Robot Learning

July 21, 2022

Stuttgart ELLIS Unit Kick-off Event

ellis

European Laboratory for Learning and Intelligent Systems

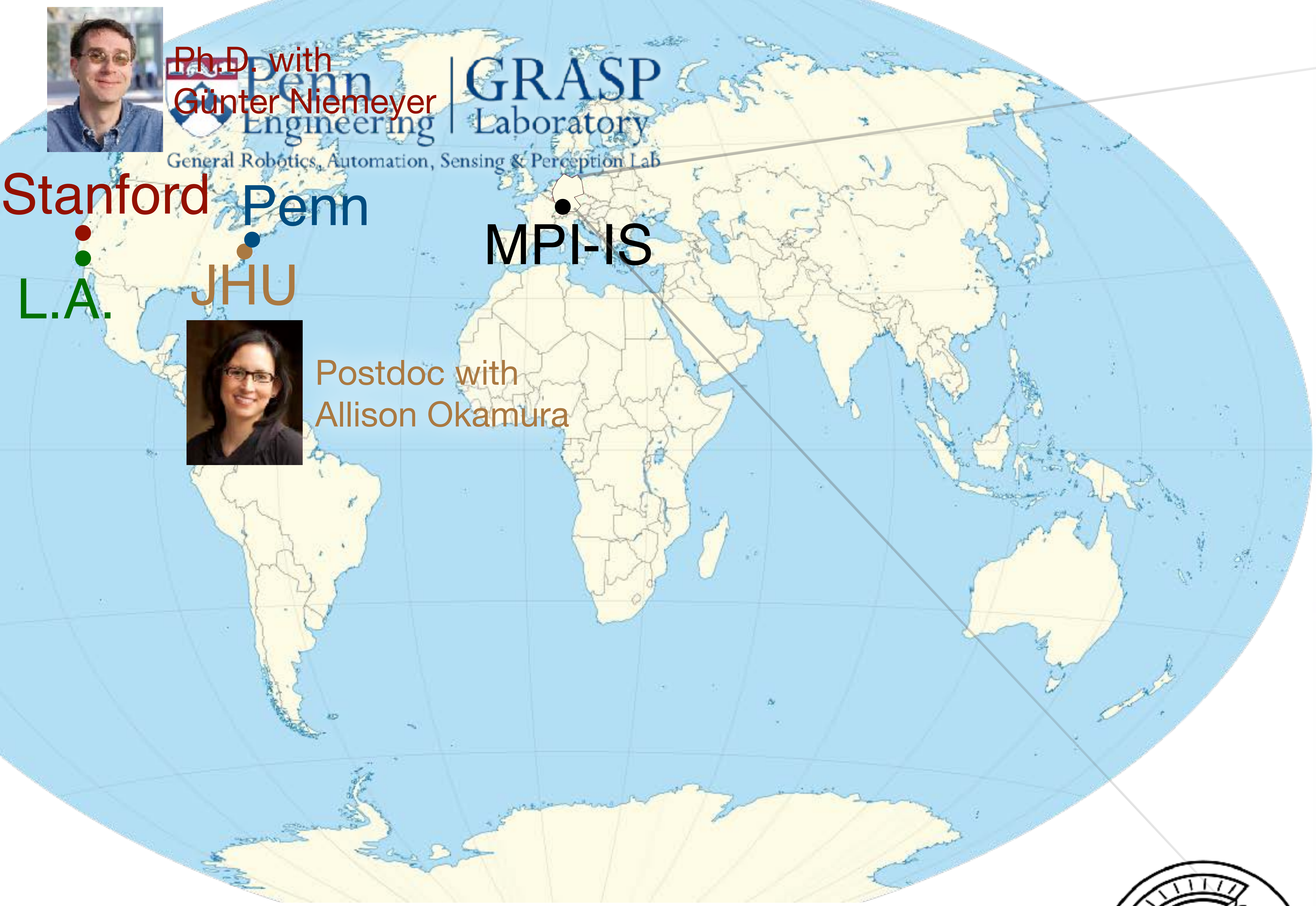
Katherine J. Kuchenbecker

MPI for Intelligent Systems

Stuttgart, Germany

HAPTIC INTELLIGENCE

MAX PLANCK INSTITUTE FOR INTELLIGENT SYSTEMS



MAX PLANCK INSTITUTE
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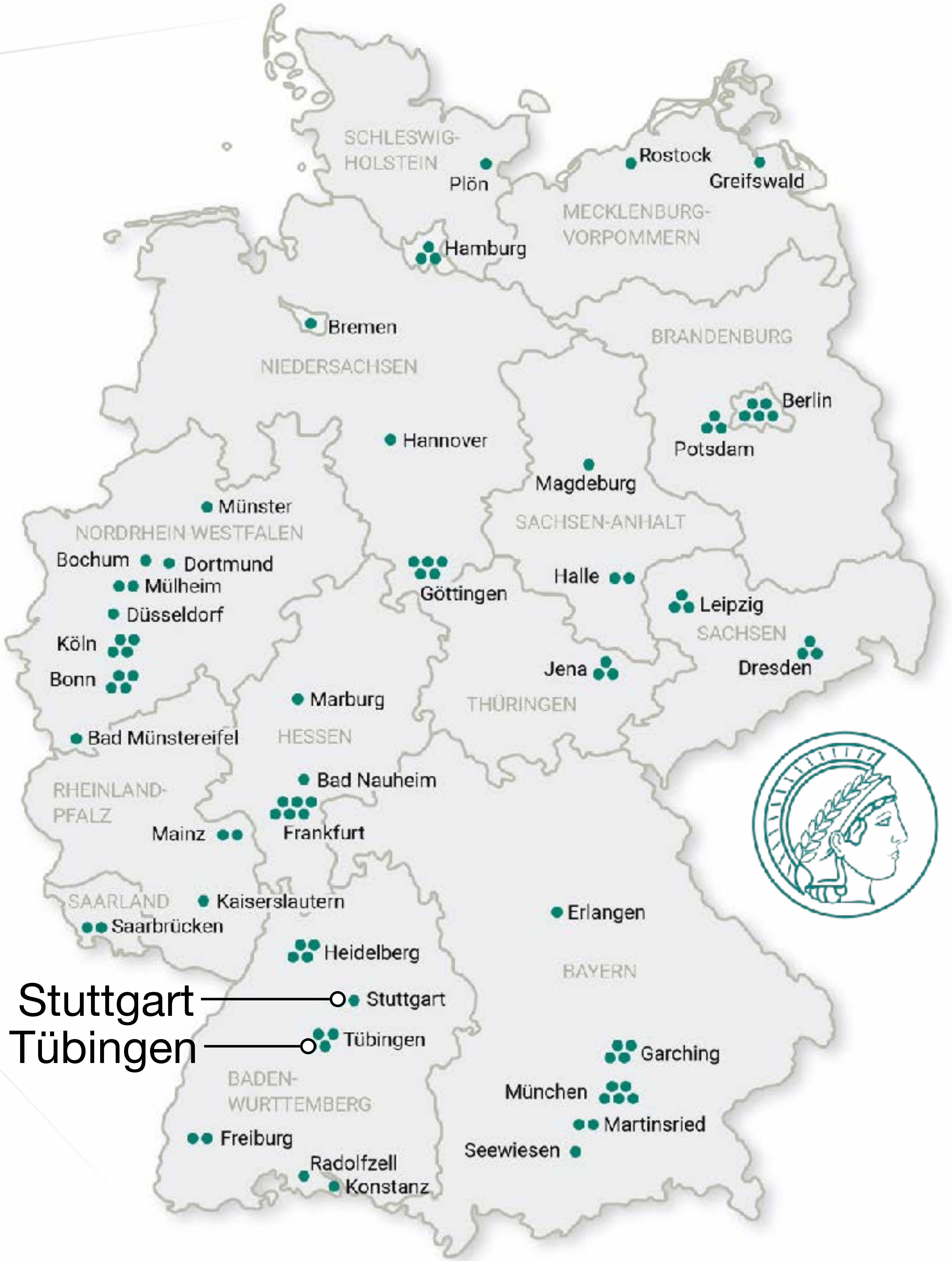
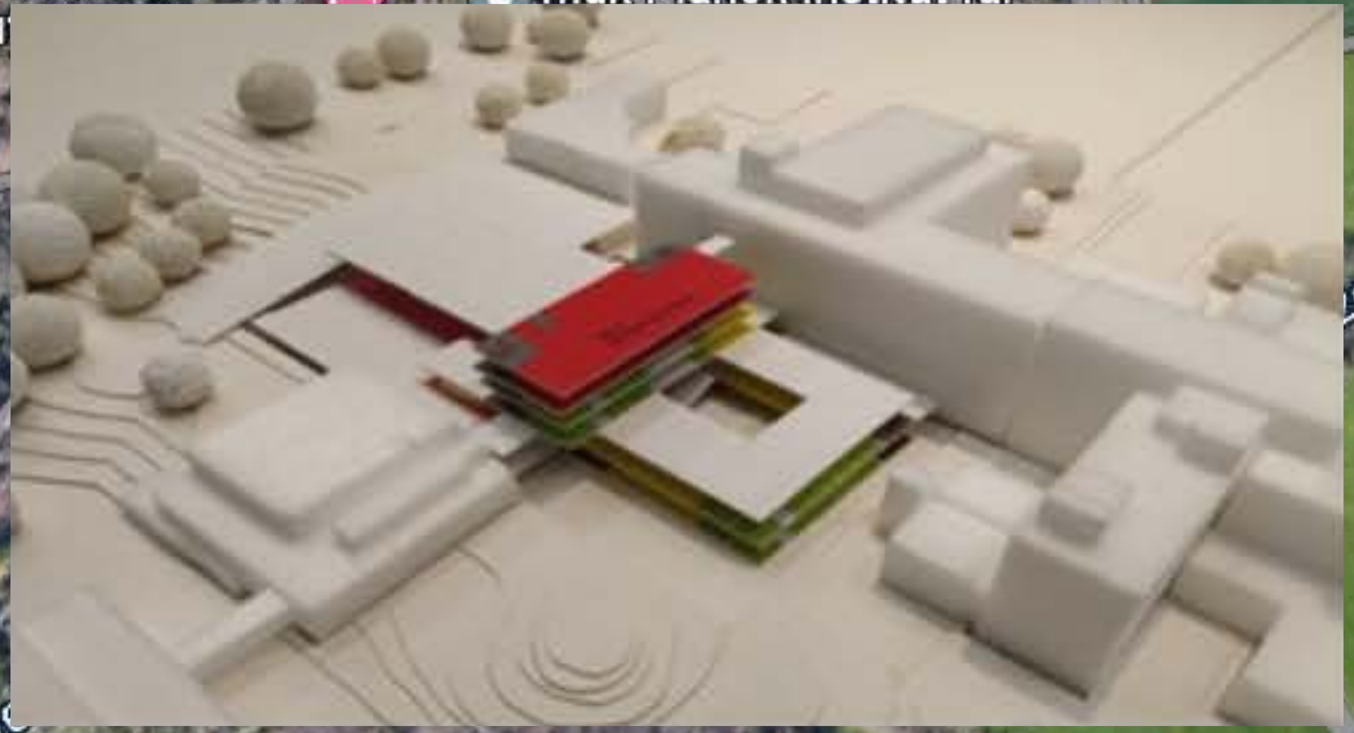
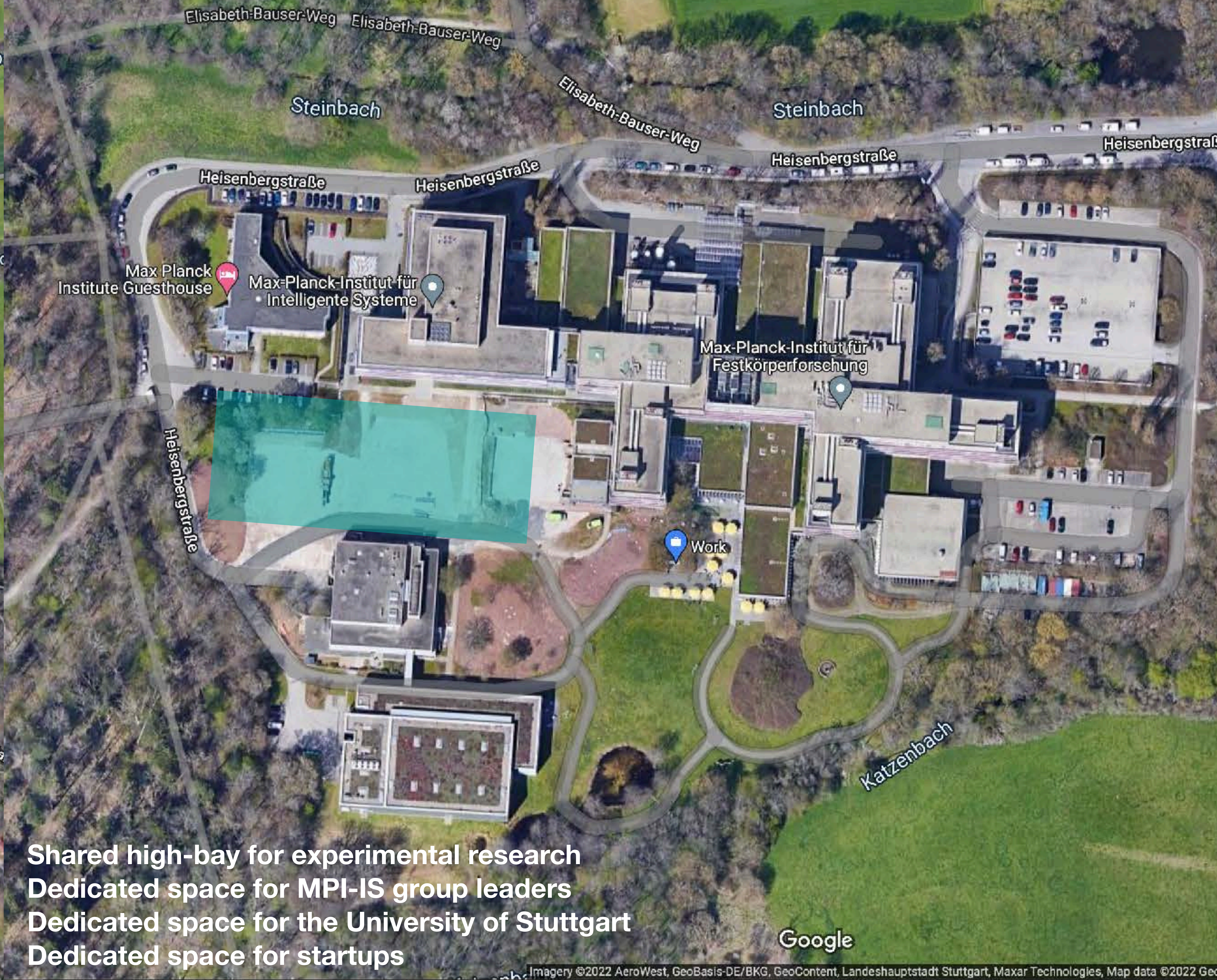


+ Jupiter (Florida, USA), Rome (Italy), Florence (Italy), Luxembourg, Manaus (Brazil), and Nijmegen (The Netherlands)


MAX PLANCK INSTITUTE
FOR INTELLIGENT SYSTEMS
Universität Stuttgart
Büsnauer Wiesental
Max-Planck-Institut für Intelligente Systeme
Trattoria Da Franco
Deutsches Zentrum für Luft- und Raumfahrt eV
Sporthalle Keltenschanze
Parkplatz
Universität Stuttgart Campus Vaihingen
Pfaffenwaldring
Pfaffenhof I
Frischemarkt Roth
Pfaffenwaldring 47, 70569 Stuttgart
Katzenbach
Büsnauer Str.
Steinbach
Unisee
U&D Wiese
Temporarily closed
Allmandring I
Parkplatz Allmandring
Allmandring III
Allmandring
DHL Packstation 165
Taverna Elia
Unithekle CampusBar
Institut für Zellbiologie und Immunologie (IZI)
Hochschule der Medien
Parkplatz HdM
Department of Sport and Exercise Science...
Fraunhofer-Institut für Produktionstechnik...
Fraunhofer-Institut für Grenzflächen- und...
Fraunhofer-Institut für Arbeitswirtschaft...
Nobelstraße
Universität Stuttgart - ...
rümpel-to-go
The Bic A Hairgarage
Amala Haus Seminarraum
Pflanzenhof Vaihingen Rainer Hatt eK
Römerhof Hotelbetriebs
Zentrum für Sonnenenergie- und...
Naturfreundehaus Vaihingen
Büsnauer Rain
Netto Marken-Discount
Patch Fitness Center
Patch Thrift Shop
Patch Car Wash
Universitätsstraße
Spielplatz
Google
Layers

Cyber Valley





Shared high-bay for experimental research
Dedicated space for MPI-IS group leaders
Dedicated space for the University of Stuttgart
Dedicated space for startups


MPI-IS is hiring at all levels!
Michael J. Black
Perceiving Systems
Moritz Hardt
Social Foundations of Computing
Bernhard Schölkopf
Empirical Inference
Christoph Keplinger
Robotic Materials
Metin Sitti
Physical Intelligence
Katherine J. Kuchenbecker
Haptic Intelligence
Caterina De Bacco
Physics for Inference and Optimization
Georg Martius
Autonomous Learning
Ludovic Righetti
Movement Generation and Control
Jörg Stückler
Embodied Vision
Alexander Badri-Spröwitz
Dynamic Locomotion
Ardian Jusufi
Locomotion in Biorobotic and Somatic Systems
Wieland Brendel
Robust Machine Learning
Falk Lieder
Rationality Enhancement
Michael Mühlebach
Learning and Dynamical Systems
Samira Samadi
Fairness in Machine Learning
Justus Thies
Neural Capture and Synthesis
Wenqi Hu
Bioinspired Autonomous Miniature Robots
Ksenia Keplinger
Organizational Leadership and Diversity
Tübingen
Cyber Valley
imprs-is
MAX PLANCK INSTITUTE
FOR INTELLIGENT SYSTEMS
Stuttgart

Max Planck Lecture & Summer Colloquium

Tomorrow on the MPI-IS campus

Lecture Hall 2D5, Heisenbergstr. 1, Stuttgart

Starting at 1:30 p.m. with a barbecue

The talks will also be live-streamed

https://is.mpg.de/events/intelligent-systems-summer-colloquium-2022

13:30

Opening by Metin Sitti
Managing Director
Max Planck Institute for Intelligent Systems

13:35 - 14:35

2022 Max Planck Lecture
Zhenan Bao
Skin-Inspired Organic Electronics
Abstract and speaker's short biography >>

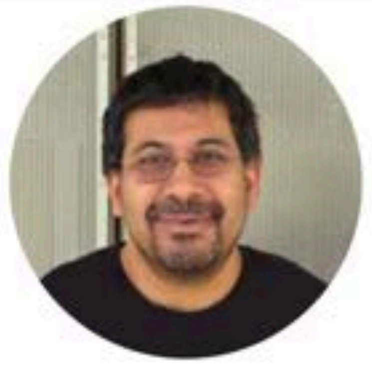
14:35 - 15:00 Discussion

15:00 - 15:30 Break

15:30 - 16:10

Intelligent Systems Summer Colloquium
Wieland Brendel
A more principled way towards machines that see the world like humans
Abstract and speaker's short biography >>

16:10 - 16:50



Intelligent Systems Summer Colloquium
Sayan Mukherjee
Modeling shapes and surfaces
Abstract and speaker's short biography >>

16:50 - 17:30

Intelligent Systems Summer Colloquium
Betty Mohler
Self-Avatars & Body Perception
Abstract and speaker's short biography >>

17:30

Closing by Metin Sitti
Managing Director
Max Planck Institute for Intelligent Systems

17:35 - 19:30

Summer party
Canteen & Garden, Heisenbergstr. 1, Stuttgart

Rachael B. Burns
Ph.D. Student

Iris Andrussow
Co-Advised Ph.D. Student

Arnaud Allemang--Trivalle
Co-Advised Ph.D. Student

Dominika Lisy
Recent Ph.D. Visitor

Rachael L'Orsa
Recent Ph.D. Visitor

Cara Nunez
Recent Ph.D. Visitor

Yoojin Oh
Visiting Ph.D. Student

Fayo Ojo
Recent Ph.D. Visitor

Christian Schöffmann
Recent Ph.D. Visitor

Neha Thomas
Recent Ph.D. Visitor

Guido Caccianiga
Ph.D. Student

Summer Interns
(several)

Joey Burns
IT Administrator

Nati Egana Rosa
Technical Assistant

Ilona Jacobi
Department Assistant

Bernard Javot
Research Engineer

Paul Kress
Research Engineer

Lijuan Wang
Research Engineer

We enjoy hosting visiting Ph.D. students and interns!

Farimah Fazlollahi
Ph.D. Student

Maria-Paola Forte
Co-Advised Ph.D. Student

Ifat Gertler
Ph.D. Student

Yijie Gong
Ph.D. Student

Behnam Khojasteh
Ph.D. Student

Mayumi Mohan
Ph.D. Student

Saekwang Nam
Ph.D. Student

Julian Nubert
Co-Advised Ph.D. Student

Benjamin Richardson
Ph.D. Student

Nataliya Rokhmanova
Co-Advised Ph.D. Student

HI MPI-IS

poster
lightning talk
attending

Could members of my team please stand up?

Alexis E. Block
Recent Doctoral Grad

Ravali Gourishetti
Postdoctoral Researcher

Haliza Mat Husin
Postdoctoral Researcher

Gökhan Serhat
Research Scientist

Yitian Shao
Postdoctoral Researcher

Natalia Sanchez-Tamayo
Co-Advised Ph.D. Student

HAPTIC INTELLIGENCE
MAX PLANCK INSTITUTE FOR INTELLIGENT SYSTEMS

Katherine J. Kuchenbecker
Director

David Gueorguiev
Scientist (CNRS)

Hyosang Lee
Scientist (Uni. Stuttgart)

Hasti Seifi
Scientist (U. Copenhagen)

Yasemin Vardar
Scientist (TU Delft)

Naomi Tashiro
Ph.D. Student

Underlying Motivation

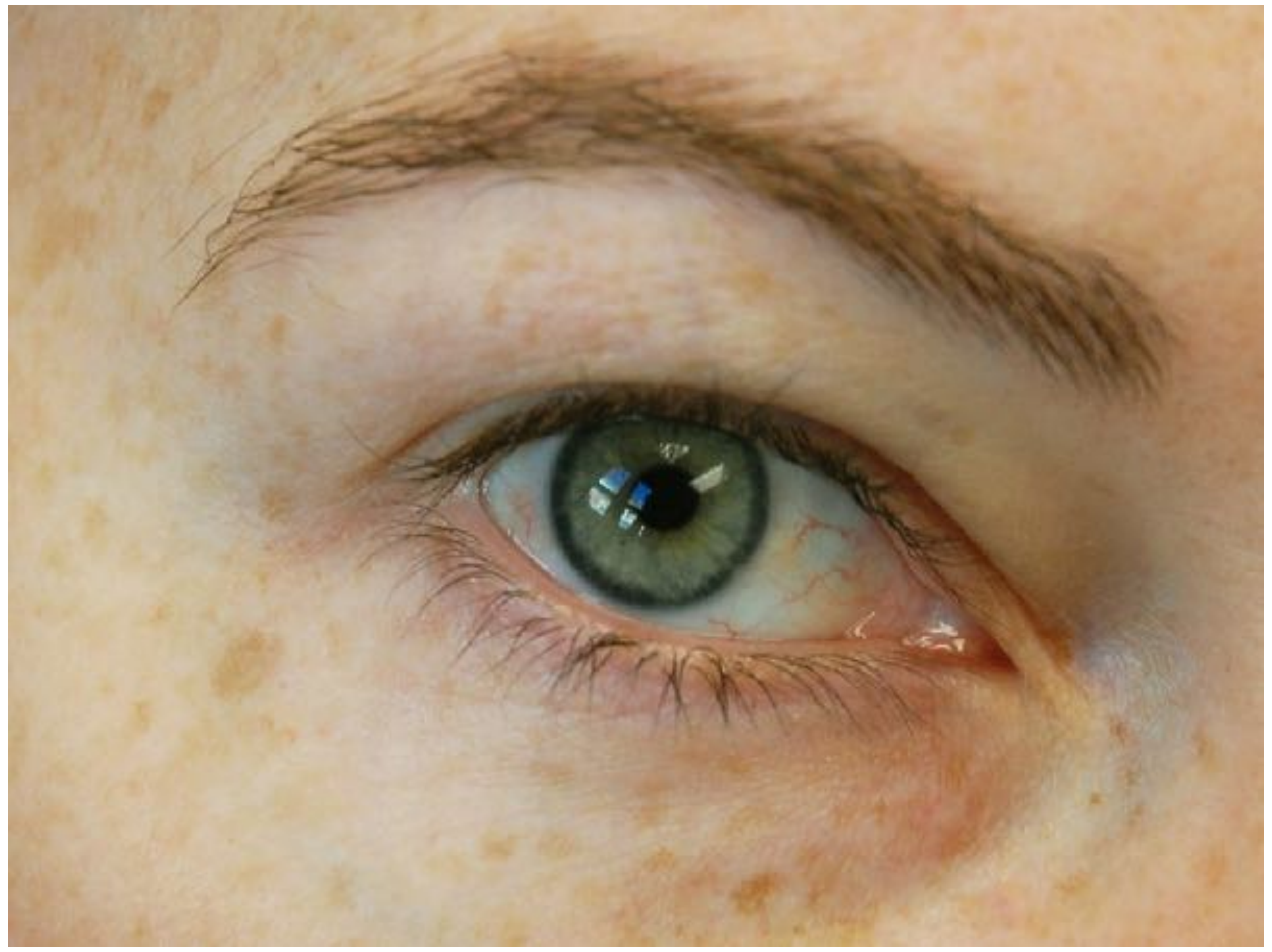
Underlying Motivation

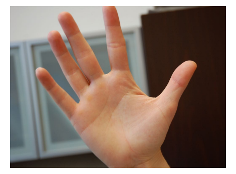
- The sense of **touch** is fundamental for humans:
  - First sense to evolve
  - Difficult to live without
  - Deeply coupled to physical action and social interaction
  - Spread throughout the body with myriad channels


haptic =
★tactile
cutaneous
+
kinesthetic
proprioceptive
contact location
pressure
stretch
slip
vibration
temperature
hair follicle motion
receptor density varies spatially
muscle length
muscle velocity
tendon force
ligament force
joint receptors

Underlying Motivation

- The sense of **touch** is fundamental for humans:
  - First sense to evolve
  - Difficult to live without
  - Deeply coupled to physical action and social interaction
  - Spread throughout the body with myriad channels
- But, most engineered systems **ignore the sense of touch**.





