pointed touch	
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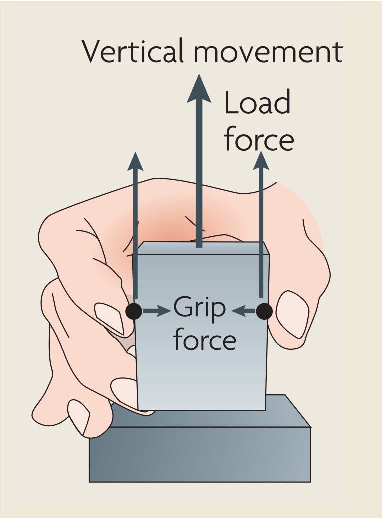
Johansson and Flanagan, Nature Reviews Neuroscience, 2009


EMILE ZOLA
LA CURÉE

Johansson and Flanagan, Nature Reviews Neuroscience, 2009



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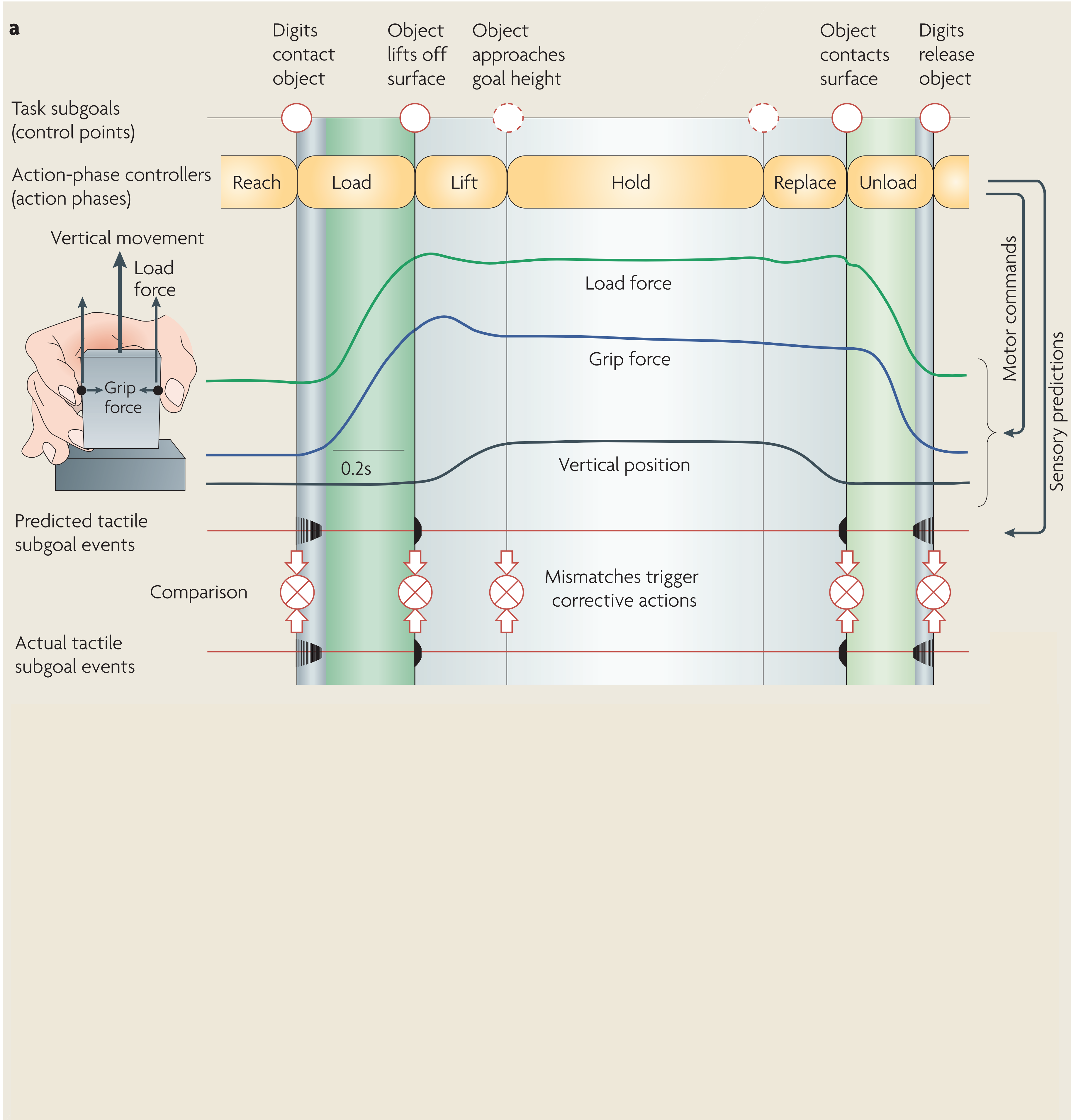

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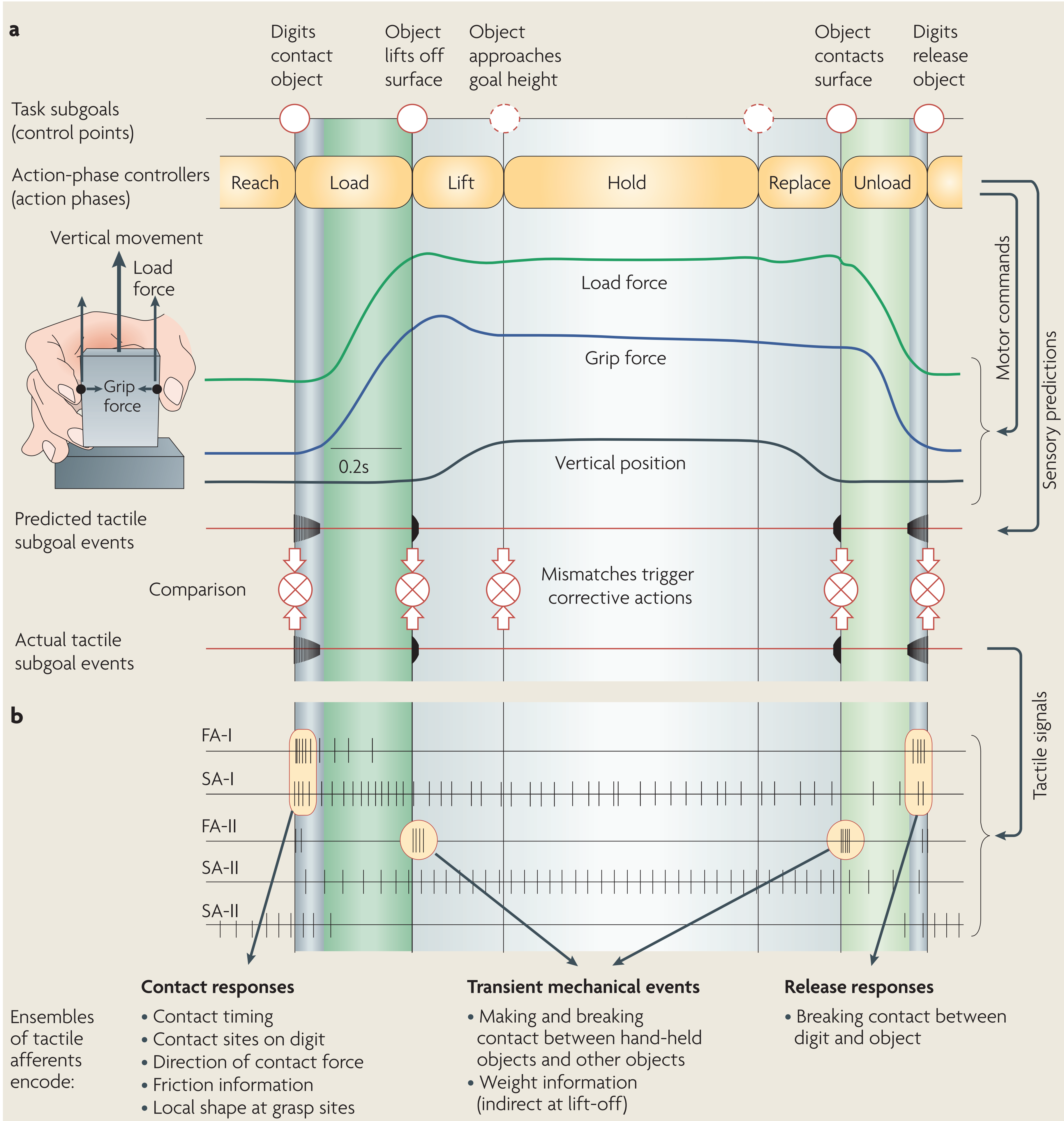

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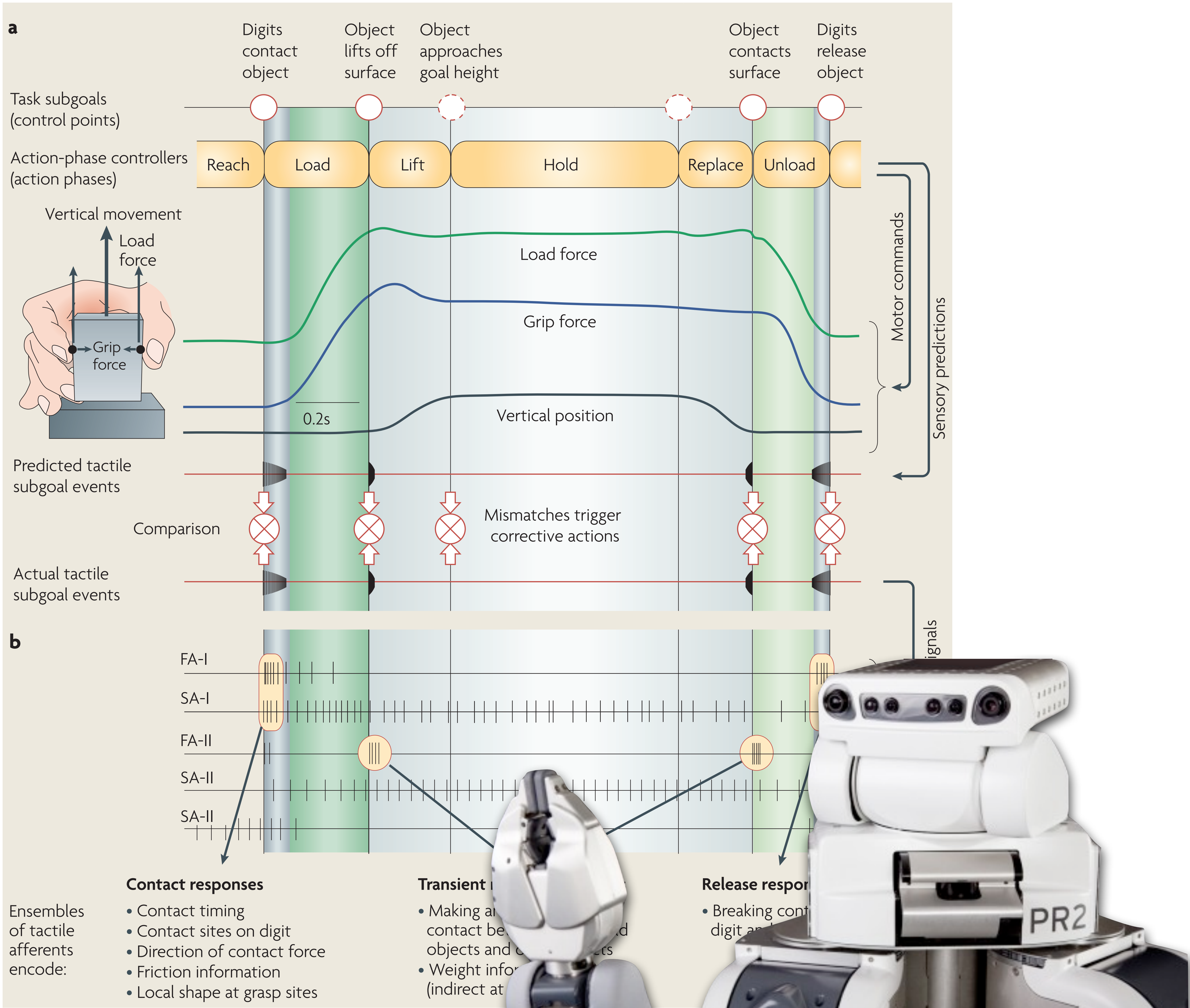

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PR2

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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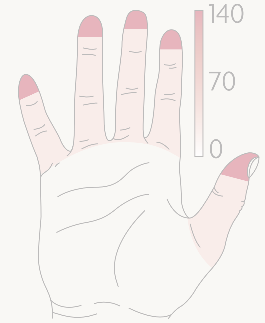
FA-I (fast-adapting type I) Meissner endings • Sensitive to dynamic skin deformation of relatively high frequency (~5–50 Hz) • Insensitive to static force • Transmit enhanced representations of local spatial discontinuities (e.g., edge contours and Braille-like stimuli)	 Weak pointed touch	
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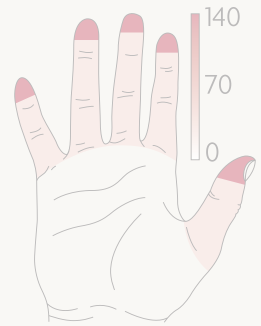
FA-I (fast-adapting type I) Meissner endings • Sensitive to dynamic skin deformation of relatively high frequency (~5–50 Hz) • Insensitive to static force • Transmit enhanced representations of local spatial discontinuities (e.g., edge contours and Braille-like stimuli)	 Weak pointed touch	
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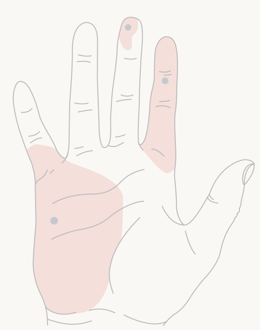
FA-II (fast-adapting type II) Pacini ending • Extremely sensitive to mechanical transients and high-frequency vibrations (~40–400 Hz) propagating through tissues • Insensitive to static force • Respond to distant events acting on hand-held objects	 Light tapping	
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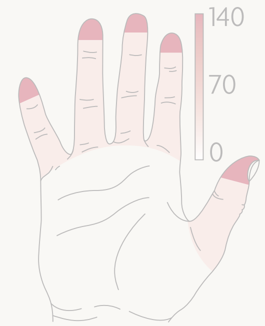
FA-I (fast-adapting type I) Meissner endings • Sensitive to dynamic skin deformation of relatively high frequency (~5–50 Hz) • Insensitive to static force • Transmit enhanced representations of local spatial discontinuities (e.g., edge contours and Braille-like stimuli)	 Weak pointed touch	
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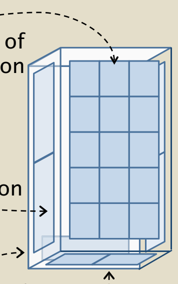
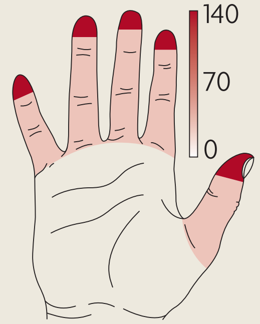


$$F_{gl} = \sum_{i=1}^{3}\sum_{j=1}^{5} f_{l(i,j)}$$

Johansson and Flanagan, Nature Reviews Neuroscience, 2009

Robotic Tactile Signals

Afferent type (and response properties)	Receptive field (and probe)	Density (afferents per cm²)
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	
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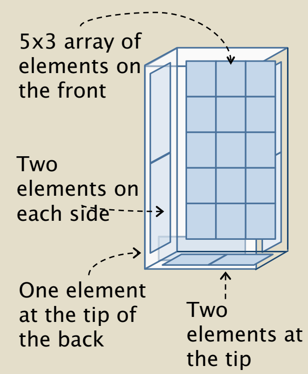

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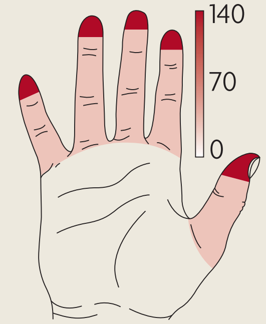
FA-I (fast-adapting type I) Meissner endings • Sensitive to dynamic skin deformation of relatively high frequency (~5–50 Hz) • Insensitive to static force • Transmit enhanced representations of local spatial discontinuities (e.g., edge contours and Braille-like stimuli)	 Weak pointed touch	
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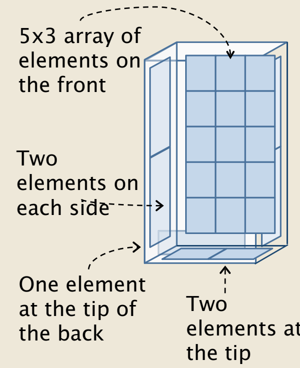
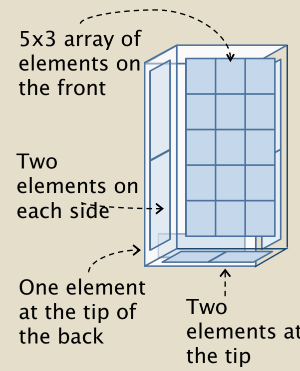


$$\widetilde{F}_{gl}(z) = \sum_{i=1}^{3}\sum_{j=1}^{5} H_F(z) f_{l(i,j)}(z)$$

↑ 5 Hz high-pass



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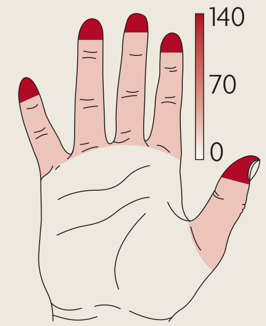
FA-I (fast-adapting type I) Meissner endings • Sensitive to dynamic skin deformation of relatively high frequency (~5–50 Hz) • Insensitive to static force • Transmit enhanced representations of local spatial discontinuities (e.g., edge contours and Braille-like stimuli)	 Weak pointed touch	
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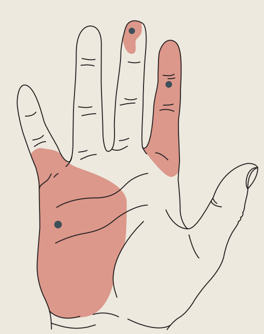
FA-II (fast-adapting type II) Pacini ending • Extremely sensitive to mechanical transients and high-frequency vibrations (~40–400 Hz) propagating through tissues • Insensitive to static force • Respond to distant events acting on hand-held objects	 Light tapping	
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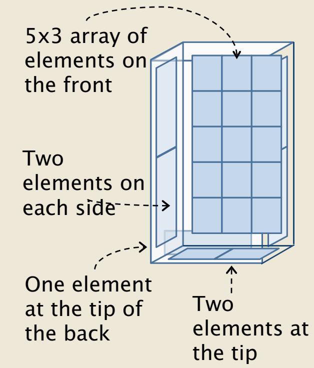

