The Future of Friendly Mobile Manipulation

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https://charliekemp.com

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Georgia Tech
Wallace H. Coulter Department of Biomedical Engineering
EMORY UNIVERSITY

Charlie’s Conflict of Interest Statement

Dr. Kemp is both an associate professor at Georgia Tech and the chief technology officer (CTO) of Hello Robot Inc. where he works part time. **He owns equity** in Hello Robot Inc. and is an inventor of Georgia Tech intellectual property (IP) licensed by Hello Robot Inc. Consequently, **he receives royalties** through Georgia Tech for sales made by Hello Robot Inc. He also benefits from increases in the value of Hello Robot Inc.

Summary: If Hello Robot does well, Charlie does well.

Georgia Tech

hello robot™

The Future of **Friendly** Mobile Manipulation

What I mean by “Friendly”*

- Helpful
- Easy to use
- Safe

** Unpacking Minsky’s Suitcase*

friendly 1 of 3 adjective

friend·ly ˈfren(d)-lē

friendlier; friendliest

Synonyms of *friendly* ›

1 : of, relating to, or befitting a friend: such as

a : showing kindly interest and goodwill

friendly neighbors

b : not hostile

a *friendly* merger offer

also : involving or coming from actions of one's own forces

friendly fire

c : CHEERFUL, COMFORTING

the *friendly* glow of the fire

2 serving a beneficial or helpful purpose

A *friendly* breeze finally drove the boat into harbor.

3 a easy to use or understand

friendly computer software

→ often used in combination

a reader-*friendly* layout

b : designed or intended to accommodate particular needs, users, etc. → usually used in combination

a kid-*friendly* restaurant

... providing a more business-*friendly* and professional environment ...
– Matt Miller

→ see also USER-FRIENDLY

4 not causing or likely to cause harm

environmentally *friendly* packaging [=packaging that does not damage the environment]

→ often used in combination

an eco-*friendly* vehicle

Definition from https://www.merriam-webster.com/dictionary/friendly

I don’t mean “Friendly” in a social interaction sense

- Sometimes beneficial
- Sometimes unnecessary
- A subset of friendly mobile manipulation

friendly 1 of 3 **adjective**

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Definition from https://www.merriam-webster.com/dictionary/friendly

I’m Only Talking about Indoor Mobile Manipulation

- Designed & Built for People
  - Flat floors
  - Cartesian structure
  - Human scale [1]
- Diverse inhabitants
  - Children
  - Older adults
  - People with disabilities
  - Pets
- Examples in the United States
  - 127M Occupied housing units [2]
  - 6M Commercial buildings [3]

[1] https://en.wikipedia.org/wiki/Human_scale
[2] https://data.census.gov/table?q=housing&tid=ACSST1Y2021.S2504
[3] https://css.umich.edu/publications/factsheets/built-environment/commercial-buildings-factsheet

Home & workplace images
https://en.wikipedia.org/wiki/House#/media/File:Noto_Emoji_v2.034_1f3e0.svg
https://www.psdgraphics.com/psd/small-store-icon-psd/

“The Future”

A Plausible Future in the Next 10 Years

Pithy Title with Ambiguity

The Future of Friendly Mobile Manipulation

Fully-expanded Translation

My Speculations about the Next 10 Years for Helpful, Easy to Use, and Safe Mobile Manipulators in Indoor Human Environments

We can only see the past

images from:
Willow Garage
https://fetchrobotics.com/fetch-mobile-manipulator/
https://pal-robotics.com/robots/tiago/
https://hello-robot.com

“For a successful technology, reality must take precedence over public relations, for nature cannot be fooled.”

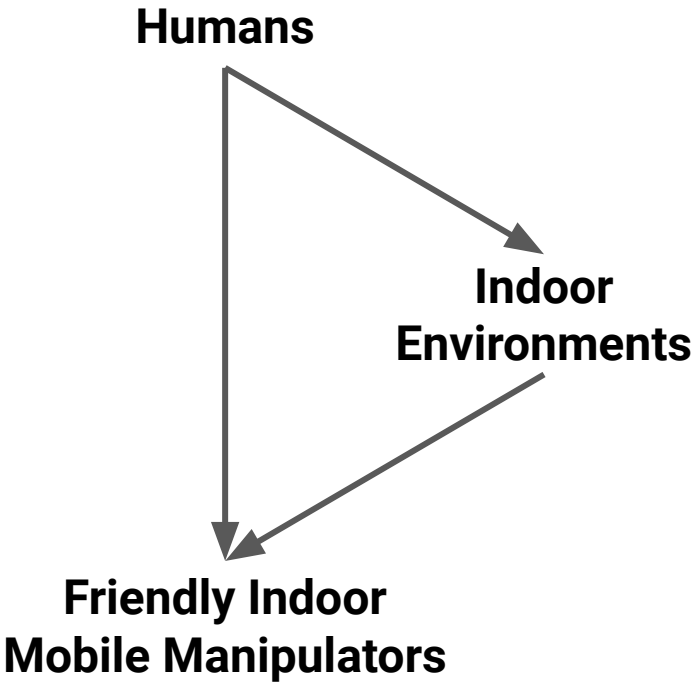
Richard P. Feynman, "Appendix F – Personal Observations on Reliability of Shuttle", NASA,1986.

https://en.wikipedia.org/wiki/Rogers_Commission_Report#Role_of_Richard_Feynman
https://en.wikipedia.org/wiki/Richard_Feynman#/media/File:Richard_Feynman_Nobel.jpg

The Robot’s Body Depends on Our Bodies

The Robot's Body Depends on Our Bodies

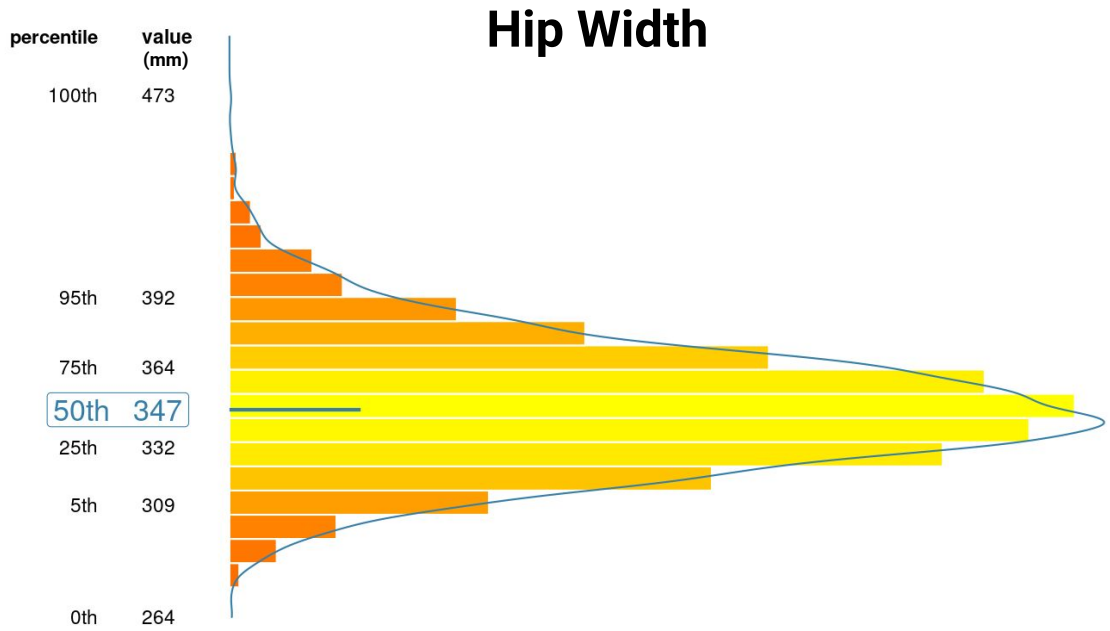
and the human body is unlikely to change significantly