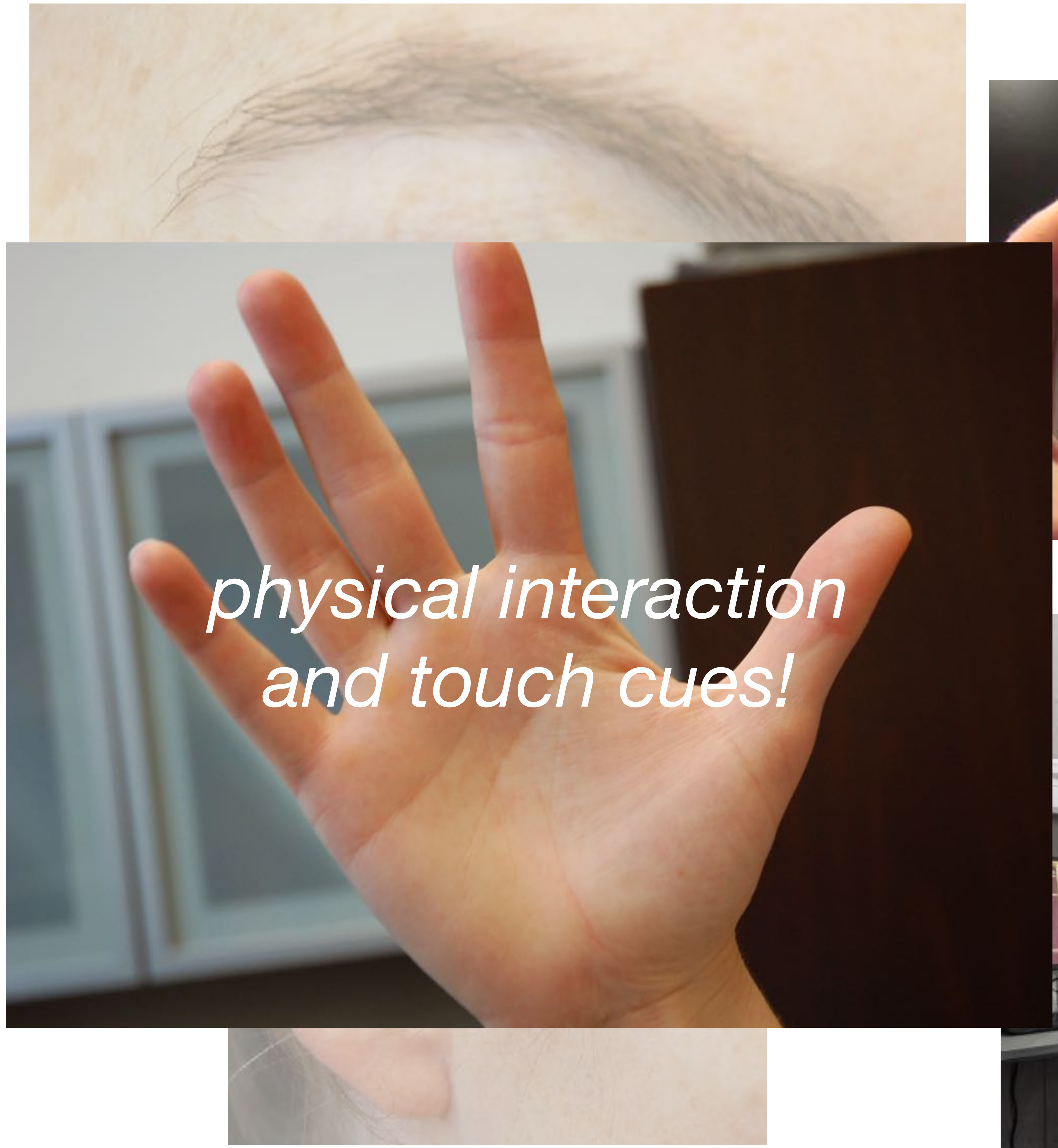

touchscreens


virtual reality


PR2
robot manipulation


robotic surgery


social
robots


physical interaction
and touch cues!


touchscreens

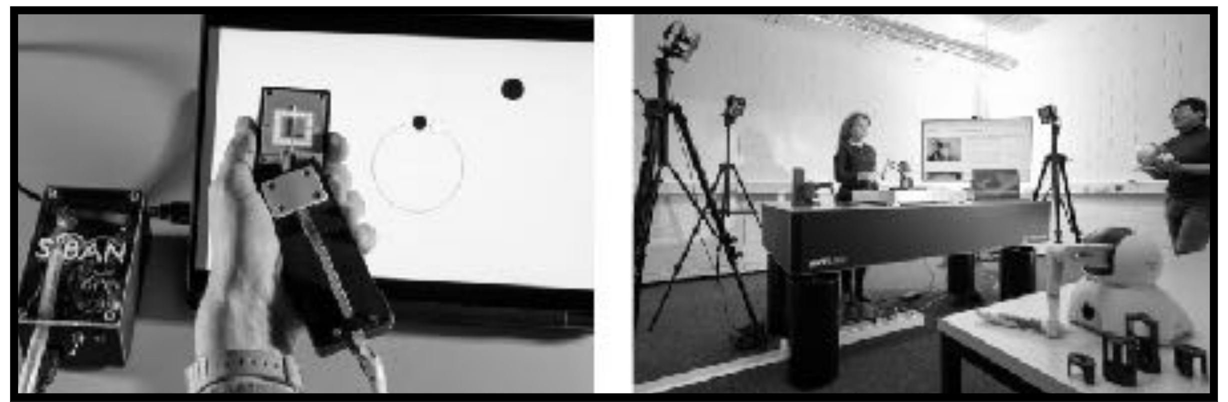

virtual reality


PR2
robot manipulation


robotic surgery


social
robots

Fingertip Haptics



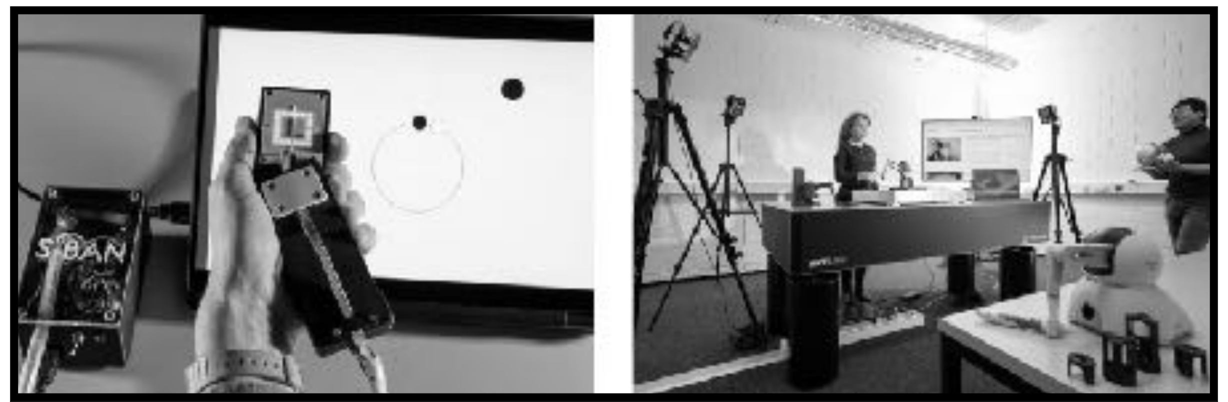
Haptic Interface Technology

Teleoperation Interfaces

Physical Human-Robot Interaction

Touch Sensing

Fingertip Haptics



Haptic Interface Technology

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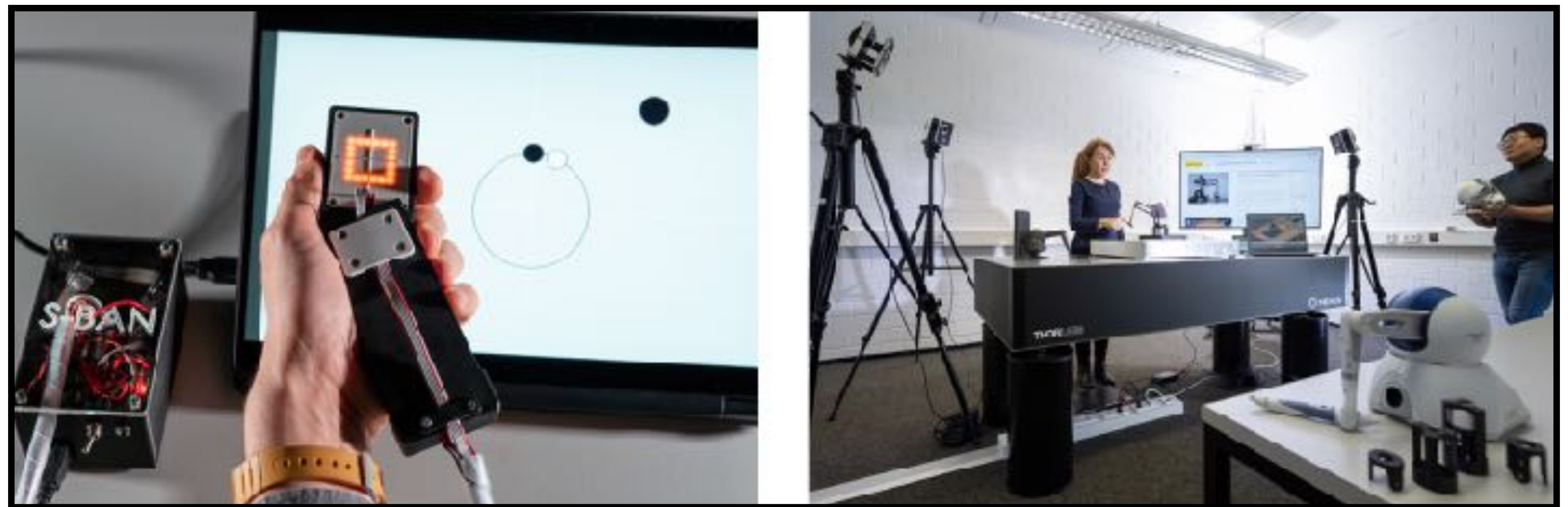

Haptic Interface Technology

Teleoperation Interfaces

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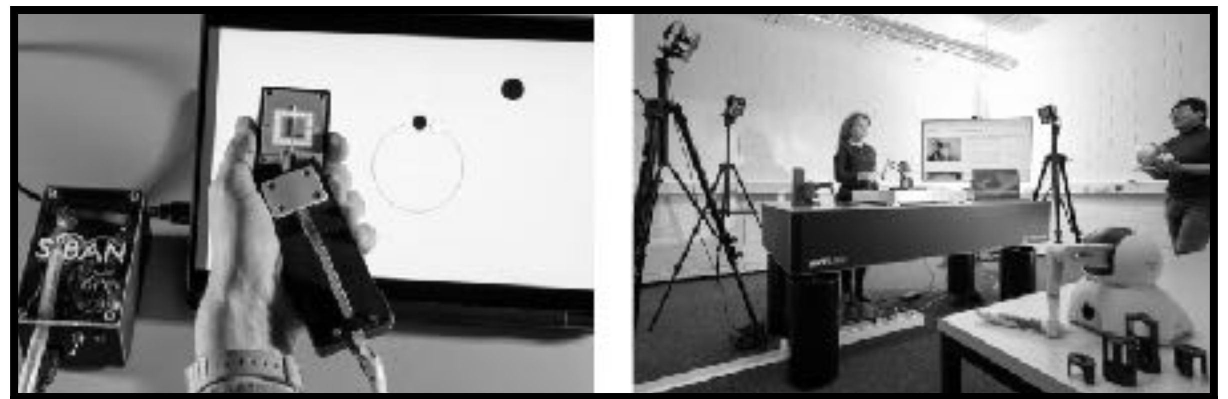
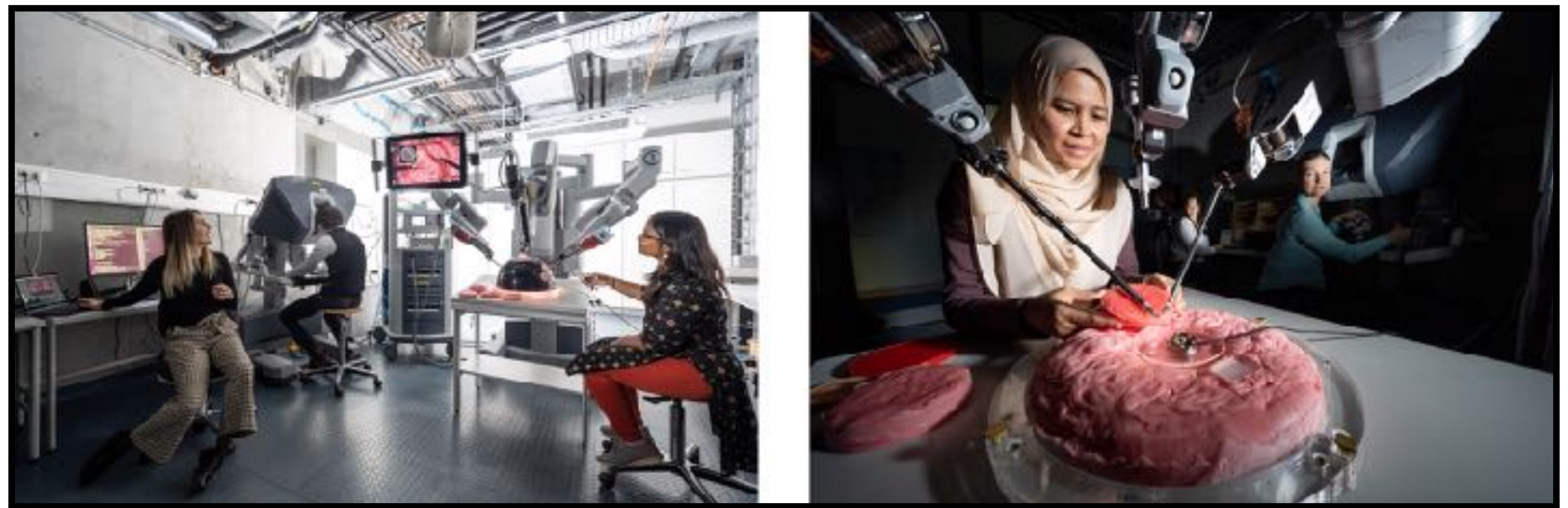

Haptic Interface Technology


Teleoperation Interfaces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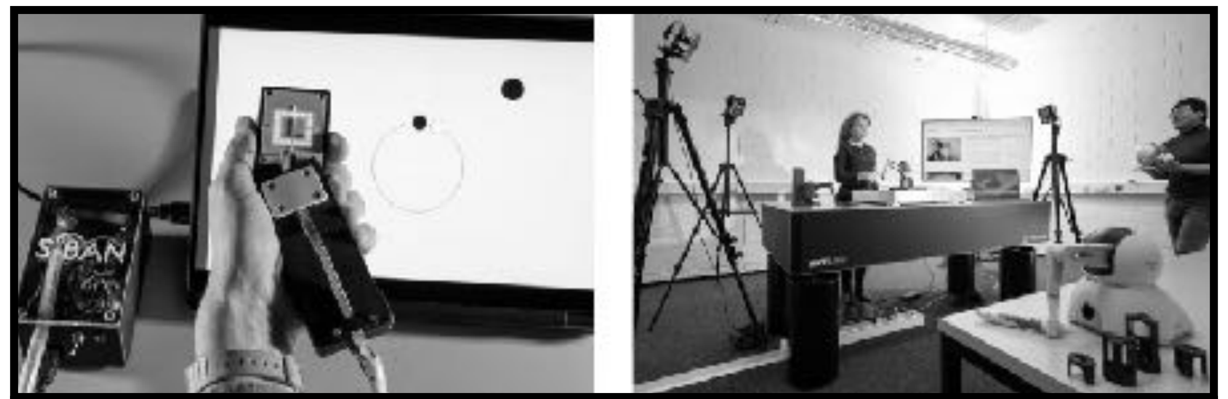

Haptic Interface Technology

Teleoperation Interfaces

Physical Human-Robot Interaction

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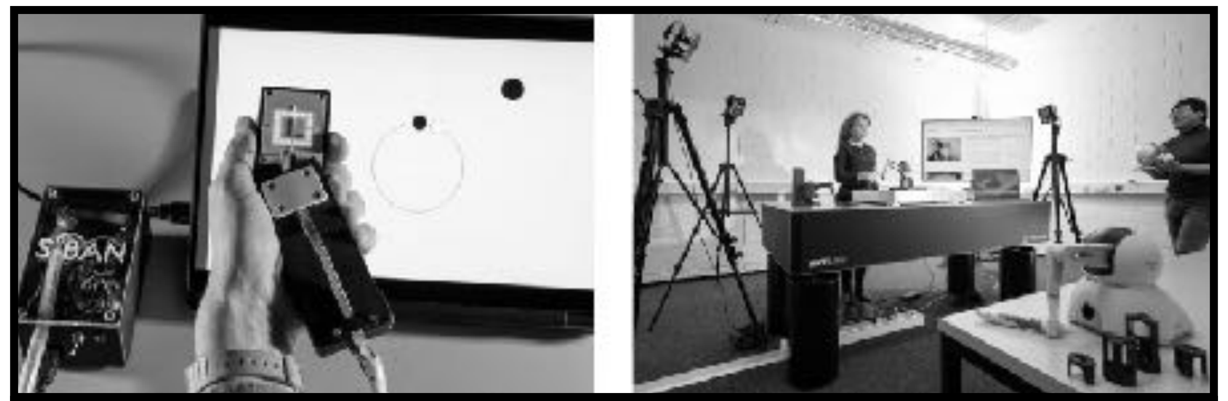
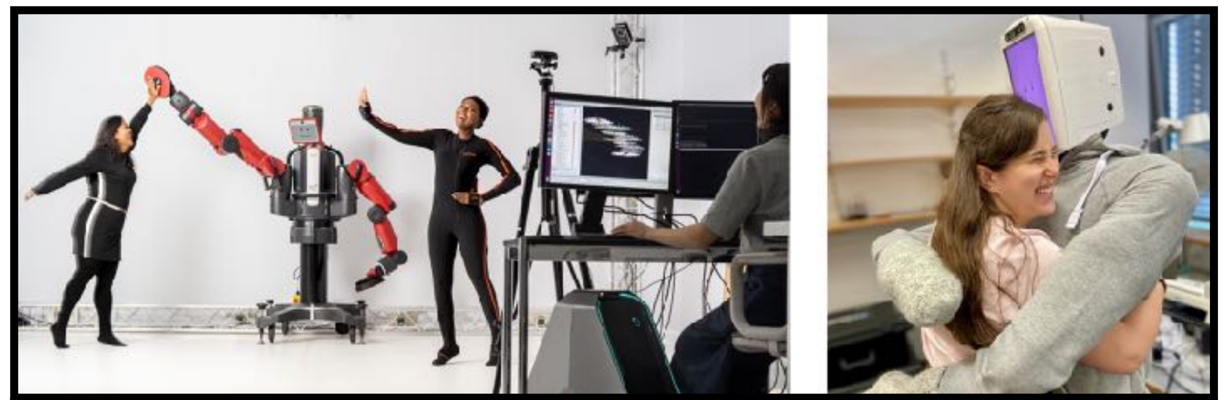

Haptic Interface Technology


Teleoperation Interfaces


Physical Human-Robot Interaction


Touch Sensing



Physical Human-Robot Interaction

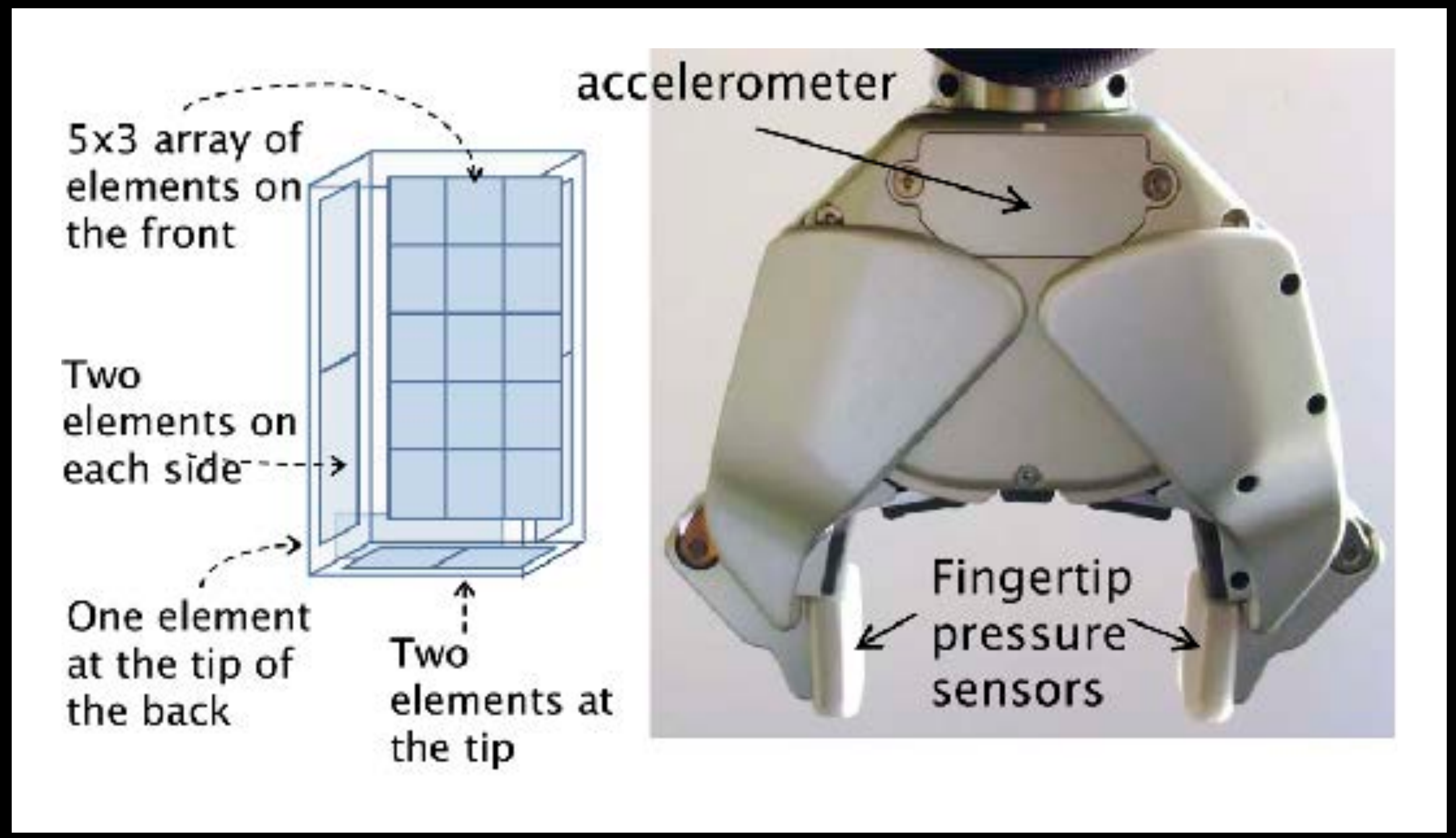
Touch Sensing

Touch Sensing

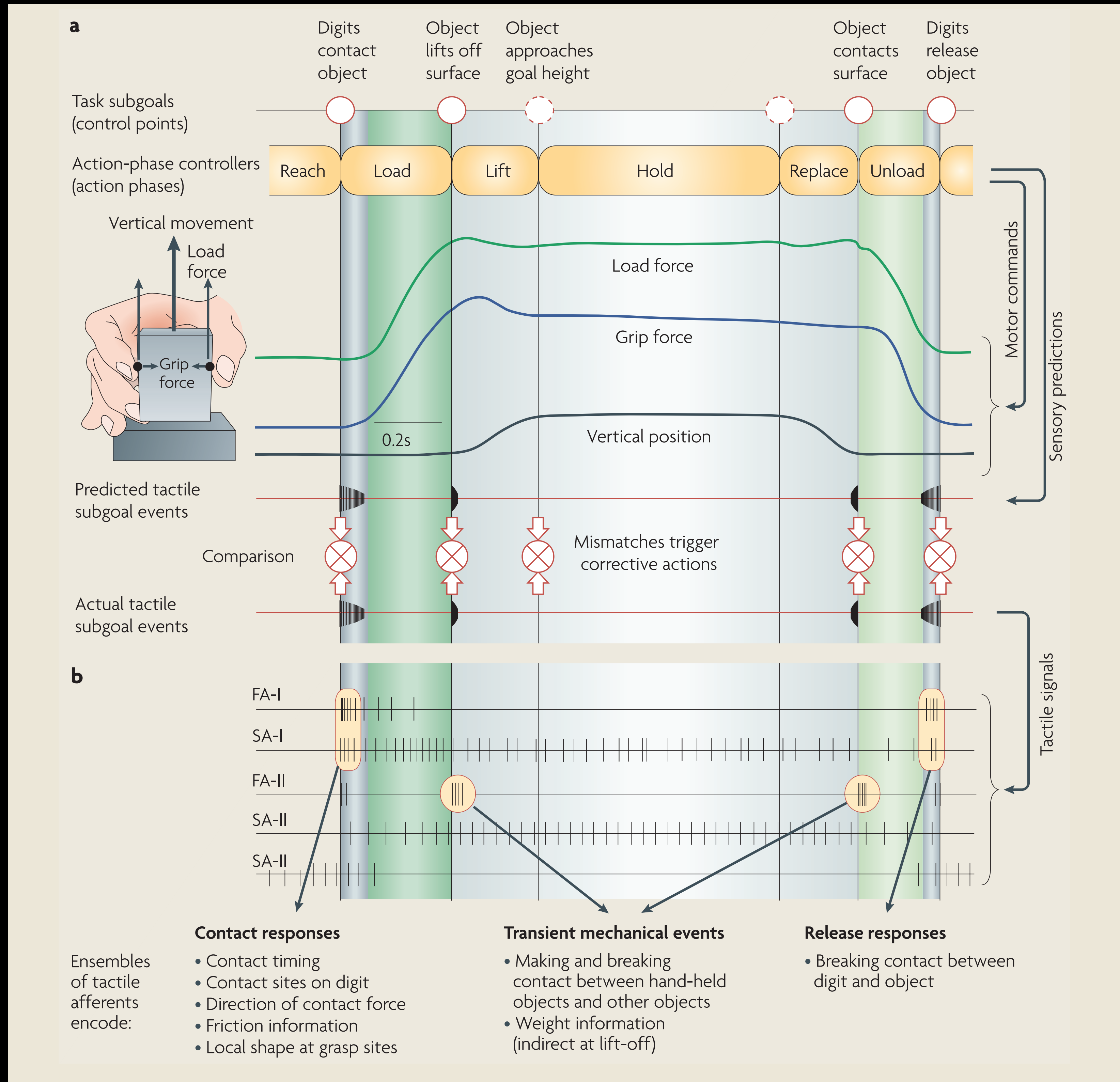
Physical Human-Robot Interaction

How did I start working in these research areas?

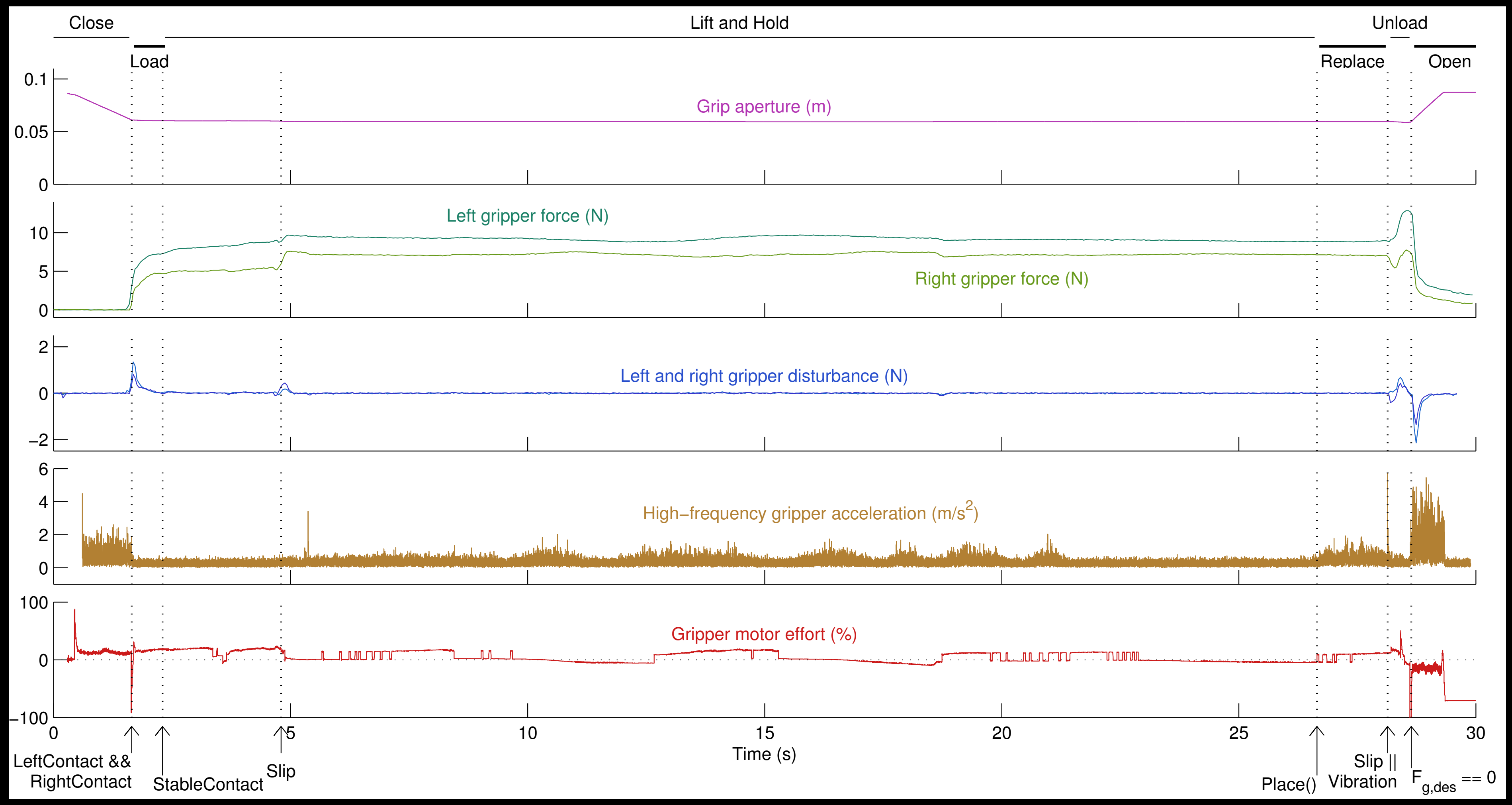
Joe Romano
Penn Ph.D. Student
Intern at Willow Garage
Now at Berkshire Grey

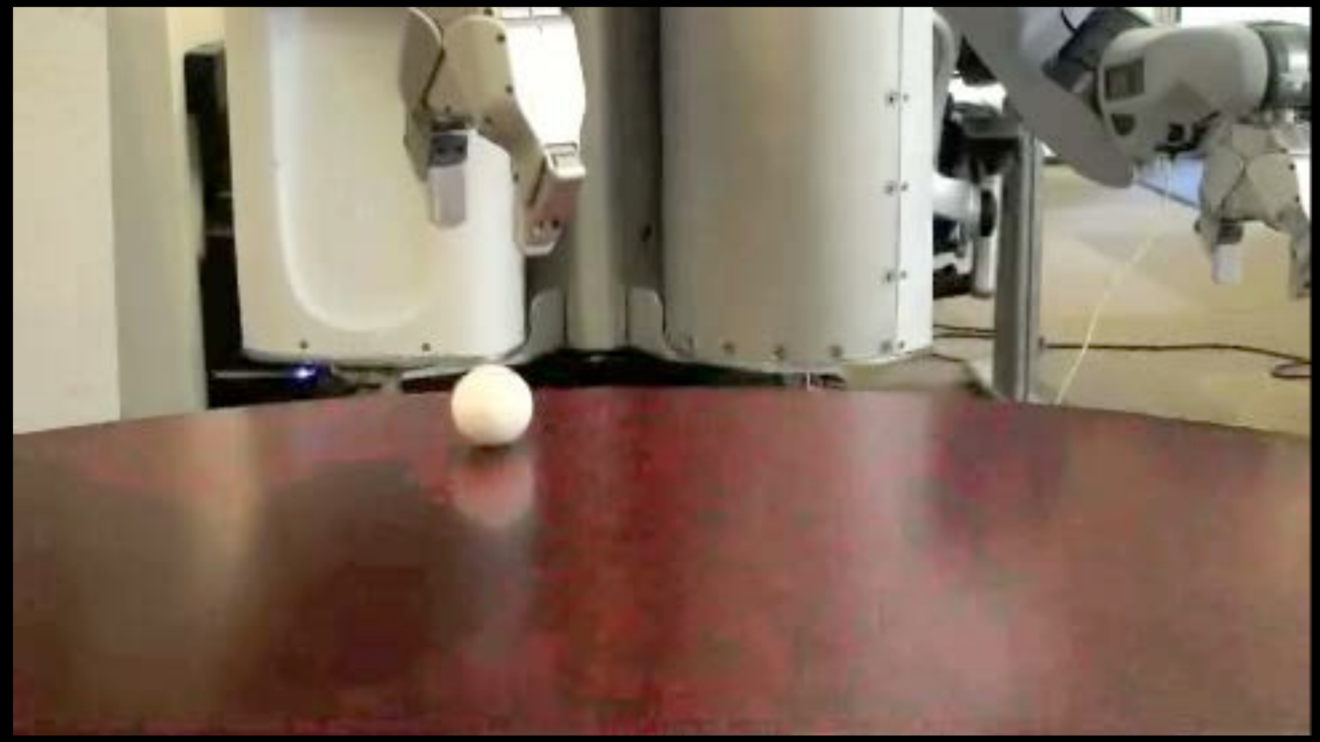


inspiration from human sensorimotor control



Roland S. Johansson and J. Randall Flanagan.
Coding and use of tactile signals from the fingertips in object manipulation tasks.
Nature Reviews: Neuroscience, 10:345–359, 2009.