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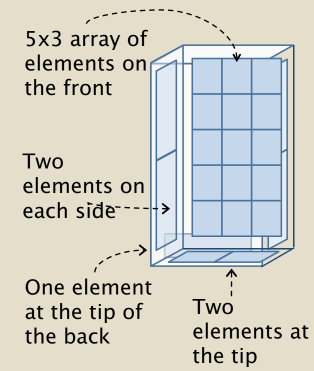

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Johansson and Flanagan, Nature Reviews Neuroscience, 2009

Robotic Tactile Signals

Afferent type (and response properties)	Receptive field (and probe)	Density (afferents per cm²)

FA-I (fast-adapting type I)
Meissner endings

- Sensitive to dynamic skin deformation of relatively high frequency (~5–50 Hz)
- Insensitive to static force
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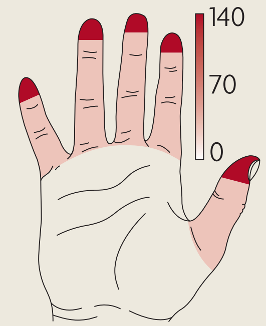
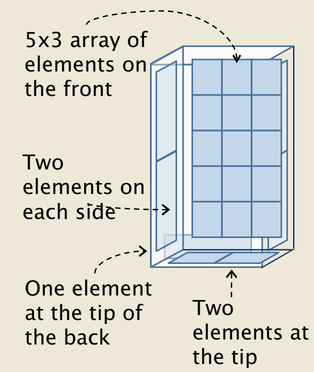
Weak pointed touch





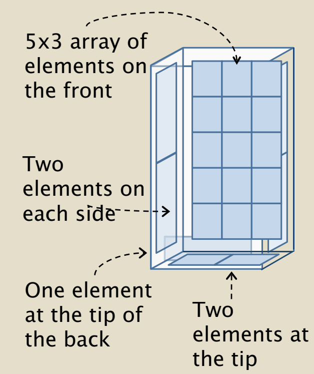
$$\widetilde{F}_{gl}(z) = \sum_{i=1}^{3}\sum_{j=1}^{5} H_F(z) f_{l(i,j)}(z)$$

↑ 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

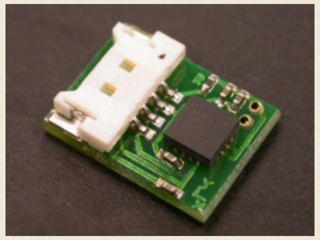


$$F_{gl} = \sum_{i=1}^{3}\sum_{j=1}^{5} f_{l(i,j)}$$

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 ↓

$$\widetilde{a}_h(z) = \sqrt{(H_a(z)a_{h,x})^2 + (H_a(z)a_{h,y})^2 + (H_a(z)a_{h,z})^2}$$

SA-II (slowly-adapting type II)
Ruffini-like endings

- Low dynamic sensitivity
- Sensitive to static force
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Touch or skin stretch

Johansson and Flanagan, Nature Reviews Neuroscience, 2009

Robotic Tactile Signals

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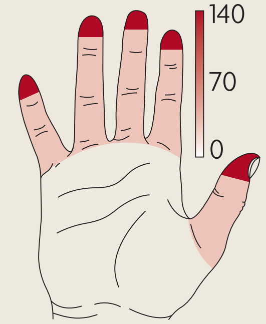

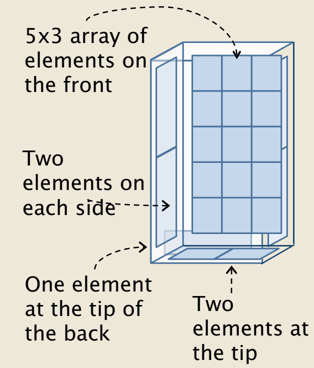

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5 Hz high-pass

SA-I (slowly-adapting type I)
Merkel endings

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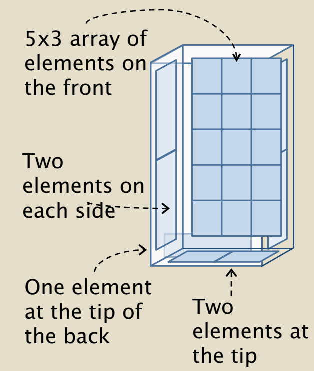
Weak pointed touch



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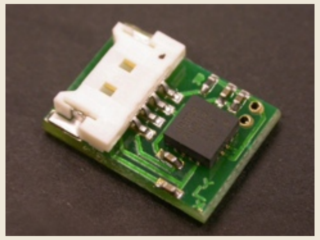
Light tapping



50 Hz high-pass

$$\widetilde{a}_h(z) = \sqrt{(H_a(z)a_{h,x})^2 + (H_a(z)a_{h,y})^2 + (H_a(z)a_{h,z})^2}$$

SA-II (slowly-adapting type II)
Ruffini-like endings

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Touch or skin stretch

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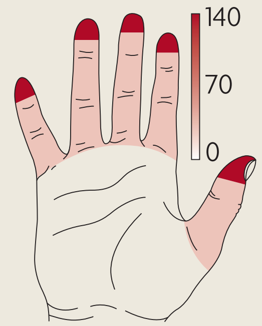
FA-I (fast-adapting type I) Meissner endings • Sensitive to dynamic skin deformation of relatively high frequency (~5–50 Hz) • Insensitive to static force • Transmit enhanced representations of local spatial discontinuities (e.g., edge contours and Braille-like stimuli)	 Weak pointed touch	
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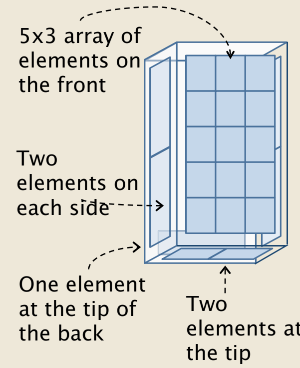

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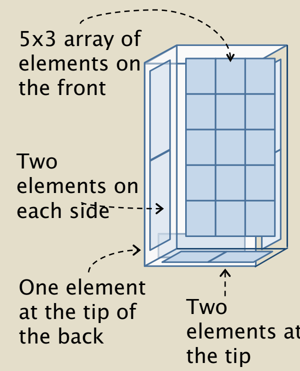
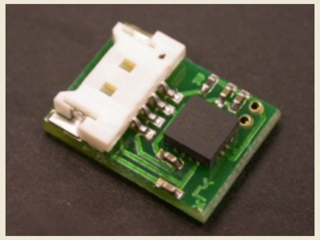
5 Hz high-pass



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



50 Hz high-pass

$$\widetilde{a}_h(z) = \sqrt{(H_a(z)a_{h,x})^2 + (H_a(z)a_{h,y})^2 + (H_a(z)a_{h,z})^2}$$

not possible on the PR2

Johansson and Flanagan, Nature Reviews Neuroscience, 2009

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

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

Gripper Position Controller

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

Gripper Force Controller

Gripper Position Controller

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

Gripper Force Controller

$$F_{g,min} = \min\left(F_{gl}, F_{gr}\right)$$

Gripper Position Controller

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

Gripper Force Controller

$$F_{g,min} = \min\left(F_{gl}, F_{gr}\right)$$

$$v_{g,des} = \mathrm{KF} \cdot (F_{g,min} - F_{g,des})$$

Gripper Position Controller

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

Gripper Force Controller

$$F_{g,min} = \min\left(F_{gl}, F_{gr}\right)$$

$$v_{g,des} = \mathrm{KF} \cdot (F_{g,min} - F_{g,des})$$

$$\mathrm{KF} = \begin{cases} \mathrm{KFCLOSE} & \text{if } F_{g,min} - F_{g,des} < 0, \\ \mathrm{KFOPEN} & \text{otherwise} \end{cases}$$

Robotic Tactile Signals

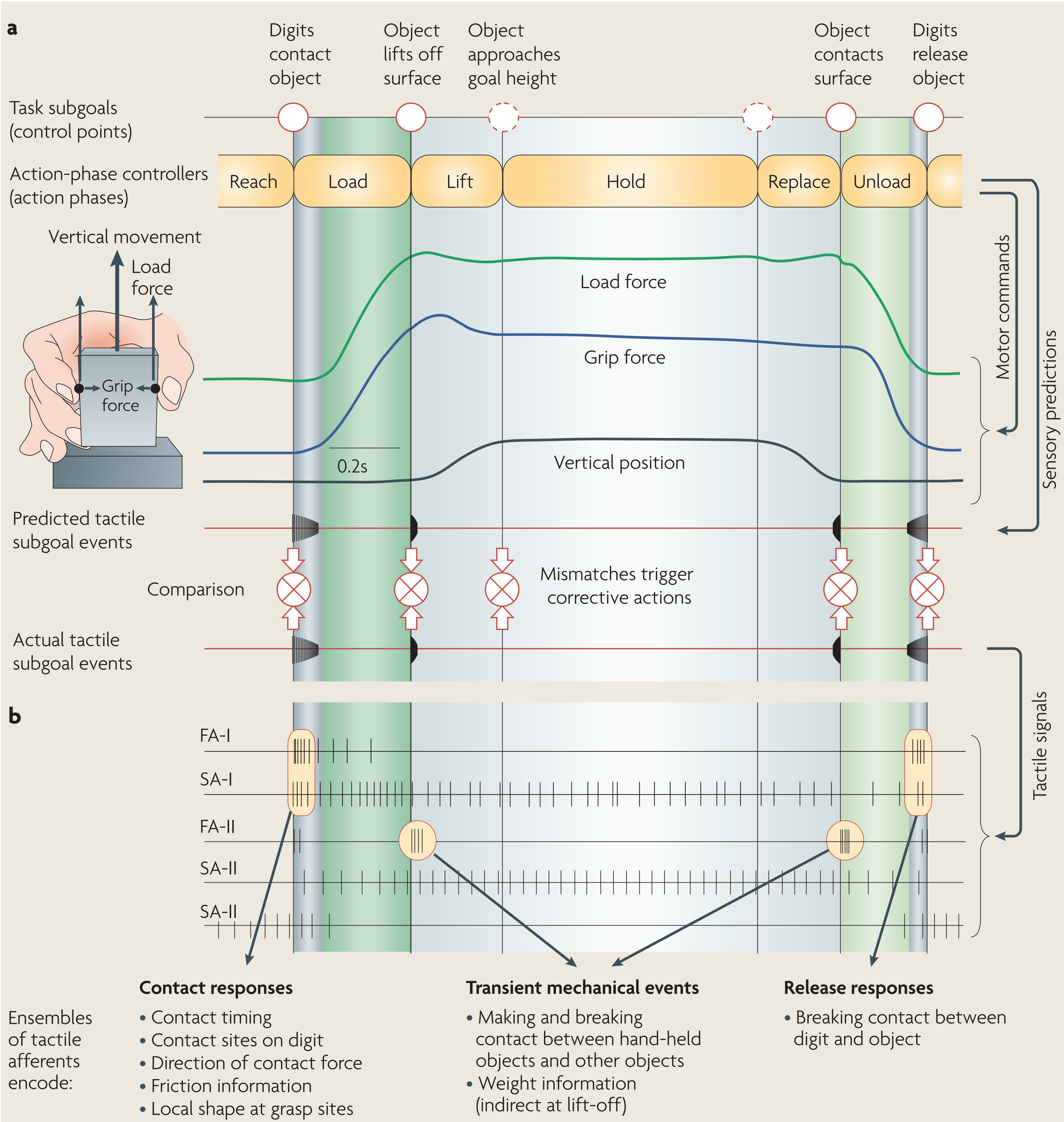
Gripper Position and Force Controllers

Action-Phase Grasp Controller

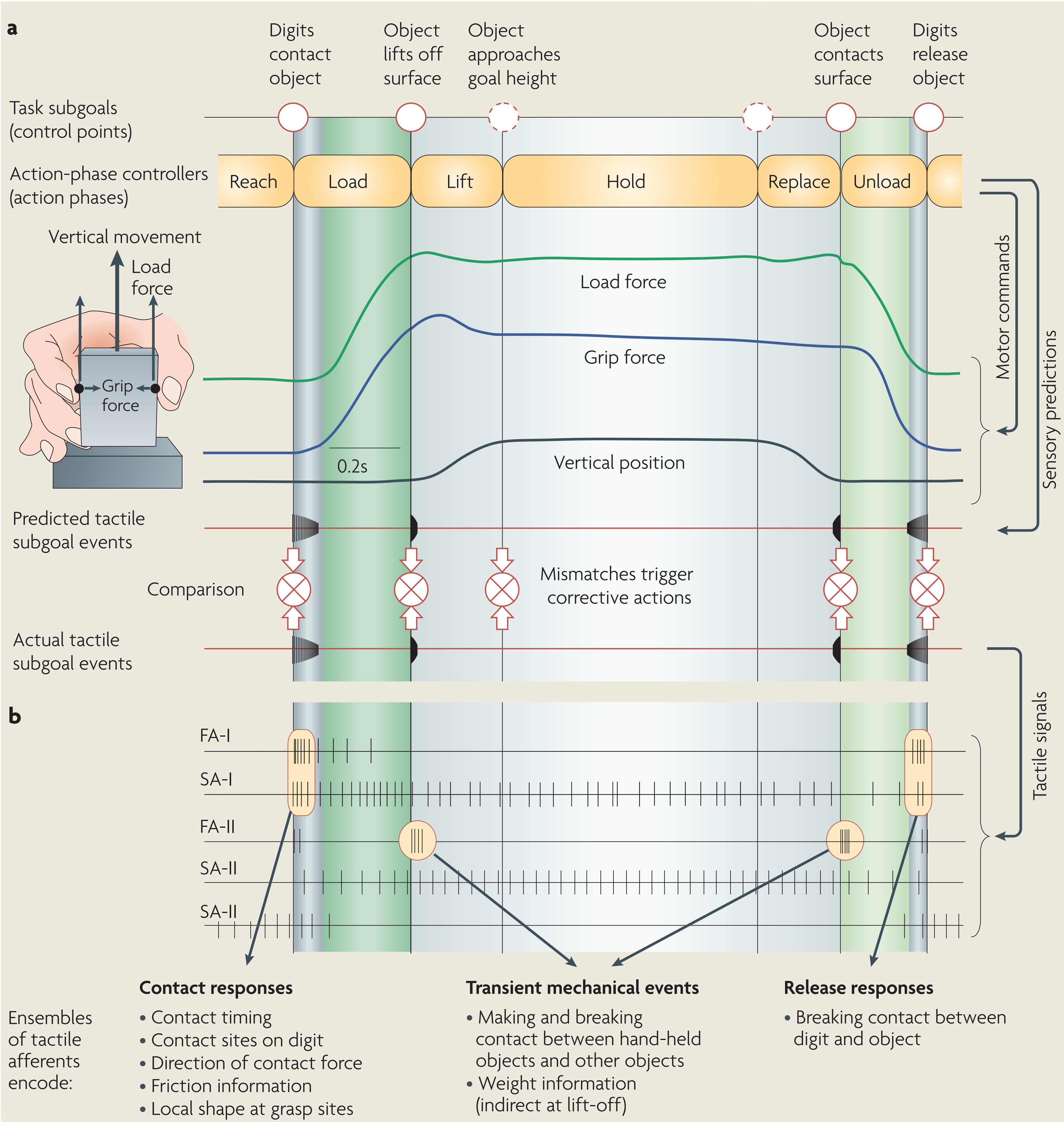
Robotic Tactile Signals

Gripper Position and Force Controllers

Action-Phase Grasp Controller



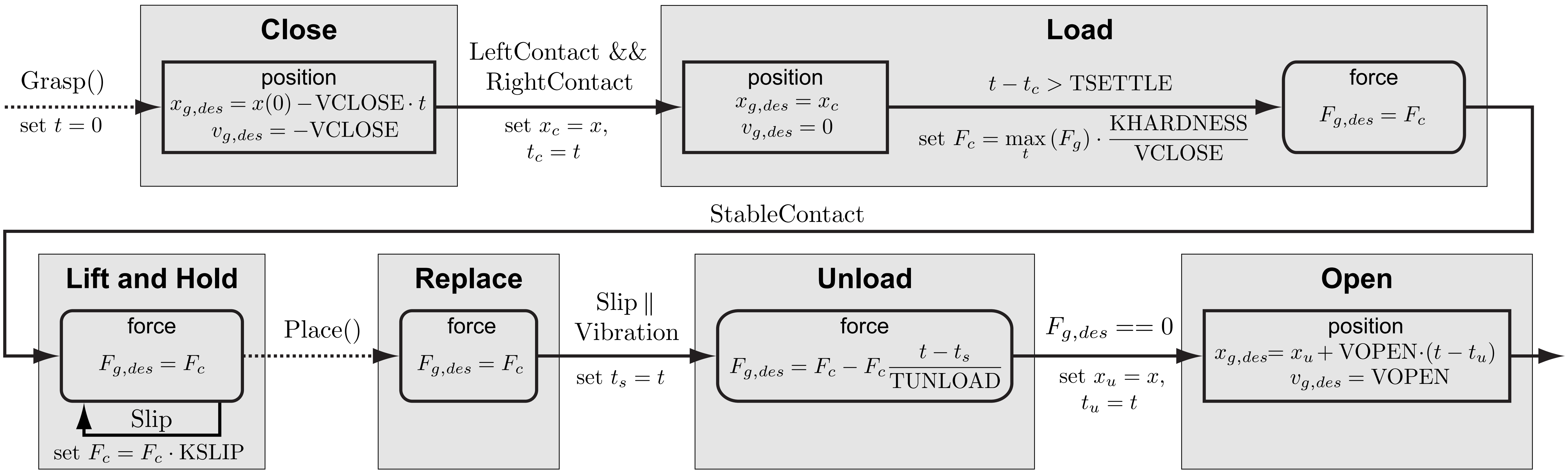
Johansson and Flanagan, Nature Reviews Neuroscience, 2009