The Robot's Body Depends on Our Bodies

and the human body is unlikely to change significantly

- Helpful
  - Reaches what matters
  - Perceives what matters
- Easy to use
  - Easy to transport
  - Easy to predict motions
- Safe
  - Low risk of falling
  - Low risk of pinch points
  - Force sensitive



https://en.wikipedia.org/wiki/Anthropometry
https://en.wikipedia.org/wiki/Human_factors_and_ergonomics
Histogram from Open design lab, Data Explorer II, Anthropometric Survey of US Army Personnel (ANSUR 2) at http://tools.openlab.psu.edu/tools/explorer.php with attributes: gender - both, variable name - hipbreadth
The Design of Stretch: A Compact, Lightweight Mobile Manipulator for Indoor Human Environments, Charles C. Kemp, Aaron Edsinger, Henry M. Clever and Blaine Matulevich, IEEE International Conference on Robotics and Automation (ICRA), 2022.

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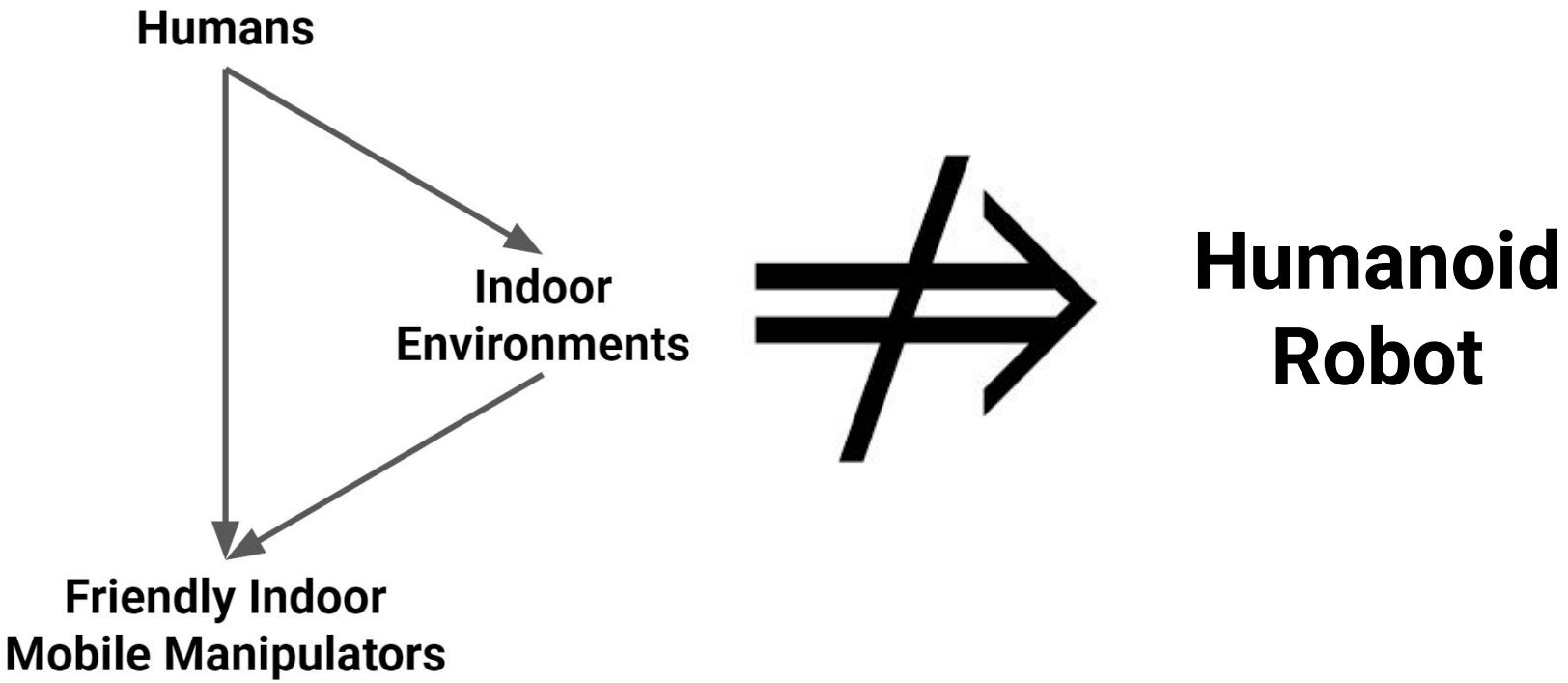
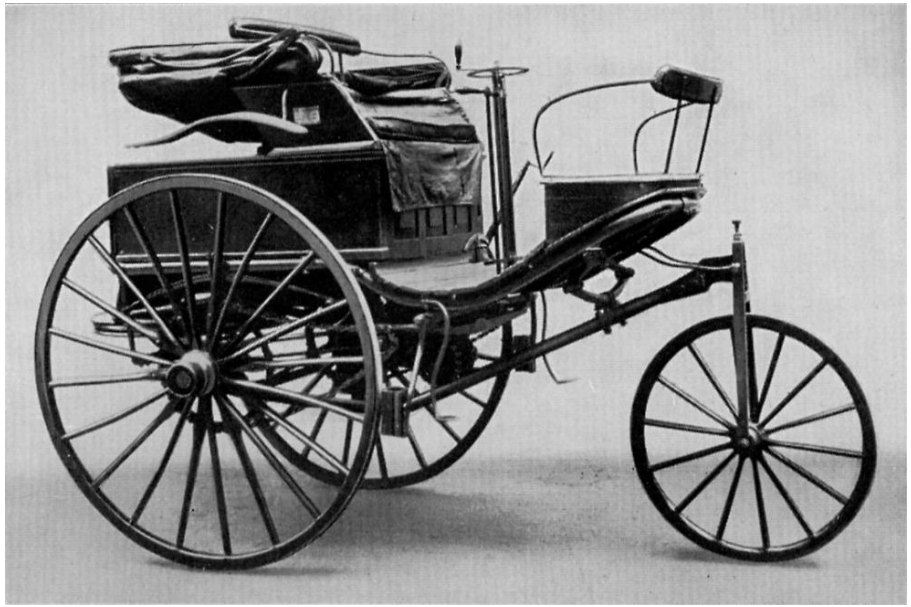