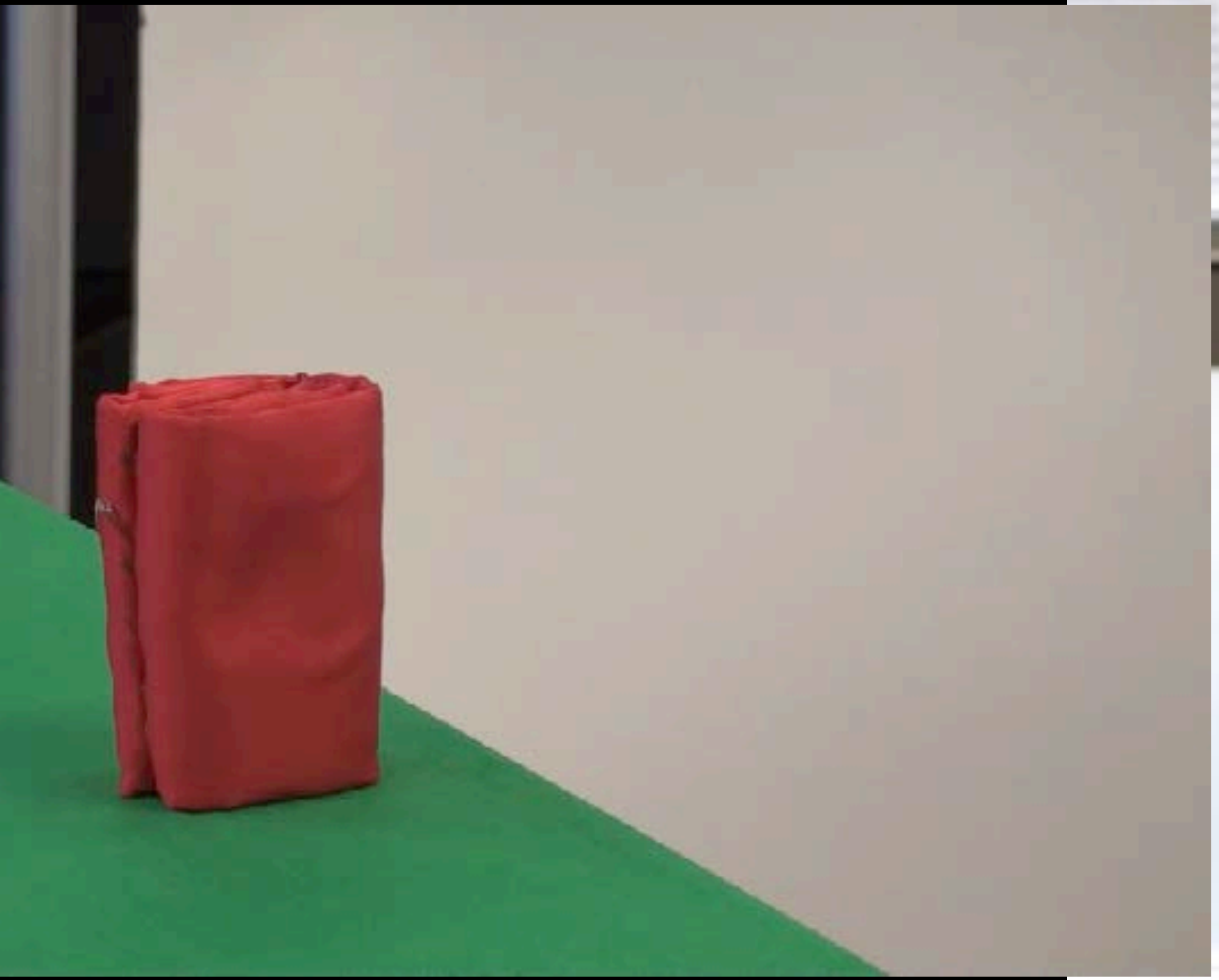
Joseph M. Romano, Kaijen Hsiao, Günter Niemeyer, Sachin Chitta, and Katherine J. Kuchenbecker.
Human-inspired robotic grasp control with tactile sensing. *IEEE Transactions on Robotics*, 27(6):1067–1079, 2011.

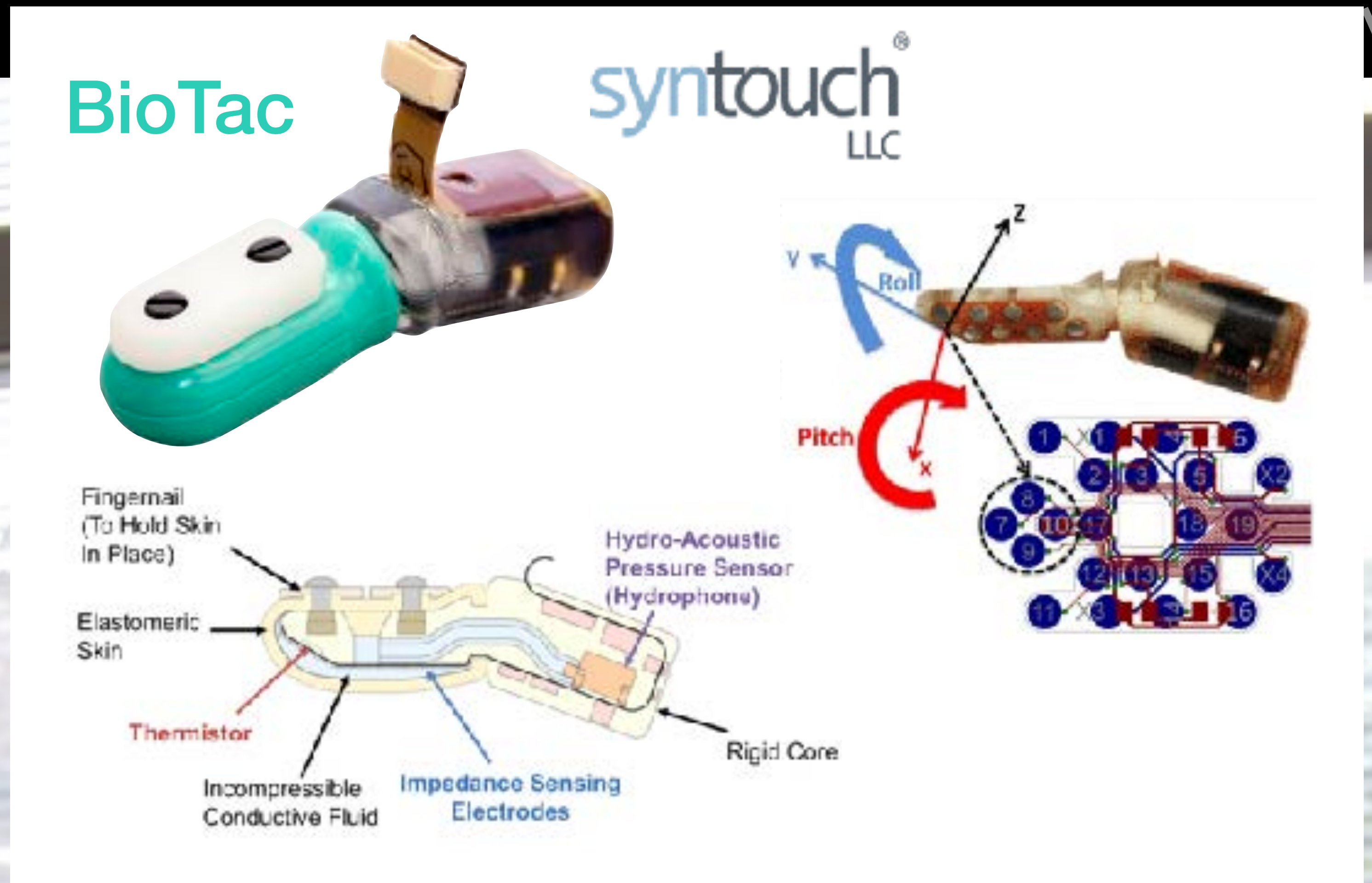
Joe Romano
Penn Ph.D. Student
Intern at Willow Garage
Now at Berkshire Grey

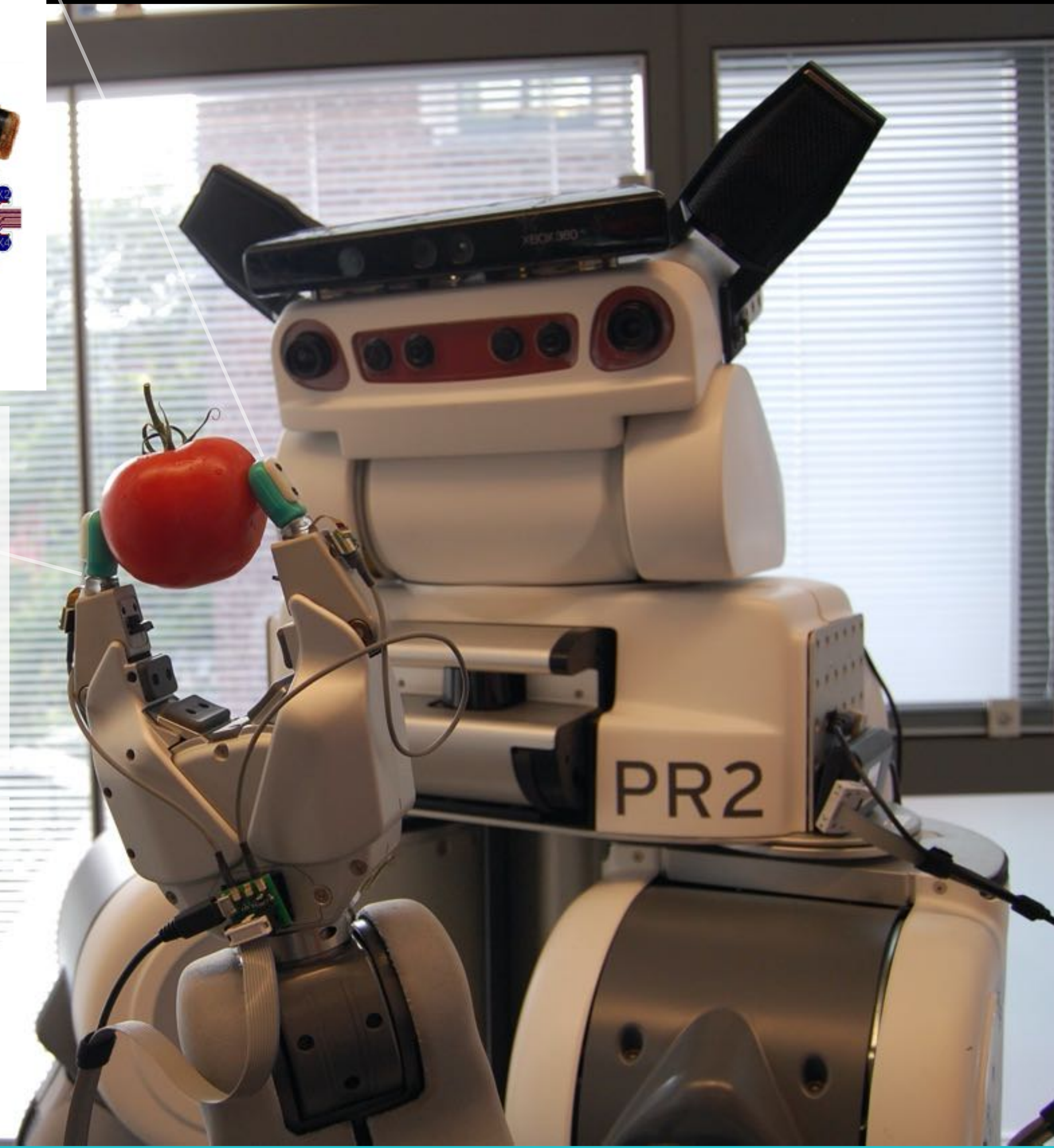
Vivian Chu
Penn Masters Student
Now at Diligent Robotics

Ian McMahon
Penn Masters Student
Now at Toyota RI

Lorenzo Riano
Berkeley Postdoc
Now at Waymo



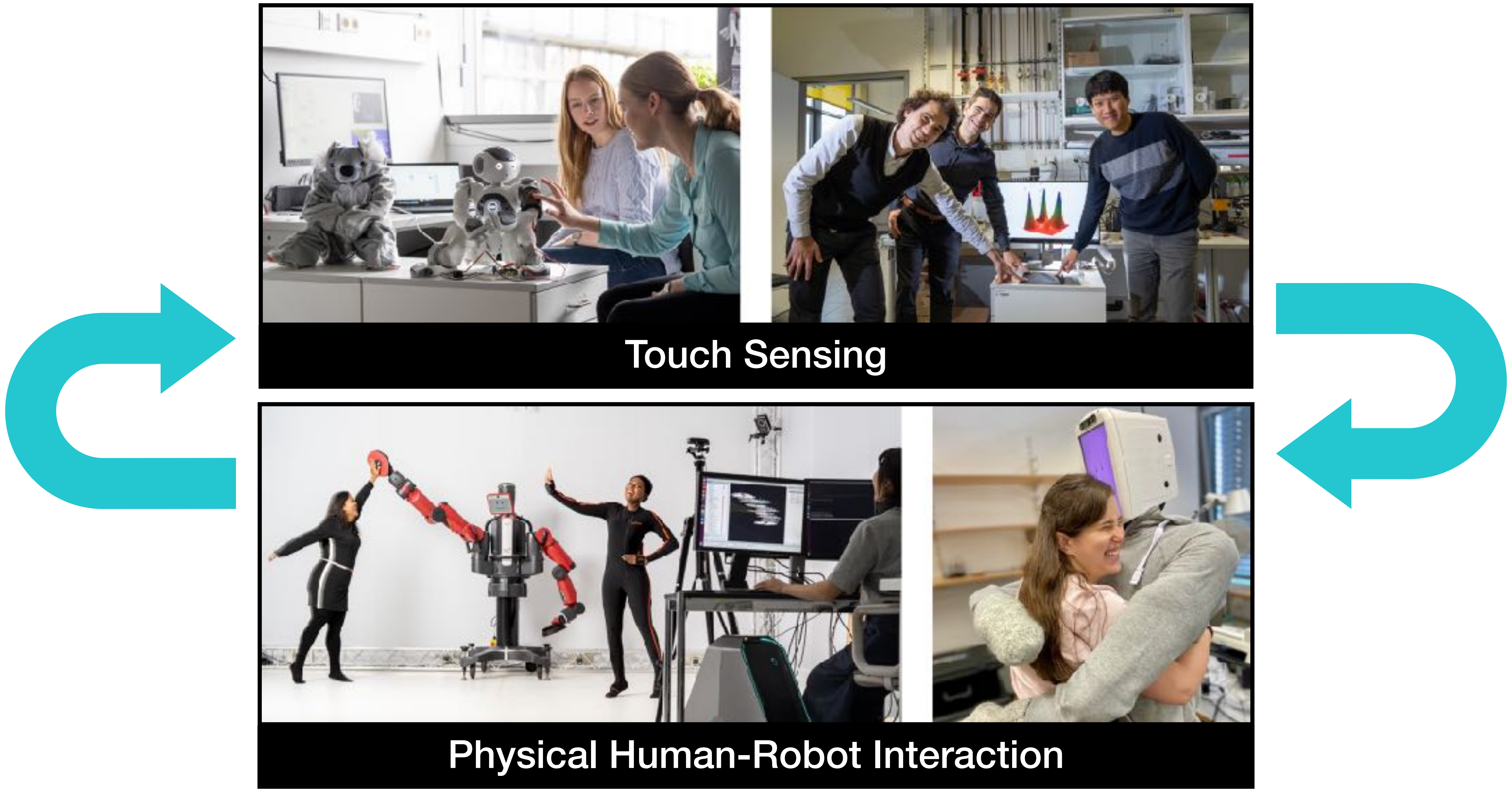




- Multimodal: ~shape, internal pressure, vibration, temperature
- 19 electrode impedance outputs cannot be physically interpreted
- Compact 3D form but small sensitive area
- Delicate, difficult to integrate, and quite expensive

What about other parts of the robot?

Vivian Chu*, Ian McMahon*, Lorenzo Riano*, Craig G. McDonald, Qin He, Jorge Martinez Perez-Tejada, Michael Arrigo, Trevor Darrell, and Katherine J. Kuchenbecker. Robotic learning of haptic adjectives through physical interaction. *Robotics and Autonomous Systems*, 63(3):279–292, 2015. Corrigendum published in June 2016.



My ideal touch sensors:

- are soft
- cover my robot
- detect new contact
- have high dynamic range
- respond quickly
- provide useful information
- are robust and reliable
- integrate easily with my robot
- are low cost and accessible

Insight

HuggieBot

Insight

Huanbo Sun
MPI-IS Ph.D. Student
advised by Georg Martius
just graduated!

Katherine J. Kuchenbecker
Director, MPI-IS

Georg Martius
Max Planck Research
Group Leader, MPI-IS

Iris Andrussow
MPI-IS Ph.D. Student
co-advised by KJK
and Georg Martius

nature machine intelligence

ARTICLES
https://doi.org/10.1038/s42256-021-00439-3

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OPEN

A soft thumb-sized vision-based sensor with accurate all-round force perception

Huanbo Sun[1]✉, Katherine J. Kuchenbecker[2] and Georg Martius[1]✉

Vision-based haptic sensors have emerged as a promising approach to robotic touch due to affordable high-resolution cameras and successful computer vision techniques; however, their physical design and the information they provide do not yet meet the requirements of real applications. We present a robust, soft, low-cost, vision-based, thumb-sized three-dimensional haptic sensor named Insight, which continually provides a directional force-distribution map over its entire conical sensing surface. Constructed around an internal monocular camera, the sensor has only a single layer of elastomer over-moulded on a stiff frame to guarantee sensitivity, robustness and soft contact. Furthermore, Insight uniquely combines photometric stereo and structured light using a collimator to detect the three-dimensional deformation of its easily replaceable flexible outer shell. The force information is inferred by a deep neural network that maps images to the spatial distribution of three-dimensional contact force (normal and shear). Insight has an overall spatial resolution of 0.4 mm, a force magnitude accuracy of around 0.03 N and a force direction accuracy of around five degrees over a range of 0.03–2 N for numerous distinct contacts with varying contact area. The presented hardware and software design concepts can be transferred to a wide variety of robot parts.

Robots have the potential to perform useful physical tasks in a wide range of application areas[1–4]. To robustly manipulate objects in complex and changing environments, a robot must be able to perceive when, where and how its body is contacting other things. Although widely studied and highly successful for environment perception at a distance, centrally mounted cameras and computer vision are poorly suited to real-world robot contact perception due to occlusion and the small scale of the deformations involved. Robots instead need touch-sensitive skin, but few haptic sensors exist that are suitable for practical applications.

Recent developments have shown that machine-learning-based approaches are especially promising for creating dexterous robots[2,5,6]. In such self-learning scenarios and real-world applications, the need for extensive data makes it particularly critical that sensors are robust and keep providing good readings over thousands of hours of rough interaction. Importantly, machine learning also opens new possibilities for tackling this haptic sensing challenge by replacing handcrafted numeric calibration procedures with end-to-end mappings learned from data[7].

Many researchers have created haptic sensors[8] that can quantify contact across a robot's surfaces: previous successful designs produced measurements using resistive[9–13], capacitive[14–16], ferroelectric[17], triboelectric[18] and optoresistive[19,20] transduction approaches. More recently, vision-based haptic sensors[21–26] have demonstrated a new family of solutions, typically using an internal camera that views the soft contact surface from within; however, these existing sensors tend to be fragile, bulky, insensitive, inaccurate and/or expensive. By considering the goals and constraints from a fresh perspective, we have invented a vision-based sensor that overcomes these challenges and is thus suitable for robotic dexterous manipulation.

Table 1 provides a detailed comparison of representative state-of-the-art sensors. We highlight the most important differences and refer the reader to the Methods for a more thorough examination. The mechanical designs of all previous sensors employ multiple functional layers, which are complex to fabricate and can be delicate. Insight is the only sensor with a single soft layer. Many tasks benefit from a large three-dimensional sensing surface rather than small two-dimensional sensing patches; however, only a few other sensors offer three-dimensional surfaces[25,27–29]. Some of them require special lenses[25] or use multiple cameras[27], whereas others are more fragile[28,29]. Insight needs only a single camera and simple manufacturing techniques. Depending on their mechanical design, sensors also have widely varying sensing surface area and sensor volume. We provide area per volume (A/V) in Table 1 as a measure of compactness and find that Insight is among the most compact vision-based sensors with the largest sensing surface.

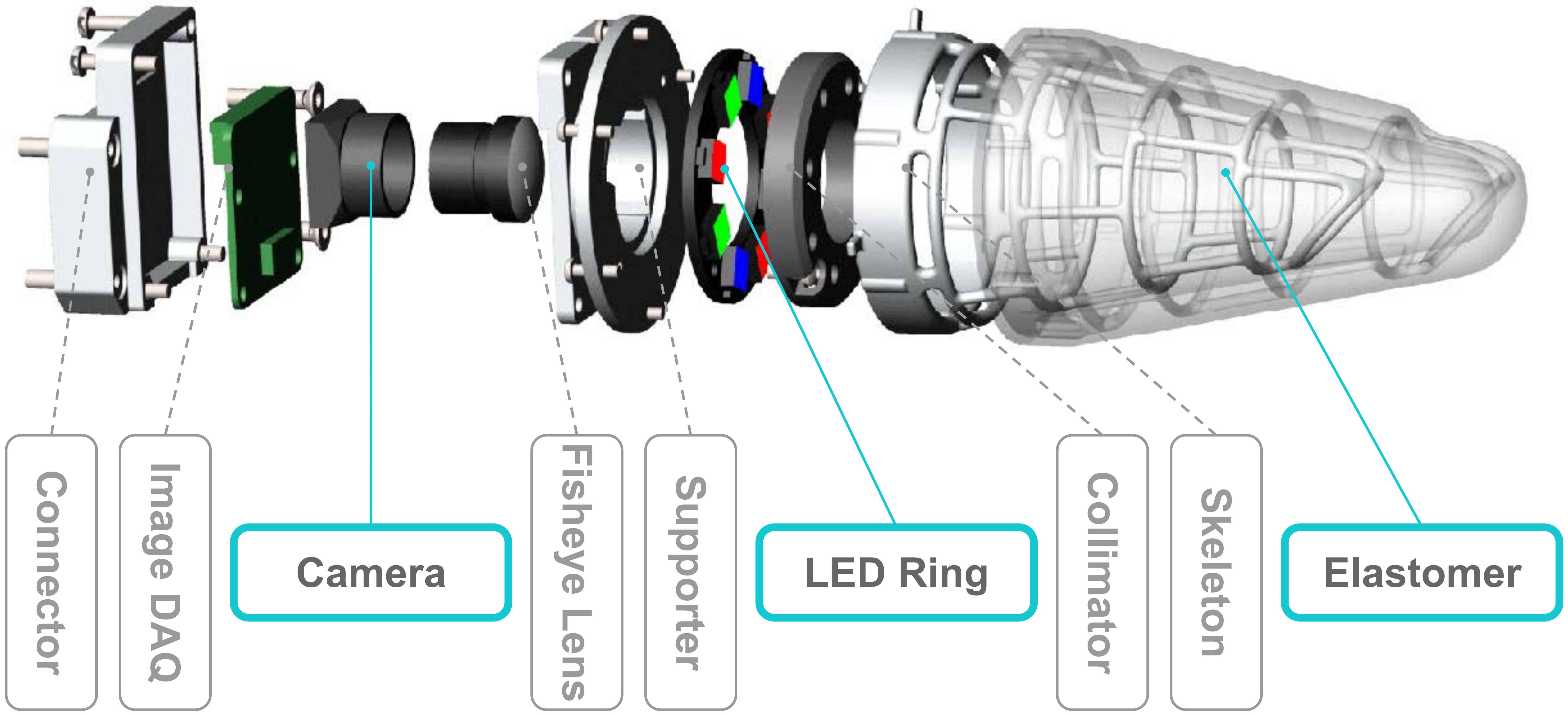
Most existing sensors provide only localization of a single contact[20,25,27,28,30]; some also provide a force magnitude[9,23,31] without force direction. Others are specialized for measuring contact area shape[21,29,32]. Although real contacts will be multiple and complex, a spatially extended map of three-dimensional contact forces over the surface, which we call a force map, is only rarely provided (for example, ref. [22]). Insight is the only sensor that provides a force map across a three-dimensional surface such that a robot can have detailed directional information about simultaneous contacts. Many sensors rely on analytical data processing[22,25,28,33], which requires careful calibration; it is difficult to obtain correct force amplitudes with such an approach as materials are often inhomogeneous and the assumption of linearity between deformation and force is often violated. Data-driven approaches such as those used with a BioTac[9], GelSight[21], OmniTact[27] and Insight can deal with these problems but require copious quality data.

This paper presents a new soft thumb-sized sensor with all-round force-sensing capabilities enabled by vision and machine learning; it is durable, compact, sensitive, accurate and affordable (less than $100). As it consists of a flexible shell around a vision sensor, we name it Insight. Although initially designed for dexterous manipulation and behavioural learning, our sensor is suitable for many other applications and our technology can be adapted to create a variety of three-dimensional haptic sensing systems.

[1]Autonomous Learning Group, Max Planck Institute for Intelligent Systems, Tübingen, Germany. [2]Haptic Intelligence Department, Max Planck Institute for Intelligent Systems, Stuttgart, Germany. ✉e-mail: huanbo.sun@tuebingen.mpg.de; georg.martius@tuebingen.mpg.de

Insight

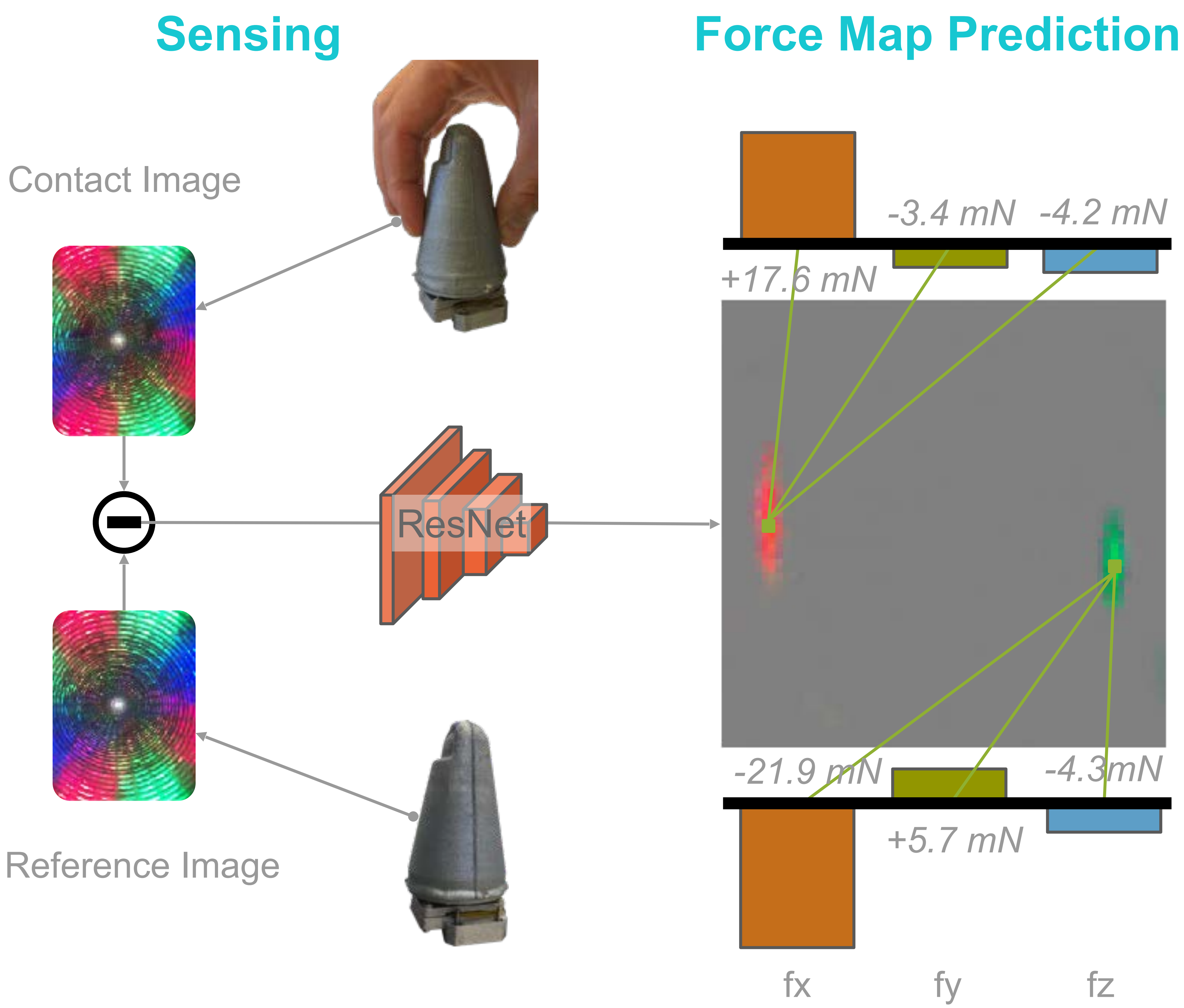
A Haptic Sensor Powered by Vision and Machine Learning

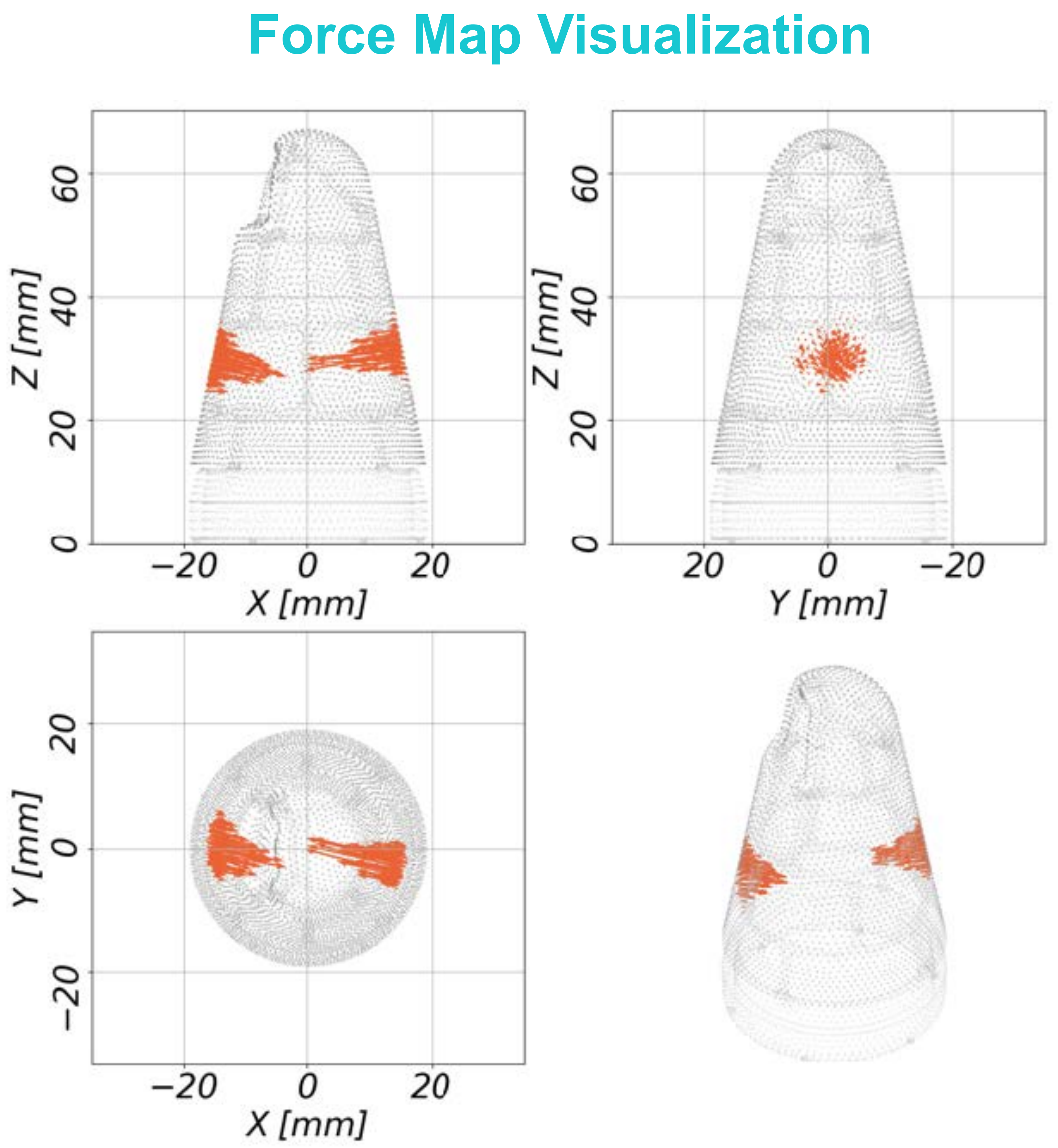


Huanbo Sun, Katherine J. Kuchenbecker, and Georg Martius. A soft thumb-sized vision-based sensor with accurate all-round force perception. *Nature Machine Intelligence*, 4: 135–145, February 2022.