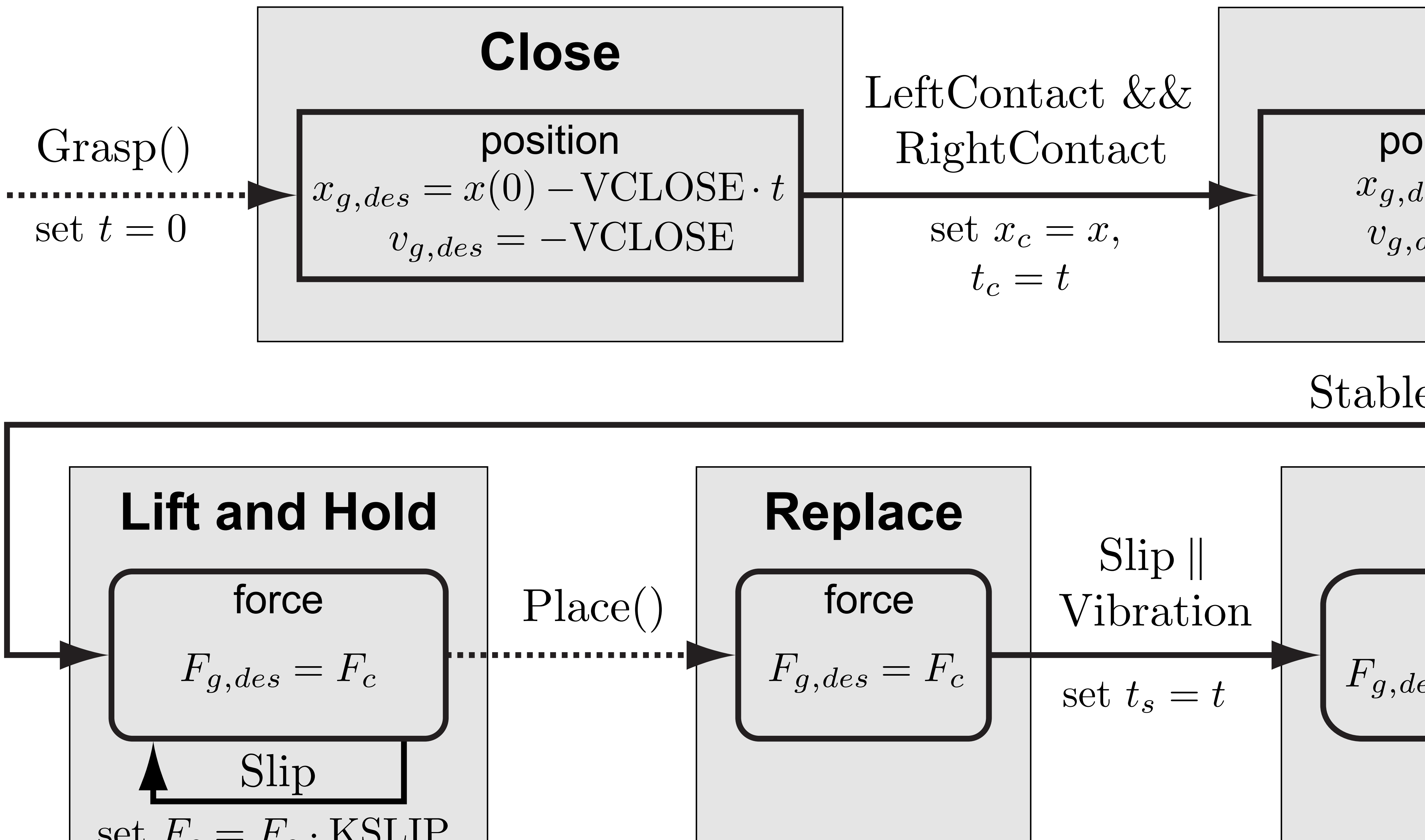
Johansson and Flanagan, Nature Reviews Neuroscience, 2009

- Close
- Load
- Lift & Hold
- Replace
- Unload
- Open

Action-Phase Grasp Controller



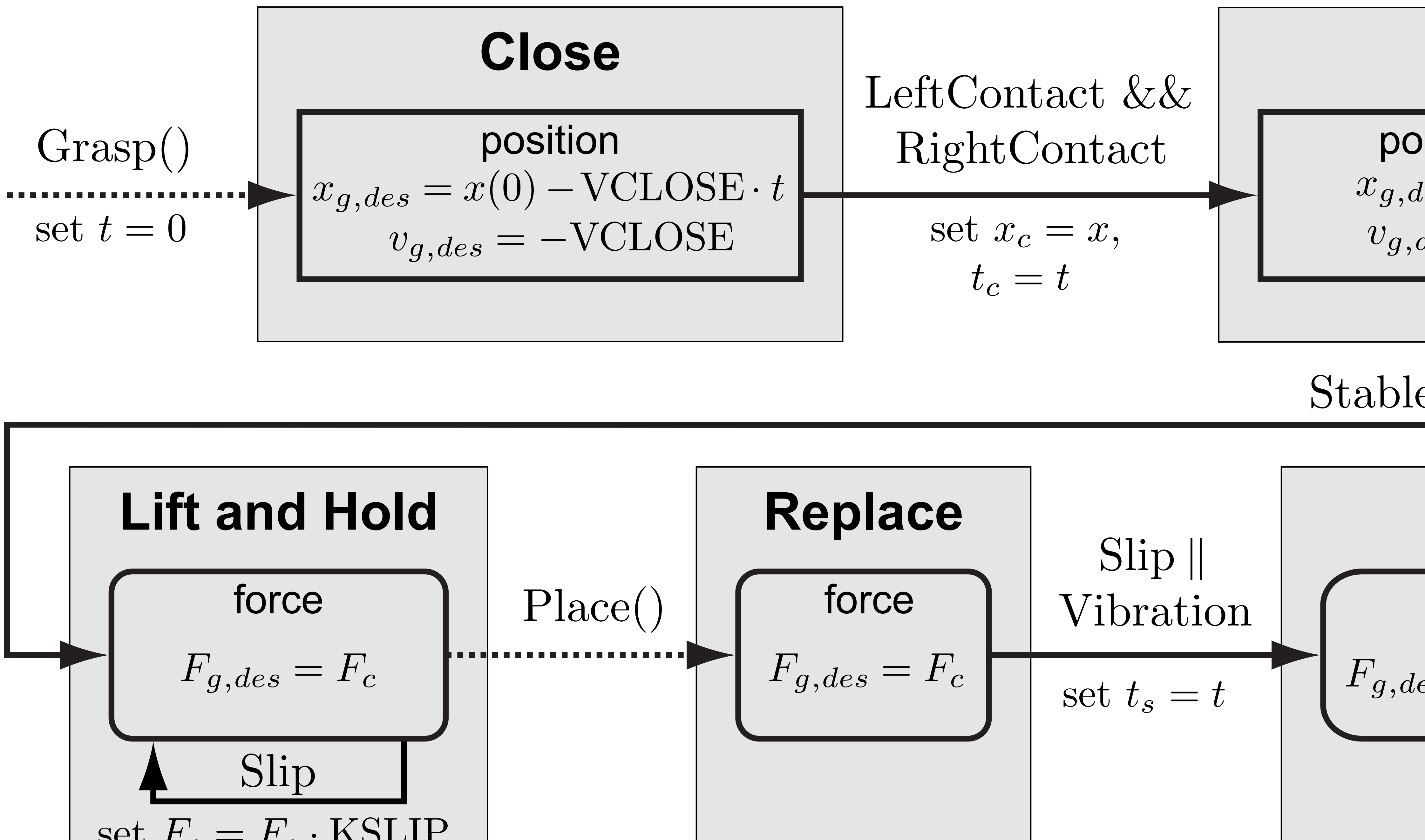
Action-Phase Grasp Controller



Action-Phase Grasp Controller

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

$$\text{RightContact} = (F_{gr} > \text{FLIMIT}) \parallel (\widetilde{F}_{gr} > \text{DLIMIT})$$



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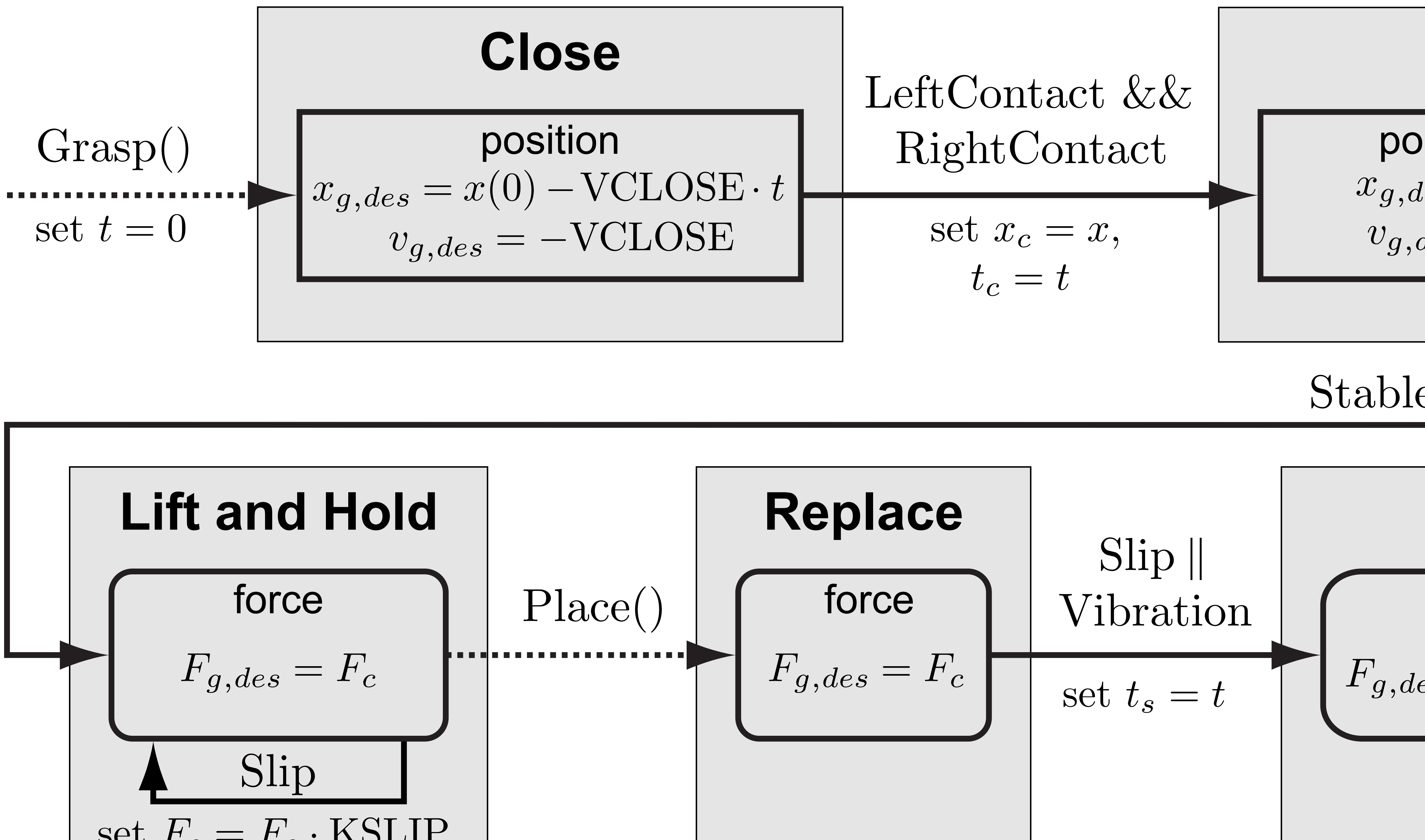
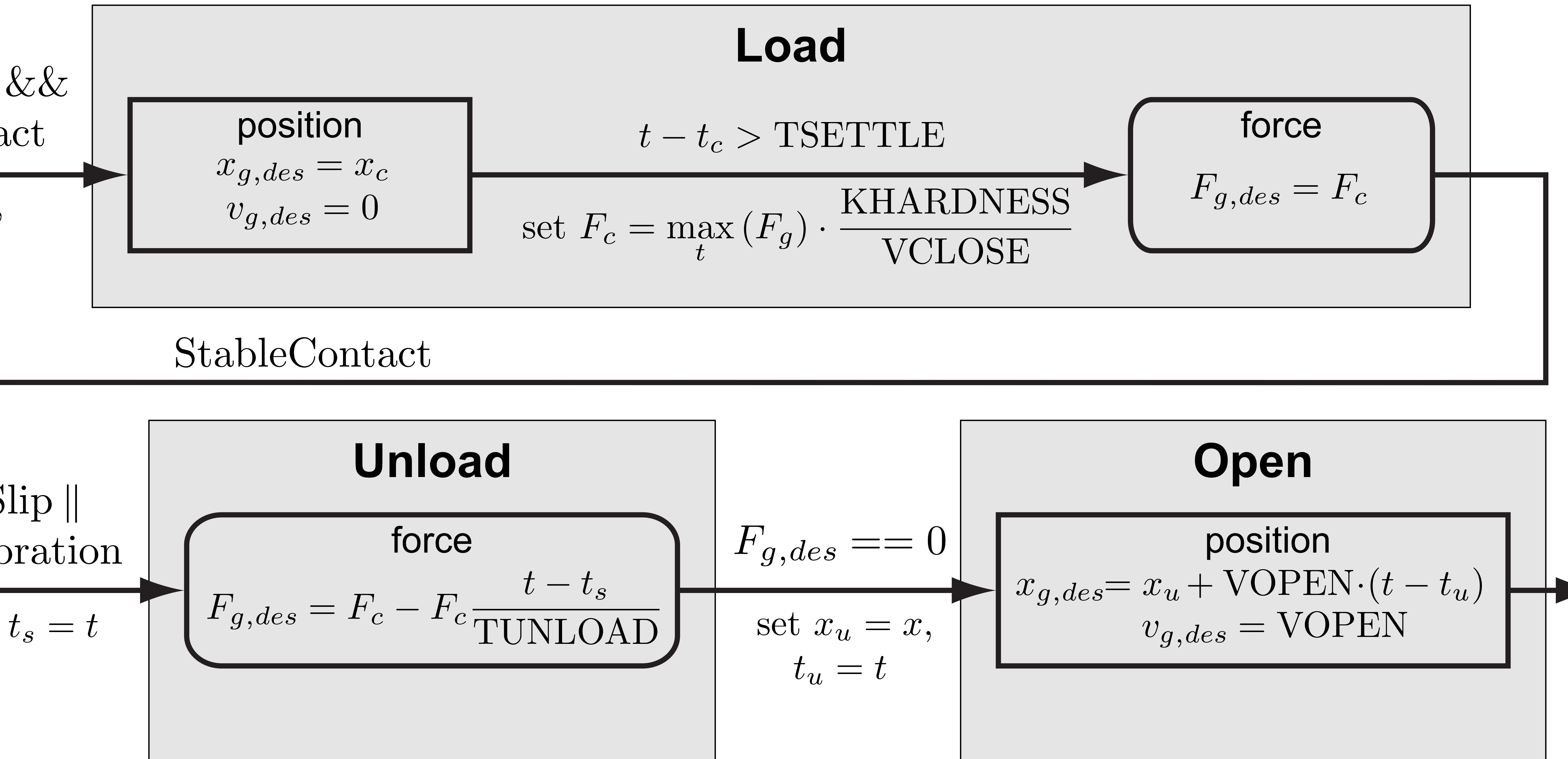
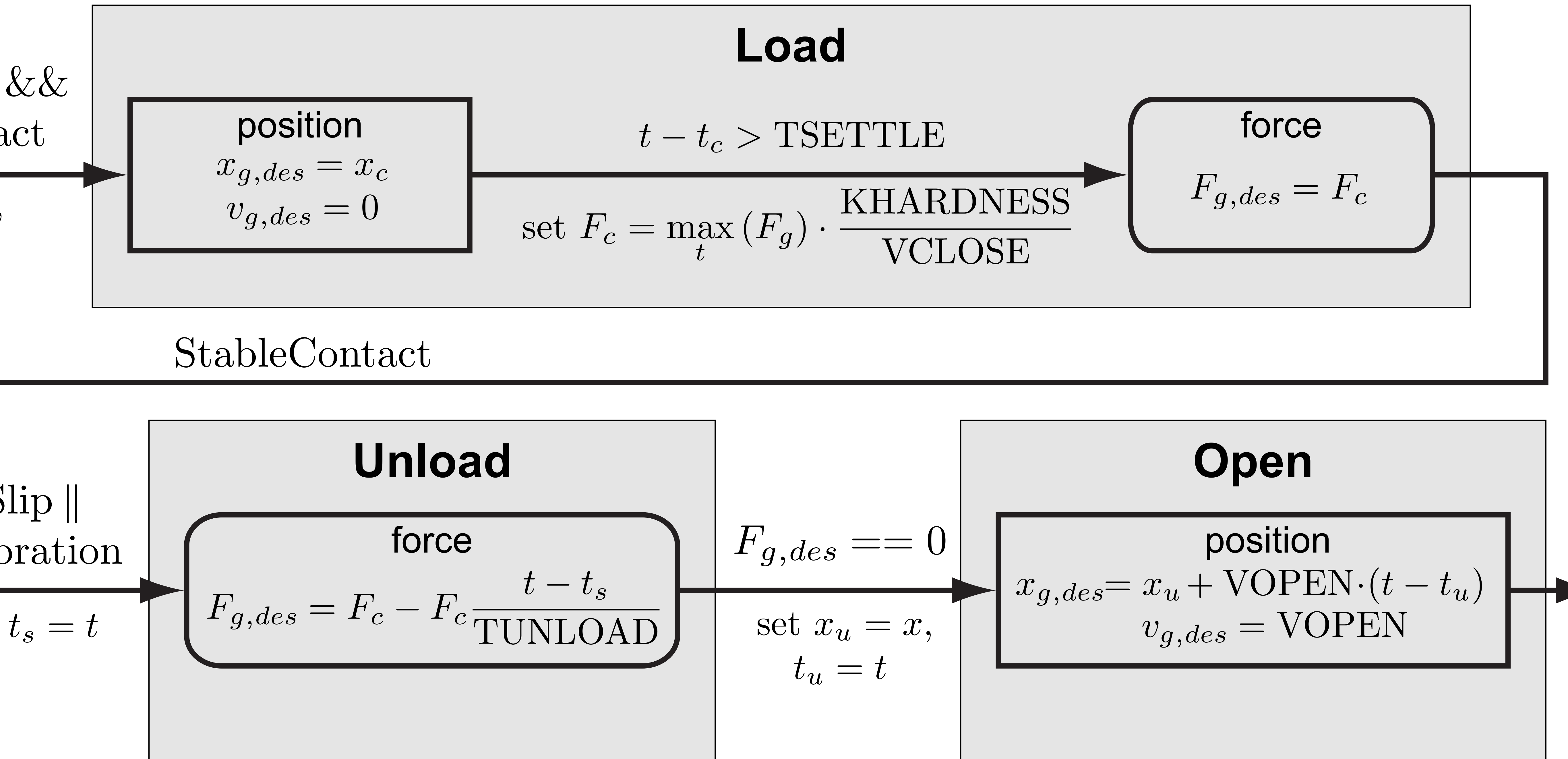