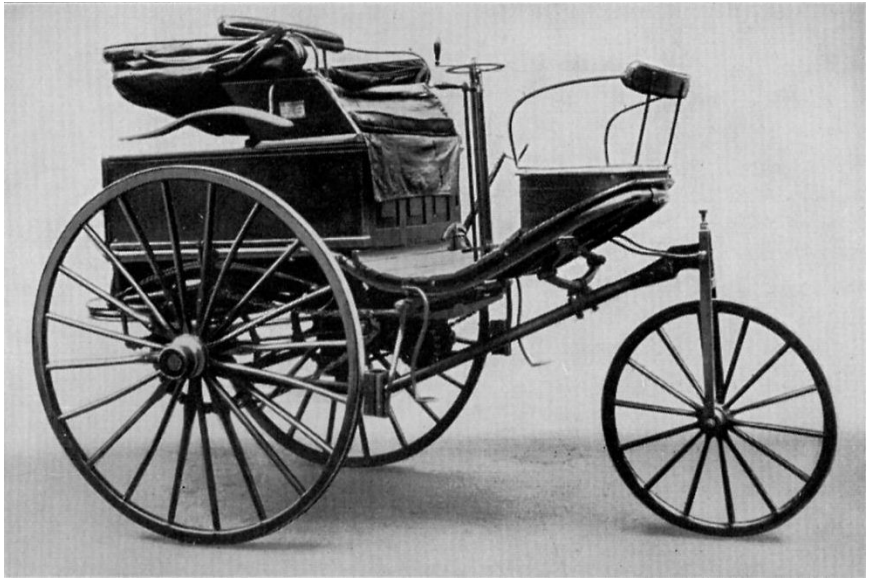
What does this look like?



Benz Patent-Motorwagen from 1885
“widely regarded as the world's first practical modern automobile” [1]

image: https://upload.wikimedia.org/wikipedia/commons/0/0c/Motorwagen_Serienversion.jpg
[1] https://en.wikipedia.org/wiki/Benz_Patent-Motorwagen

Previous Solutions Bias New Solutions

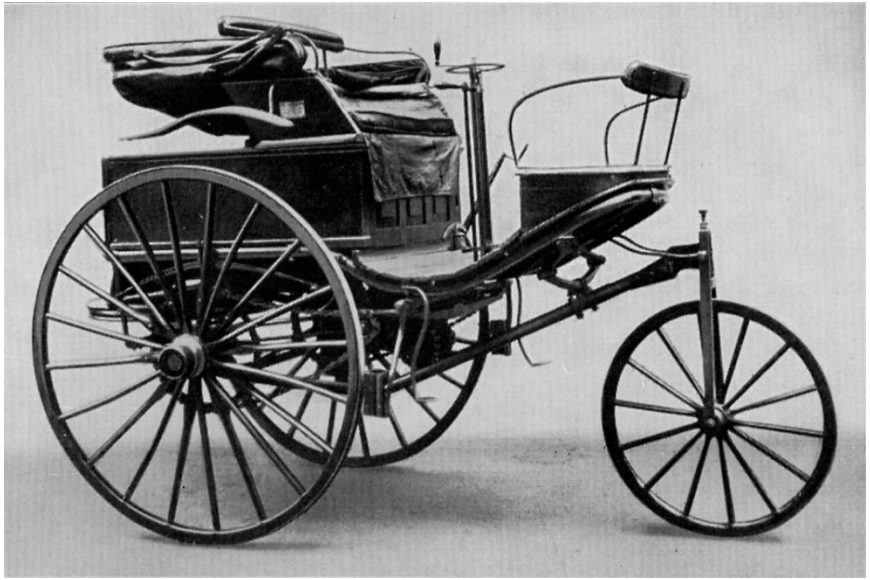


Benz Patent-Motorwagen from 1885

Horse and buggy from 1910

https://upload.wikimedia.org/wikipedia/commons/0/0c/Motorwagen_Serienversion.jpg
https://upload.wikimedia.org/wikipedia/commons/5/5a/Horse_and_buggy_1910.jpg
https://en.wikipedia.org/wiki/Benz_Patent-Motorwagen
https://en.wikipedia.org/wiki/Horse_and_buggy

Previous Solutions Bias New Solutions



Benz Patent-Motorwagen from 1885

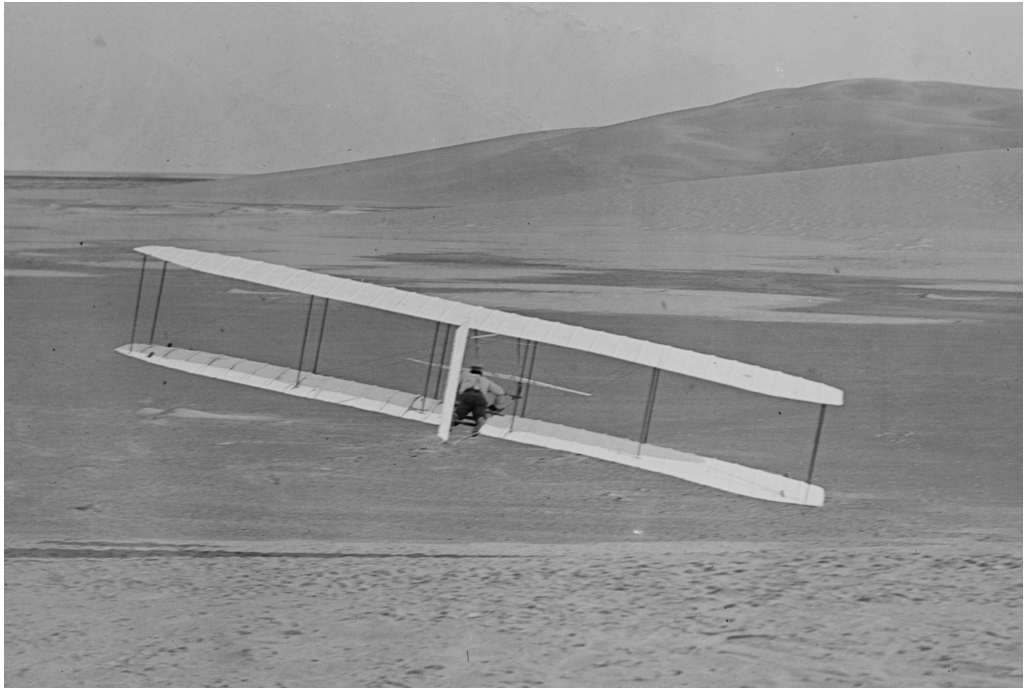
Tesla Model Y from 2022

https://upload.wikimedia.org/wikipedia/commons/0/0c/Motorwagen_Serienversion.jpg
https://upload.wikimedia.org/wikipedia/commons/5/5a/Horse_and_buggy_1910.jpg
https://en.wikipedia.org/wiki/Benz_Patent-Motorwagen

Biological Inspiration Can Be Misleading

Edward Purkis Frost's ornithopter from 1902

E. P. Frost appears to have been a respected member of the Royal Aeronautical Society, since he was its president from 1908 to 1911.