Insight

Data Processing Pipeline

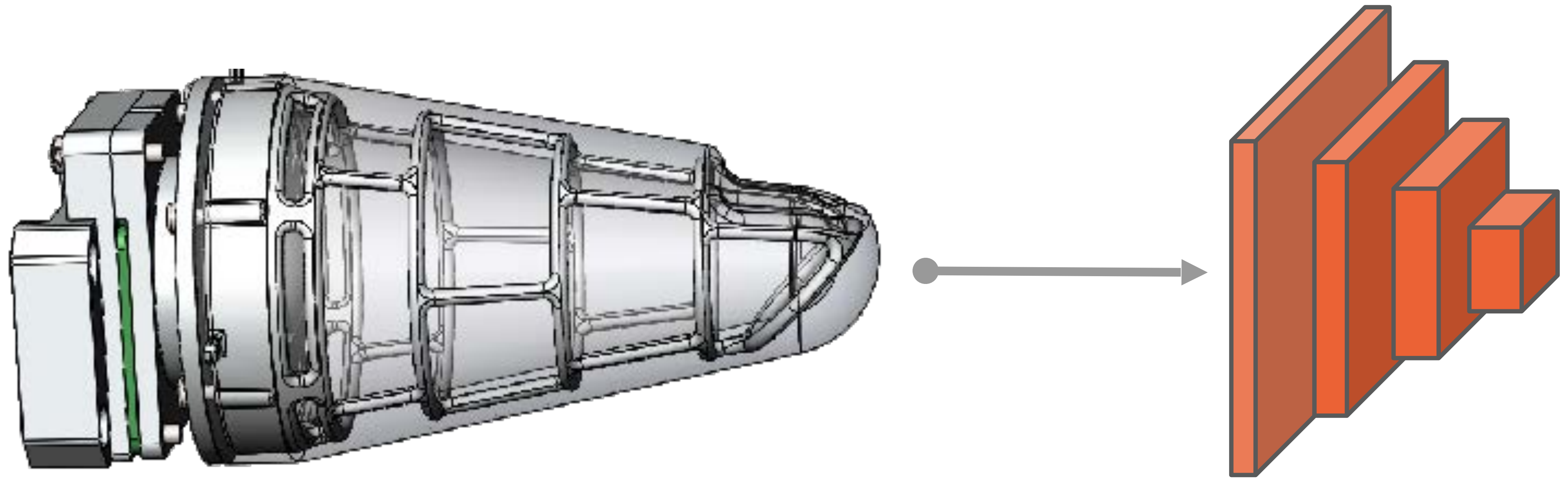


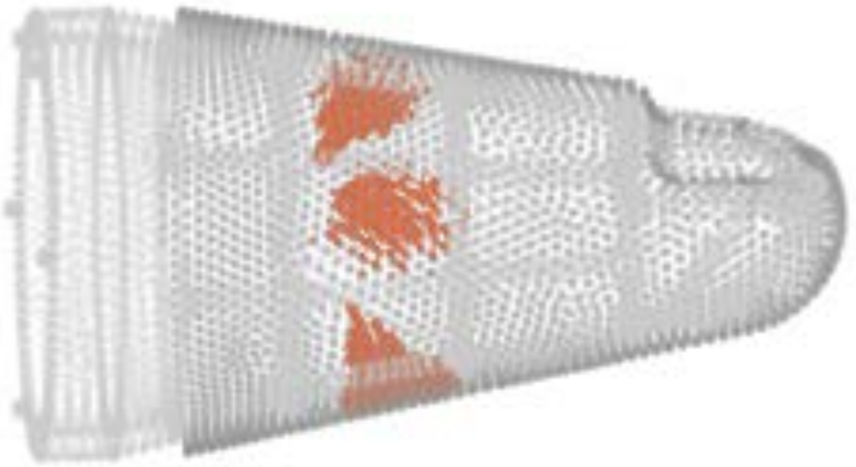


Huanbo Sun, Katherine J. Kuchenbecker, and Georg Martius. A soft thumb-sized vision-based sensor with accurate all-round force perception. *Nature Machine Intelligence*, 4: 135–145, February 2022.

Insight

Key Design Components





1. **Mechanics**: soft-rigid hybrid structure
2. **Imaging**: a single camera & structured light
3. **Data**: automatic collection
4. **AI**: deep learning

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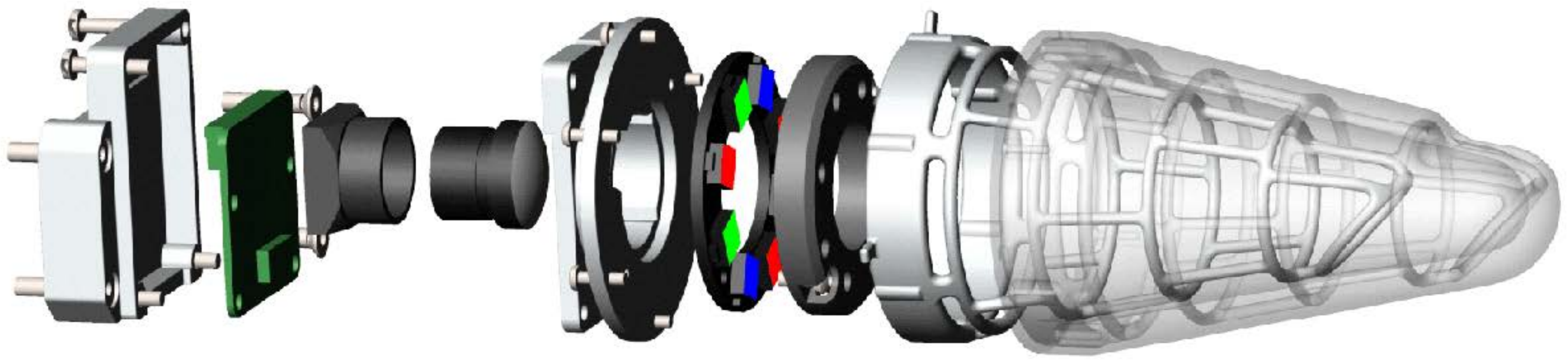
Insight

Key Design Components: 1. Mechanics



Elastomer Skin for **Sensitivity**

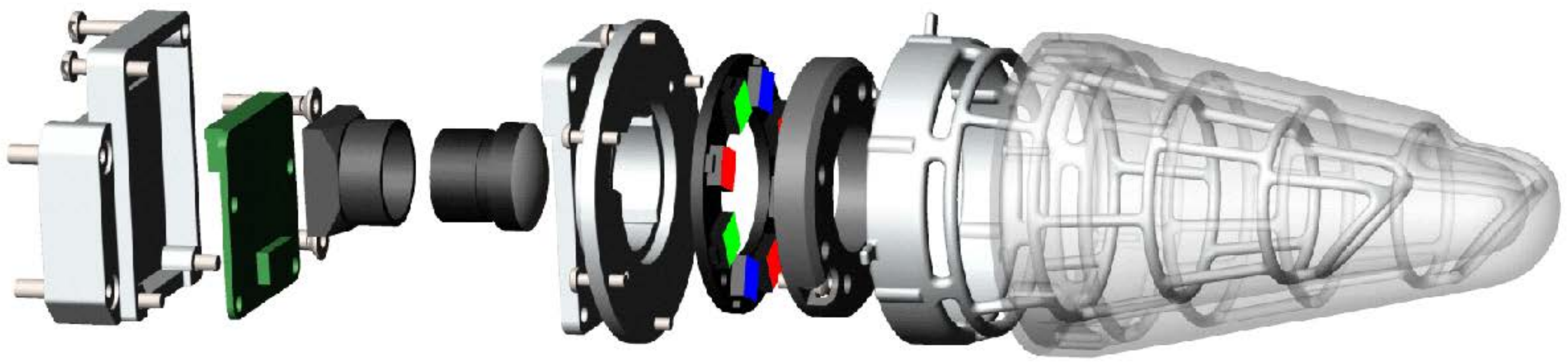
Metal Frame for **Robustness**

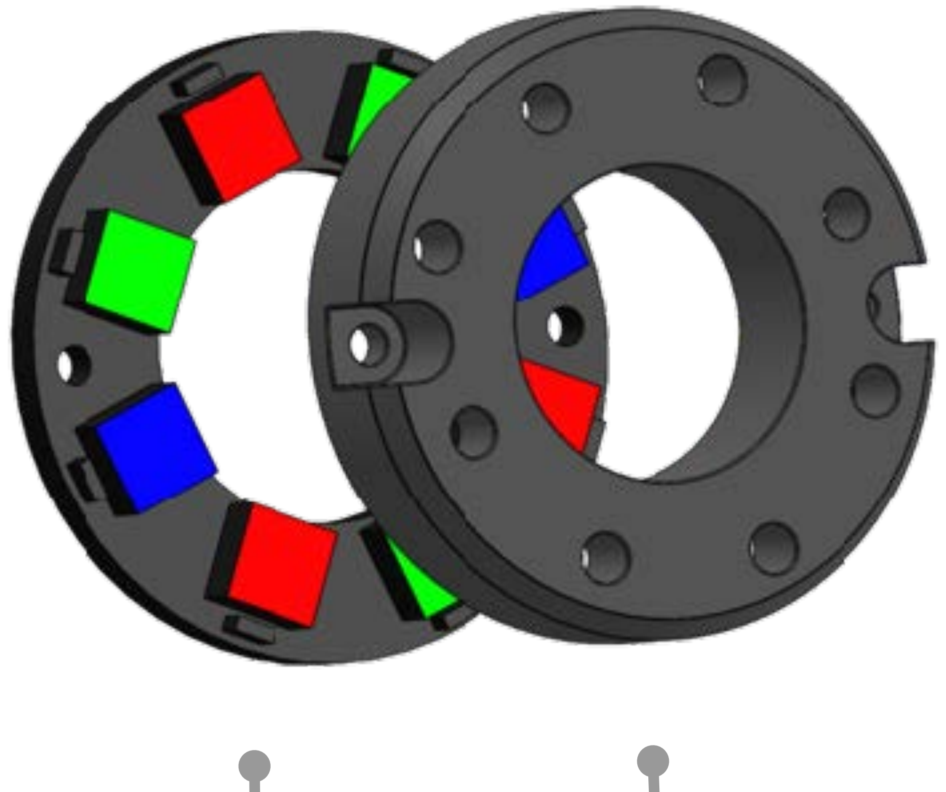
Soft-stiff Hybrid

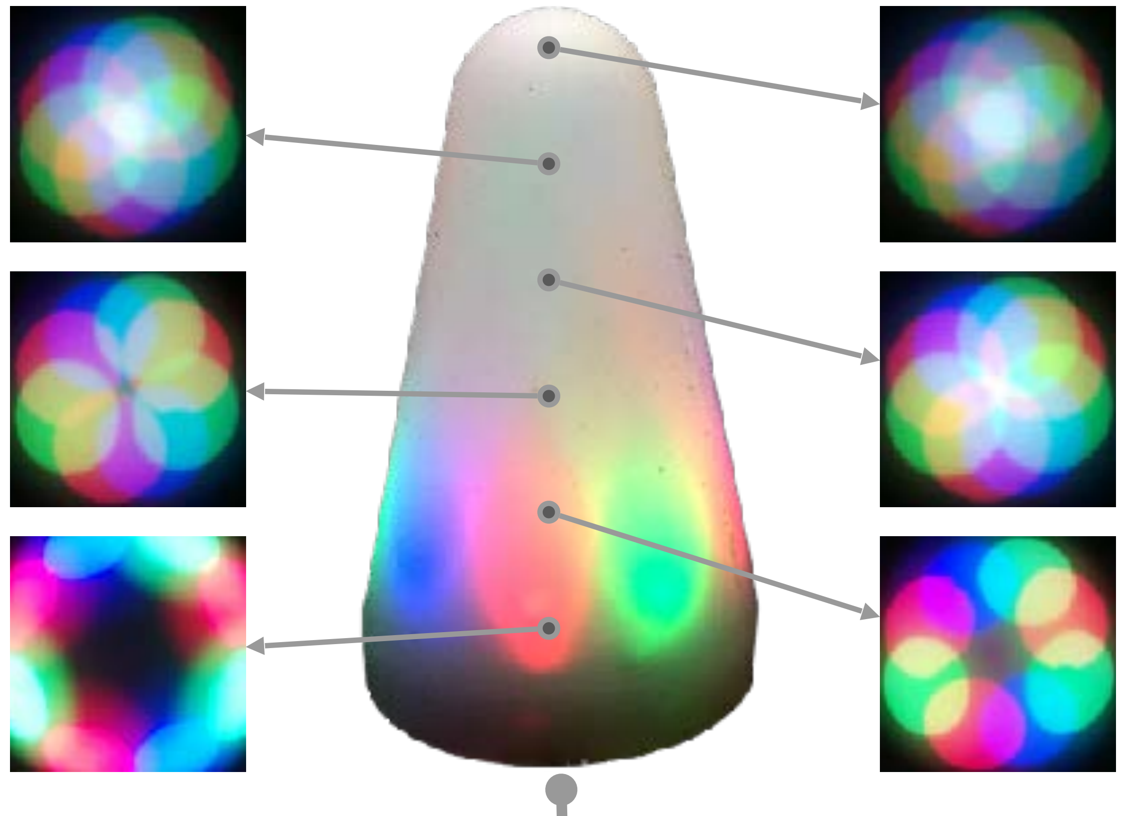
Huanbo Sun, Katherine J. Kuchenbecker, and Georg Martius. A soft thumb-sized vision-based sensor with accurate all-round force perception. *Nature Machine Intelligence*, 4: 135–145, February 2022.

Insight

Key Design Components: 2. Lighting

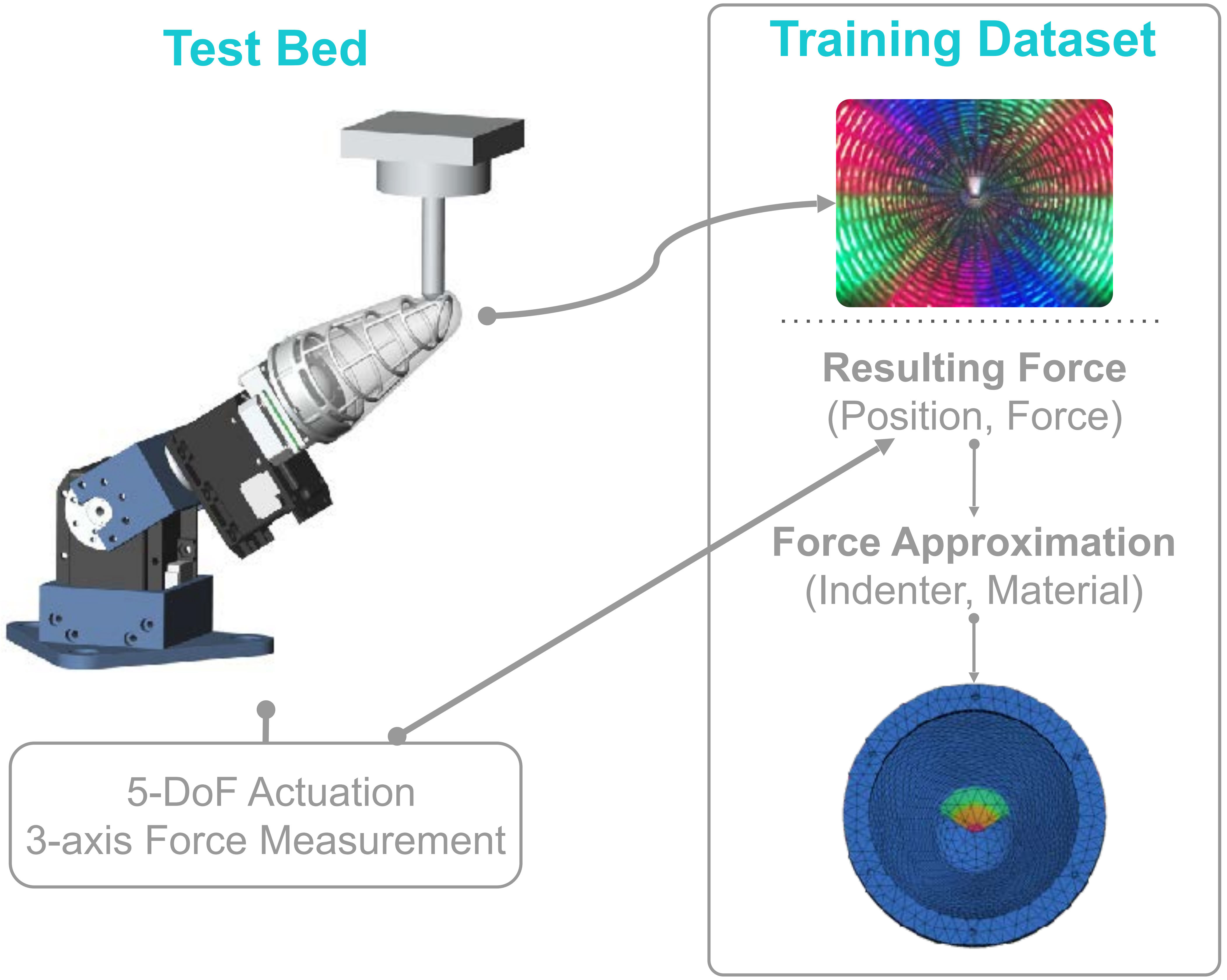


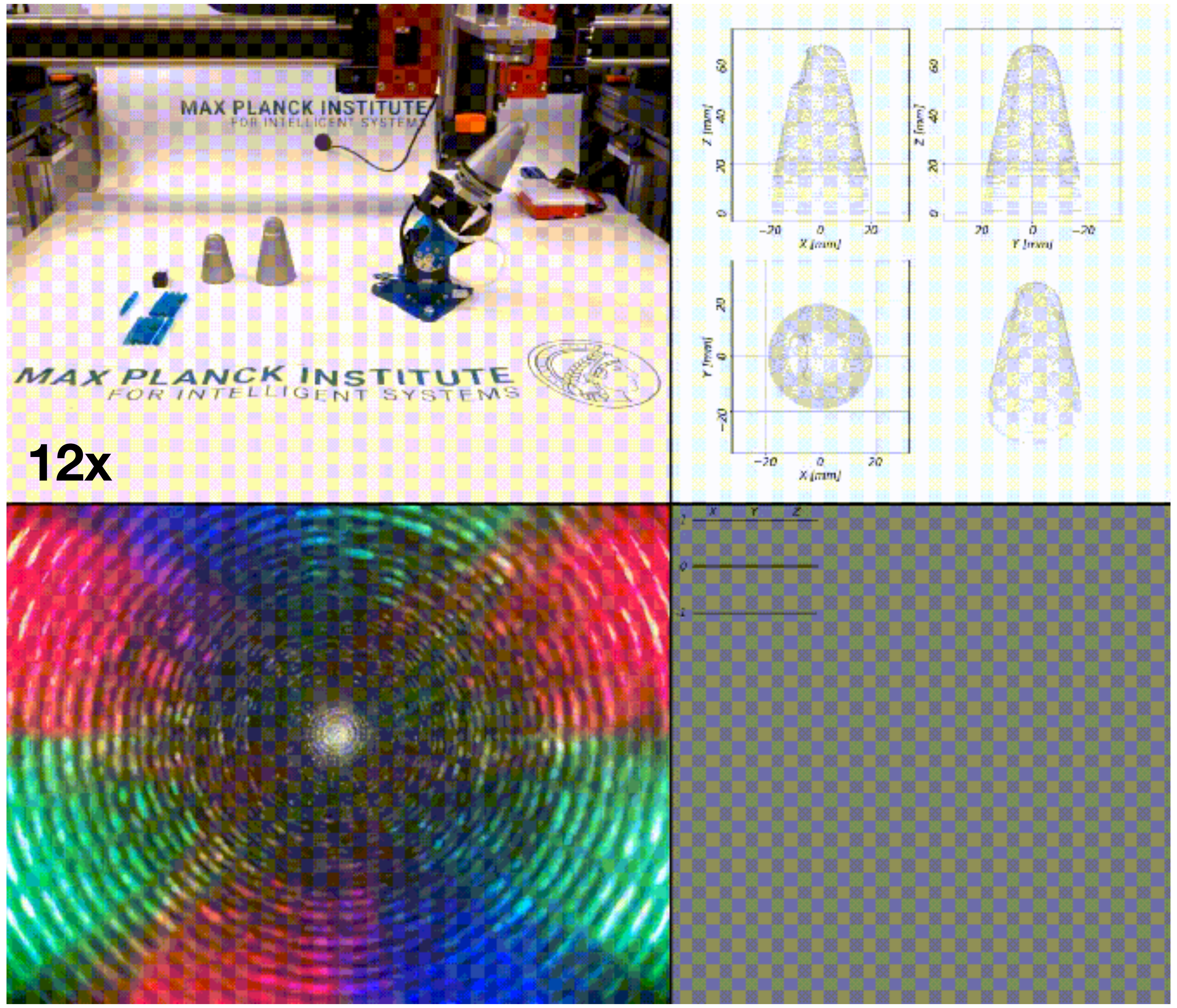




Insight

Key Design Components: 3. Data

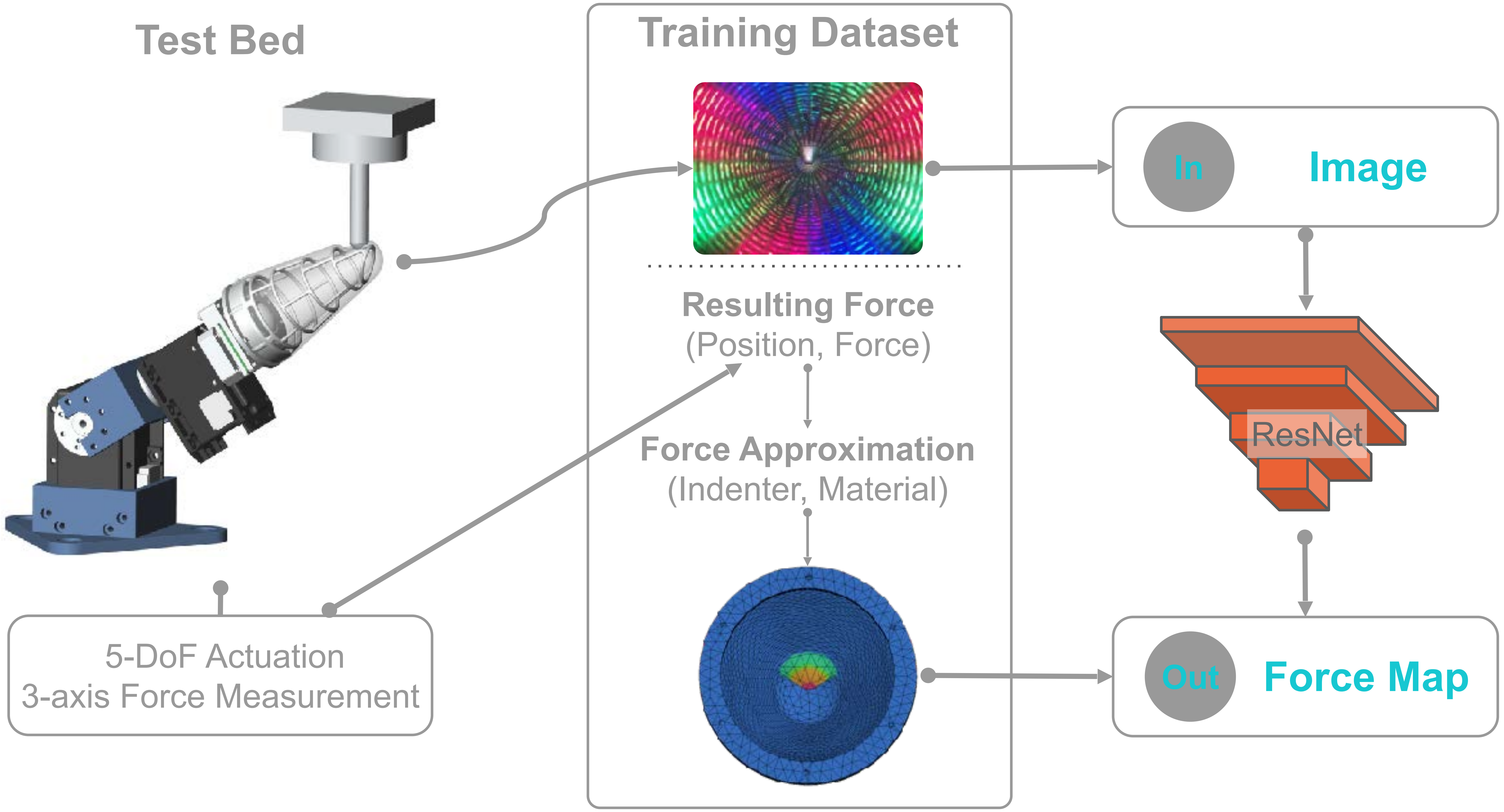




Huanbo Sun, Katherine J. Kuchenbecker, and Georg Martius. A soft thumb-sized vision-based sensor with accurate all-round force perception. *Nature Machine Intelligence*, 4: 135–145, February 2022.