Action-Phase Grasp Controller

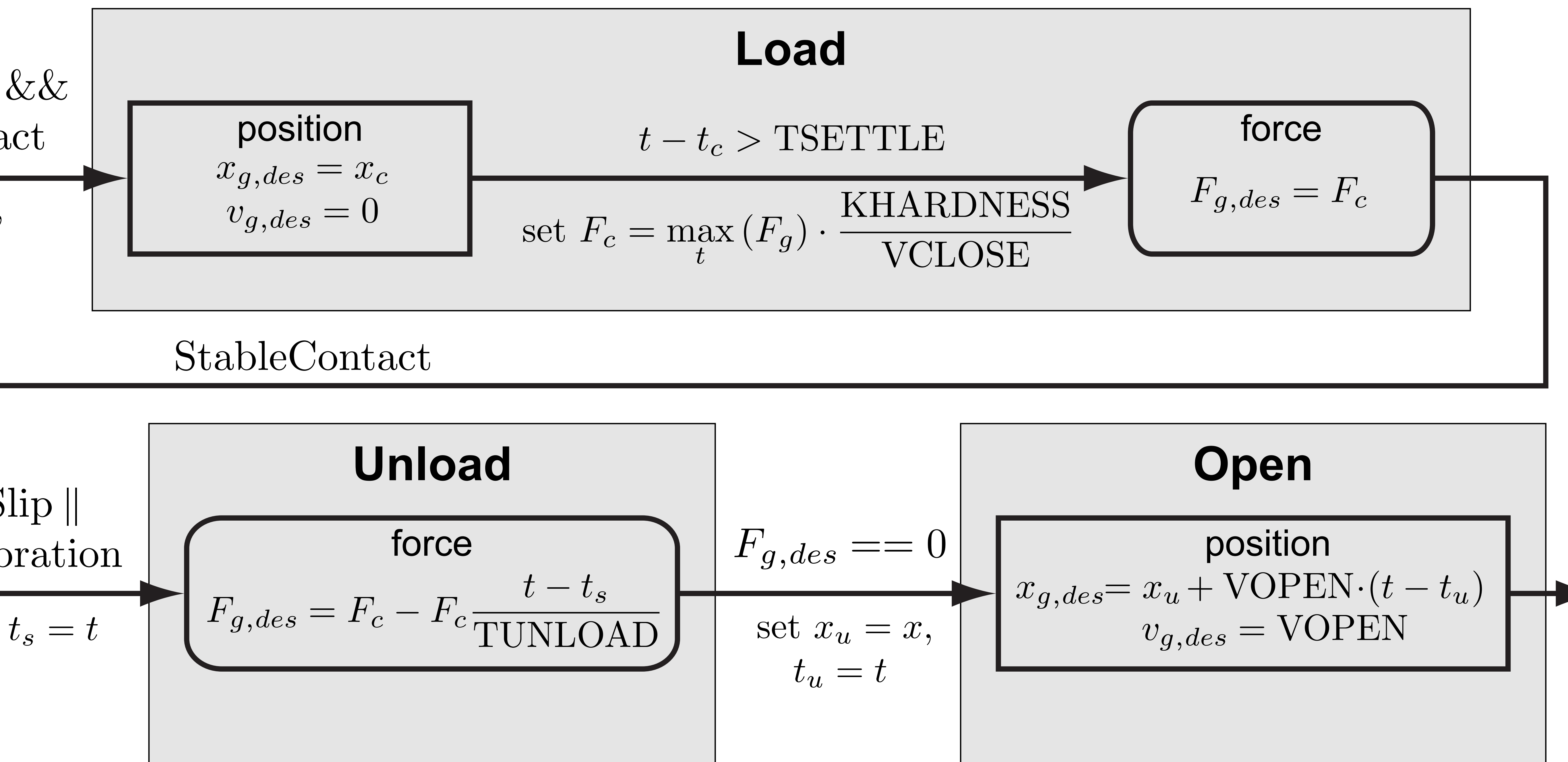


Action-Phase Grasp Controller

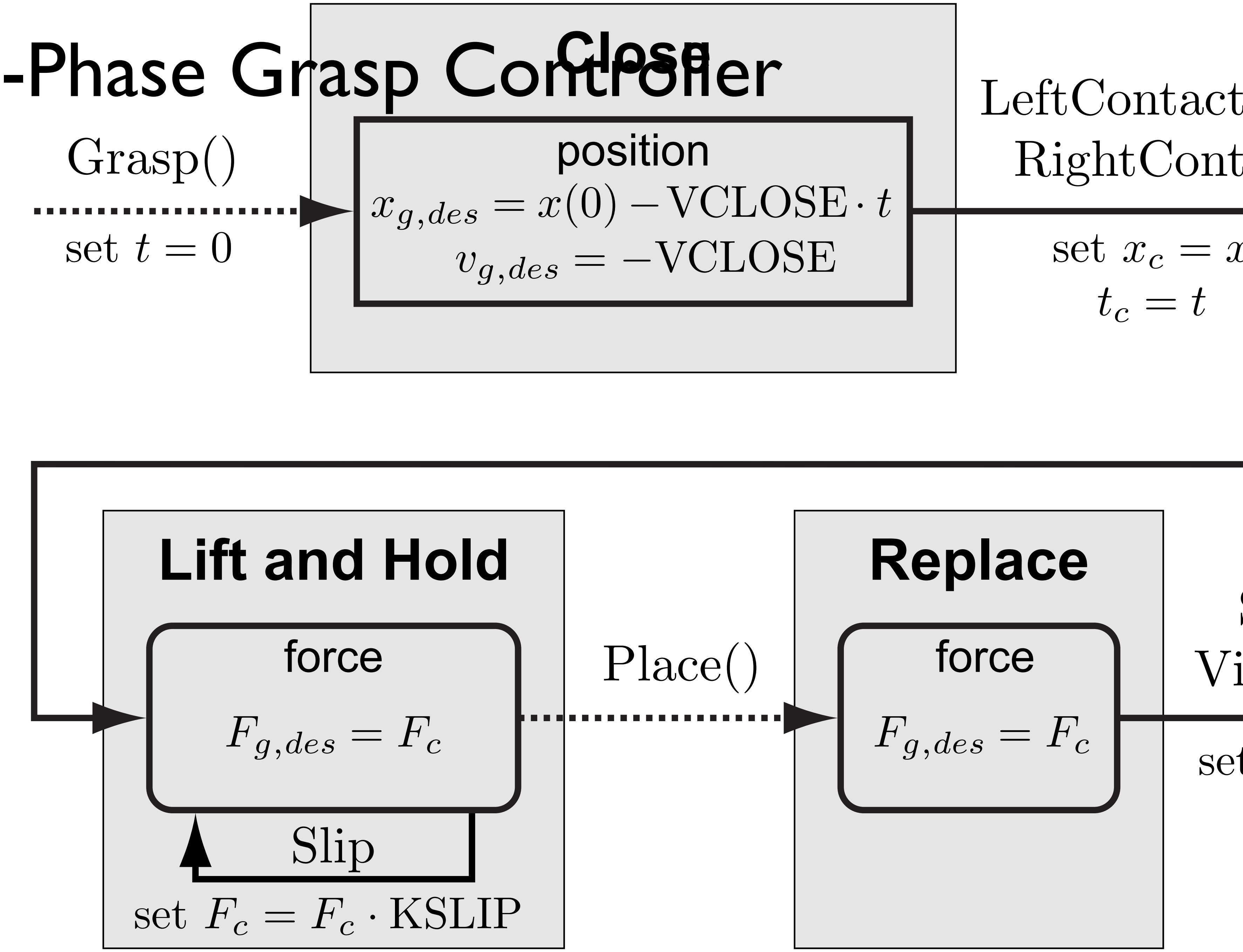
$$\text{StableContact} = (|F_{g,min} - F_{g,des}| < \text{FTHRESH}) \\ \&\& \ (|v_g| < \text{VTHRESH})$$



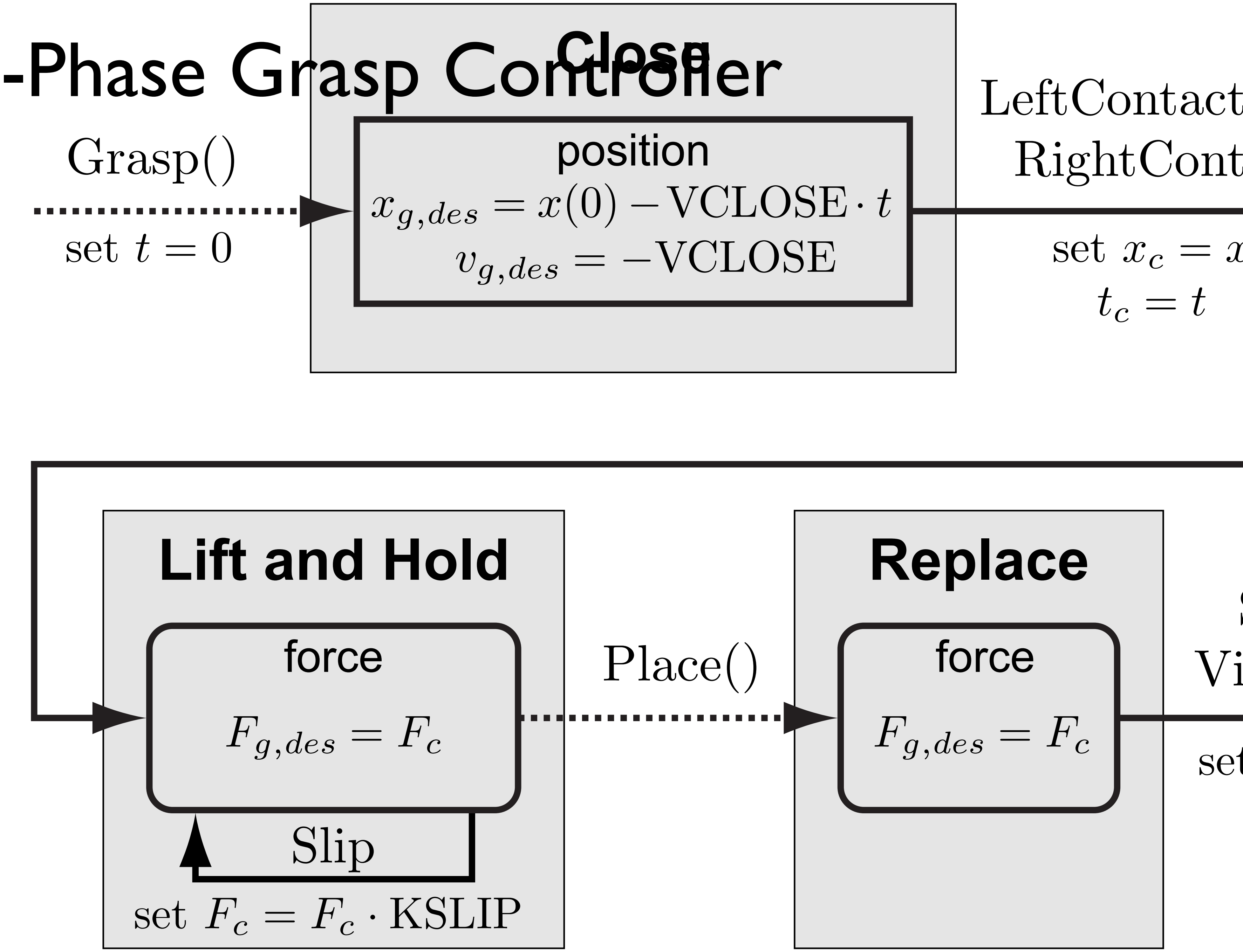
Action-Phase Grasp Controller



Action-Phase Grasp Controller

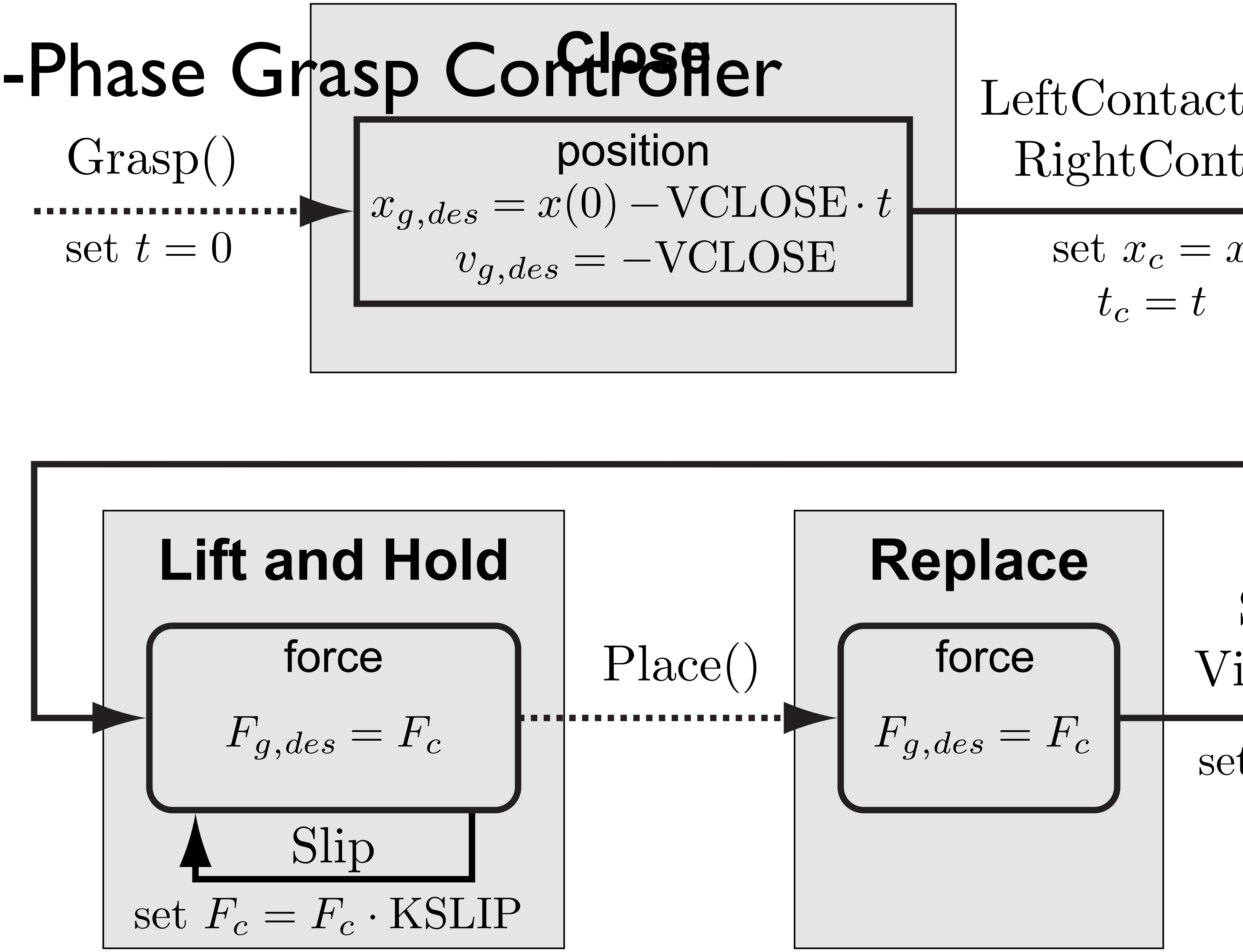


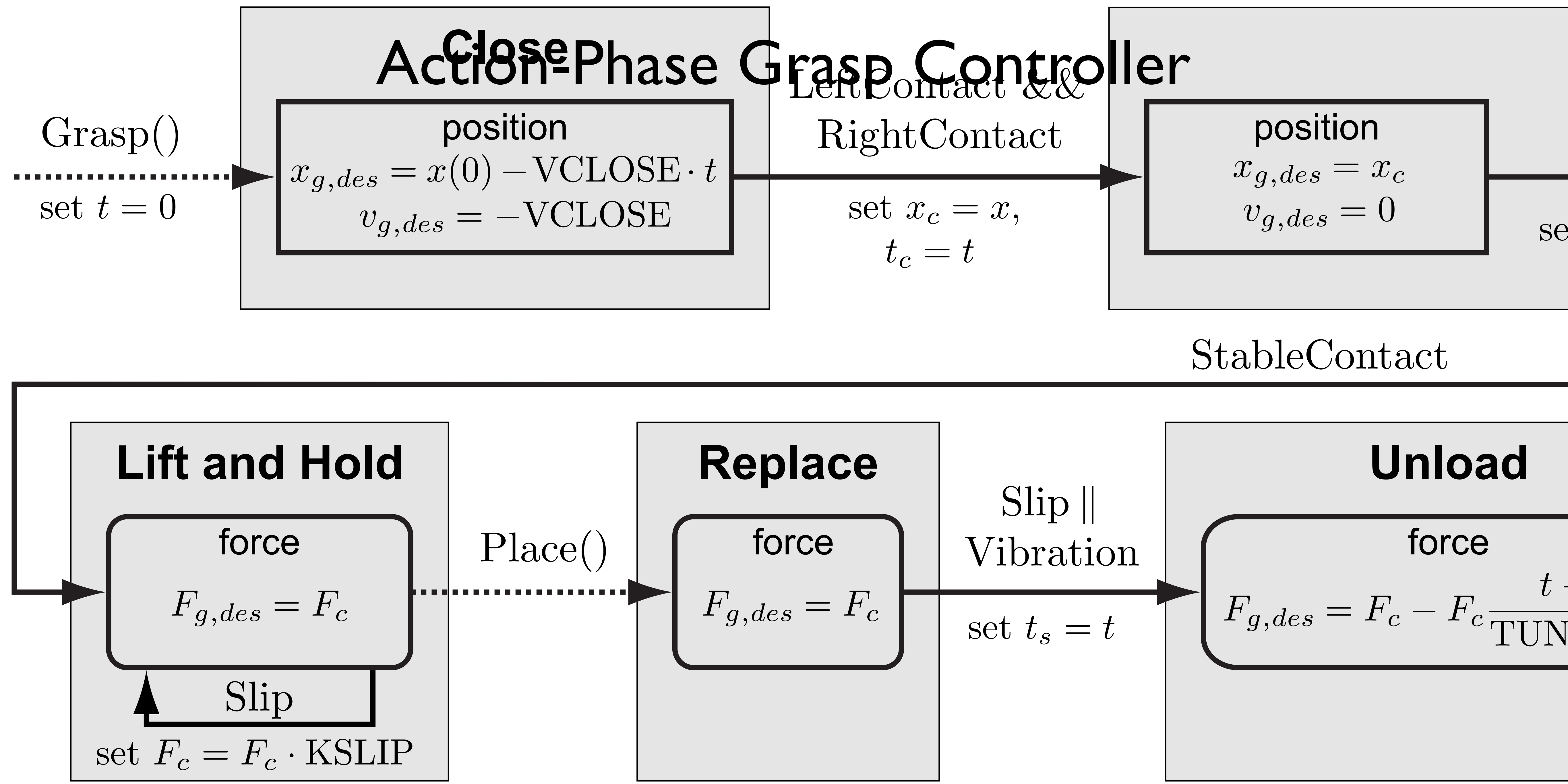
Action-Phase Grasp Controller



$$\mathrm{Slip} = \left(|\widetilde{F}_g| > F_g \cdot \mathrm{SLIPTHRESH} \right)$$
$$\&\& \ \left(F_g^{BP} < \mathrm{FBPTHRESH} \right)$$