Wright Glider from 1902

Sources:
https://www.onverticality.com/blog/e-p-frost-ornithopters
https://en.wikipedia.org/wiki/Edward_Purkis_Frost
https://upload.wikimedia.org/wikipedia/commons/2/23/1902_Wright_glider_turns.jpeg
https://en.wikipedia.org/wiki/Wright_brothers

Biological Inspiration Can Be Misleading

Ms. Krüger from 1951

Bosch from 2023

This machine helps me wash my family's dishes. I'm grateful society didn't wait for a humanoid helper.

https://en.wikipedia.org/wiki/Dishwasher
https://en.wikipedia.org/wiki/Dishwashing
https://upload.wikimedia.org/wikipedia/commons/9/9e/Bundesarchiv_Bild_183-12913-0005%2C_Berlin%2C_Abwaschen.jpg

The Robot's Body Depends on Our Bodies

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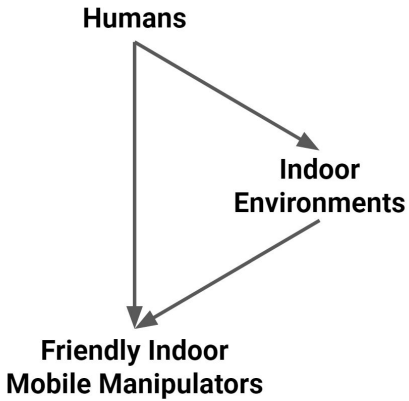
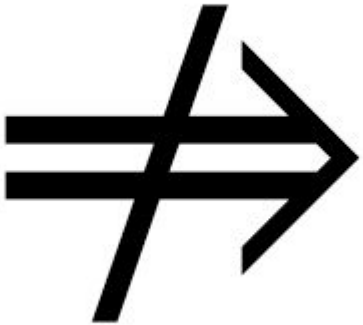




Humanoid Robot

Safety

:(

Your PC ran into a problem and needs to restart. We're just collecting some error info, and then we'll restart for you.

20% complete

For more information about this issue and possible fixes, visit https://www.windows.com/stopcode

If you call a support person, give them this info:

Stop code: CRITICAL_PROCESS_DIED

Have you ever?

Had a device run out of batteries unexpectedly (e.g., phone, laptop)?

Had a computer fail unexpectedly (e.g., blue screen of death)?

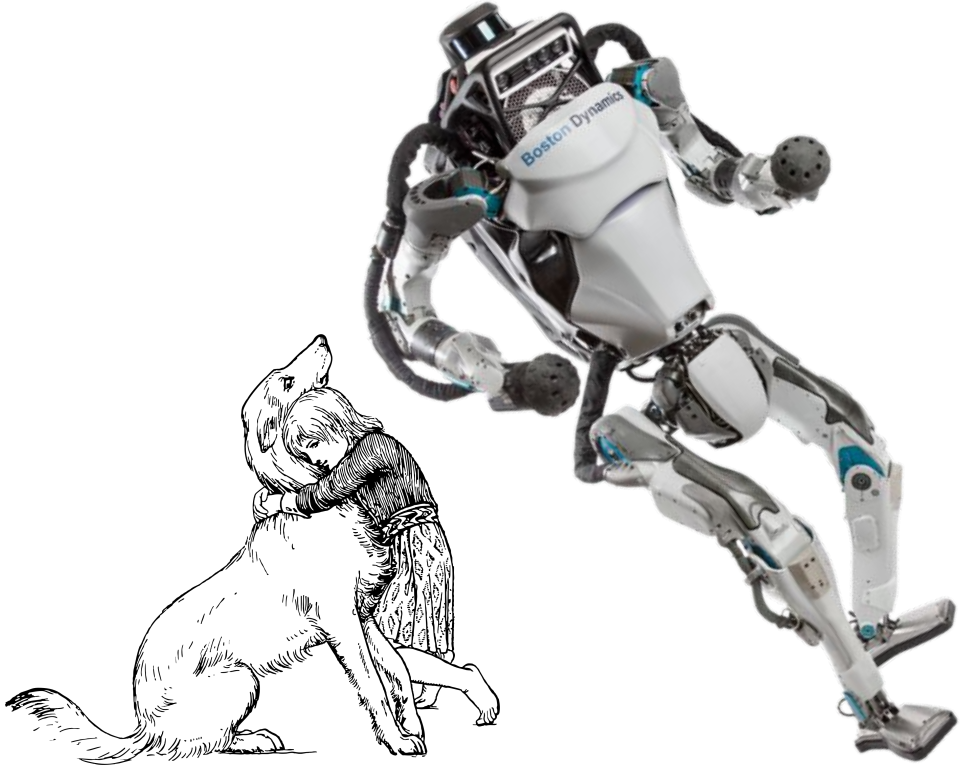
Had a kid or pet do something unexpected around you?

Been careful around an older adult due to concerns about them falling?

Stumbled in your own home?

Image in previous slide from: https://en.wikipedia.org/wiki/Screen_of_death

It Just Takes One Fall



Images from
https://openclipart.org/detail/314874/little-girl-hugging-dog
https://ozrobotics.com/tag/humanoid-robot/

For the next 10 years, bipedal locomotion and two-wheeled balancing are unlikely to be the dominant approaches for human-scale mobile manipulators in **inclusive indoor environments**.

How can we use first principles to compare mobile manipulator designs?

Cost of Transport

$$\mathrm{COT} \triangleq \frac{E}{mgd} = \frac{P}{mgv}$$

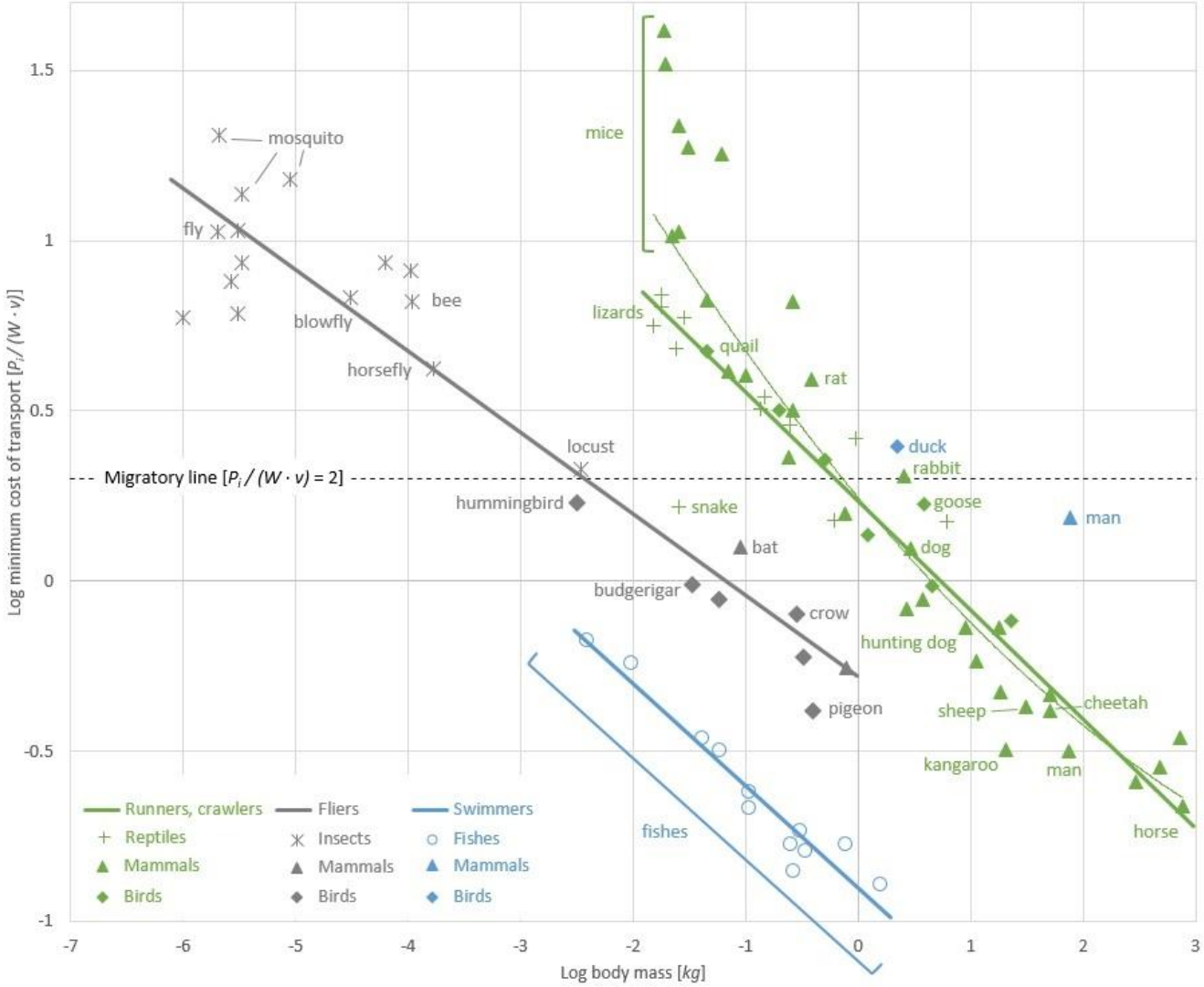
m : mass
g : gravitational acceleration (9.8 m/s^2)