Insight

Key Design Components: 4. AI



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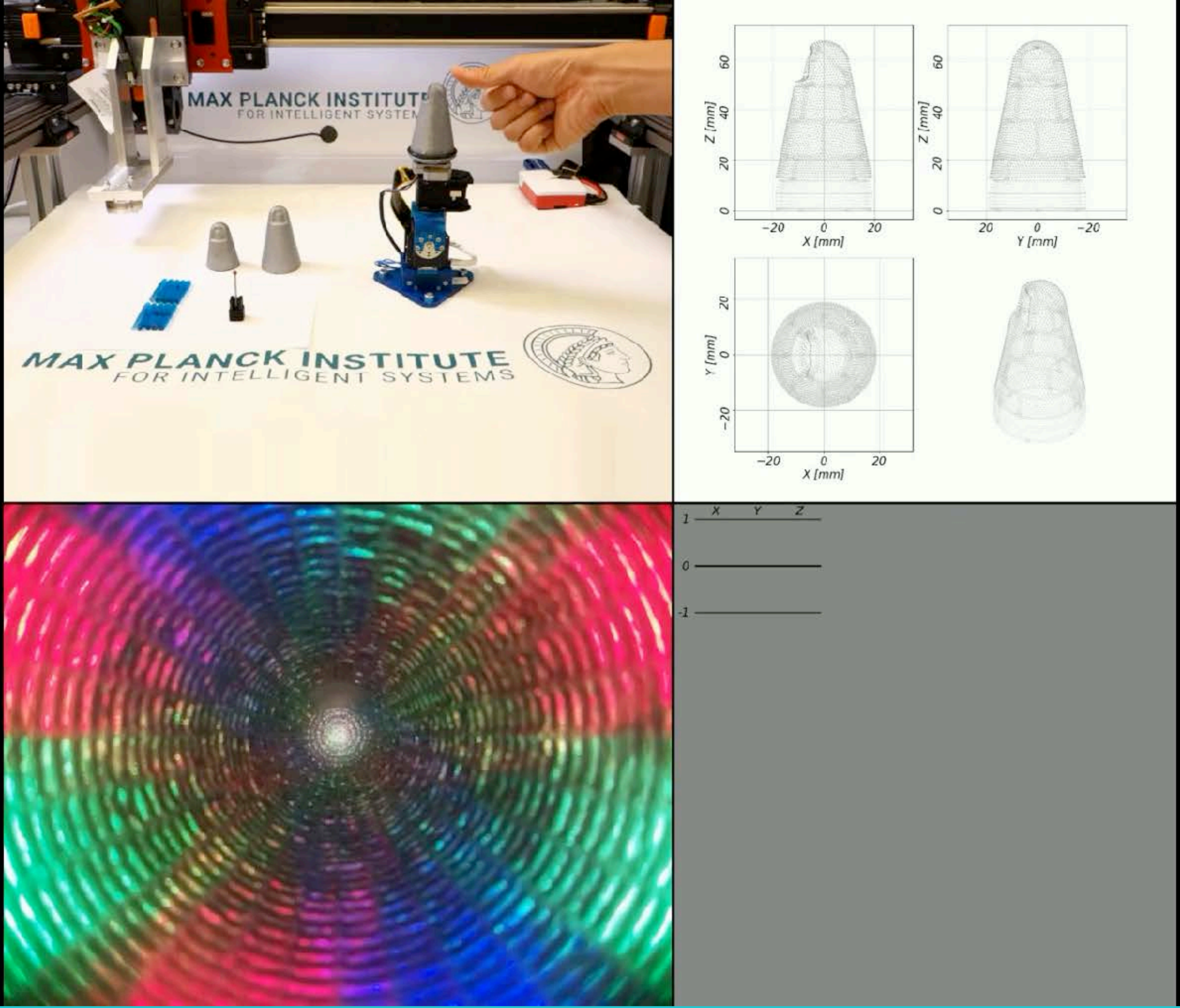

0.5x

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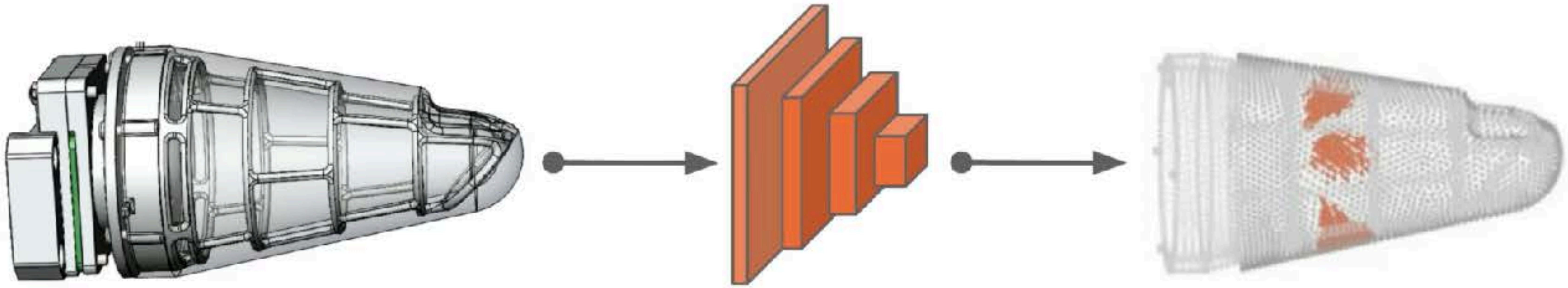


1. **Mechanics**: soft-rigid hybrid structure
2. **Imaging**: a single camera & structured light
3. **Data**: automatic collection
4. **AI**: deep learning

Overall spatial resolution of about 0.4 mm

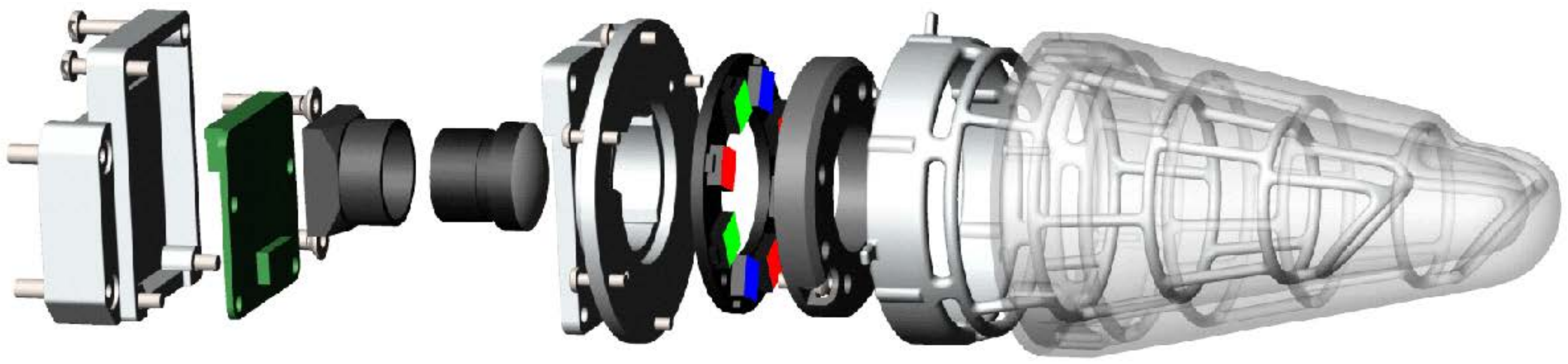
Force magnitude accuracy of about 0.03 N

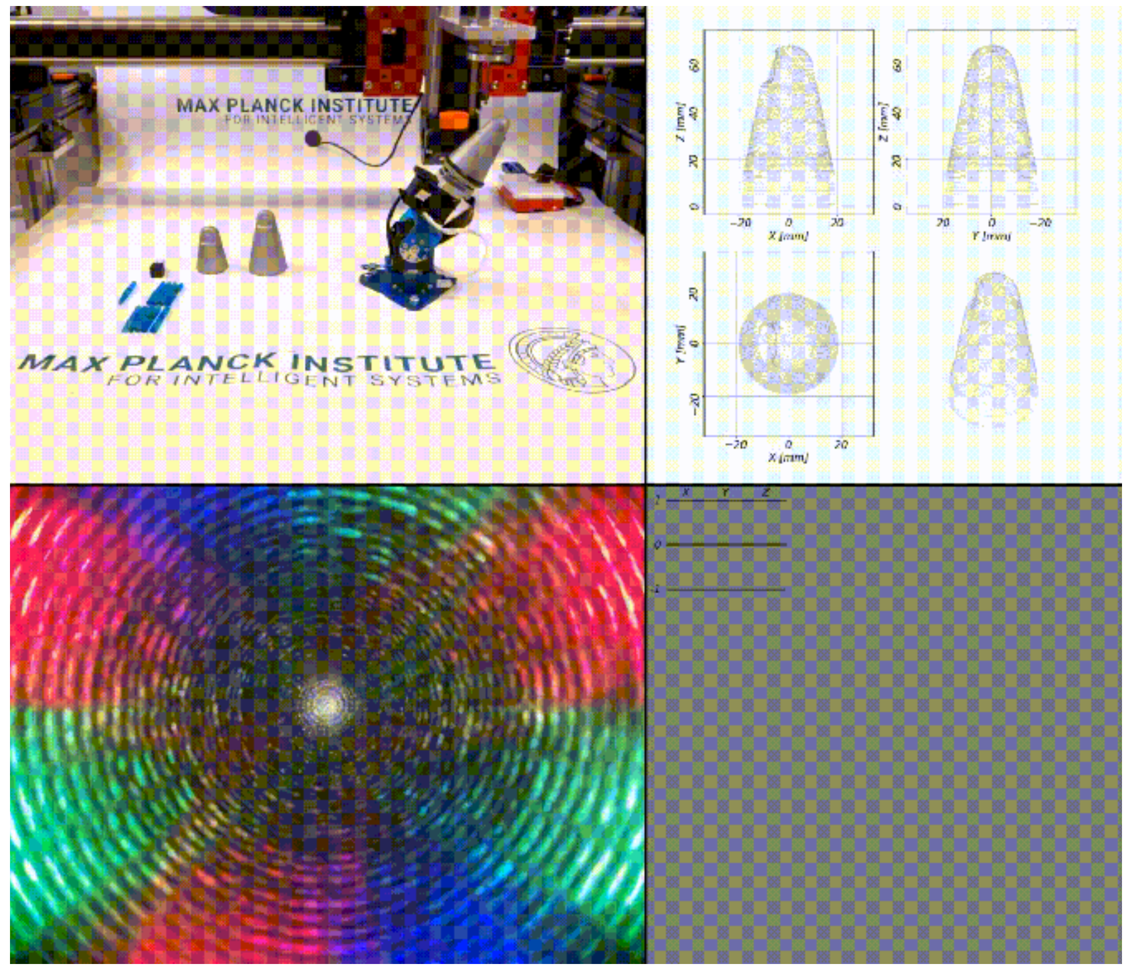
Force direction accuracy around 5 degrees over a range of 0.03 N to 2.00 N

Insight can even discern its own orientation relative to gravity

Huanbo Sun, Katherine J. Kuchenbecker, and Georg Martius. A soft thumb-sized vision-based sensor with accurate all-round force perception. *Nature Machine Intelligence*, 4: 135–145, February 2022.

Insight





Huanbo Sun
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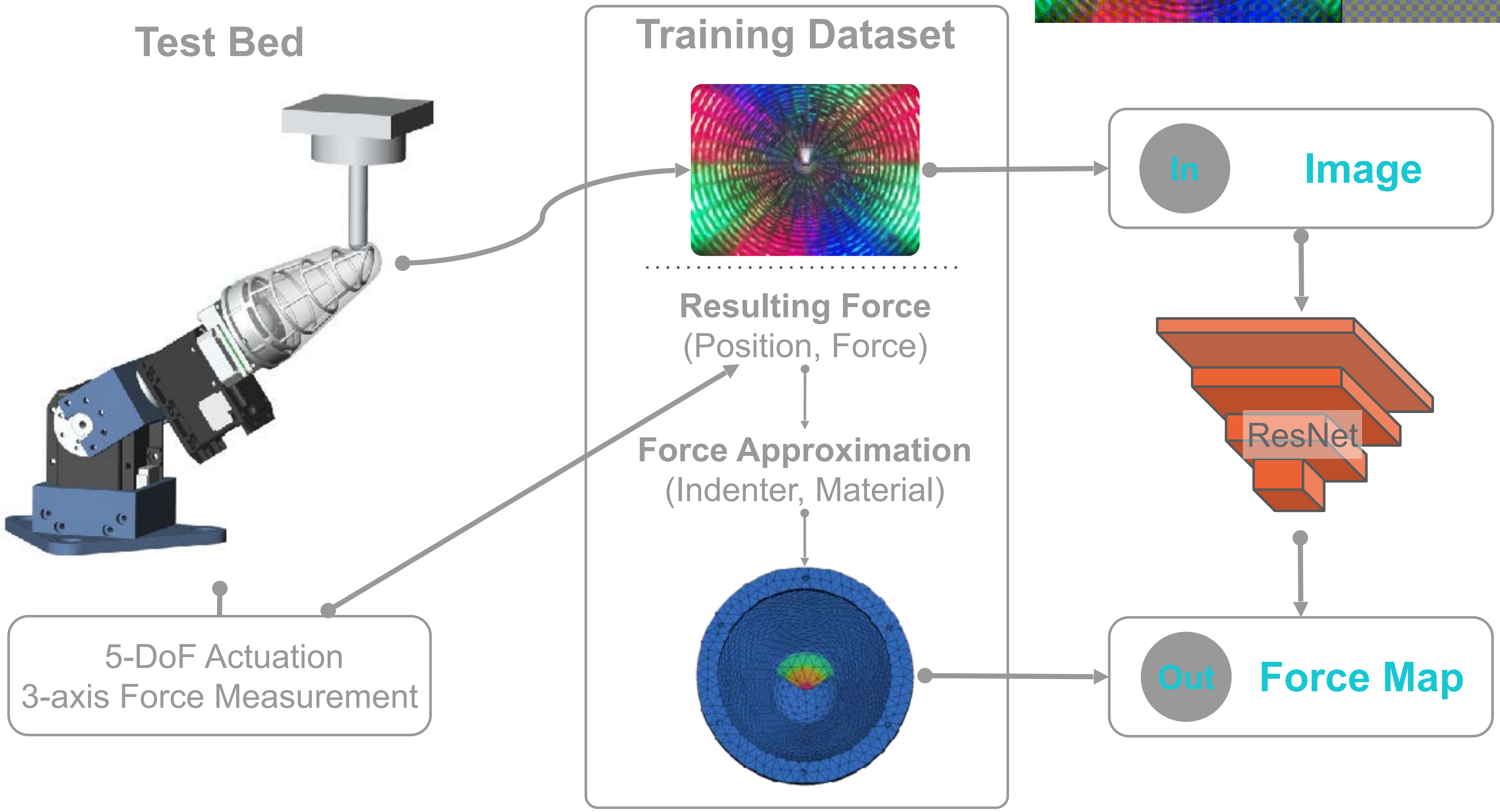
advised by Georg Martius
just graduated!

Katherine J. Kuchenbecker
Director, MPI-IS

Georg Martius
Max Planck Research
Group Leader, MPI-IS

Iris Andrussow
MPI-IS Ph.D. Student
co-advised by KJK
and Georg Martius



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ARTICLES

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A soft thumb-sized vision-based sensor with accurate all-round force perception

Huanbo Sun[1] ✉, Katherine J. Kuchenbecker[2] and Georg Martius[1] ✉

Vision-based haptic sensors have emerged as a promising approach to robotic touch due to affordable high-resolution cameras and successful computer vision techniques; however, their physical design and the information they provide do not yet meet the requirements of real applications. We present a robust, soft, low-cost, vision-based, thumb-sized three-dimensional haptic sensor named Insight, which continually provides a directional force-distribution map over its entire conical sensing surface. Constructed around an internal monocular camera, the sensor has only a single layer of elastomer over-moulded on a stiff frame to guarantee sensitivity, robustness and soft contact. Furthermore, Insight uniquely combines photometric stereo and structured light using a collimator to detect the three-dimensional deformation of its easily replaceable flexible outer shell. The force information is inferred by a deep neural network that maps images to the spatial distribution of three-dimensional contact force (normal and shear). Insight has an overall spatial resolution of 0.4 mm, a force magnitude accuracy of around 0.03 N and a force direction accuracy of around five degrees over a range of 0.03–2 N for numerous distinct contacts with varying contact area. The presented hardware and software design concepts can be transferred to a wide variety of robot parts.

Robots have the potential to perform useful physical tasks in a wide range of application areas[1–4]. To robustly manipulate objects in complex and changing environments, a robot must be able to perceive when, where and how its body is contacting other things. Although widely studied and highly successful for environment perception at a distance, centrally mounted cameras and computer vision are poorly suited to real-world robot contact perception due to occlusion and the small scale of the deformations involved. Robots instead need touch-sensitive skin, but few haptic sensors exist that are suitable for practical applications.

Recent developments have shown that machine-learning-based approaches are especially promising for creating dexterous robots[2,5,6]. In such self-learning scenarios and real-world applications, the need for extensive data makes it particularly critical that sensors are robust and keep providing good readings over thousands of hours of rough interaction. Importantly, machine learning also opens new possibilities for tackling this haptic sensing challenge by replacing handcrafted numeric calibration procedures with end-to-end mappings learned from data[7].

Many researchers have created haptic sensors[8] that can quantify contact across a robot's surfaces: previous successful designs produced measurements using resistive[9–13], capacitive[14–16], ferroelectric[17], triboelectric[18] and optoresistive[19,20] transduction approaches. More recently, vision-based haptic sensors[21–26] have demonstrated a new family of solutions, typically using an internal camera that views the soft contact surface from within; however, these existing sensors tend to be fragile, bulky, insensitive, inaccurate and/or expensive. By considering the goals and constraints from a fresh perspective, we have invented a vision-based sensor that overcomes these challenges and is thus suitable for robotic dexterous manipulation.

Table 1 provides a detailed comparison of representative state-of-the-art sensors. We highlight the most important differences and refer the reader to the Methods for a more thorough examination. The mechanical designs of all previous sensors employ multiple functional layers, which are complex to fabricate and can be delicate. Insight is the only sensor with a single soft layer. Many tasks benefit from a large three-dimensional sensing surface rather than small two-dimensional sensing patches; however, only a few other sensors offer three-dimensional surfaces[25,27–29]. Some of them require special lenses[25] or use multiple cameras[27], whereas others are more fragile[28,29]. Insight needs only a single camera and simple manufacturing techniques. Depending on their mechanical design, sensors also have widely varying sensing surface area and sensor volume. We provide area per volume (A/V) in Table 1 as a measure of compactness and find that Insight is among the most compact vision-based sensors with the largest sensing surface.

Most existing sensors provide only localization of a single contact[20,25,27,28,30]; some also provide a force magnitude[9,23,31] without force direction. Others are specialized for measuring contact area shape[21,29,32]. Although real contacts will be multiple and complex, a spatially extended map of three-dimensional contact forces over the surface, which we call a force map, is only rarely provided (for example, ref. [22]). Insight is the only sensor that provides a force map across a three-dimensional surface such that a robot can have detailed directional information about simultaneous contacts. Many sensors rely on analytical data processing[22,25,28,33], which requires careful calibration; it is difficult to obtain correct force amplitudes with such an approach as materials are often inhomogeneous and the assumption of linearity between deformation and force is often violated. Data-driven approaches such as those used with a BioTac[9], GelSight[21], OmniTact[27] and Insight can deal with these problems but require copious quality data.

This paper presents a new soft thumb-sized sensor with all-round force-sensing capabilities enabled by vision and machine learning; it is durable, compact, sensitive, accurate and affordable (less than $100). As it consists of a flexible shell around a vision sensor, we name it Insight. Although initially designed for dexterous manipulation and behavioural learning, our sensor is suitable for many other applications and our technology can be adapted to create a variety of three-dimensional haptic sensing systems.

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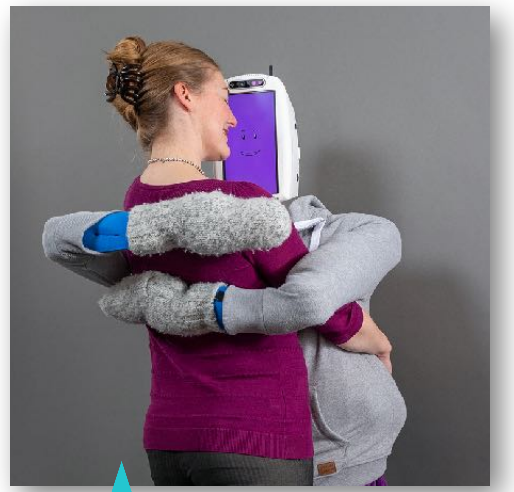
Insight

HuggieBot

Insight

HuggieBot



HuggieBot

2021 Otto Hahn Medal

Alexis E. Block
Recent MPI-IS/ETH Doctoral Graduate + Postdoc, UCLA

Sammy Christen
ETH Doctoral Student advised by Otmar Hilliges

Hasti Seifi
Recent MPI-IS Postdoc + Asst. Professor, Univ. Copenhagen, Moving to ASU

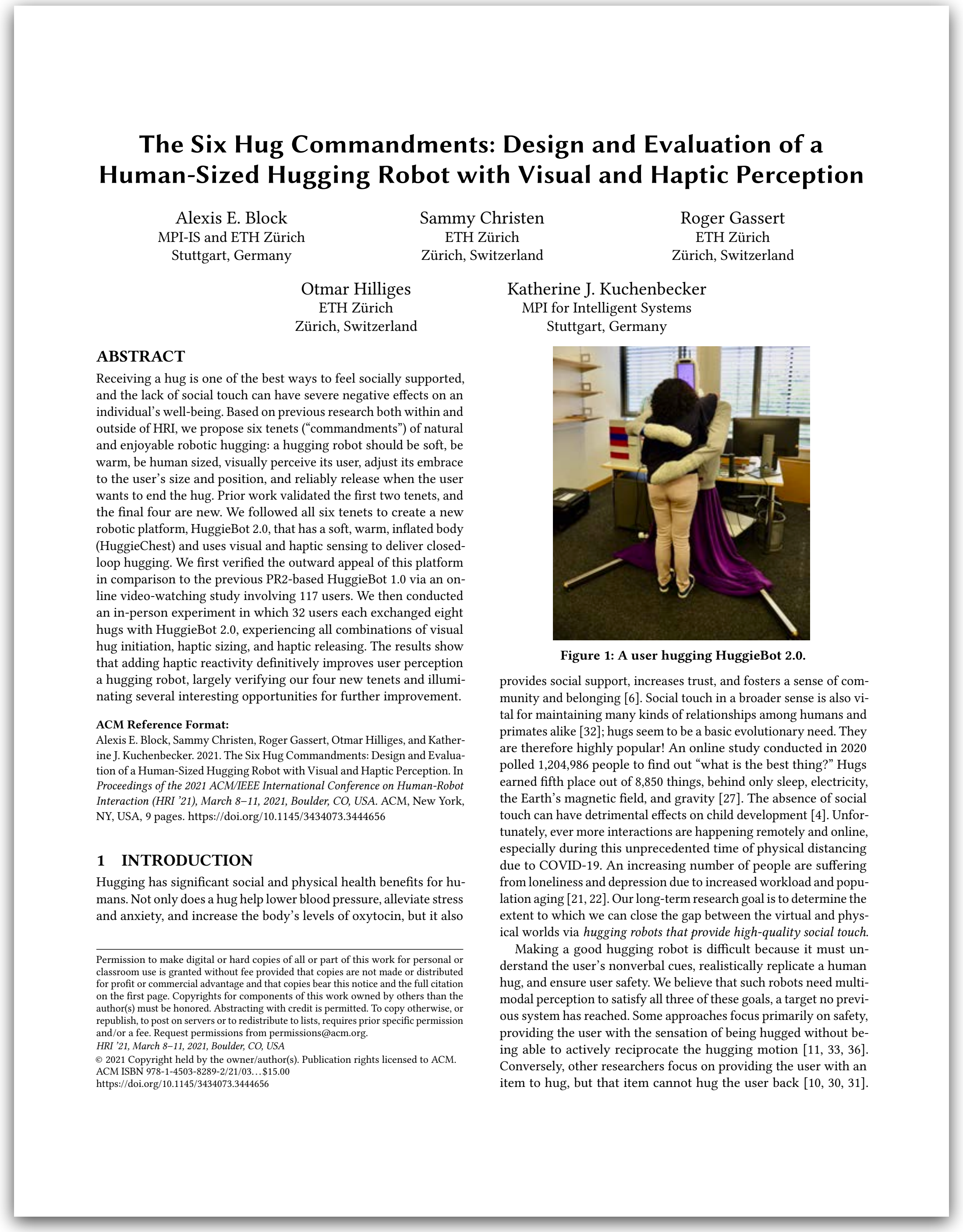
Shari L. Y. Kuchenbecker
R. W. Research

Otmar Hilliges
Professor, ETH Zürich

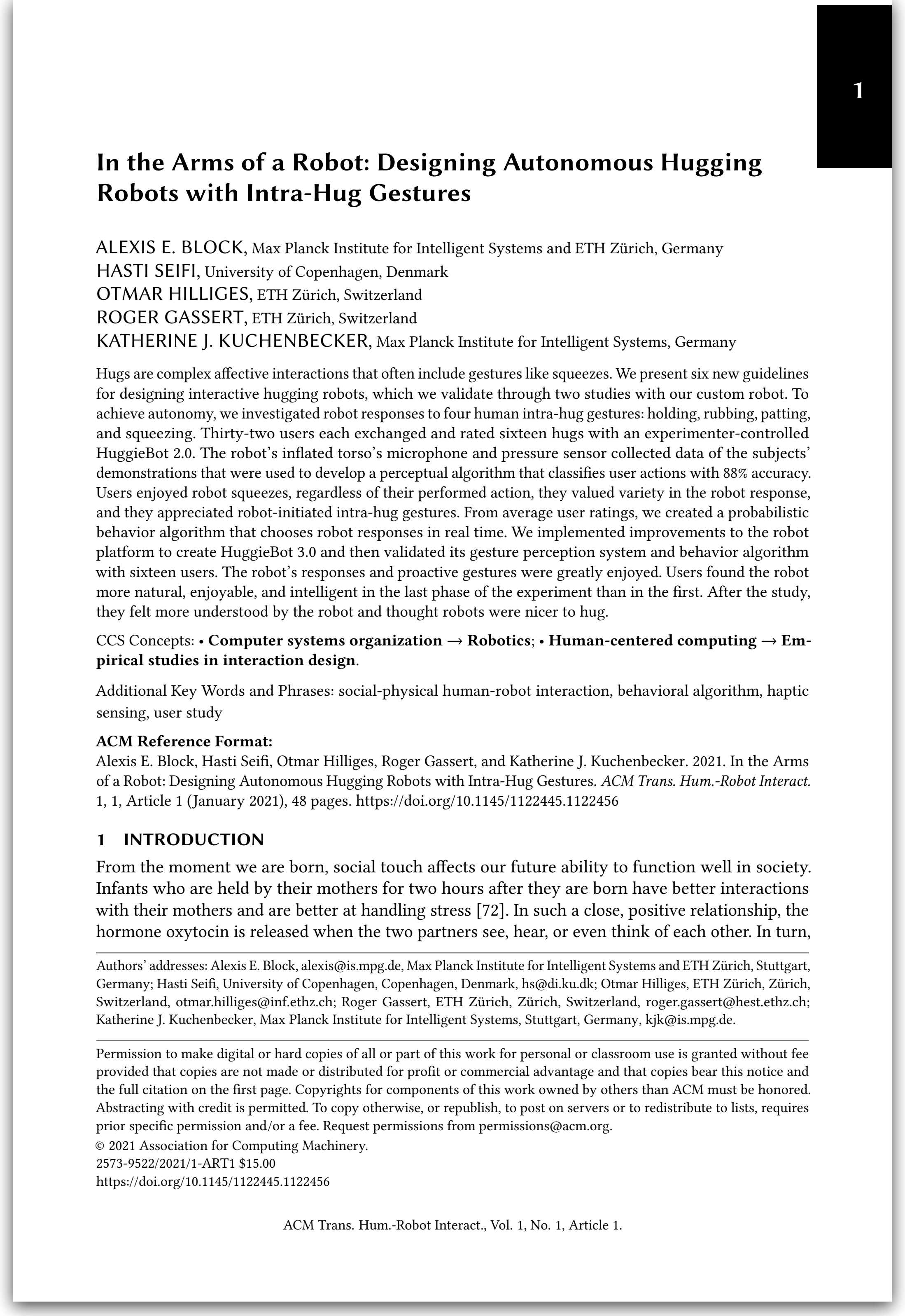
Roger Gassert
Professor, ETH Zürich

Katherine J. Kuchenbecker
Director, MPI-IS

International Journal of Social Robotics 2018



IEEE/ACM HRI 2021



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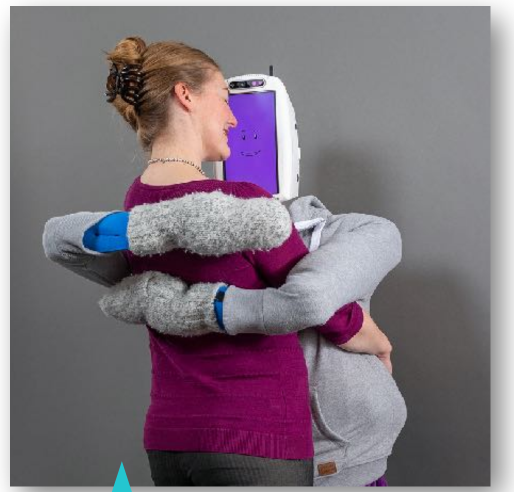

HuggieBot

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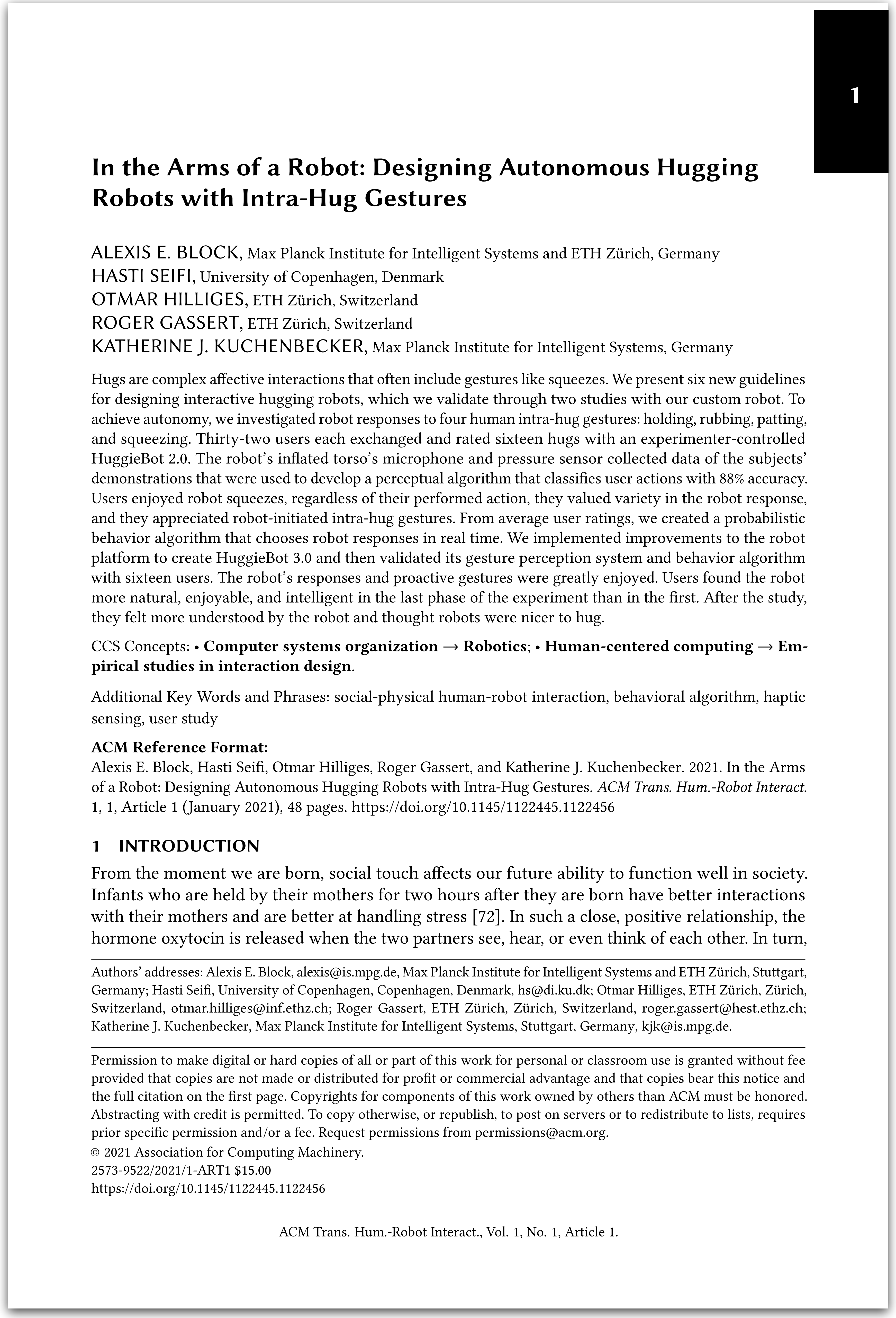

1

In the Arms of a Robot: Designing Autonomous Hugging Robots with Intra-Hug Gestures

ALEXIS E. BLOCK, Max Planck Institute for Intelligent Systems and ETH Zürich, Germany
HASTI SEIFI, University of Copenhagen, Denmark
OTMAR HILLIGES, ETH Zürich, Switzerland
ROGER GASSERT, ETH Zürich, Switzerland
KATHERINE J. KUCHENBECKER, Max Planck Institute for Intelligent Systems, Germany

Hugs are complex affective interactions that often include gestures like squeezes. We present six new guidelines for designing interactive hugging robots, which we validate through two studies with our custom robot. To achieve autonomy, we investigated robot responses to four human intra-hug gestures: holding, rubbing, patting, and squeezing. Thirty-two users each exchanged and rated sixteen hugs with an experimenter-controlled HuggieBot 2.0. The robot's inflated torso's microphone and pressure sensor collected data of the subjects' demonstrations that were used to develop a perceptual algorithm that classifies user actions with 88% accuracy. Users enjoyed robot squeezes, regardless of their performed action, they valued variety in the robot response, and they appreciated robot-initiated intra-hug gestures. From average user ratings, we created a probabilistic behavior algorithm that chooses robot responses in real time. We implemented improvements to the robot platform to create HuggieBot 3.0 and then validated its gesture perception system and behavior algorithm with sixteen users. The robot's responses and proactive gestures were greatly enjoyed. Users found the robot more natural, enjoyable, and intelligent in the last phase of the experiment than in the first. After the study, they felt more understood by the robot and thought robots were nicer to hug.