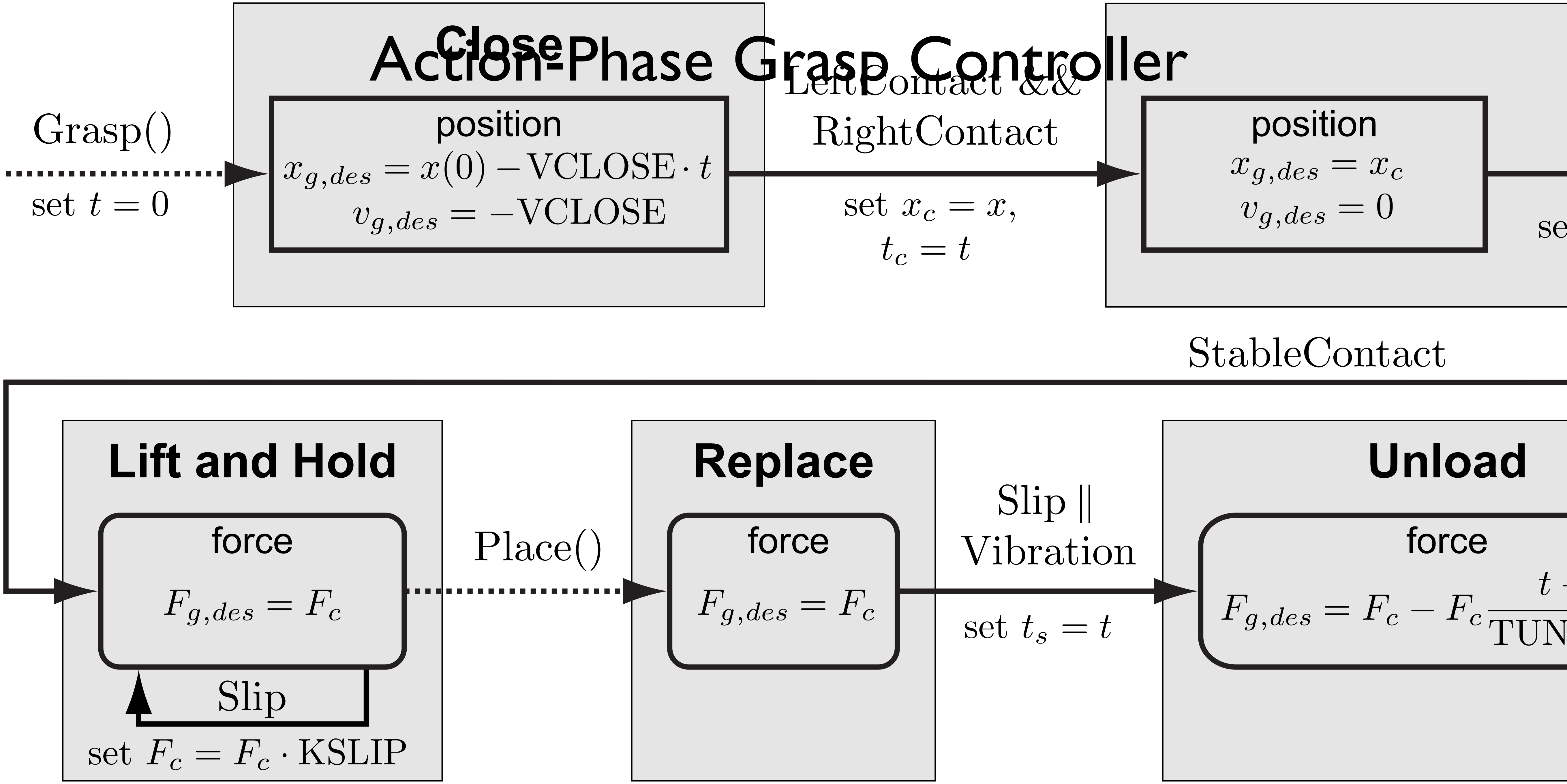
Action-Phase Grasp Controller



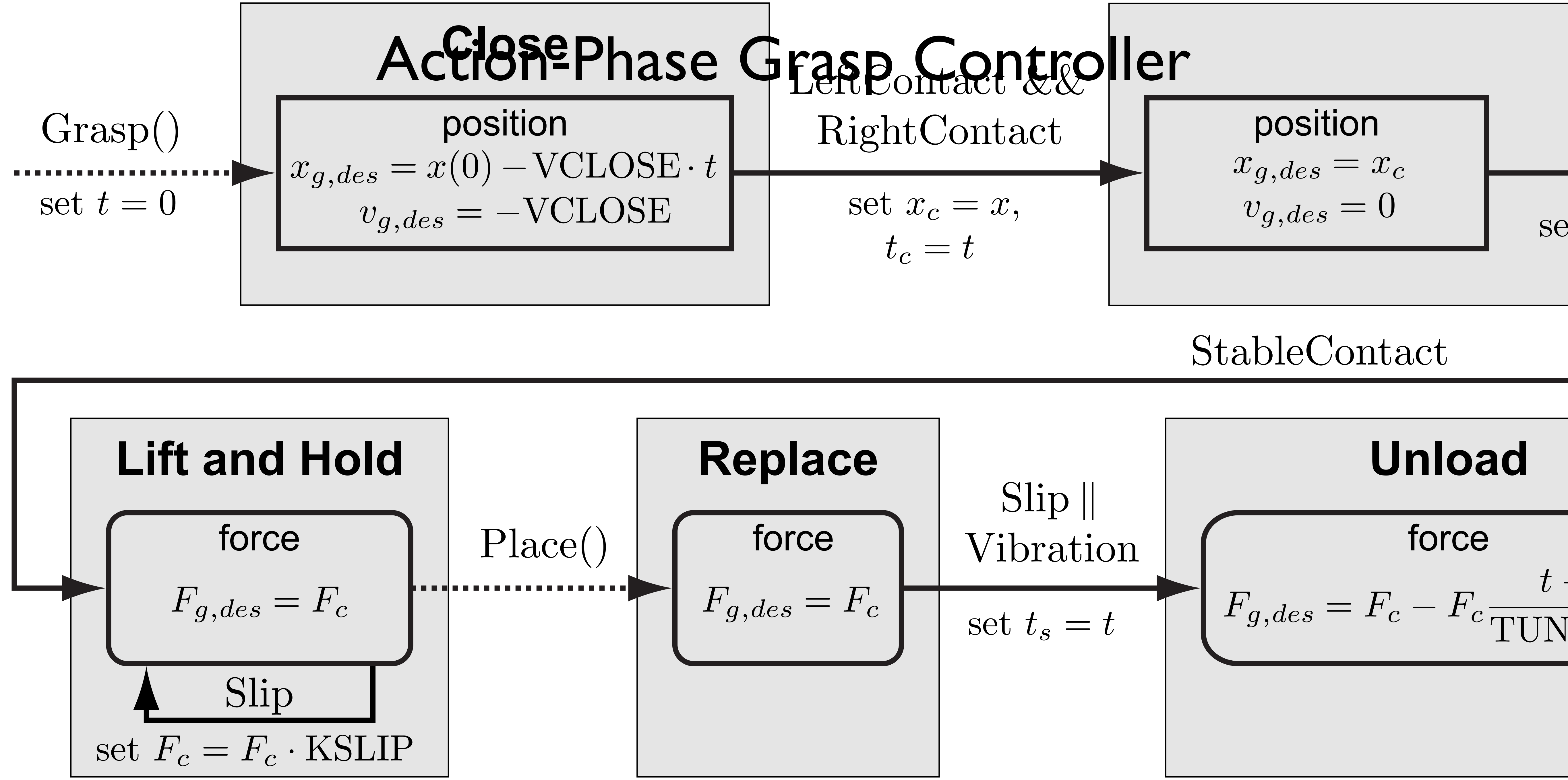


Action-Phase Grasp Controller
Close
Grasp()
set $t = 0$
position
$x_{g,des} = x(0) - \mathrm{VCLOSE} \cdot t$
$v_{g,des} = -\mathrm{VCLOSE}$
LeftContact &&
RightContact
set $x_c = x$,
$t_c = t$
position
$x_{g,des} = x_c$
$v_{g,des} = 0$
StableContact
Lift and Hold
force
$F_{g,des} = F_c$
Slip
set $F_c = F_c \cdot \mathrm{KSLIP}$
Place()
Replace
force
$F_{g,des} = F_c$
Slip ||
Vibration
set $t_s = t$
Unload
force

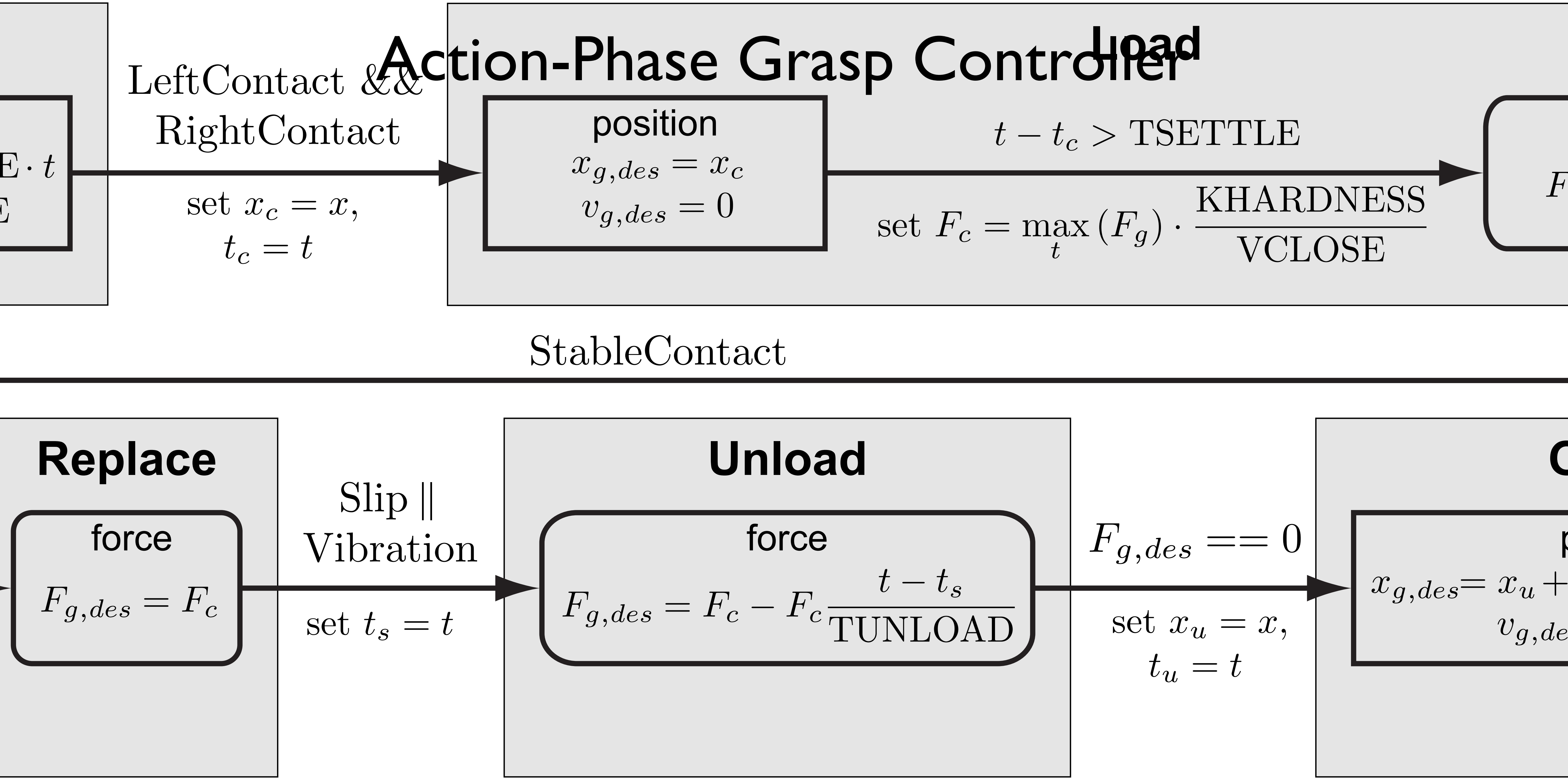
Action-Phase Grasp Controller



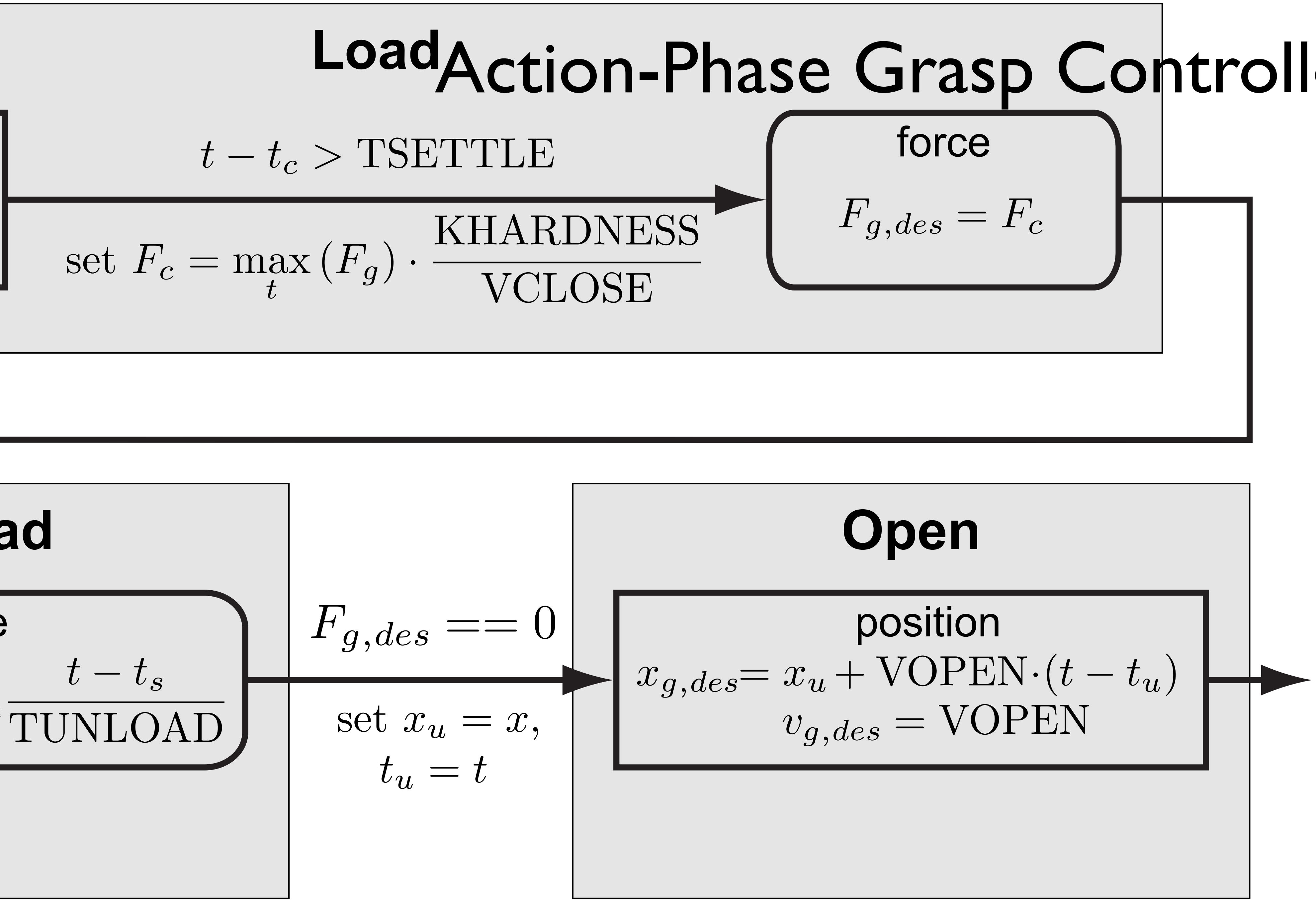
$$\text{Vibration} = (\tilde{a}_h > \text{ATHRESH})$$


Action-Phase Grasp Controller
Close
Grasp()
set $t = 0$
position
$x_{g,des} = x(0) - \text{VCLOSE} \cdot t$
$v_{g,des} = -\text{VCLOSE}$
LeftContact &&
RightContact
set $x_c = x$,
$t_c = t$
position
$x_{g,des} = x_c$
$v_{g,des} = 0$
StableContact
Lift and Hold
force
$F_{g,des} = F_c$
Slip
set $F_c = F_c \cdot \text{KSLIP}$
Place()
Replace
force
$F_{g,des} = F_c$
Slip ||
Vibration
set $t_s = t$
Unload
force