E : energy input to the system
d : distance

P : power input to the system
v : velocity

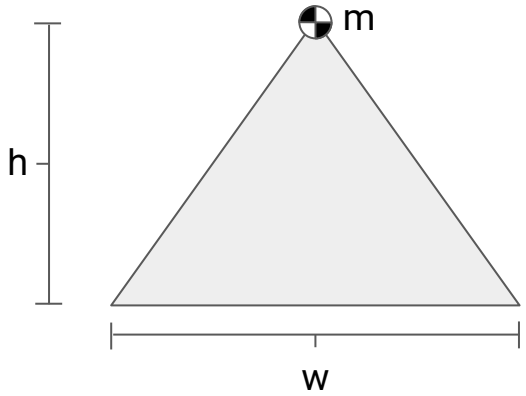
Tucker, Vance A. **"The energetic cost of moving about"** *American Scientist* 63, no. 4 (1975): 413-419.

https://commons.wikimedia.org/wiki/File:Minimum_cost_of_transport_comparison.jpg
https://en.wikipedia.org/wiki/Cost_of_transport

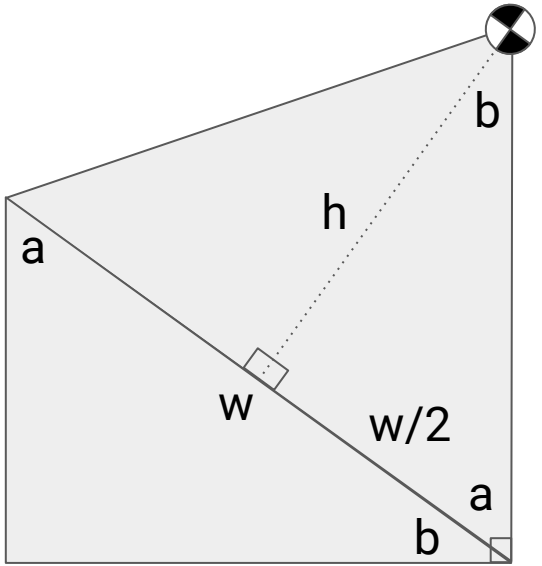


Gravitational Potential Energy as a Measure of Friendliness

- U = mgh
  - m : mass of the robot
  - g : gravitational acceleration (9.8 m/s^2)
  - h : height of the center of mass
  - SI unit : joule
- Fall risk
  - mgh models the energy transferred when the robot falls
- Difficulty moving the robot manually
  - m indicates how hard it would be to lift manually
- Robot's base width
  - h is proportional to w, the width of the robot's base required for static stability on a sloped surface



https://en.wikipedia.org/wiki/Gravitational_energy



h is proportional to the minimum width, w, of the robot's base of support for static stability on a slope with angle b