CCS Concepts: • **Computer systems organization** → **Robotics**; • **Human-centered computing** → **Empirical studies in interaction design**.

Additional Key Words and Phrases: social-physical human-robot interaction, behavioral algorithm, haptic sensing, user study

ACM Reference Format:
Alexis E. Block, Hasti Seifi, Otmar Hilliges, Roger Gassert, and Katherine J. Kuchenbecker. 2021. In the Arms of a Robot: Designing Autonomous Hugging Robots with Intra-Hug Gestures. *ACM Trans. Hum.-Robot Interact.* 1, 1, Article 1 (January 2021), 48 pages. https://doi.org/10.1145/1122445.1122456

1 INTRODUCTION

From the moment we are born, social touch affects our future ability to function well in society. Infants who are held by their mothers for two hours after they are born have better interactions with their mothers and are better at handling stress [72]. In such a close, positive relationship, the hormone oxytocin is released when the two partners see, hear, or even think of each other. In turn,

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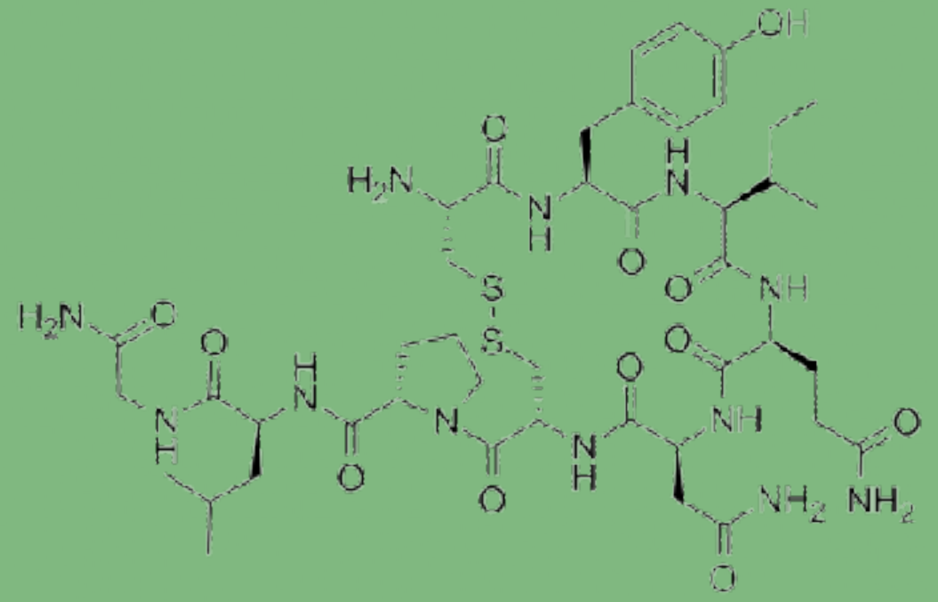
ACM Trans. Hum.-Robot Interact., Vol. 1, No. 1, Article 1.

Alexis E. Block, Hasti Seifi, Otmar Hilliges, Roger Gassert, and Katherine J. Kuchenbecker. In the Arms of a Robot: Designing Autonomous Hugging Robots with Intra-Hug Gestures. *ACM Transactions on Human-Robot Interaction*, 1–48, 2022 (accepted).

Hugging confers tremendous benefits

Provide Social Support

Strengthen Immune System



Improve Oxytocin Levels

Alleviate Stress/Anxiety

Lower Blood Pressure

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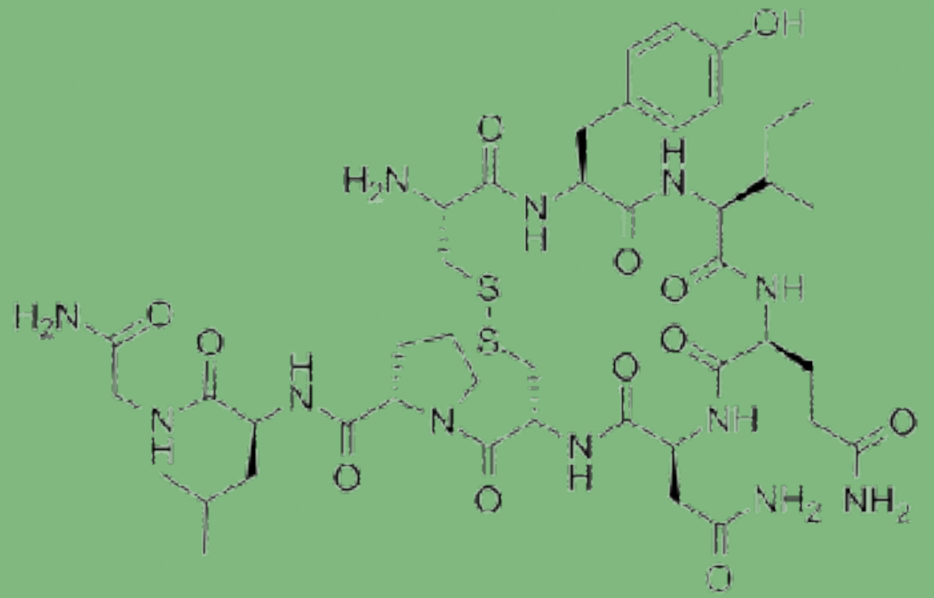
A lack of social touch causes problems

Provide Social Support

Strengthen Immune System

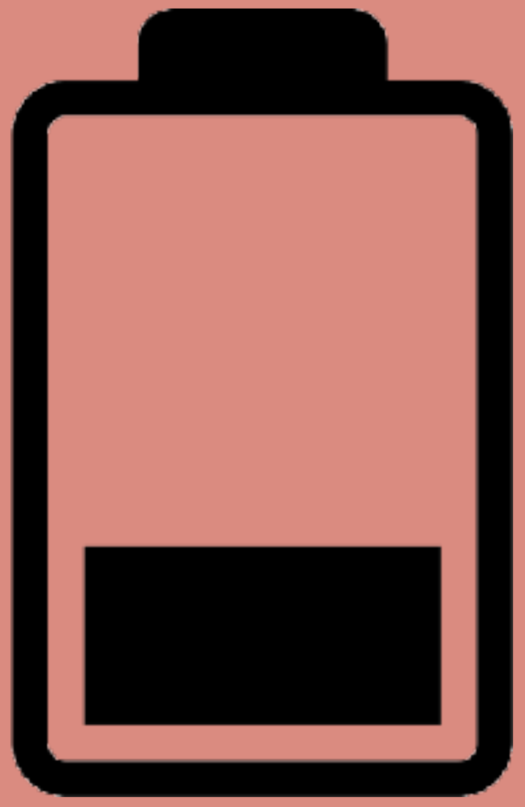


Improve Oxytocin Levels

Alleviate Stress/Anxiety

Lower Blood Pressure

Depression and Mental Health Problems



Low Self Esteem

Lower Pain Thresholds

Inability/Difficulty Forming Relationships

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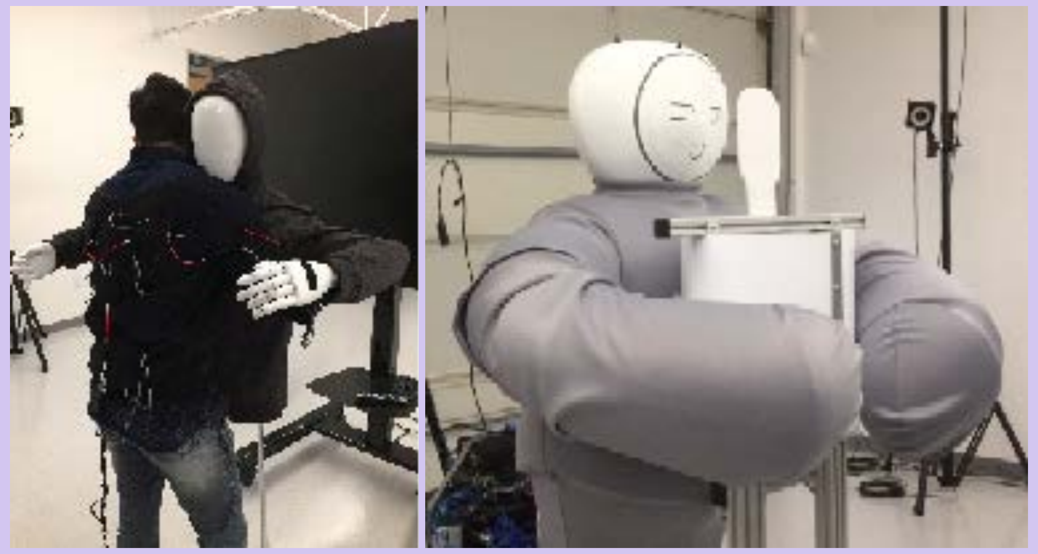
Previous hugging robots

Zoomorphic Hugging Robots

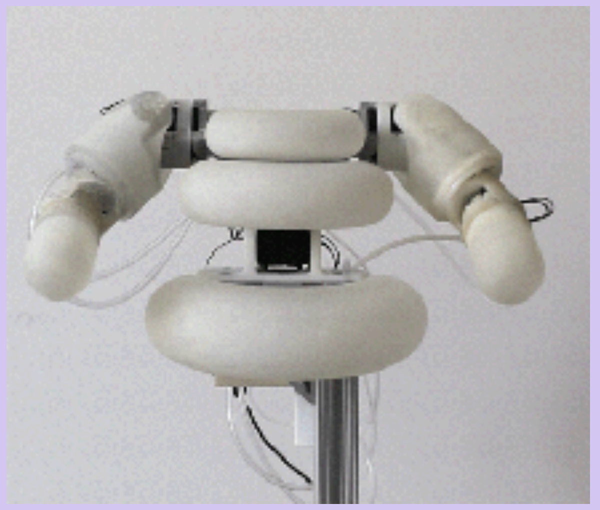
Teddy Bear Robot
Shiomi et al., 2017

HugBot
Hedayati et al., 2019

Human-Sized Anthropomorphic Hugging Robots



The Hug Robot
Kaplish and Yamane, 2019
Campbell and Yamane 2020



Disney Patent
Yamane et al., 2017

HuggieBot 1.0
Block and Kuchenbecker, 2018

HuggieBot 2.0, 3.0, and 4.0
Block et al., 2021+

Small Form-Factor Hugging Robots

Huggable
Stiehl et al., 2005

The Hug
DiSalvo et al., 2003

Hugvie
Sumioka et al., 2013

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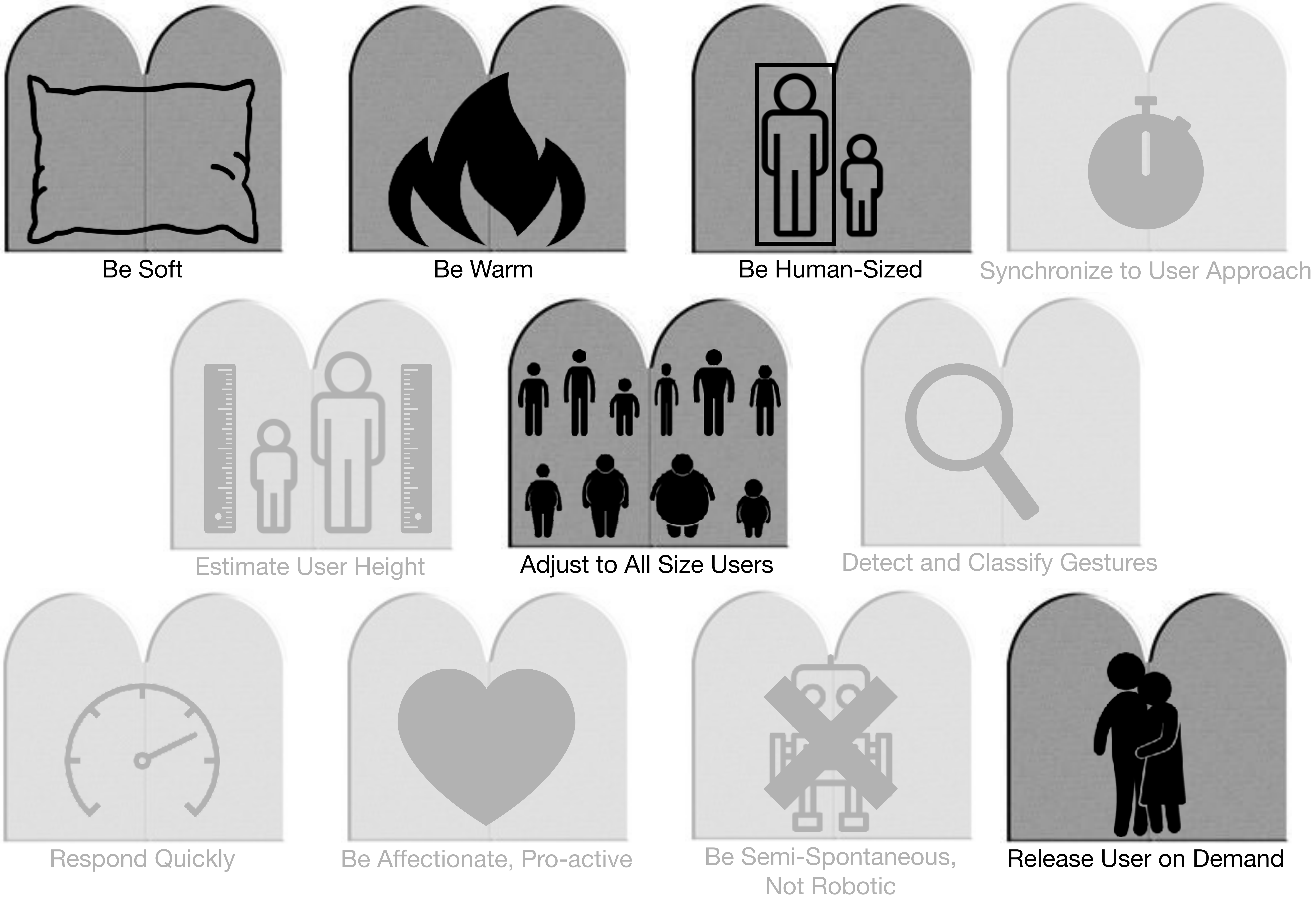
11 Design Guidelines for Hugging Robots



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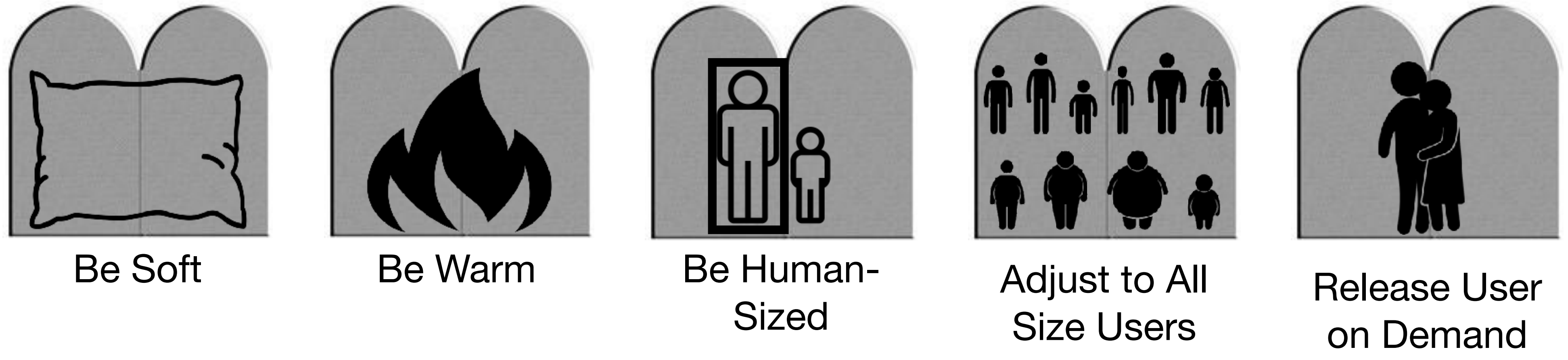
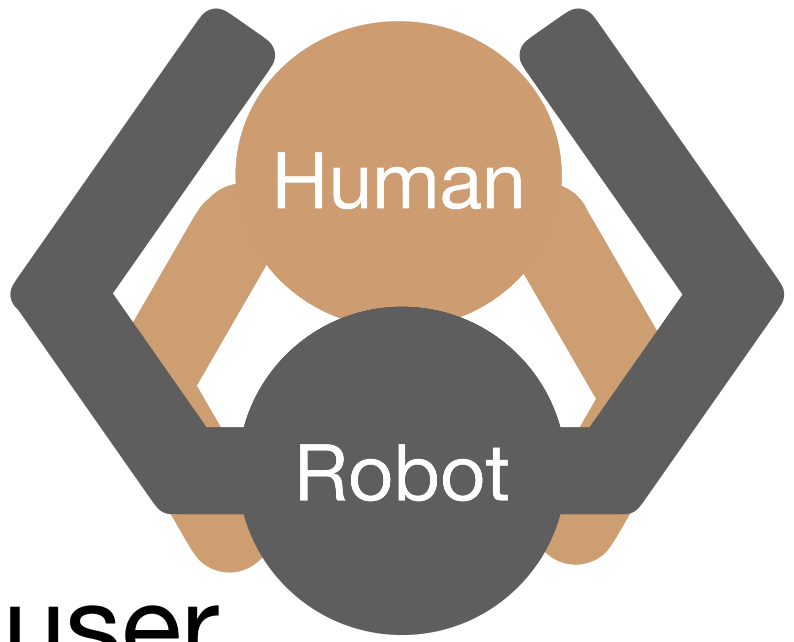
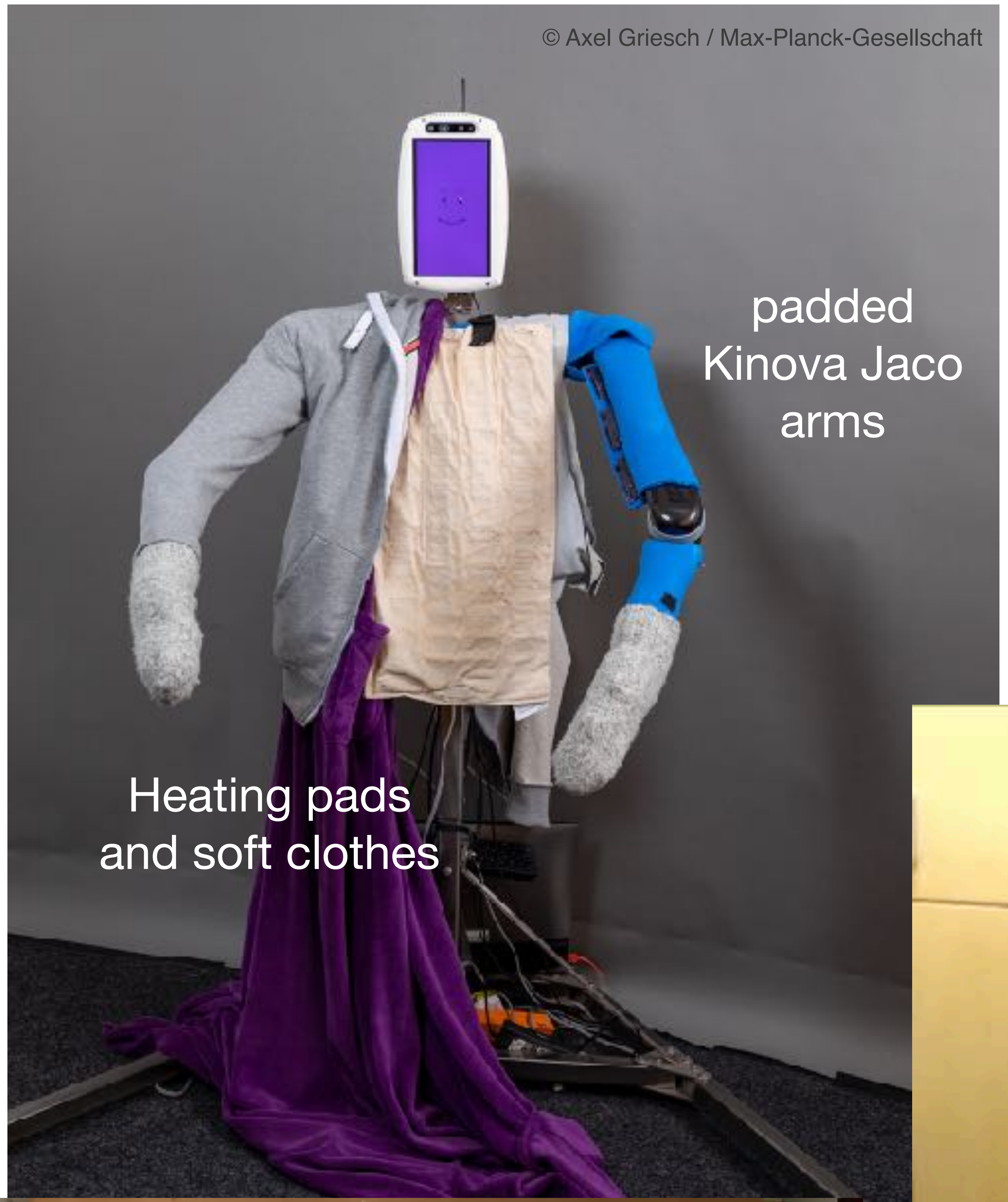
HuggieBot 2.0





- Soft, warm, quiet, easy to hug, and safe
- Robot visually perceives and reacts to approaching user
- Arms adapt to user size and location, providing a good embrace
- Robot reacts to user’s desire to end the hug by sensing:
  - a reduction in pressure inside the inflated torso
  - an increase in the torque on any arm joint



Alexis E. Block, Sammy Christen, Roger Gassert, Otmar Hilliges, and Katherine J. Kuchenbecker.
The Six Hug Commandments: Design and Evaluation of a Human-Sized Hugging Robot with Visual and Haptic Perception.
Proceedings of the ACM/IEEE International Conference on Human-Robot Interaction (HRI), 2021

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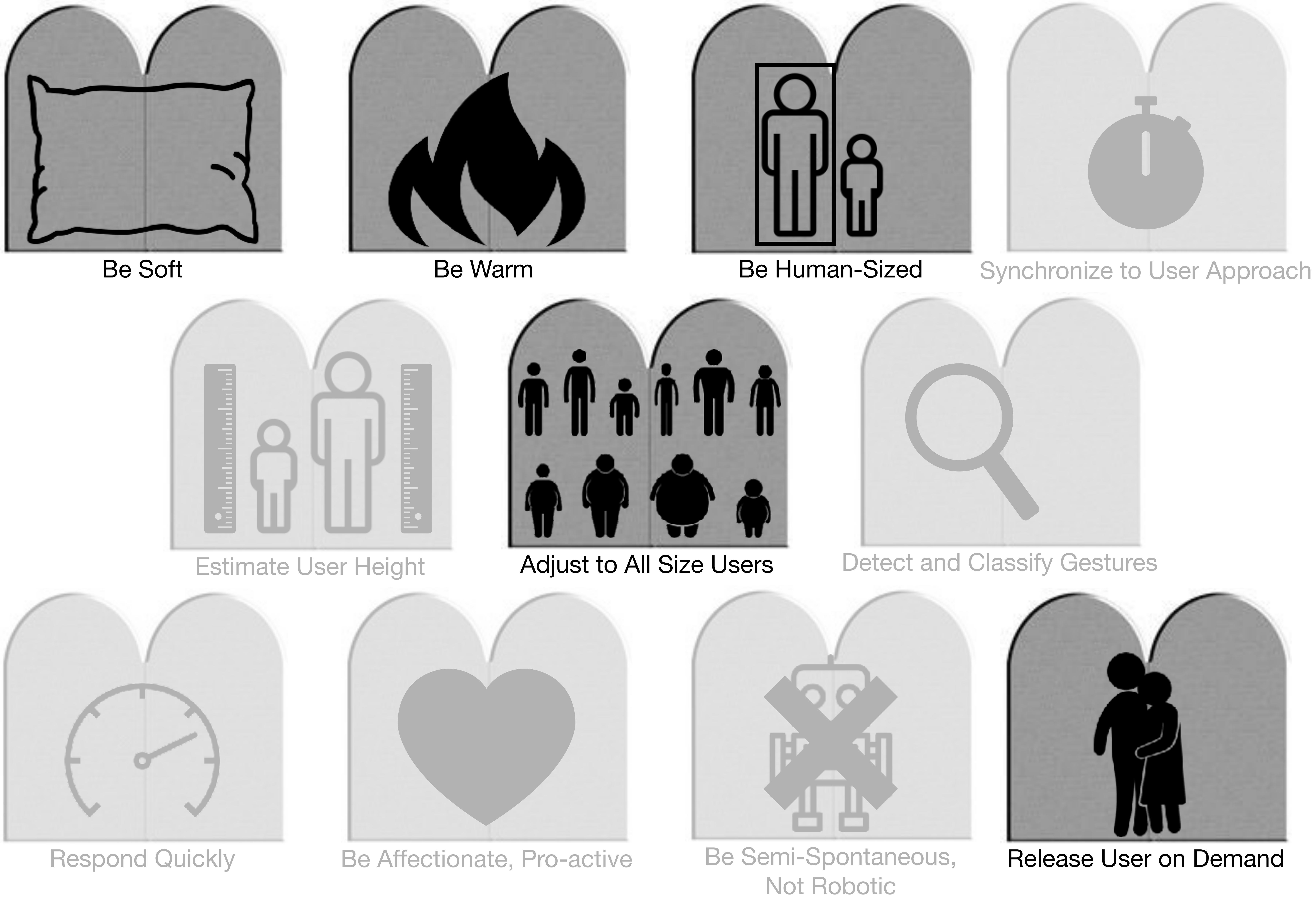

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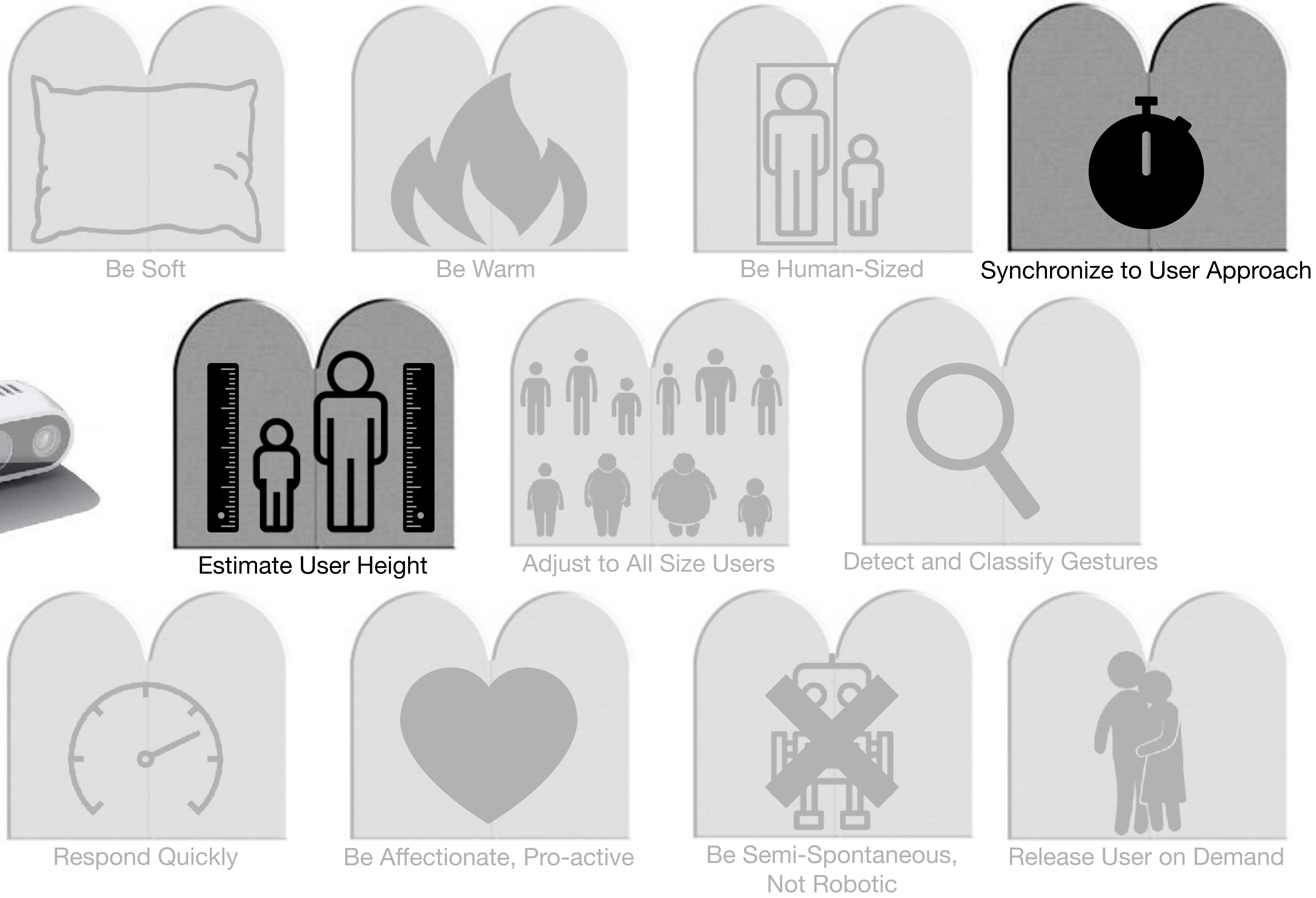
11 Design Guidelines for Hugging Robots