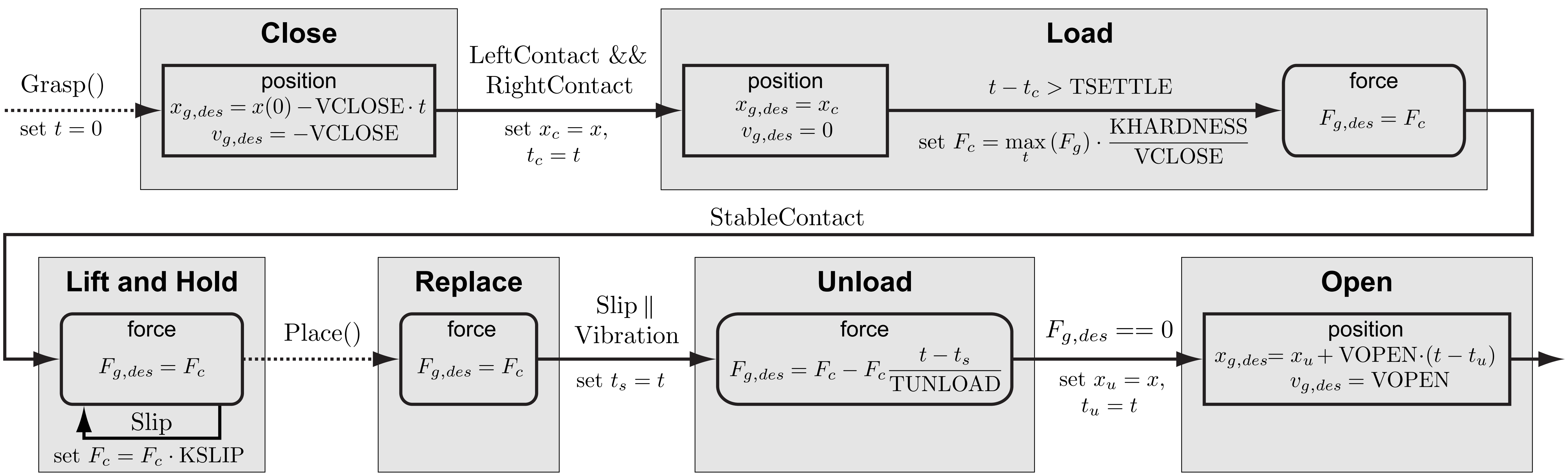
Action-Phase Grasp Controller



Action-Phase Grasp Controller

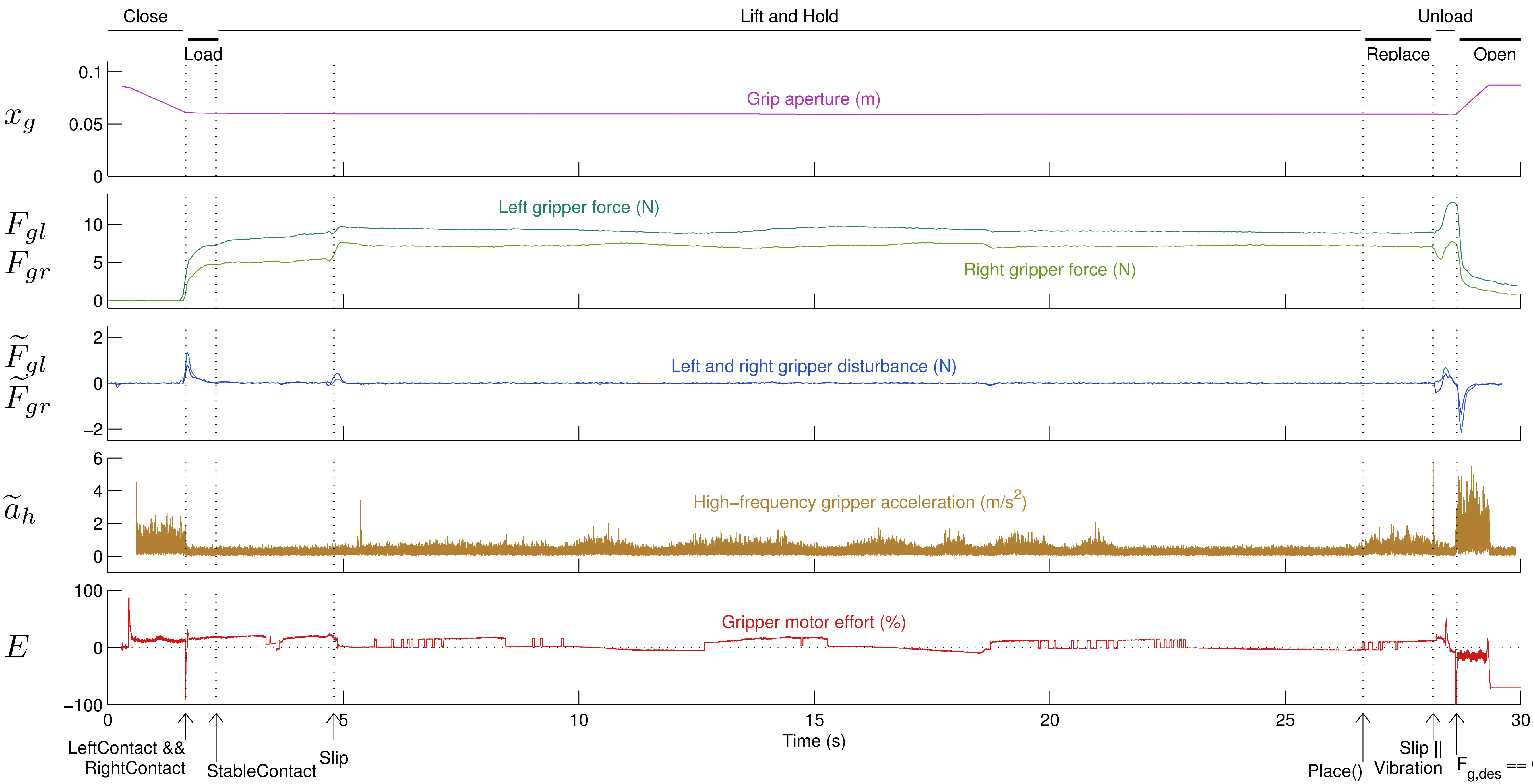


Action-Phase Grasp Controller



Sample Grasp Execution

Sample Grasp Execution



Robotic Tactile Signals

Gripper Position and Force Controllers

Action-Phase Grasp Controller

Robotic Tactile Signals

Gripper Position and Force Controllers

Action-Phase Grasp Controller


PR2

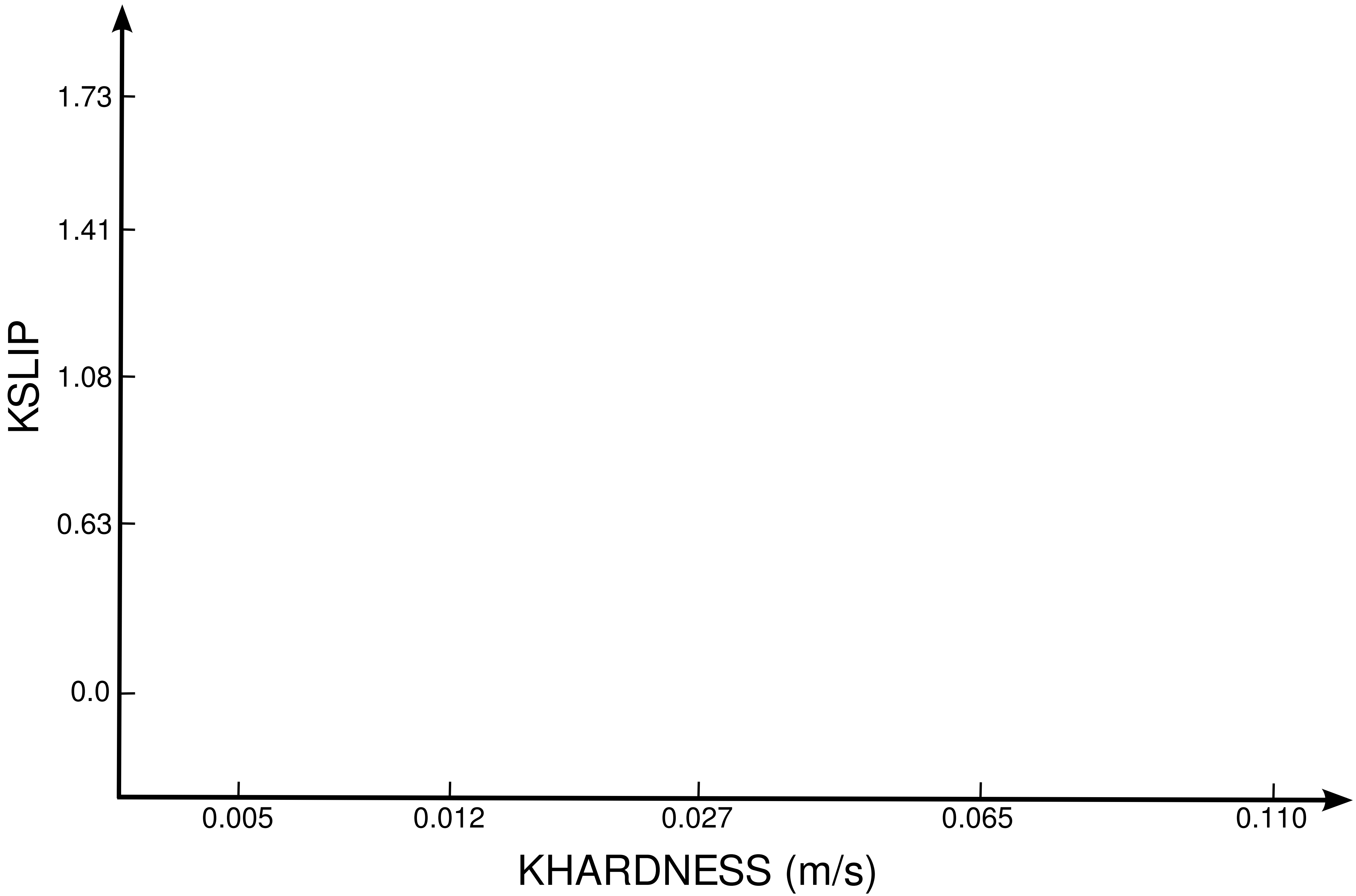

Does it work?
PR2

Control Parameter Tuning

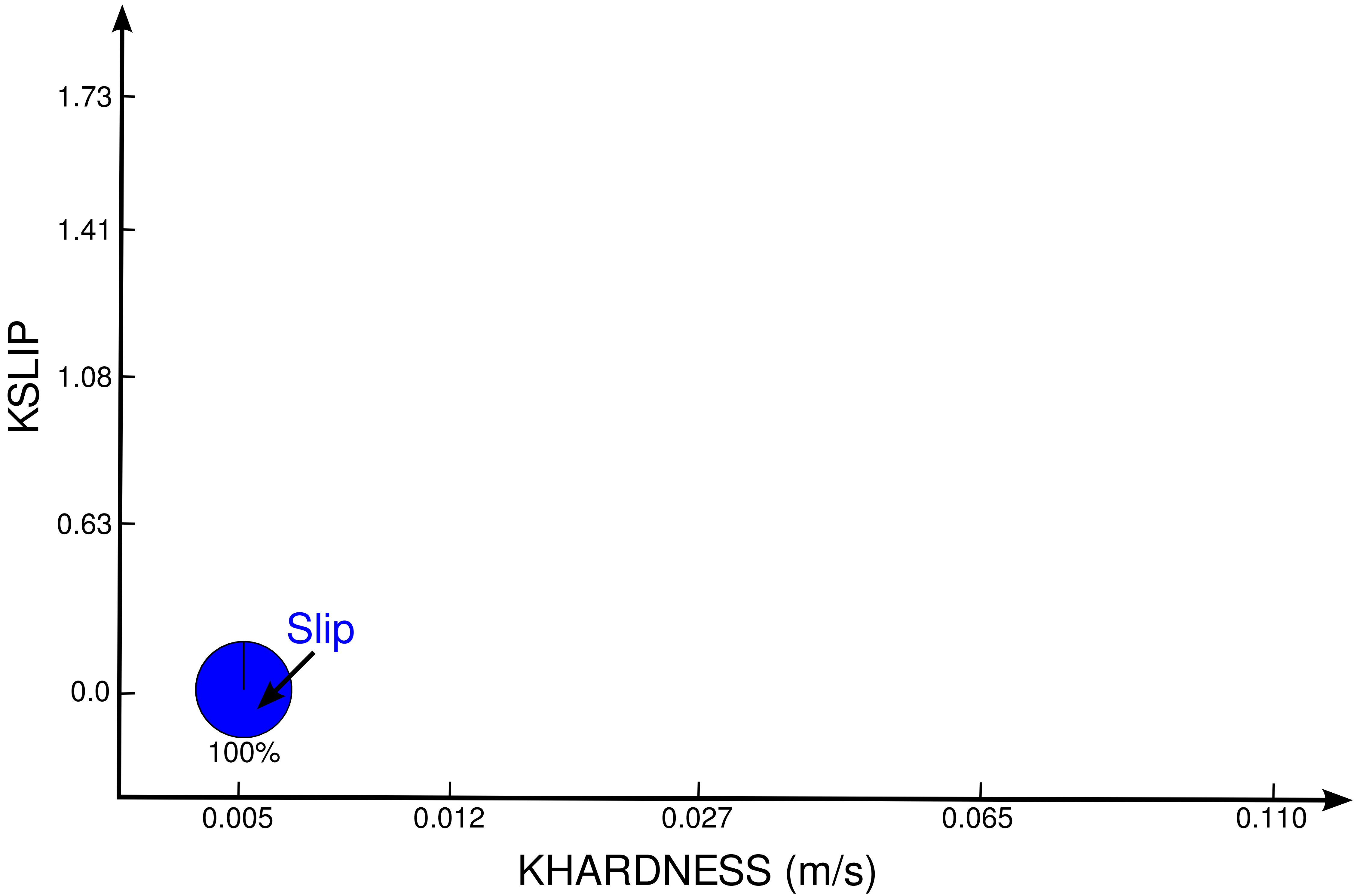
Control Parameter Tuning

Control Parameter Tuning

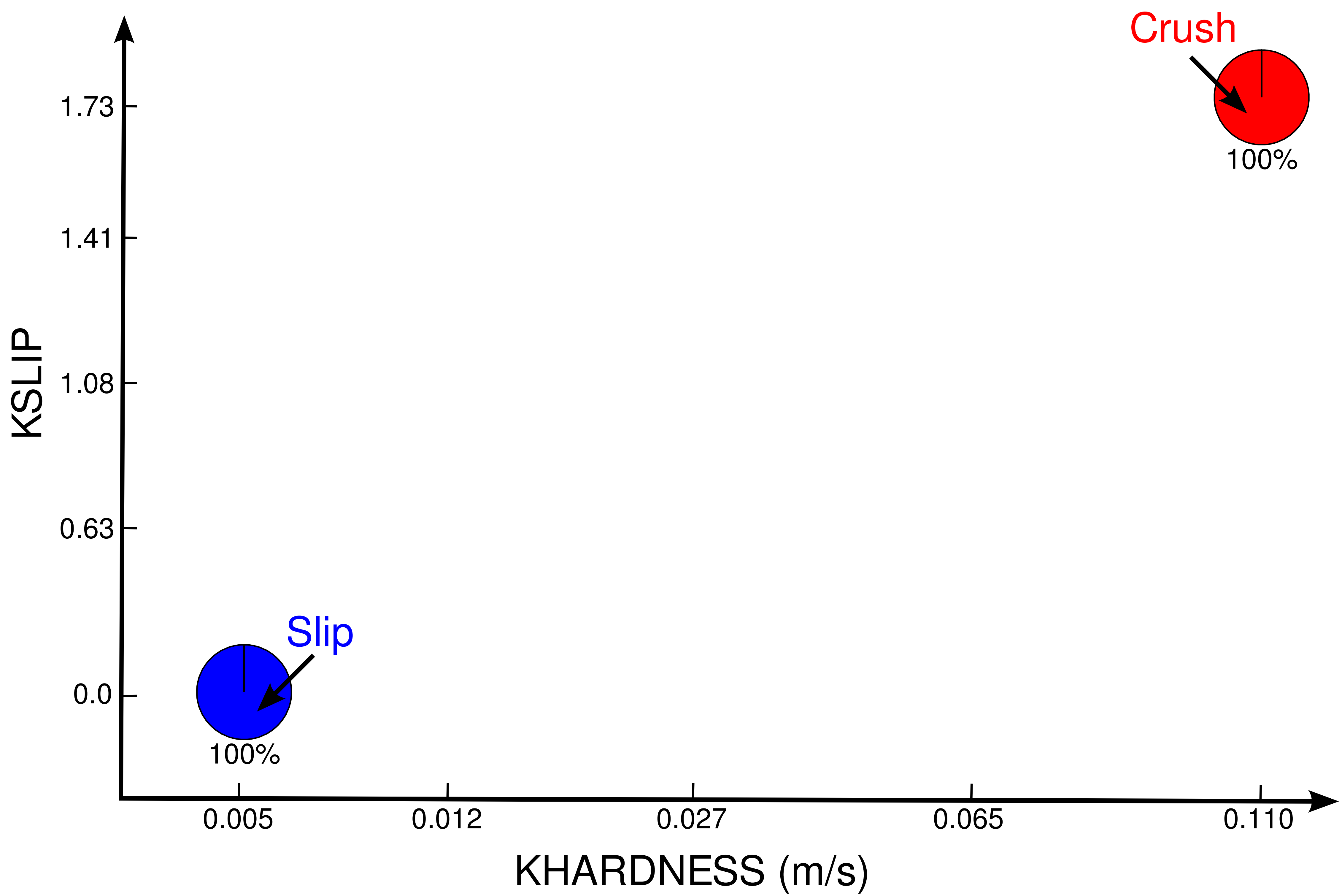
Control Parameter Tuning



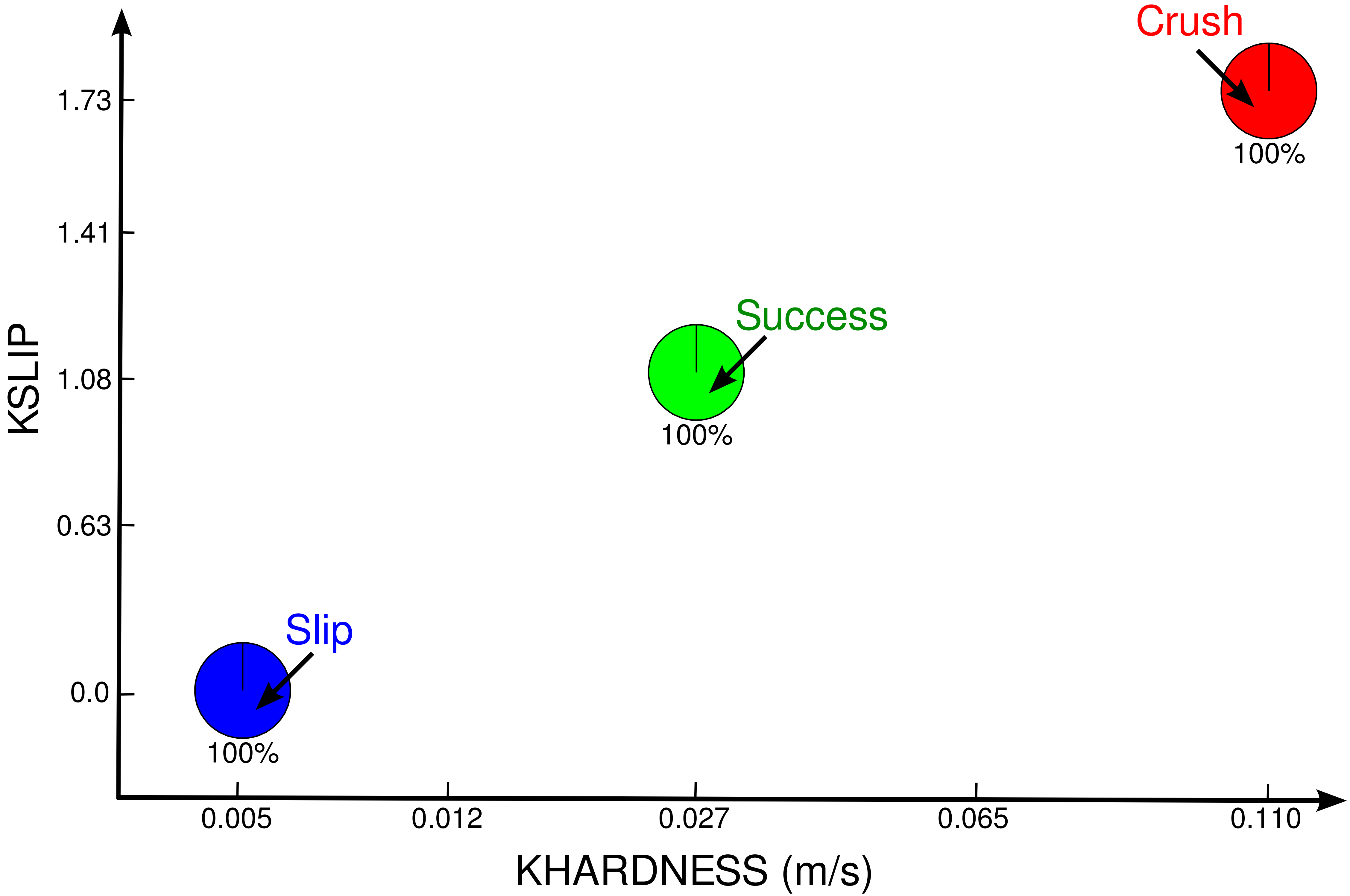
Control Parameter Tuning