$$h \propto w$$

$$\frac{\frac{w}{2}}{h} = \tan(b)$$

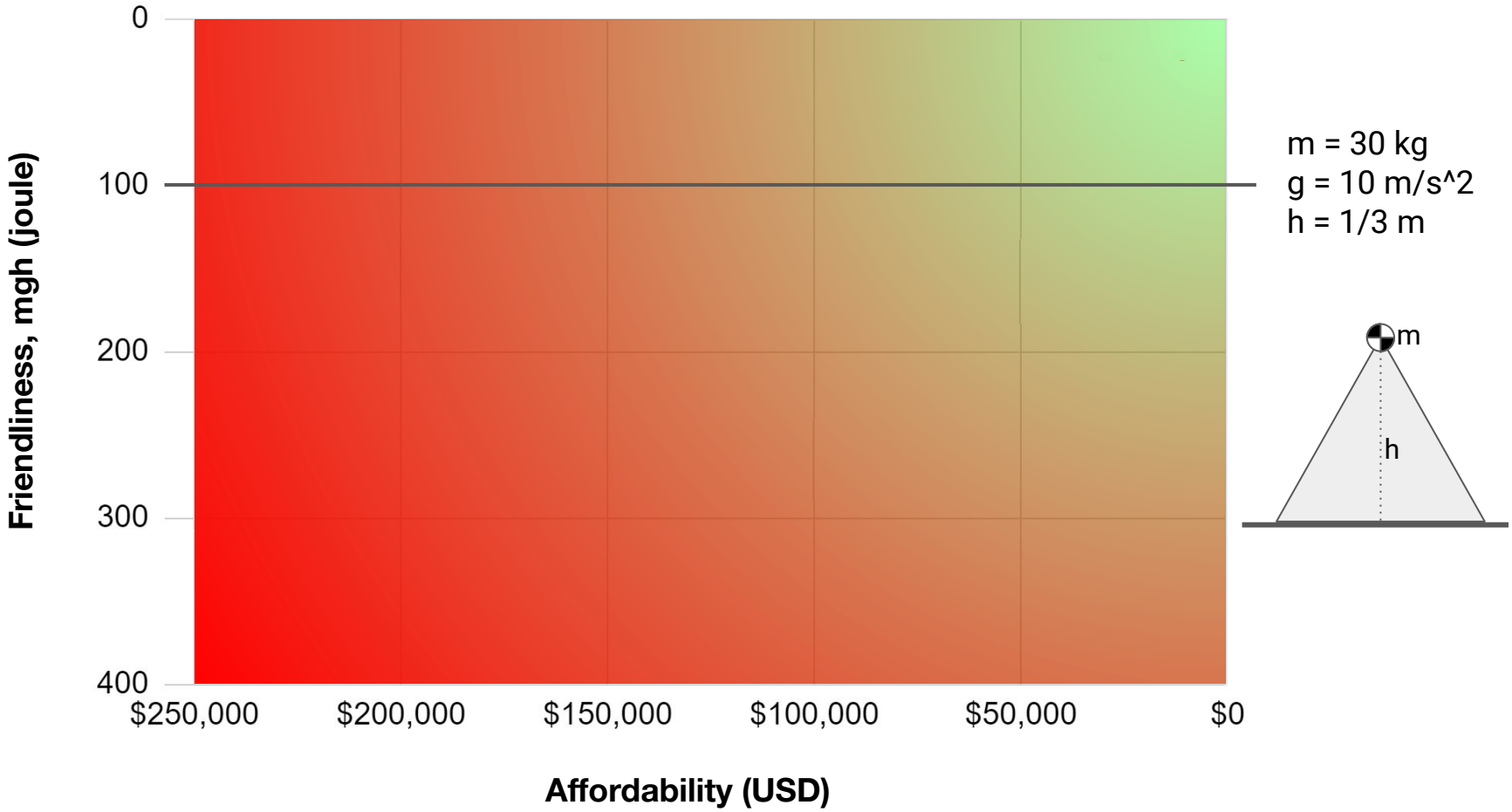
$$h = \frac{w}{2\tan(b)}$$

Where

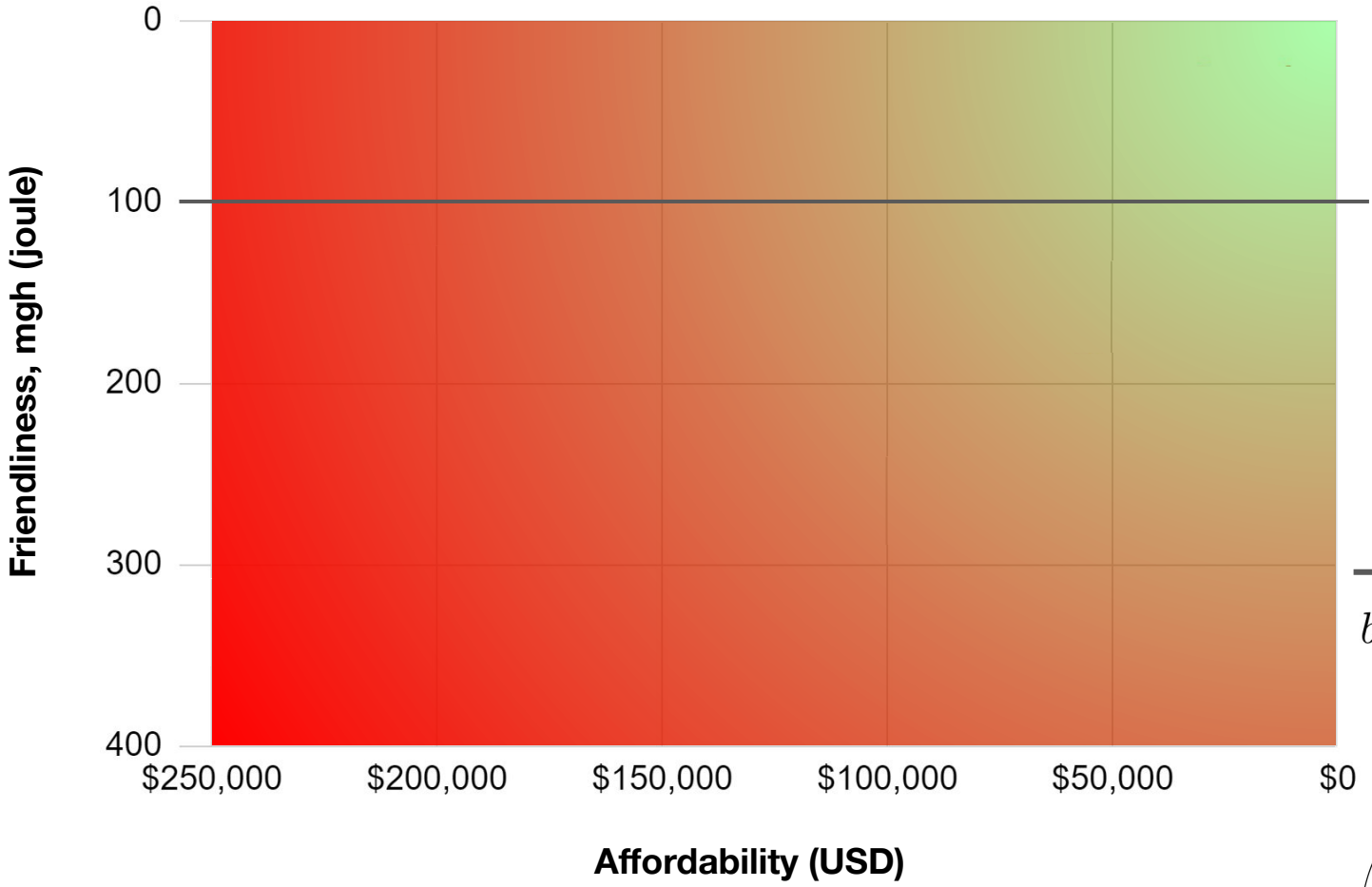
b : maximum slope before tipping
w : minimum base width before tipping

Comparing Human-scale Mobile Manipulators

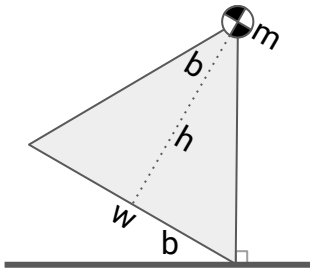
Comparing Human-scale Mobile Manipulators