Intel Real Sense
Depth-Sensing Camera



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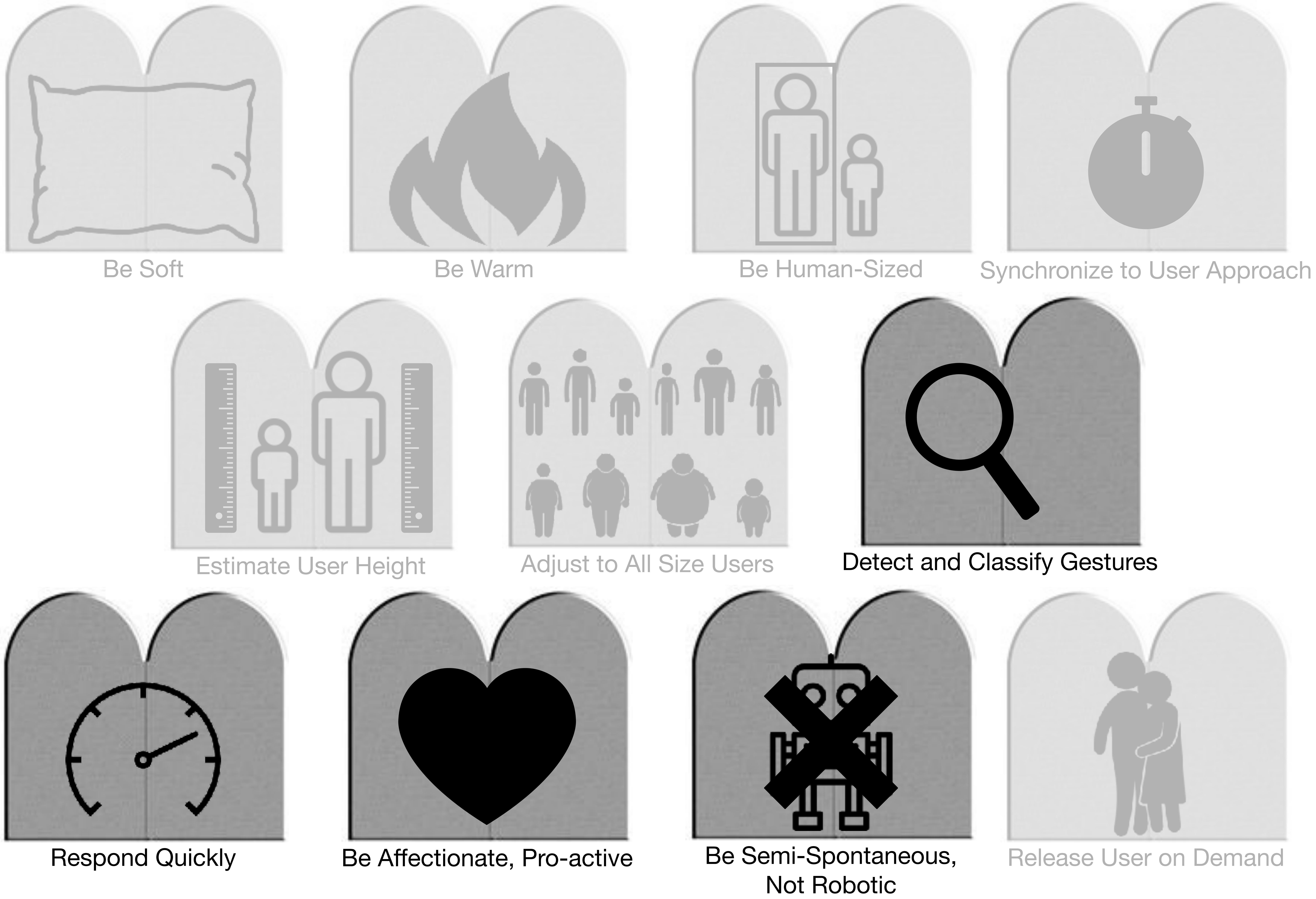

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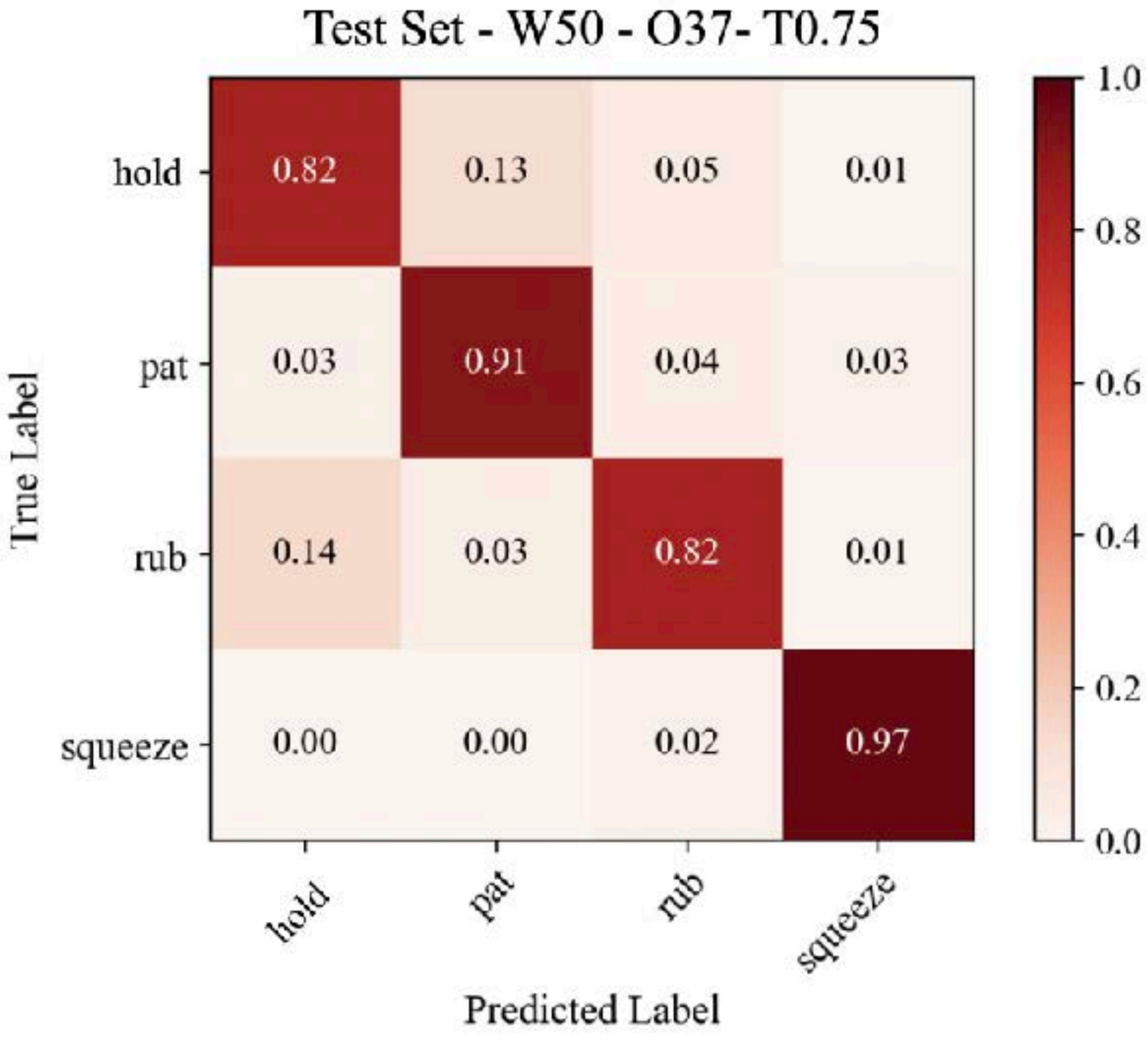
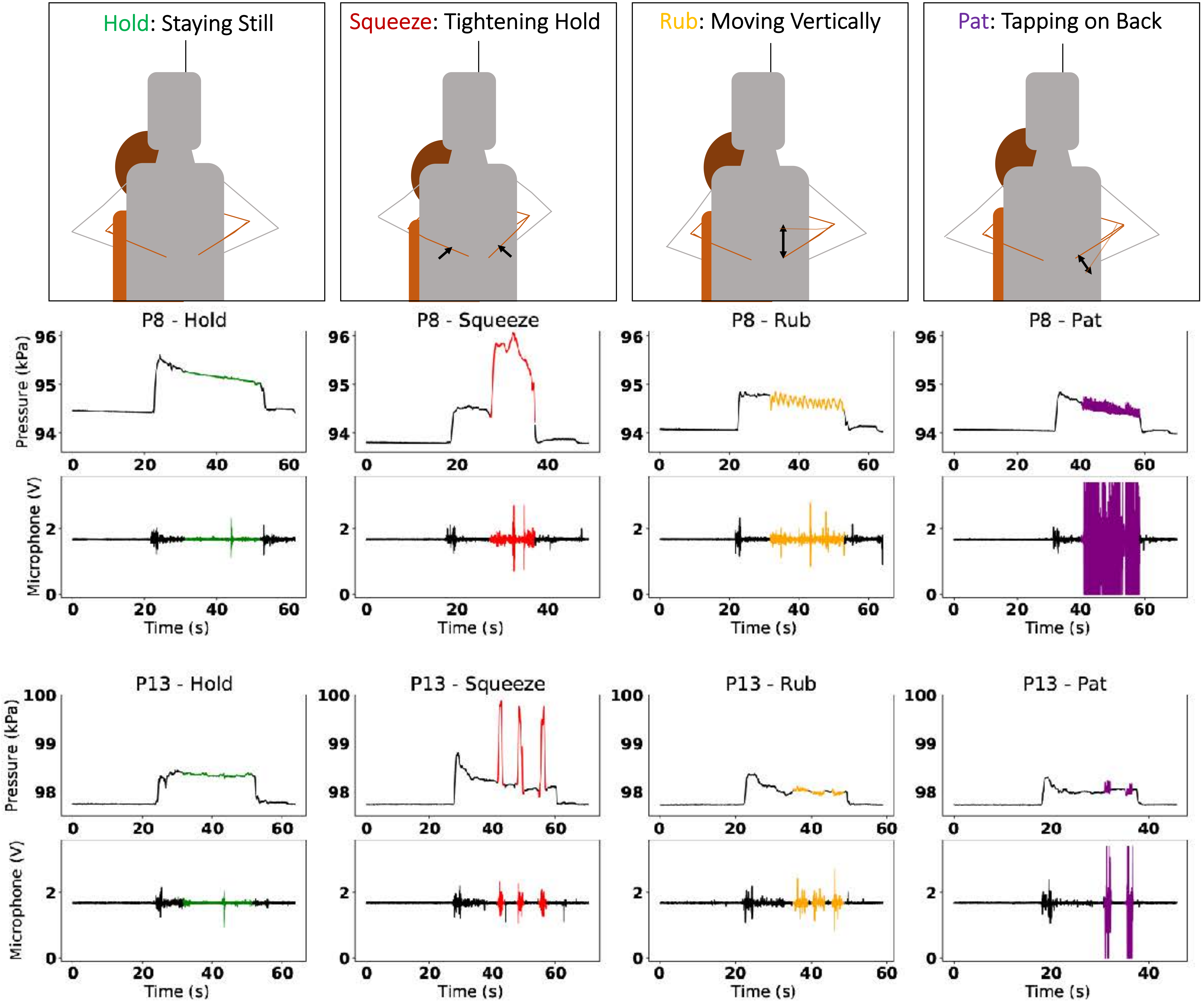
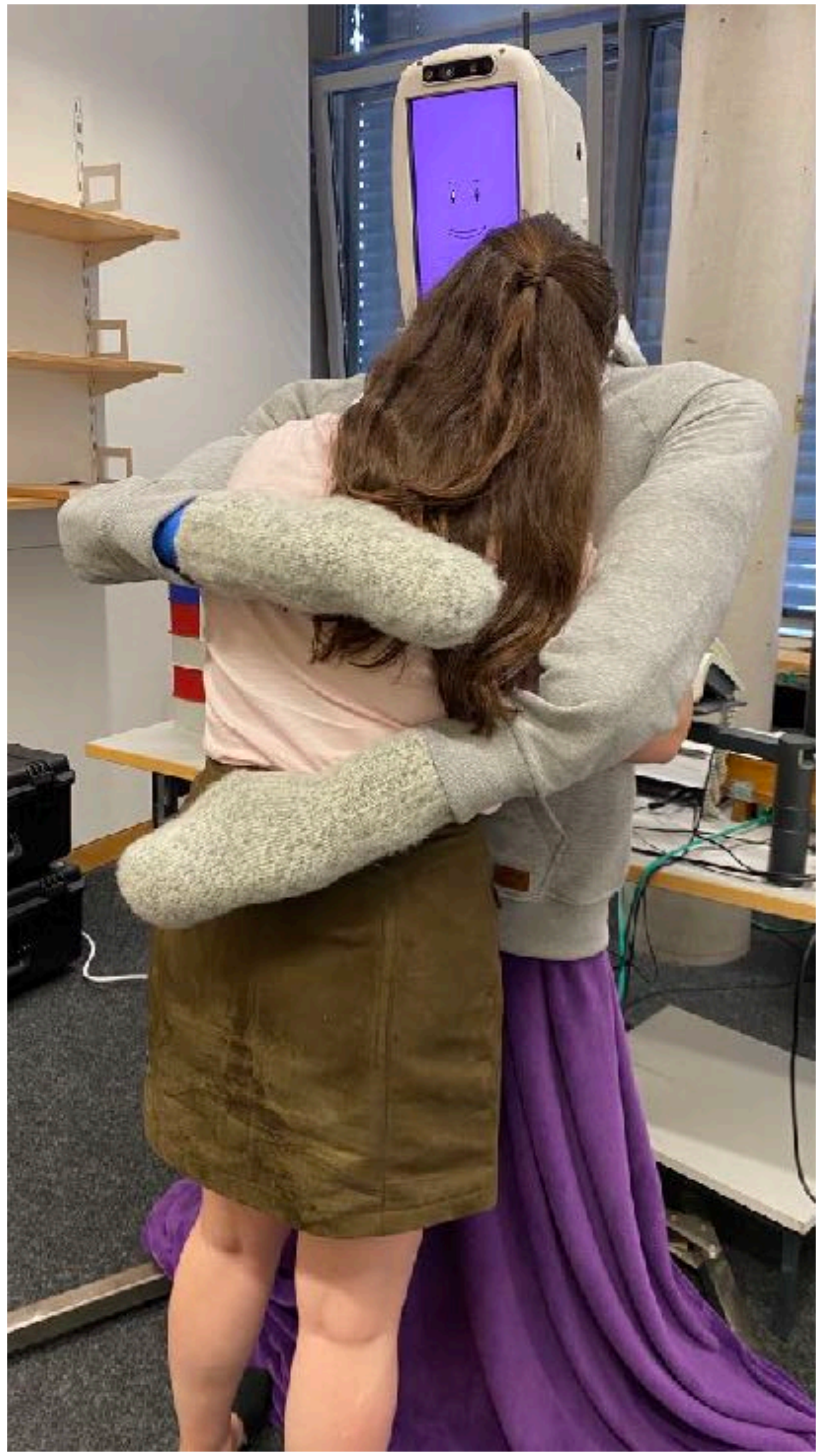
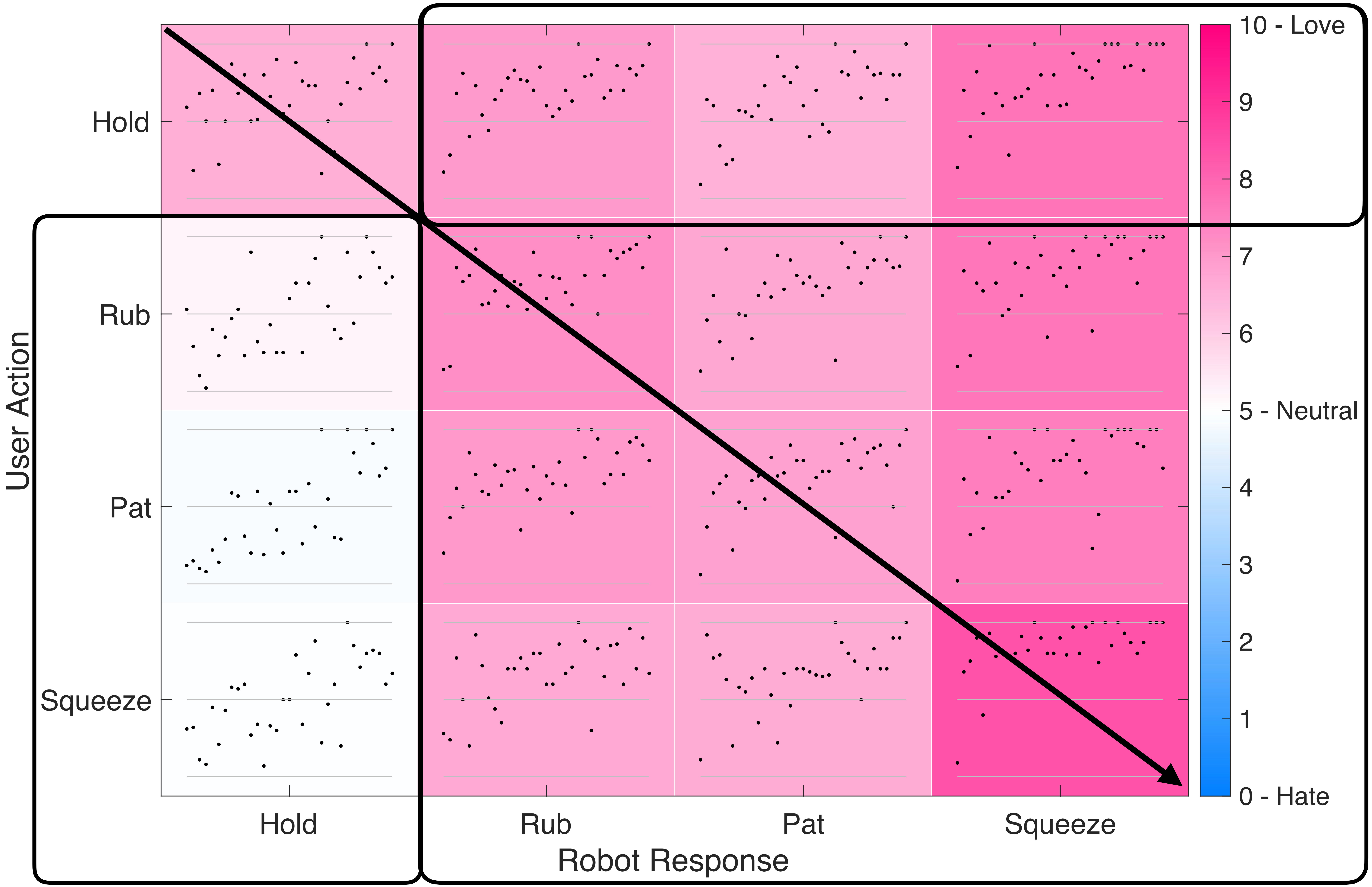
Inflated chest with internal microphone and pressure sensor









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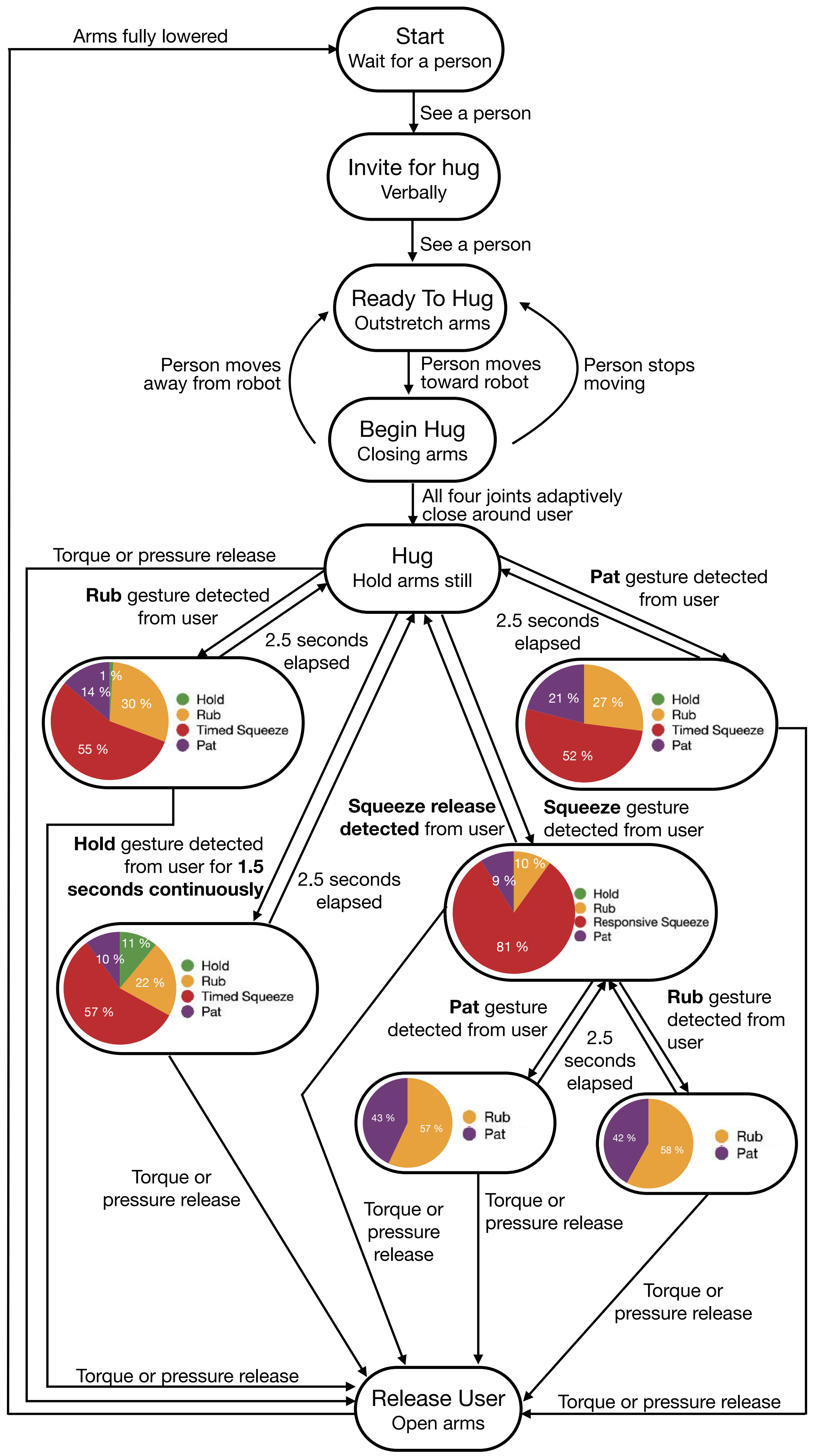
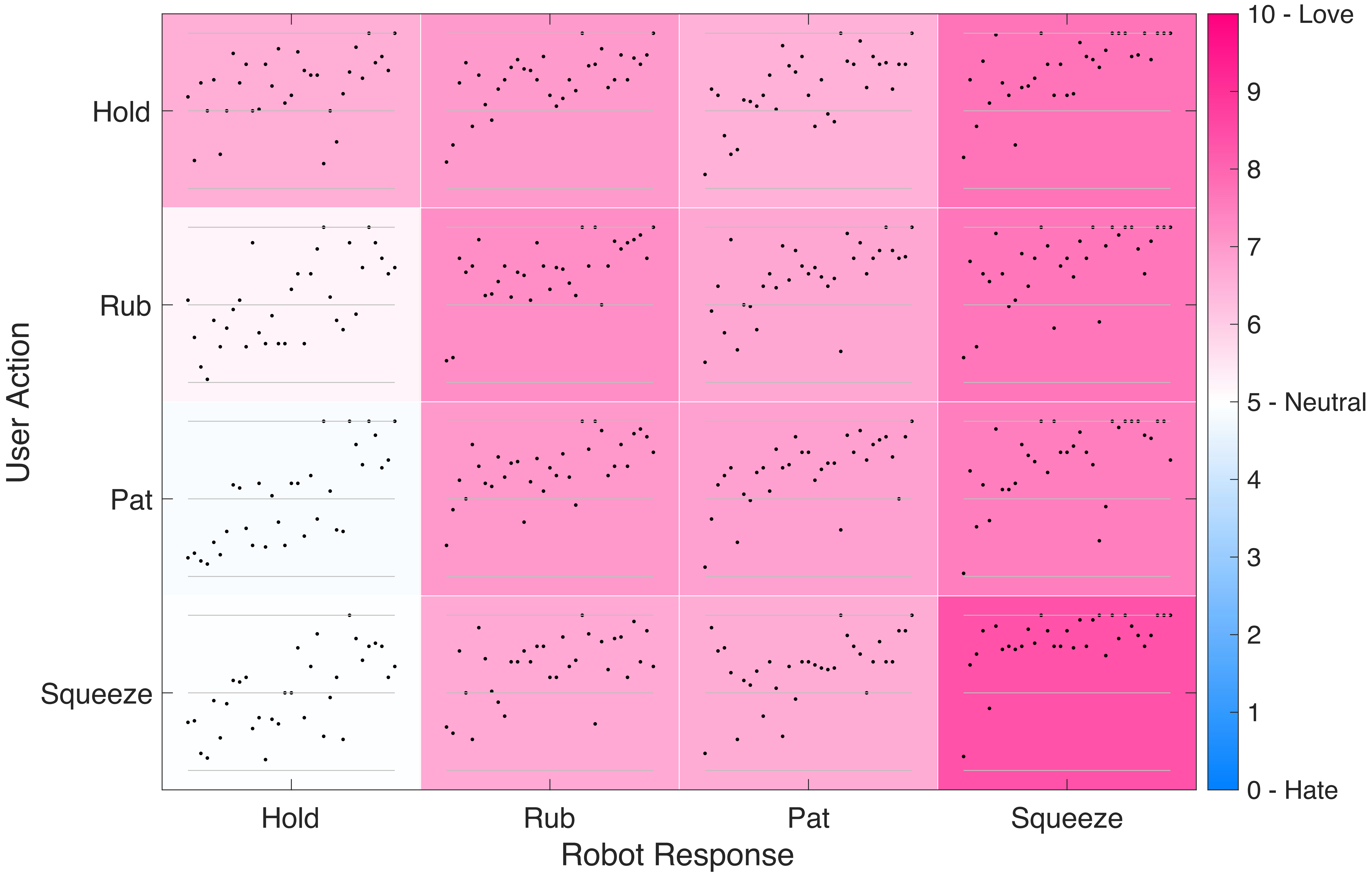
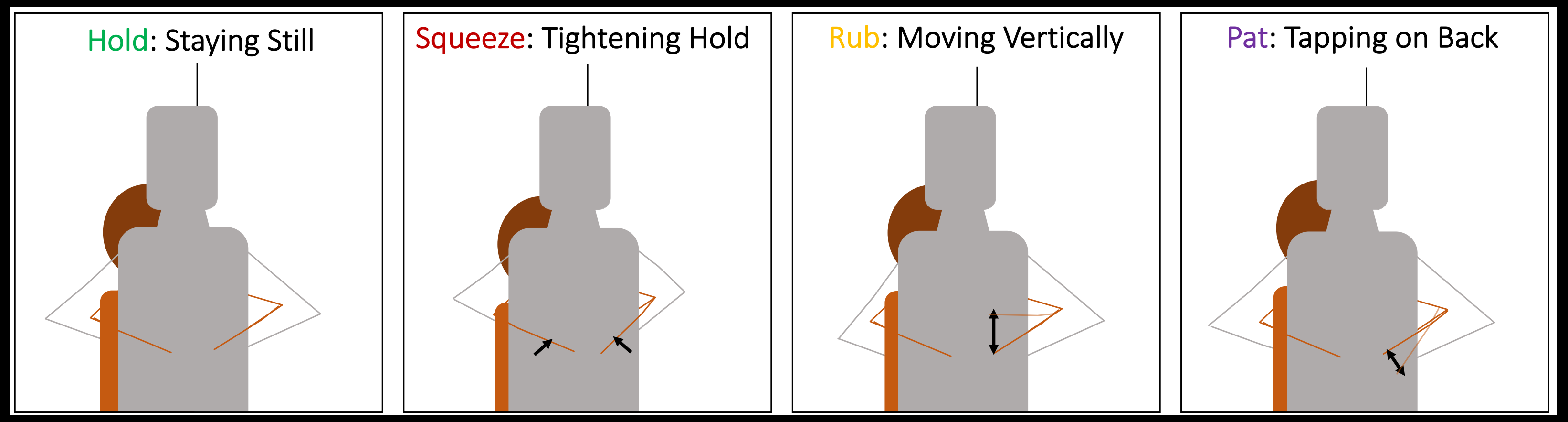
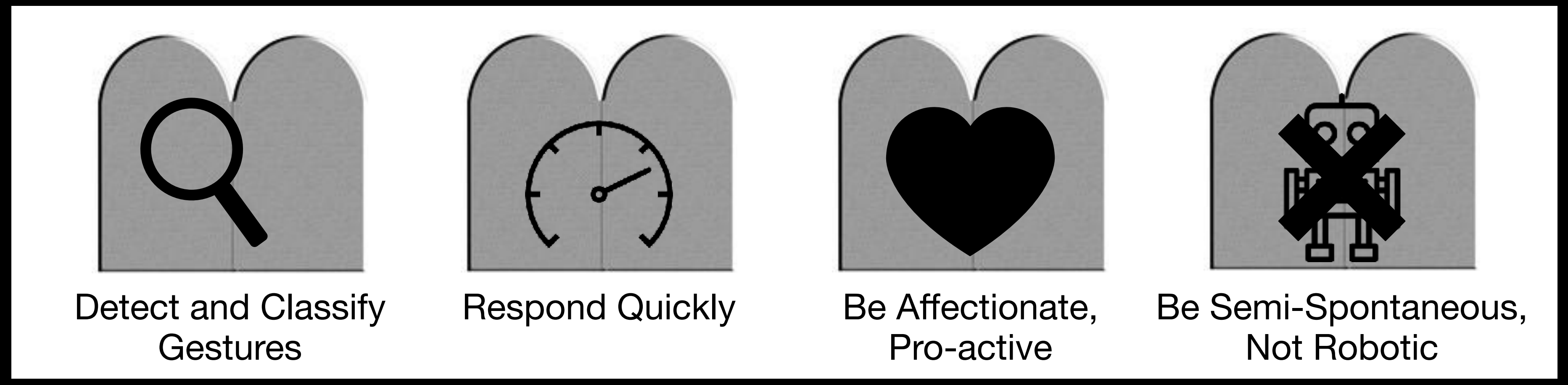