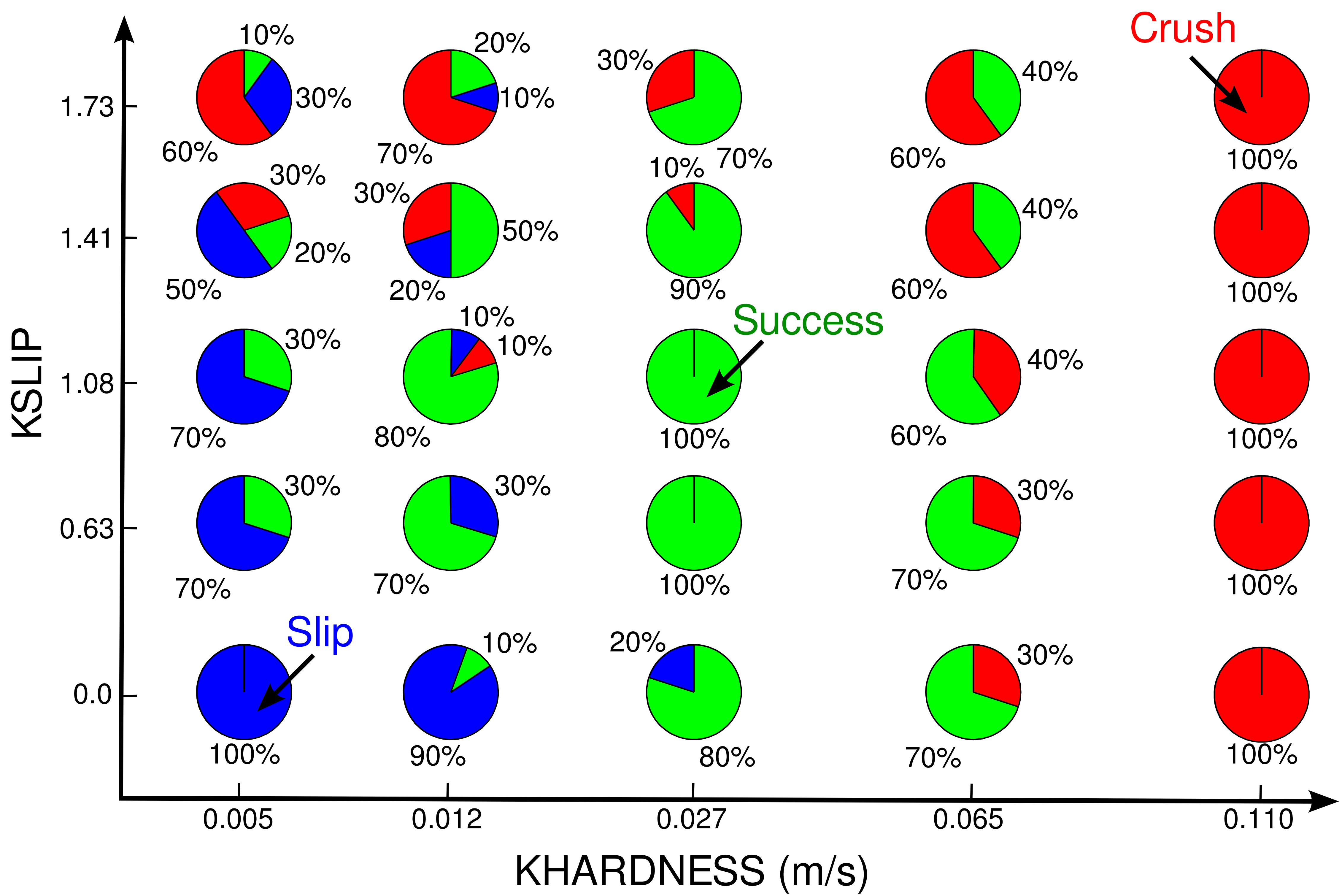
Control Parameter Tuning



Control Parameter Tuning

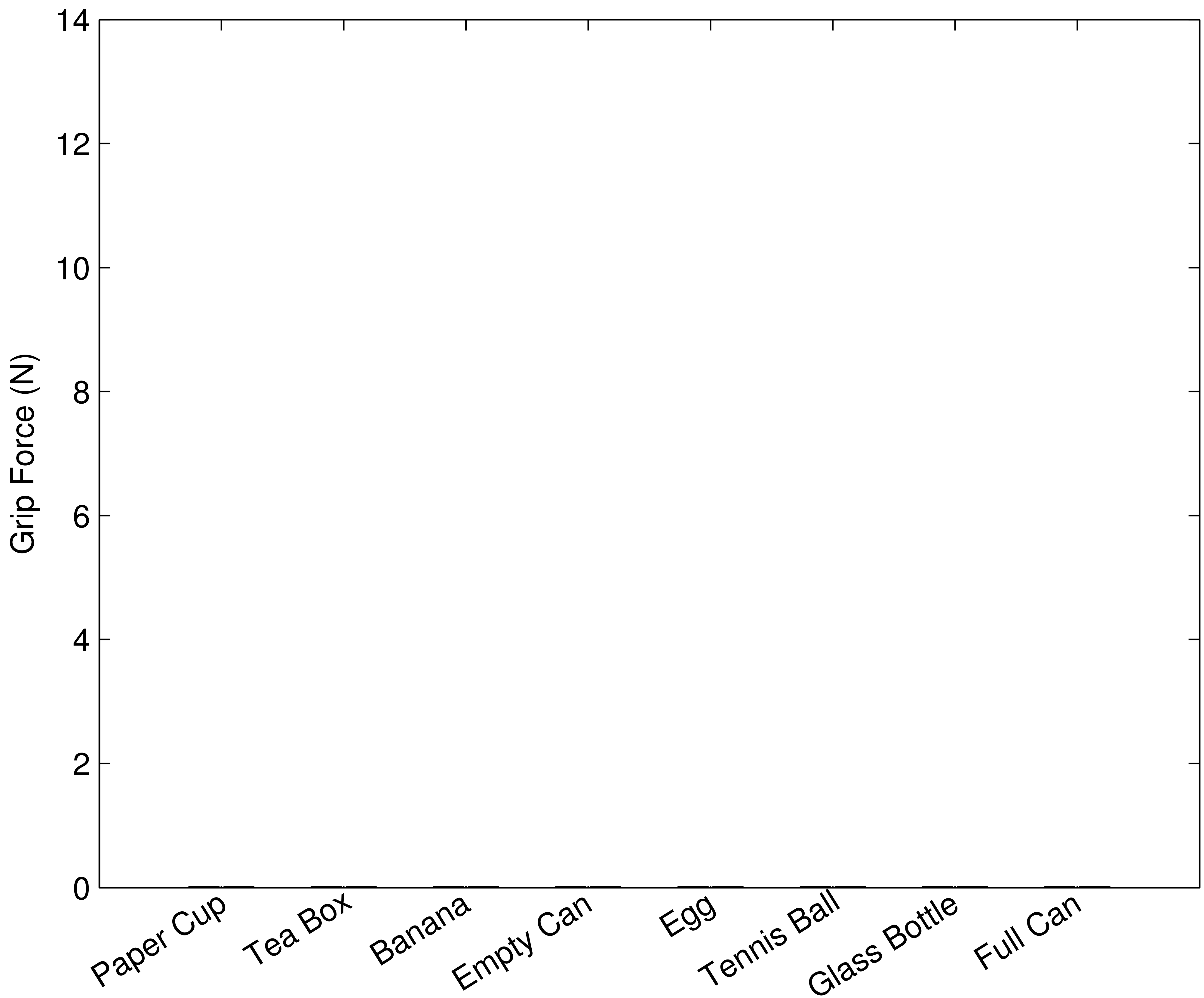


Control Parameter Tuning

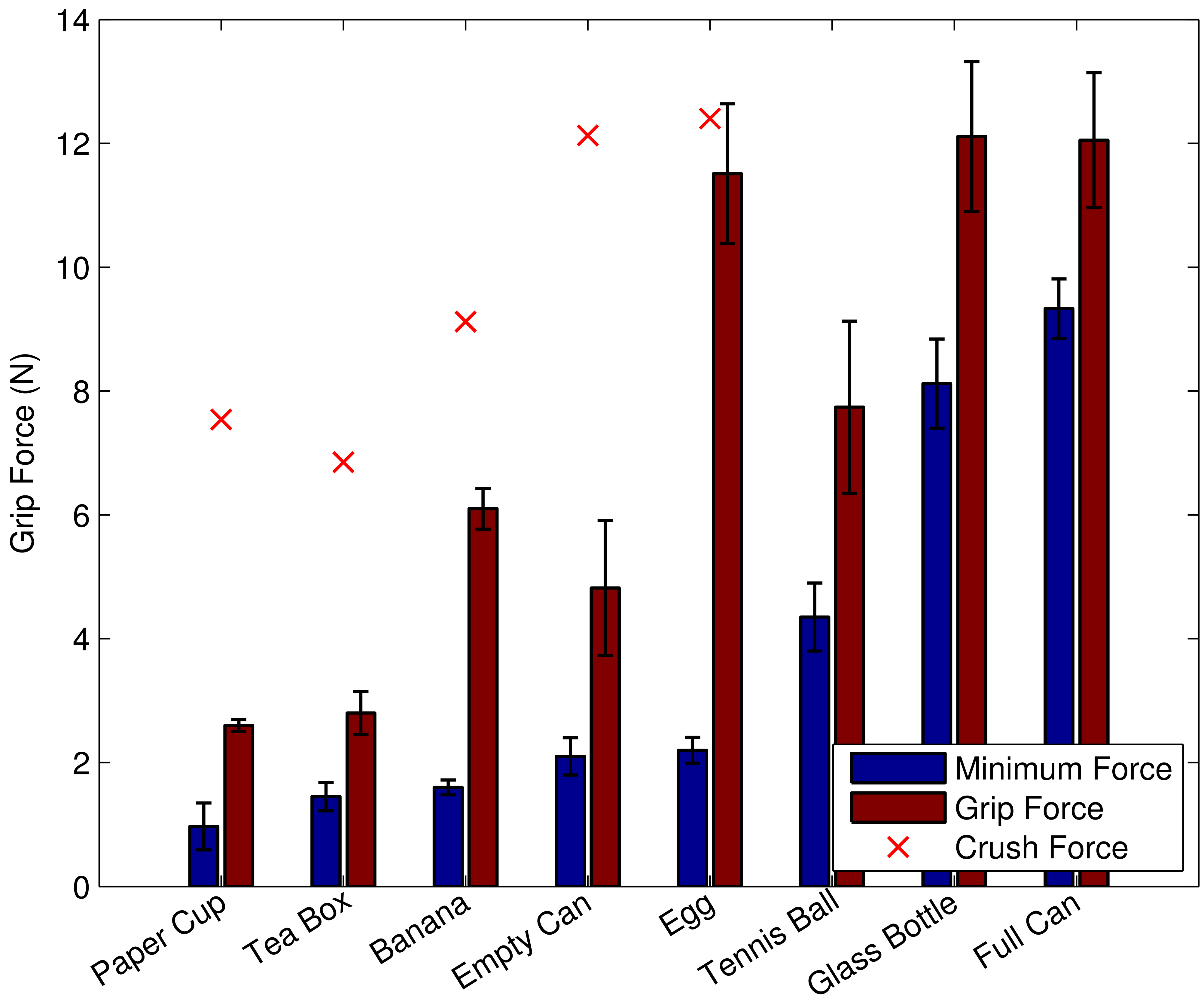


Initial Grip Force Testing

Initial Grip Force Testing

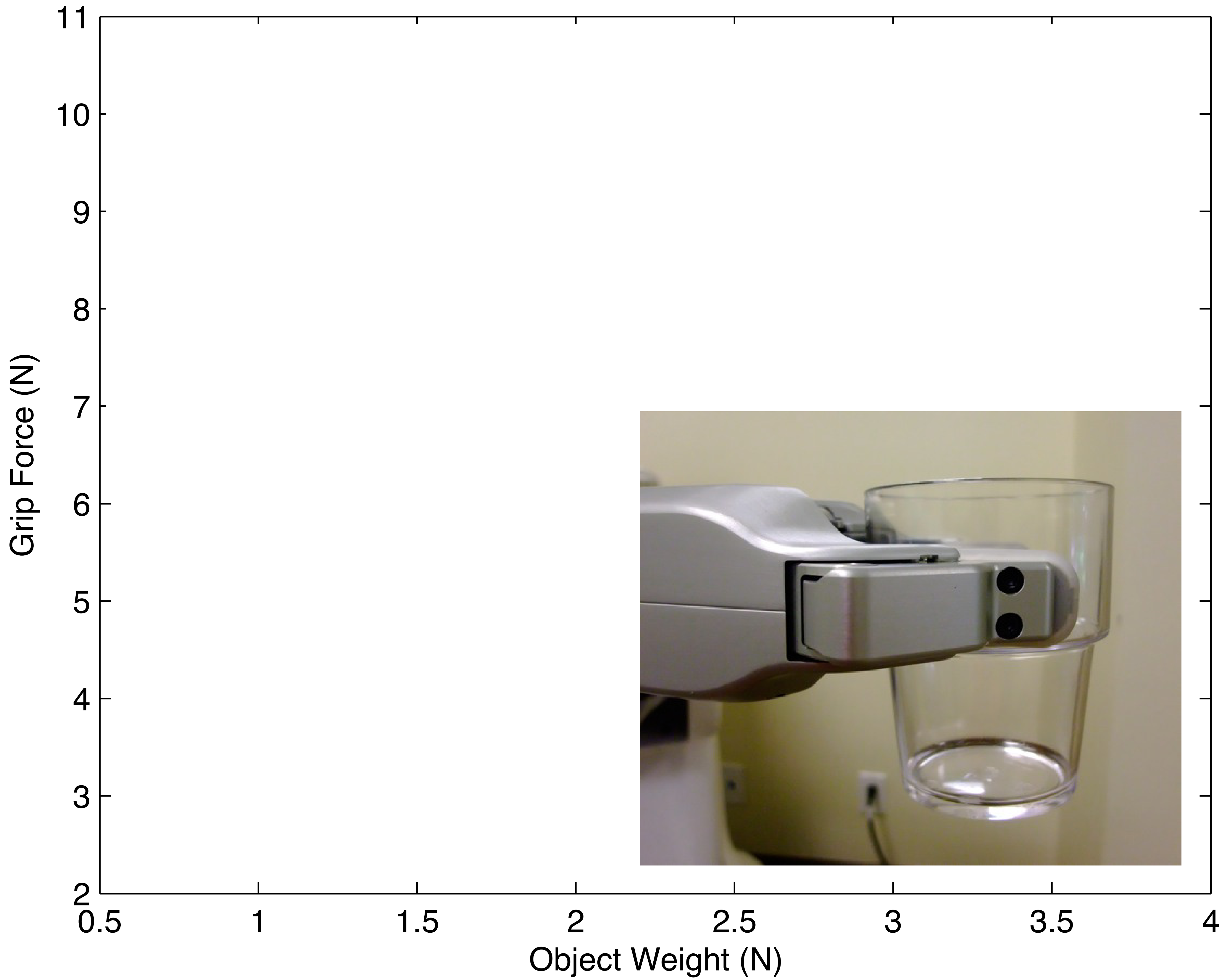


Initial Grip Force Testing

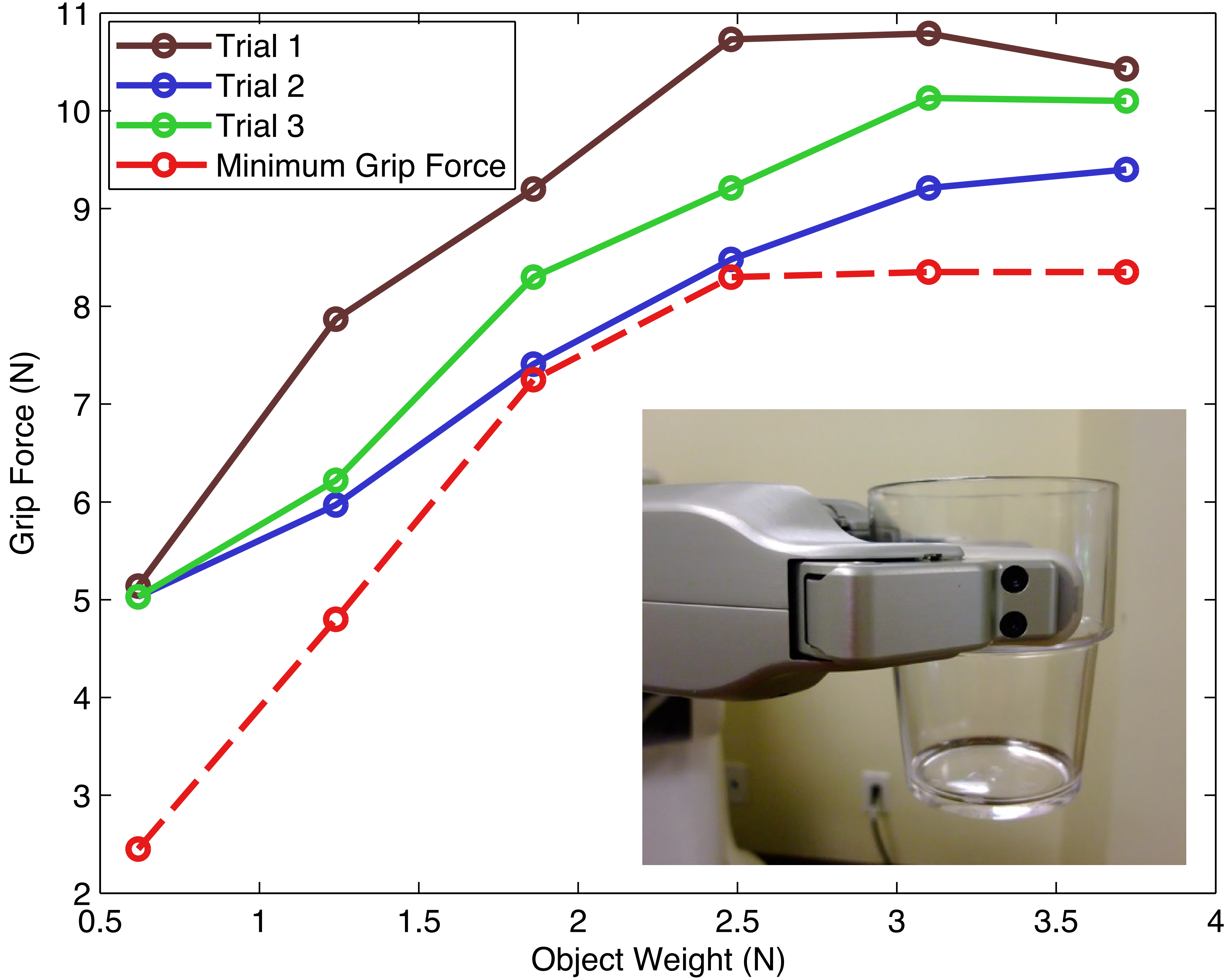


Slip Reaction Testing

Slip Reaction Testing



Slip Reaction Testing



50 Object Marathon

50 Object Marathon

https://code.ros.org   slipgrip_controller

365 ORGANIC
Organic
Honey & Nut
Morning O's
Silk
ORIGINAL
CRYSTAL GEYSER
Peppermint
BAGGED TEA
Minute Maid
100% JUICE
Scotch
HEAVY DUTY · DURABLE
SARAN
PREMIUM
WRAP
MICROWAVE SAFE
100 SQ FT

Outcomes of grasp testing with everyday objects.