Comparing Human-scale Mobile Manipulators

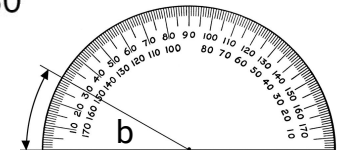


m = 30 kg
g = 10 m/s^2
h = 1/3 m

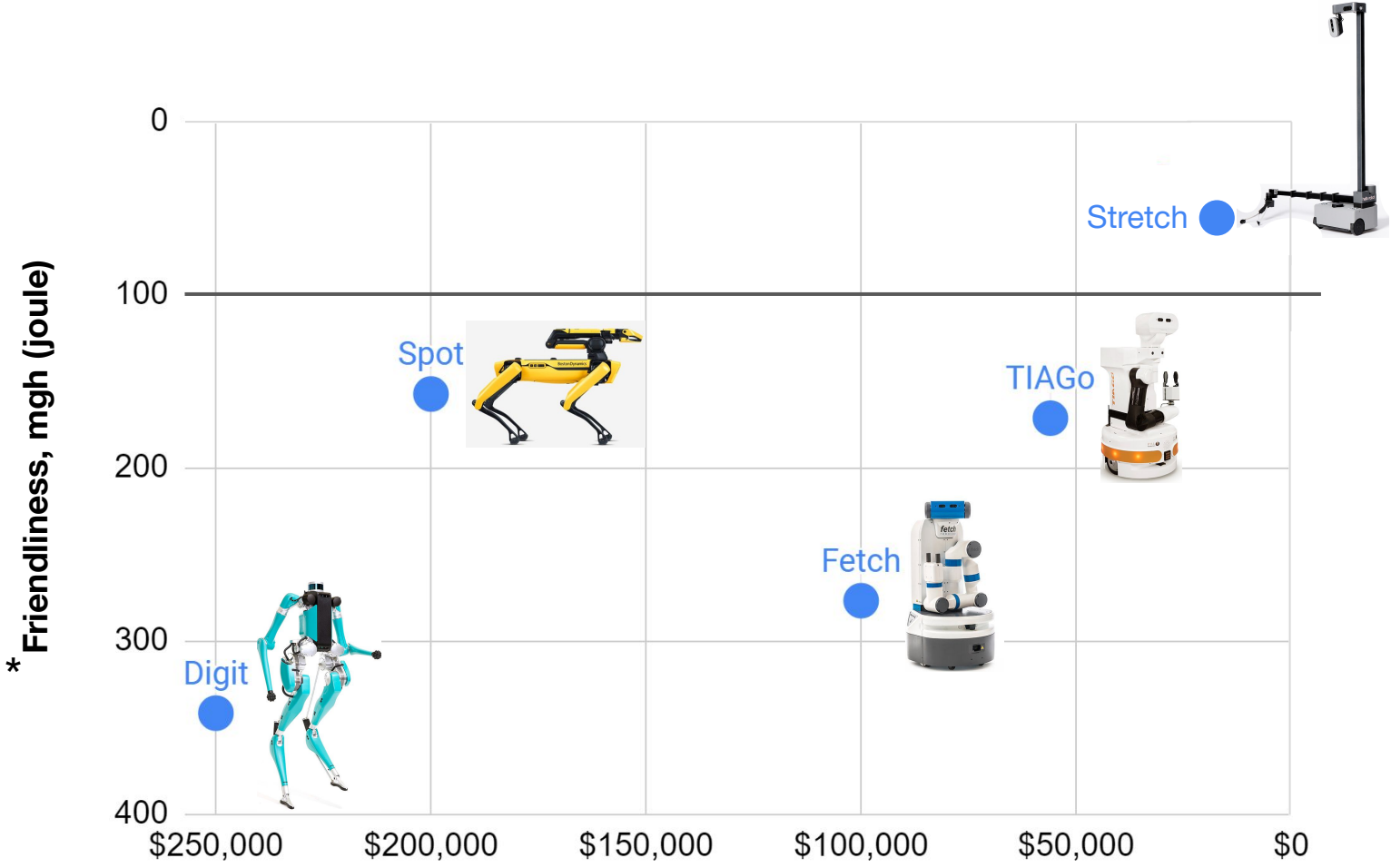


$$b = \arctan\left(\frac{w}{2h}\right)$$

w = 0.4 m
b = 31 deg



https://etc.usf.edu/clipart/42000/42005/pro_30_42005.htm



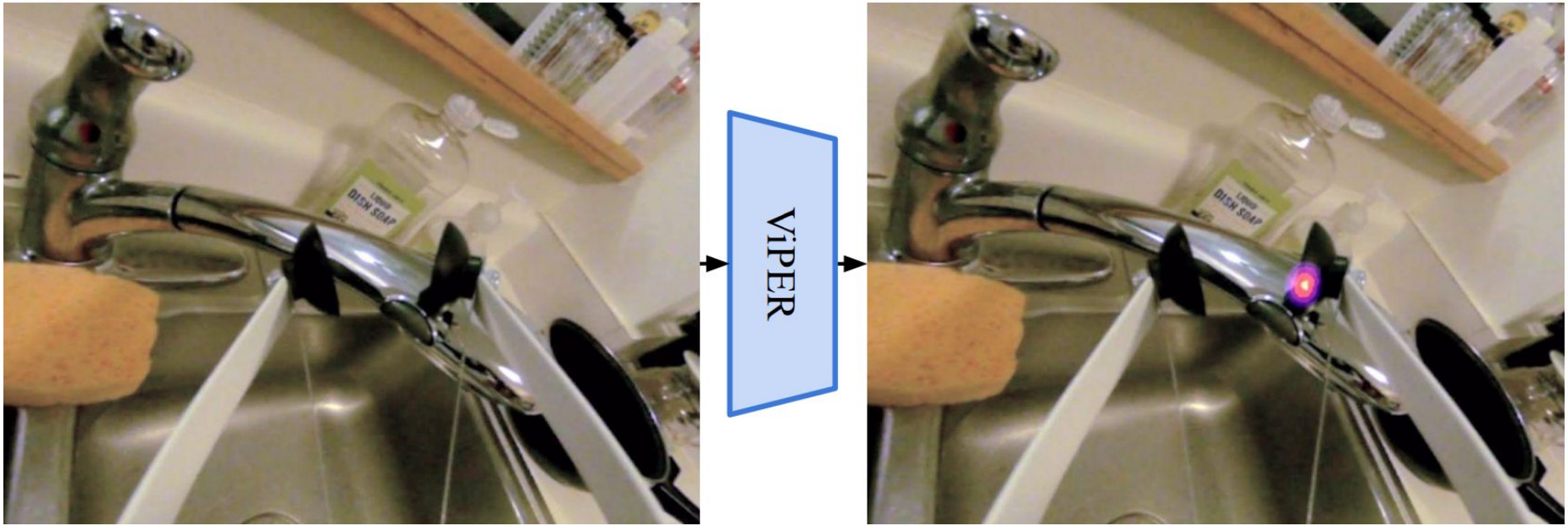
* *I estimated mgh based on published masses and dimensions with arms and lifts lowered. There could be significant errors.*

images from:
https://hello-robot.com
https://fetchrobotics.com/fetch-mobile-manipulator/
https://robotsguide.com/robots/digit https://pal-robotics.com/robots/tiago/
https://arstechnica.com/gadgets/2021/02/boston-dynamics-robot-dog-gets-an-arm-attachment-self-charging-capabilities/