Start
Wait for a person
Arms fully lowered
See a person
Invite for hug
Verbally
See a person
Ready To Hug
Outstretch arms
Person moves away from robot
Person moves toward robot
Person stops moving
Begin Hug
Closing arms
All four joints adaptively close around user
Torque or pressure release
Hug
Hold arms still
Rub gesture detected from user
Pat gesture detected from user
2.5 seconds elapsed
2.5 seconds elapsed
Hold
Rub
Timed Squeeze
Pat
Hold
Rub
Timed Squeeze
Pat
Squeeze release detected from user
Squeeze gesture detected from user
Hold gesture detected from user for 1.5 seconds continuously
2.5 seconds elapsed
Hold
Rub
Responsive Squeeze
Pat
Hold
Rub
Timed Squeeze
Pat
Pat gesture detected from user
Rub gesture detected from user
2.5 seconds elapsed
Rub
Pat
Rub
Pat
Torque or pressure release
Torque or pressure release
Torque or pressure release
Torque or pressure release
Torque or pressure release
Torque or pressure release
Release User
Open arms

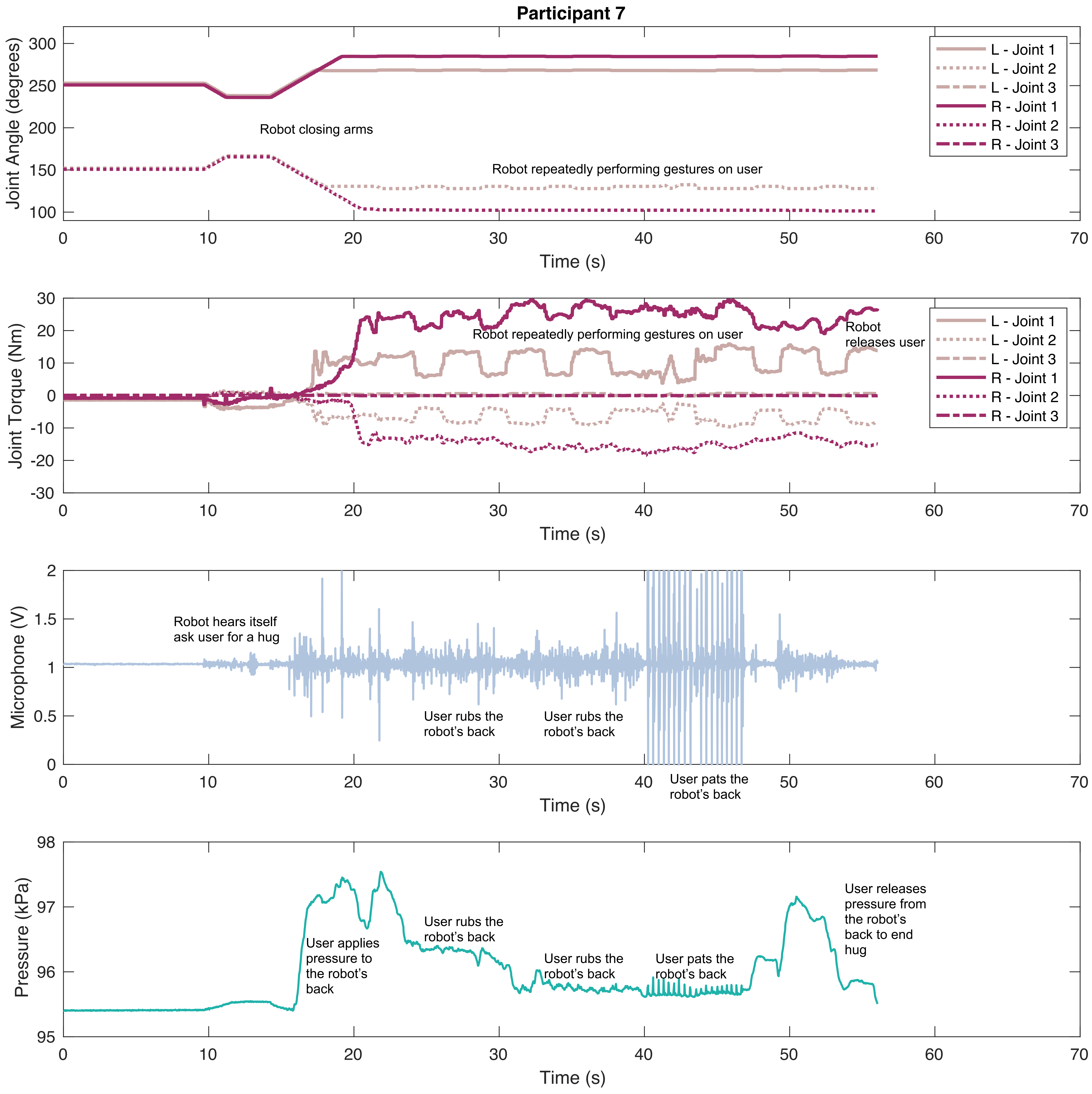

User Action
Hold
Rub
Pat
Squeeze
Robot Response
Hold
Rub
Pat
Squeeze
10 - Love
9
8
7
6
5 - Neutral
4
3
2
1
0 - Hate

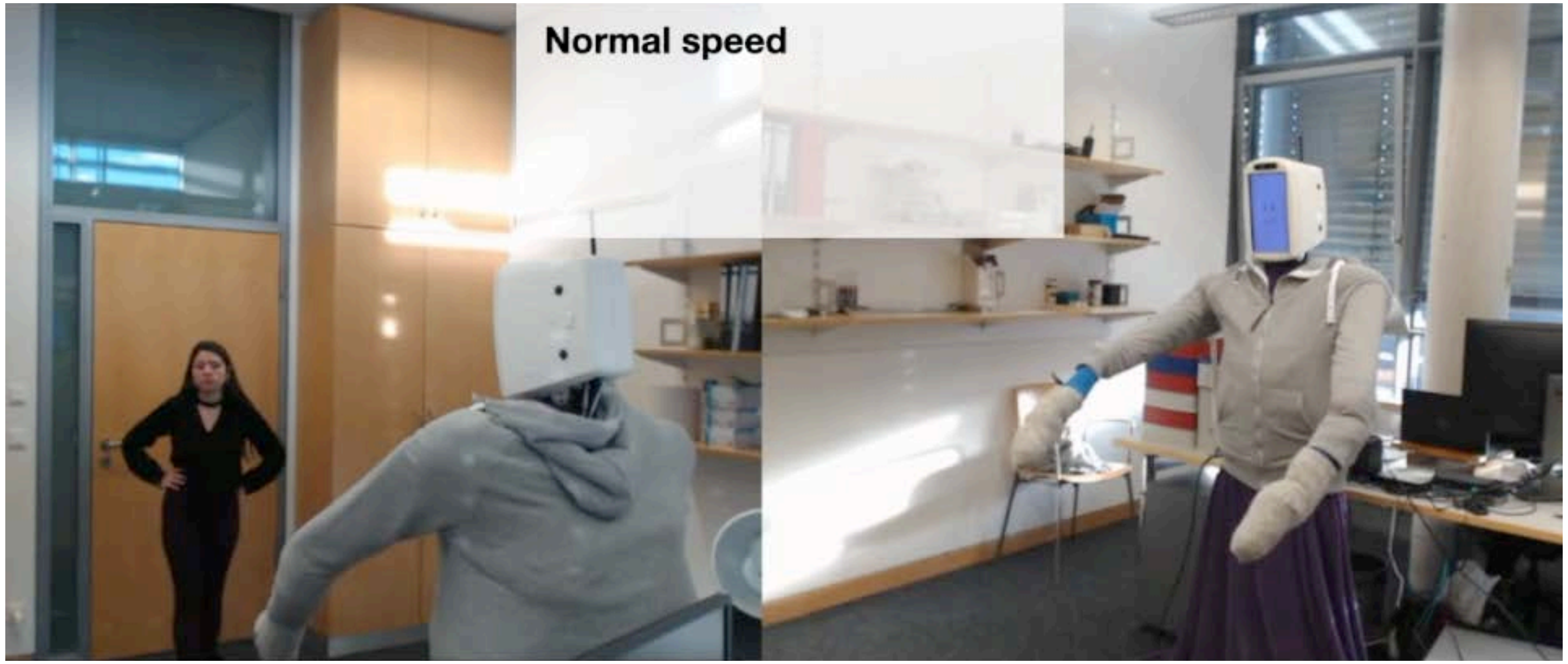
HuggieBot 3.0

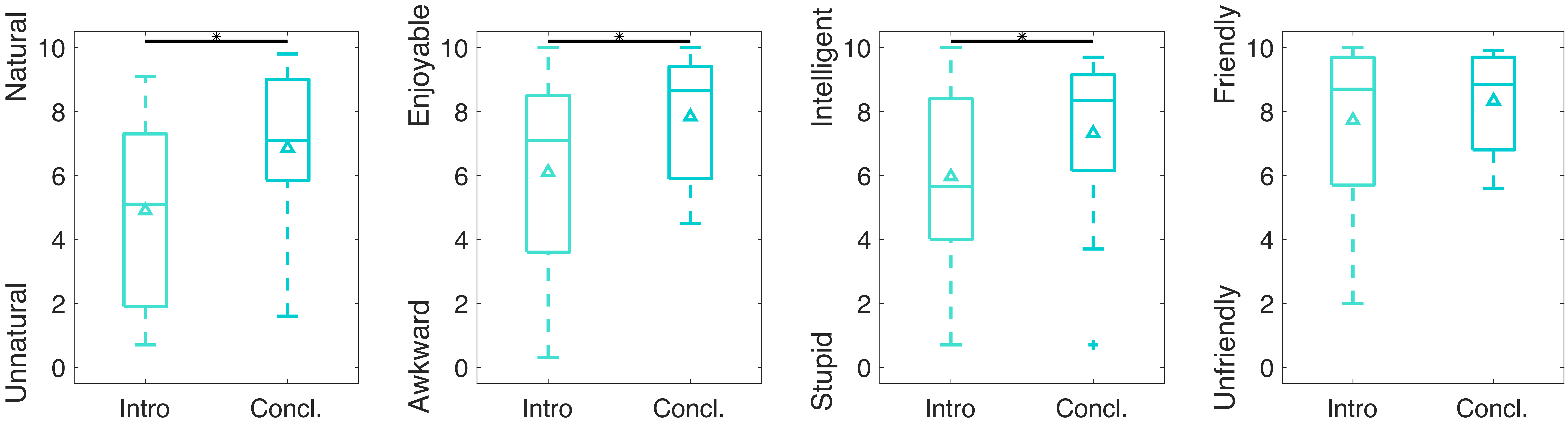




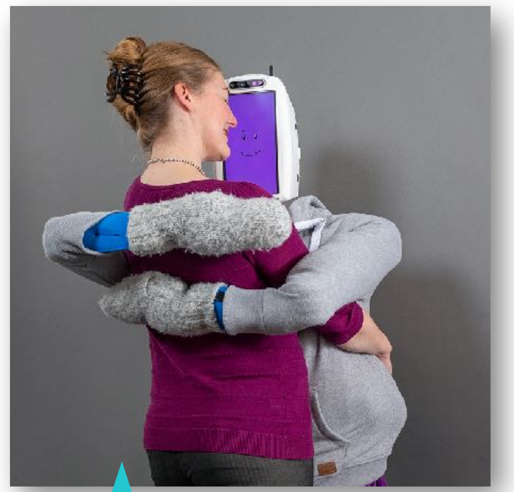
Alexis E. Block, Hasti Seifi, Otmar Hilliges, Roger Gassert, and Katherine J. Kuchenbecker. In the Arms of a Robot: Designing Autonomous Hugging Robots with Intra-Hug Gestures. *ACM Transactions on Human-Robot Interaction*, 1–48, 2022 (accepted).


Participant 7
Joint Angle (degrees)
Robot closing arms
Robot repeatedly performing gestures on user
L - Joint 1
L - Joint 2
L - Joint 3
R - Joint 1
R - Joint 2
R - Joint 3
Time (s)
Joint Torque (Nm)
Robot repeatedly performing gestures on user
Robot releases user
Microphone (V)
Robot hears itself ask user for a hug
User rubs the robot's back
User rubs the robot's back
User pats the robot's back
Pressure (kPa)
User applies pressure to the robot's back
User rubs the robot's back
User rubs the robot's back
User pats the robot's back
User releases pressure from the robot's back to end hug


Normal speed


Natural
Unnatural
Enjoyable
Awkward
Intelligent
Stupid
Friendly
Unfriendly
10
8
6
4
2
0
*
Intro
Concl.

EUROHAPTICS 2022



HuggieBot

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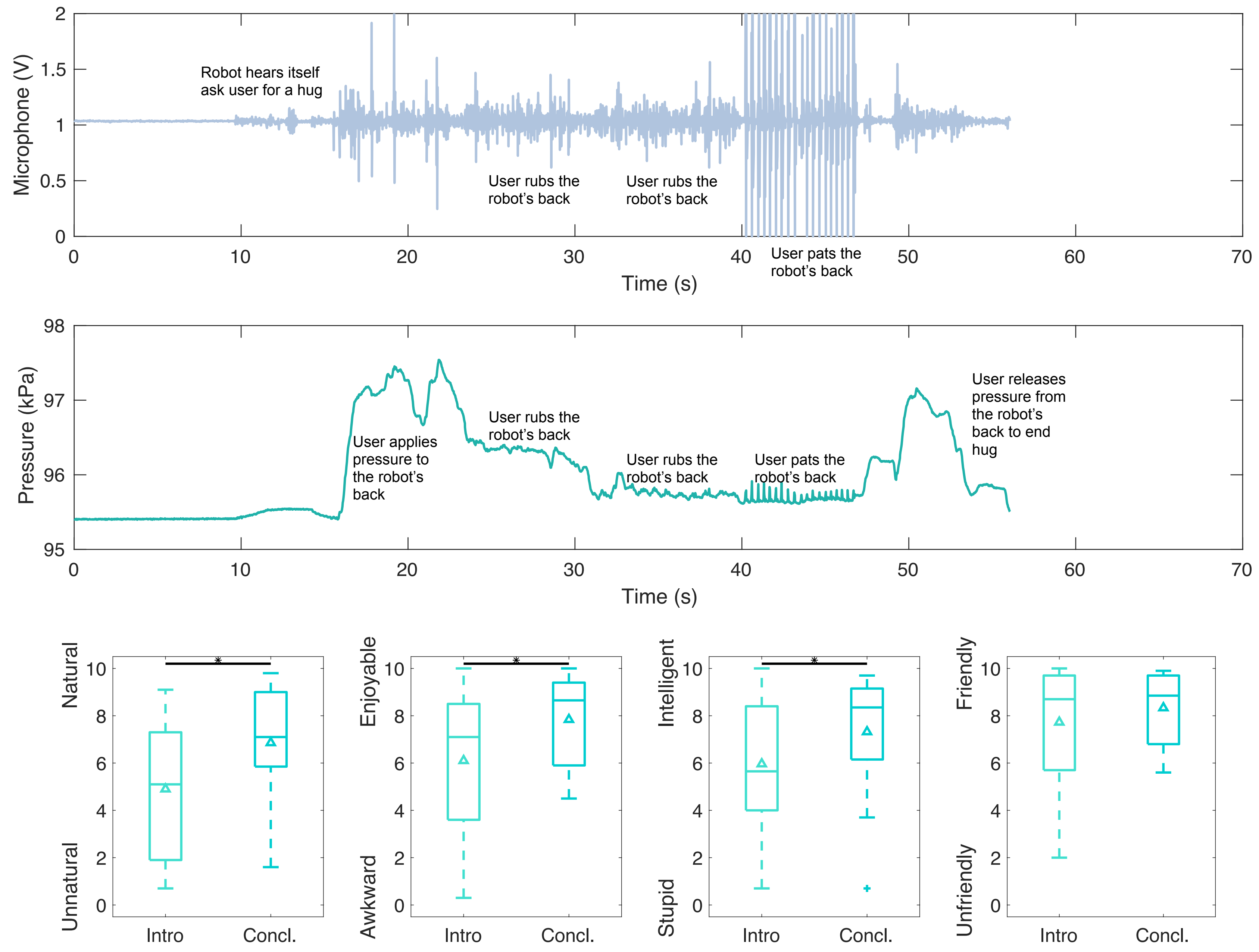

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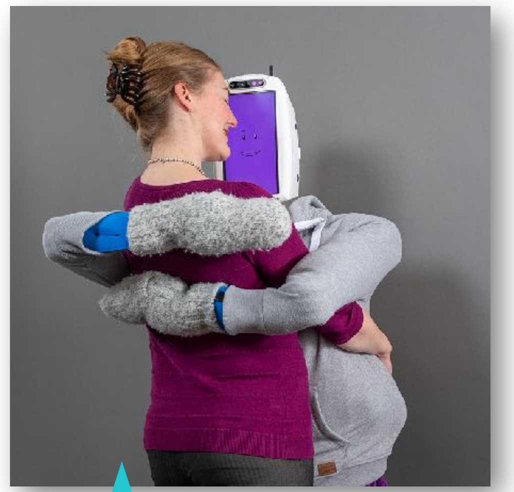

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1

In the Arms of a Robot: Designing Autonomous Hugging Robots with Intra-Hug Gestures

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HASTI SEIFI, University of Copenhagen, Denmark
OTMAR HILLIGES, ETH Zürich, Switzerland
ROGER GASSERT, ETH Zürich, Switzerland
KATHERINE J. KUCHENBECKER, Max Planck Institute for Intelligent Systems, Germany

Hugs are complex affective interactions that often include gestures like squeezes. We present six new guidelines for designing interactive hugging robots, which we validate through two studies with our custom robot. To achieve autonomy, we investigated robot responses to four human intra-hug gestures: holding, rubbing, patting, and squeezing. Thirty-two users each exchanged and rated sixteen hugs with an experimenter-controlled HuggieBot 2.0. The robot's inflated torso's microphone and pressure sensor collected data of the subjects' demonstrations that were used to develop a perceptual algorithm that classifies user actions with 88% accuracy. Users enjoyed robot squeezes, regardless of their performed action, they valued variety in the robot response, and they appreciated robot-initiated intra-hug gestures. From average user ratings, we created a probabilistic behavior algorithm that chooses robot responses in real time. We implemented improvements to the robot platform to create HuggieBot 3.0 and then validated its gesture perception system and behavior algorithm with sixteen users. The robot's responses and proactive gestures were greatly enjoyed. Users found the robot more natural, enjoyable, and intelligent in the last phase of the experiment than in the first. After the study, they felt more understood by the robot and thought robots were nicer to hug.

CCS Concepts: • **Computer systems organization** → **Robotics**; • **Human-centered computing** → **Empirical studies in interaction design**.

Additional Key Words and Phrases: social-physical human-robot interaction, behavioral algorithm, haptic sensing, user study

ACM Reference Format:
Alexis E. Block, Hasti Seifi, Otmar Hilliges, Roger Gassert, and Katherine J. Kuchenbecker. 2021. In the Arms of a Robot: Designing Autonomous Hugging Robots with Intra-Hug Gestures. *ACM Trans. Hum.-Robot Interact.* 1, 1, Article 1 (January 2021), 48 pages. https://doi.org/10.1145/1122445.1122456

1 INTRODUCTION

From the moment we are born, social touch affects our future ability to function well in society. Infants who are held by their mothers for two hours after they are born have better interactions with their mothers and are better at handling stress [72]. In such a close, positive relationship, the hormone oxytocin is released when the two partners see, hear, or even think of each other. In turn,

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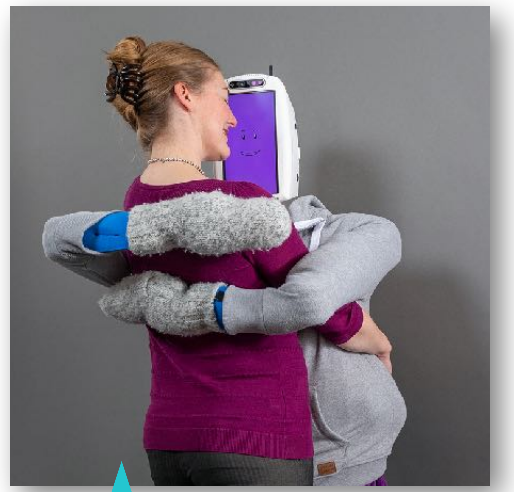

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International Journal of Social Robotics
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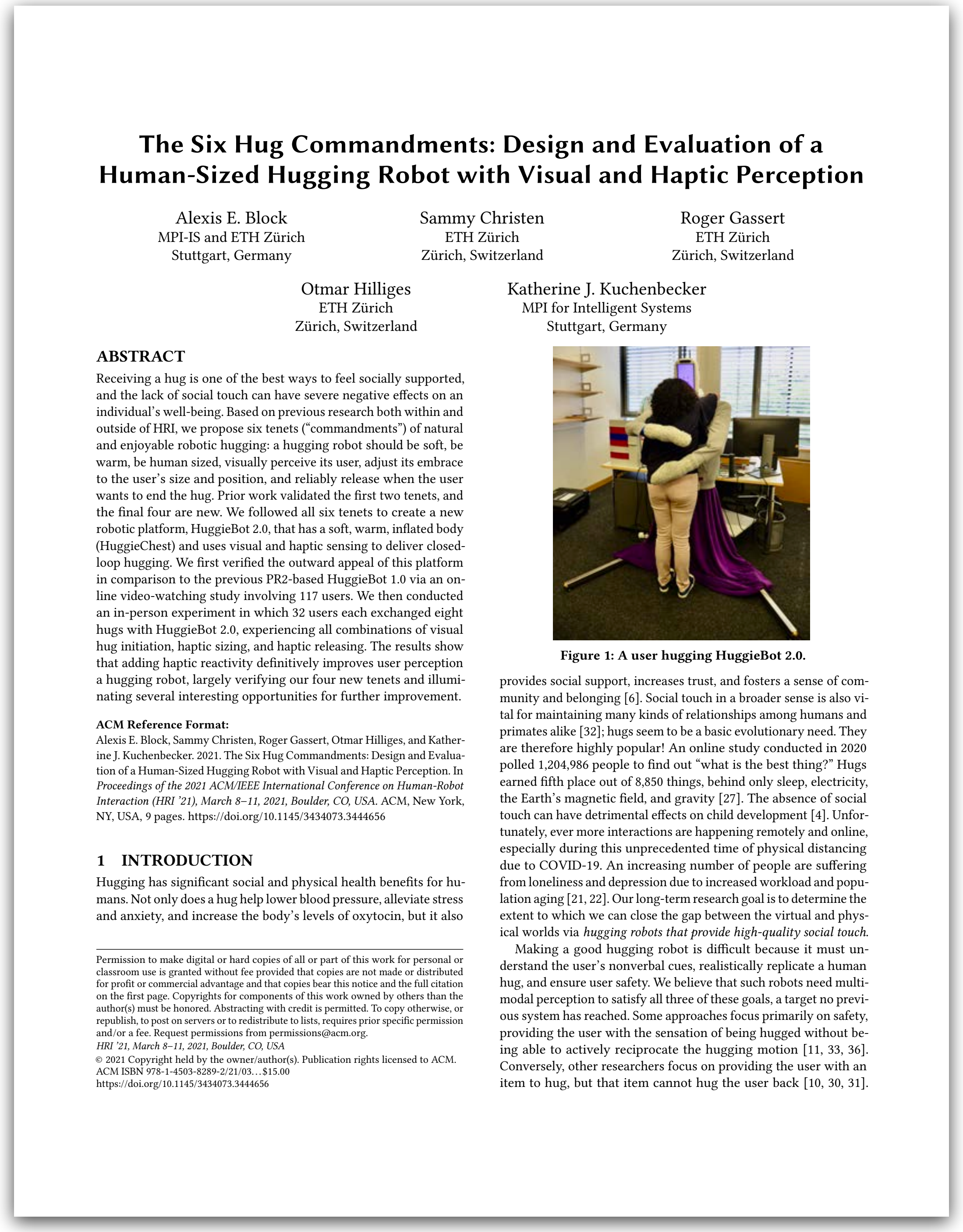
Softness, Warmth, and Responsiveness Improve Robot Hugs

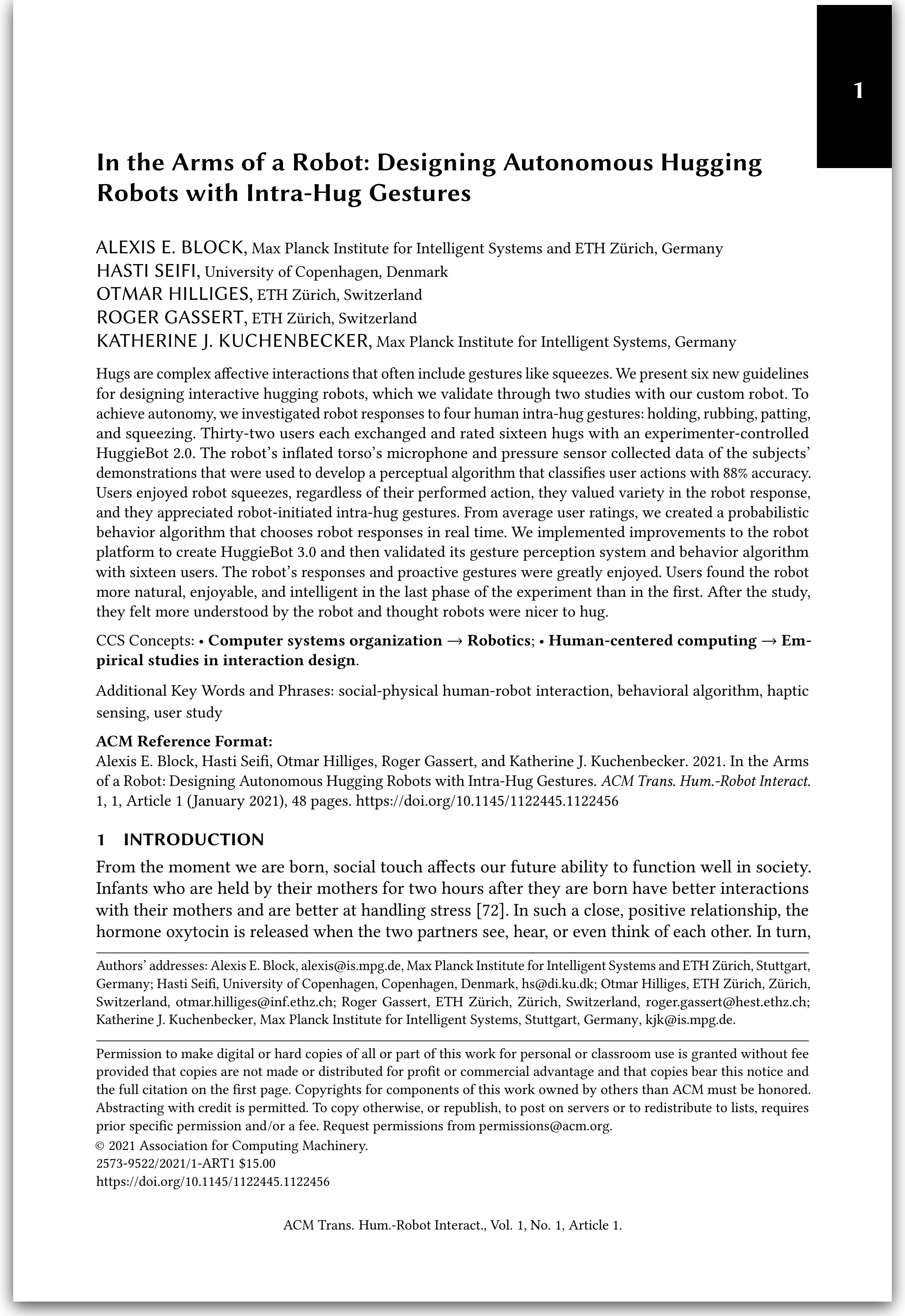
Alexis E. Block[1,2,3] · Katherine J. Kuchenbecker[1,2,3]

International Journal of Social Robotics 2018


The Six Hug Commandments: Design and Evaluation of a Human-Sized Hugging Robot with Visual and Haptic Perception

Alexis E. Block, Sammy Christen, Roger Gassert, Otmar Hilliges, Katherine J. Kuchenbecker

IEEE/ACM HRI 2021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ACM Transactions on Human-Robot Interaction 2022 (accepted)

Insight

HuggieBot

Insight

HuggieBot

Touch Sensing

Physical Human-Robot Interaction

My ideal touch sensors:

- are soft
- cover my robot
- detect new contact
- have high dynamic range
- respond quickly
- provide useful information
- are robust and reliable
- integrate easily with my robot
- are low cost and accessible

Overarching Ideas

- The sense of **touch** is important!
- Touch itself is **multimodal**, mixing many distinct modalities that are not yet standardized like visual and auditory perception.
- Tactile sensors should have should have **broad spatial sensitivity** and **high temporal bandwidth**.
- **Individual accelerometers, microphones,** and **pressure sensors** can be used to instrument large robot body parts.
- Haptic perceptual algorithms need to work in **real time** so the robot can **quickly react** to detected events.

MPI-IS Haptic Intelligence Department in October 2021

thank you

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collaborators and central services

many generous mentors

friends and family

anonymous reviewers

Questions and **comments**?

Insight

HuggieBot

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