	100% Motor Effort	Our Methods
Crushed		
Rotated Within Grasp		
Slipped Within Grasp		
Dropped		

Outcomes of grasp testing with everyday objects.

	100% Motor Effort	Our Methods
Crushed	30/30	
Rotated Within Grasp	5/50	
Slipped Within Grasp	2/50	
Dropped	2/50	

OUTCOMES OF GRASP TESTING WITH EVERYDAY OBJECTS.

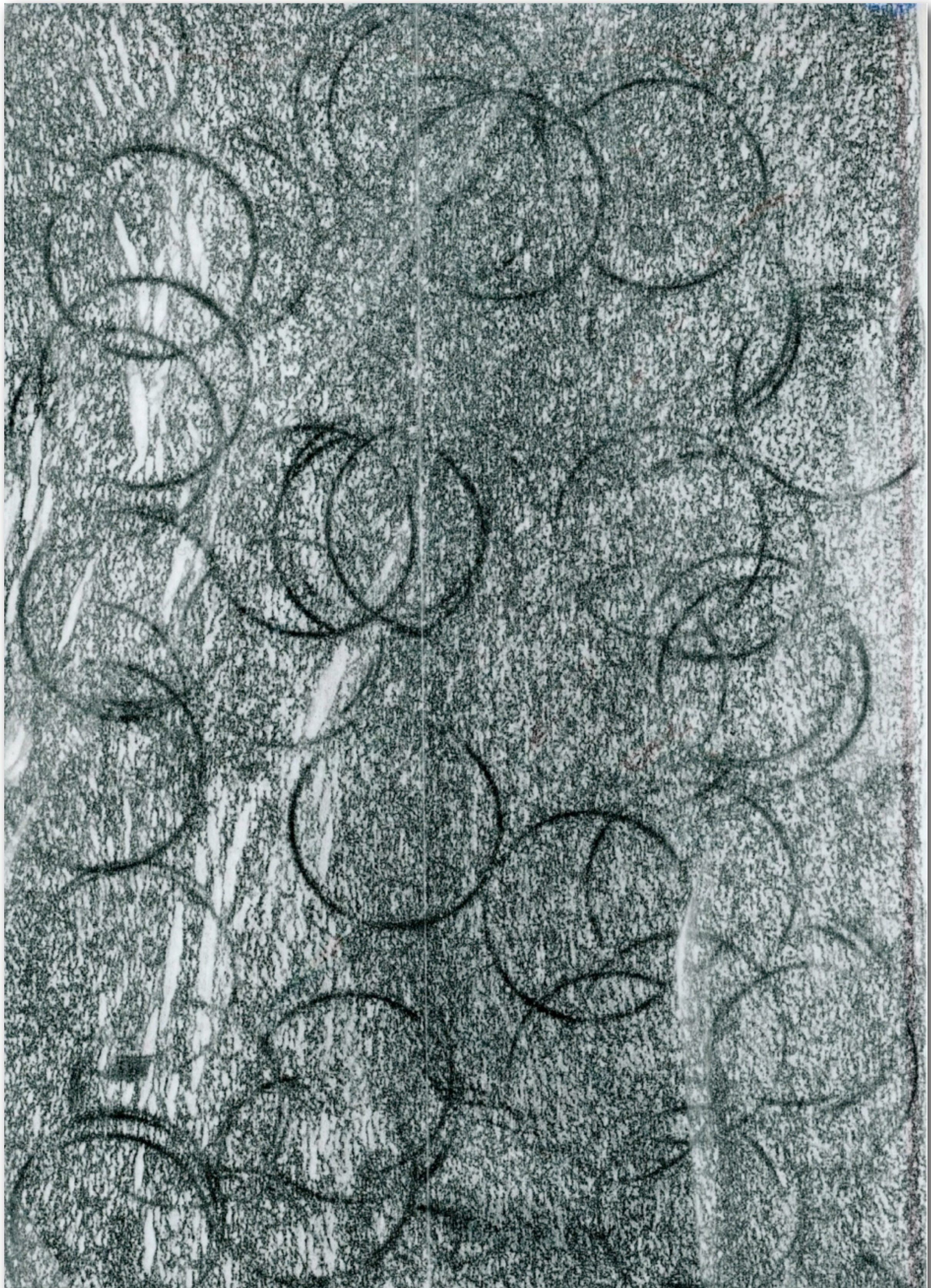
	100% Motor Effort	Our Methods
Crushed	30/30	1/30
Rotated Within Grasp	5/50	9/50
Slipped Within Grasp	2/50	4/50
Dropped	2/50	4/50

Contact Sensing During Replace

Contact Sensing During Replace

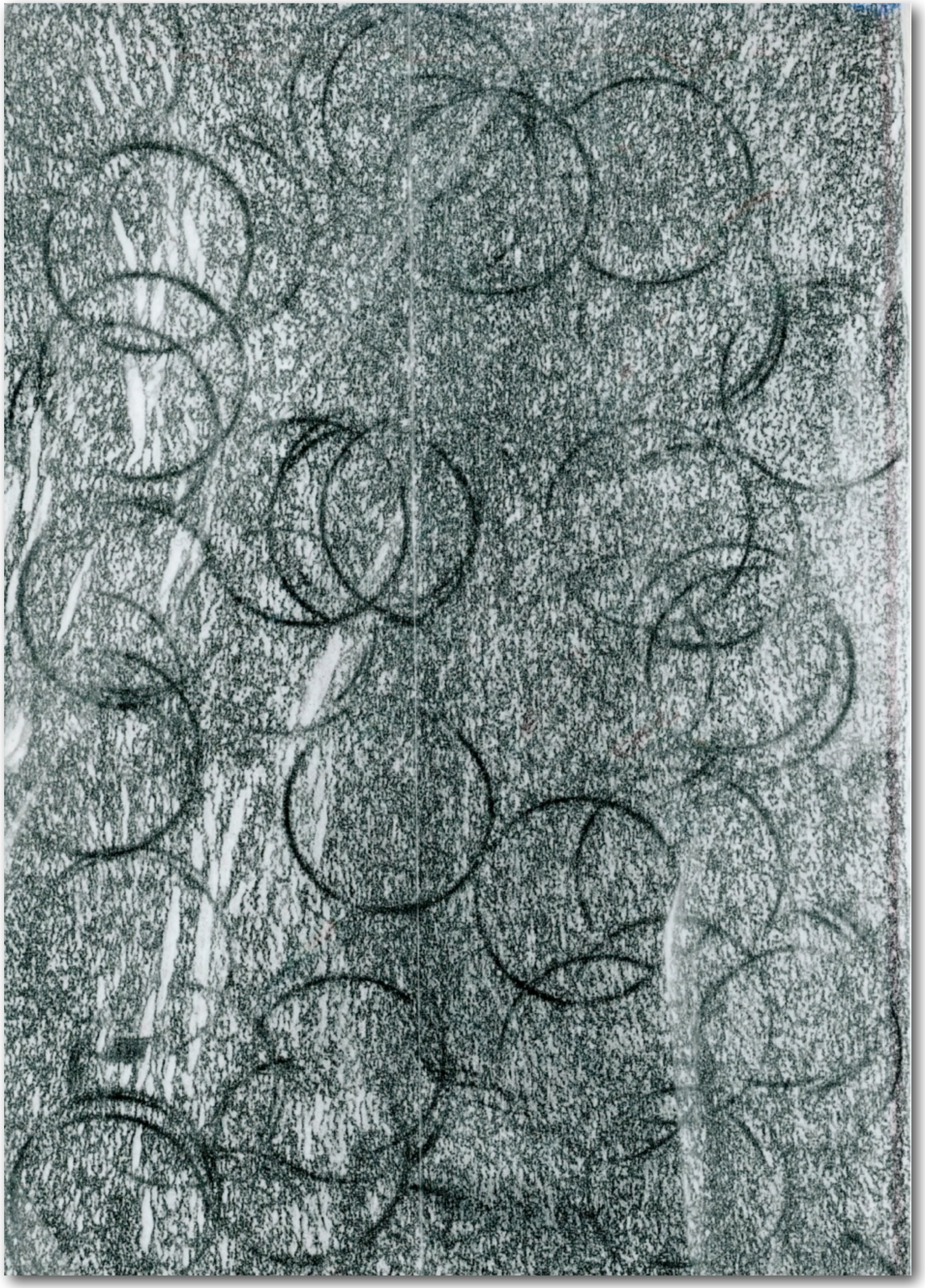
Contact Sensing During Replace

Contact Sensing During Replace



Standard Controller

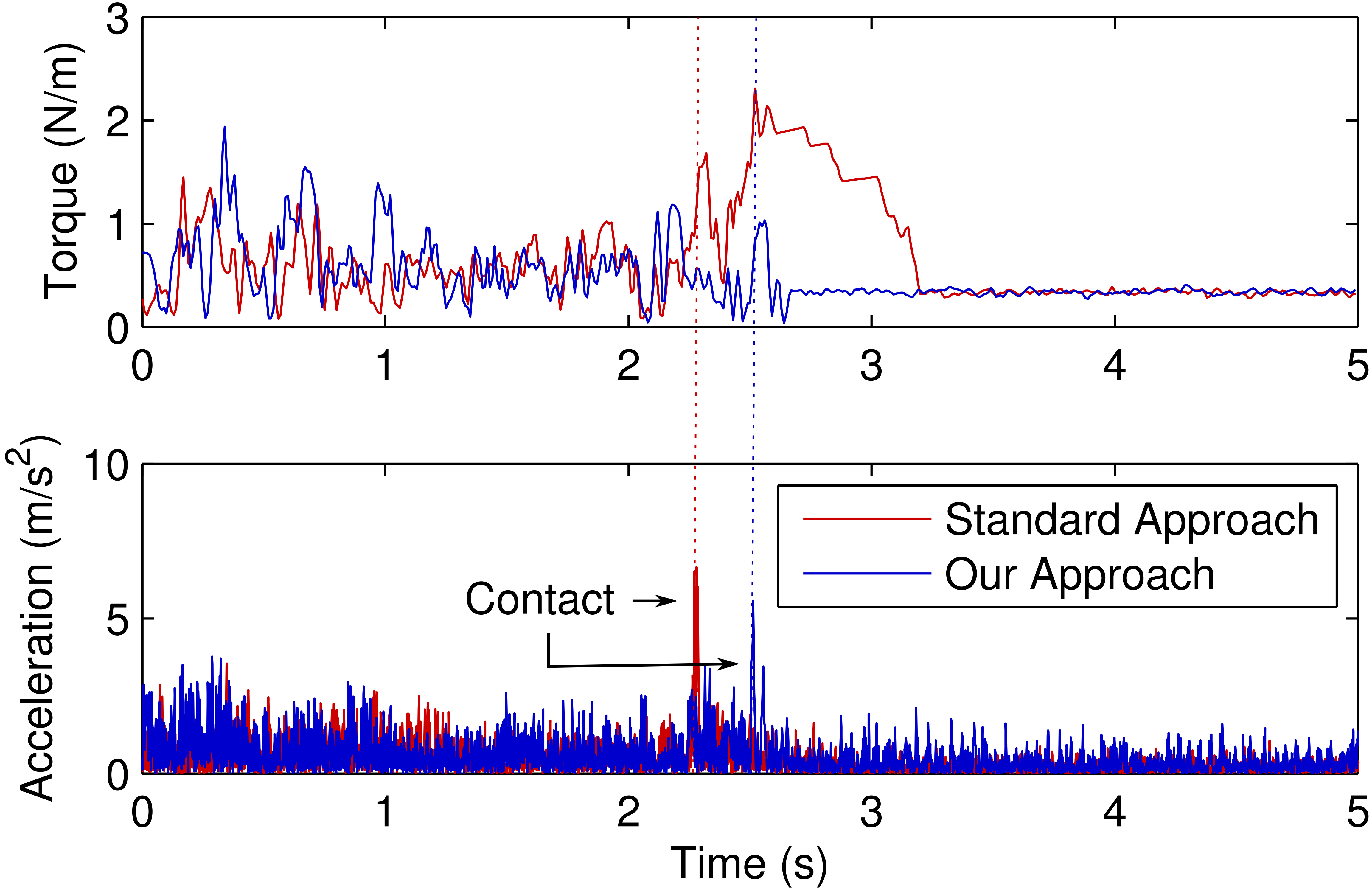
Contact Sensing During Replace



Standard Controller

Our Controller

Contact Sensing During Replace




PR2

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

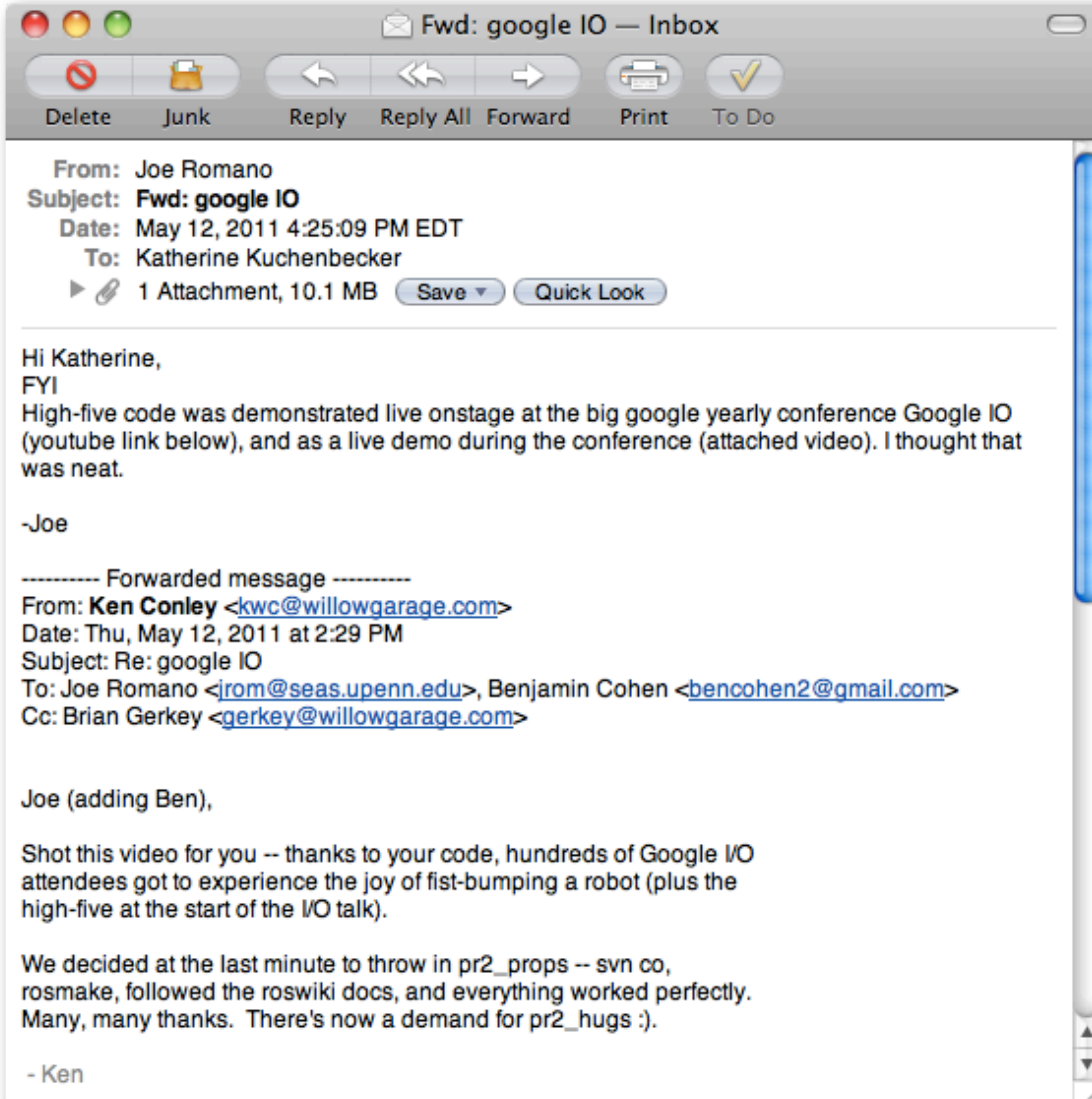
Robust performance in picking up, transporting, and setting down common objects

Another Kind of Tactile Intelligence

Another Kind of Tactile Intelligence

Demo at Google I/O on Wednesday, May 11

Demo at Google I/O on Wednesday, May 11


Fwd: google IO — Inbox

Delete Junk Reply Reply All Forward Print To Do

From: Joe Romano
Subject: **Fwd: google IO**
Date: May 12, 2011 4:25:09 PM EDT
To: Katherine Kuchenbecker
1 Attachment, 10.1 MB Save Quick Look

Hi Katherine,
FYI
High-five code was demonstrated live onstage at the big google yearly conference Google IO (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

Katherine J. Kuchenbecker
Assistant Professor

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Willow Garage Researcher

Günter Niemeyer, Ph.D.
Willow Garage Researcher

Sachin Chitta, Ph.D.
Willow Garage Researcher

Thank You

Questions?

kuchenbe@seas.upenn.edu

http://haptics.grasp.upenn.edu