Haptic Intelligence will be Increasingly Useful

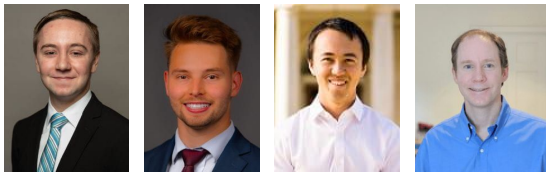
Input Image

Visually Estimated Pressure

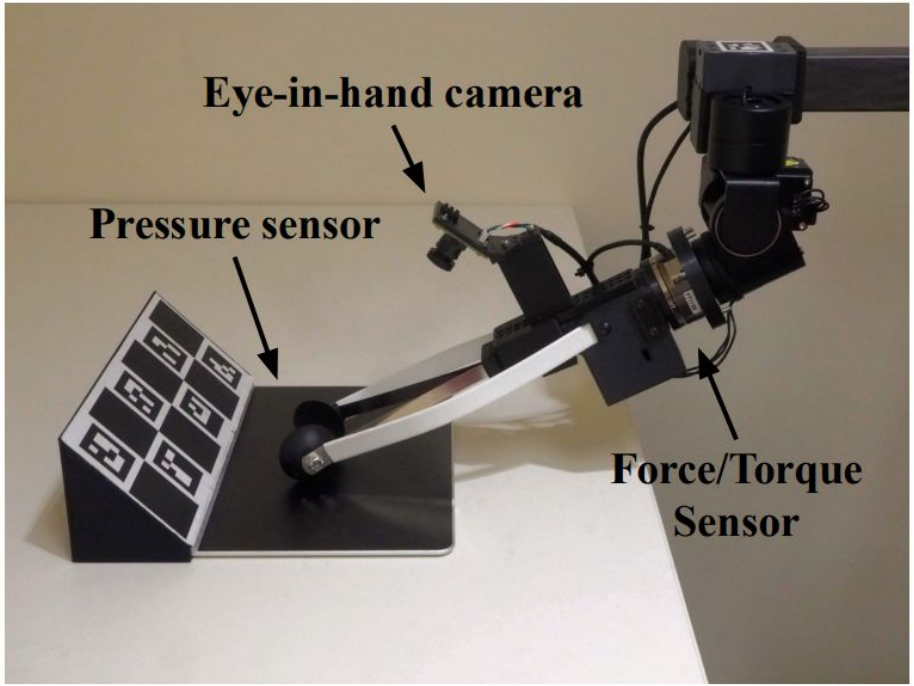


Jeremy A. Collins, Cody Houff, Patrick Grady, and Charles C. Kemp. ***Visual contact pressure estimation for grippers in the wild***. Accepted to IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2023.

https://github.com/Healthcare-Robotics/ViPER



Fully Labeled Data



Weakly Labeled Data

Inspired By: Patrick Grady, Jeremy Collins, Chengcheng Tang, Christopher Twigg, James Hays, Charles C. Kemp, Visual Estimation of Fingertip Pressure on Diverse Surfaces using Easily Captured Data,, arxiv, 2023.


Input Image
VIPER
Visually Estimated Pressure

Future Applications Look Crazy Today

Spacewar!

1962 : Created at MIT
1971 : 1st arcade video game
2023 : $188B industry

Nolan Bushnell was directly inspired by Spacewar! at the Stanford Artificial Intelligence Laboratory (SAIL), which led to the first arcade video game in 1971 and founding Atari in 1972, which released Pong in 1972 and the Atari 2600 home video game system in 1977.

Lowood, Henry. "Videogames in computer space: The complex history of pong." IEEE Annals of the History of Computing 31, no. 3 (2009): 5-19.

https://youtu.be/1EWQYAfuMYw?t=875
https://en.wikipedia.org/wiki/Spacewar!
https://en.wikipedia.org/wiki/Computer_Space
https://en.wikipedia.org/wiki/Galaxy_Game
https://en.wikipedia.org/wiki/Nolan_Bushnell
https://en.wikipedia.org/wiki/Atari,_Inc.
https://en.wikipedia.org/wiki/Video_game_industry
https://en.wikipedia.org/wiki/Film_industry
https://en.wikipedia.org/wiki/Music_industry

In 1962
Spacewar!
looked crazy!

DEC PDP-1
$1.3M
(today's dollars)
1959 release
53 shipped

https://en.wikipedia.org/wiki/PDP-1

Applications Look Less Crazy Over Time

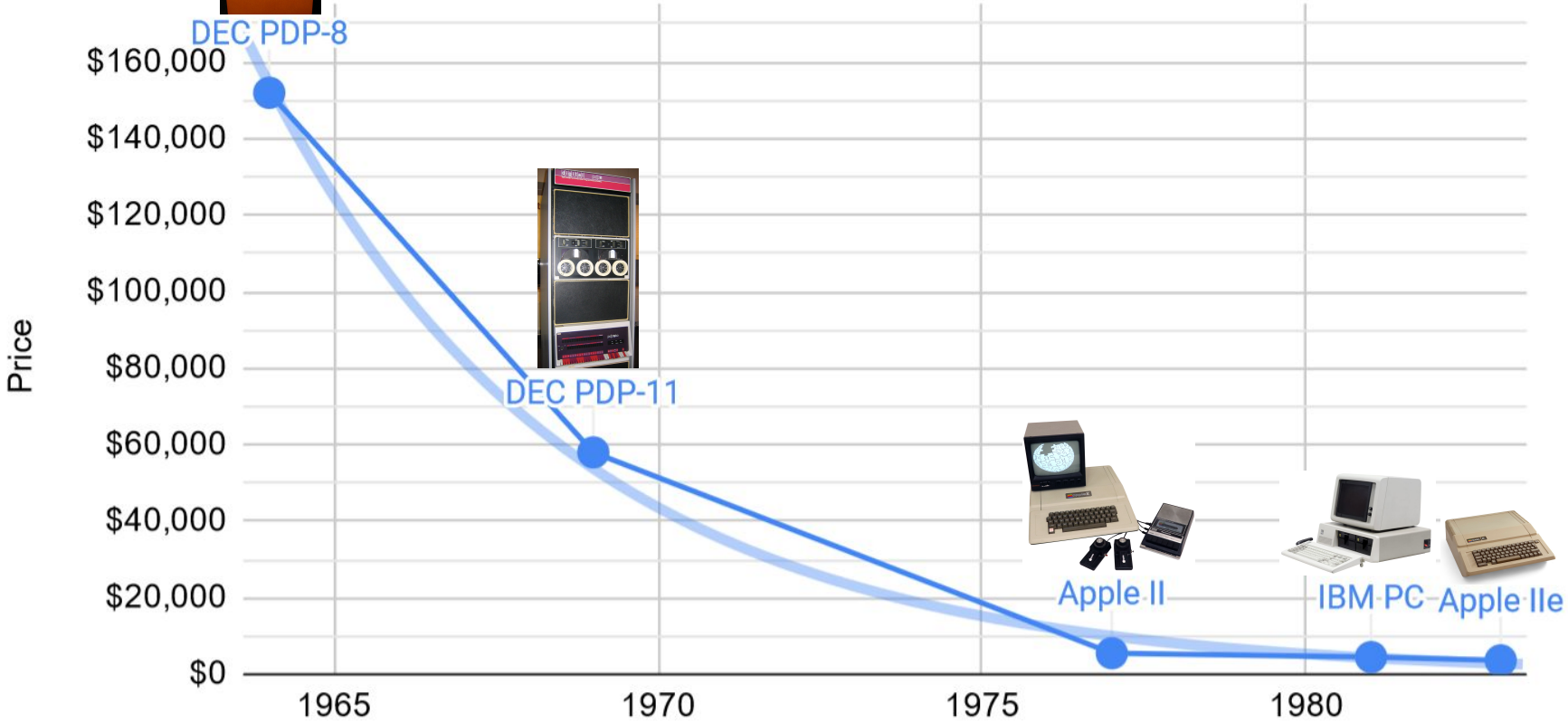
DEC PDP-8

DEC PDP-11

Apple II

IBM PC

Apple IIe



Images from:
https://en.wikipedia.org/wiki/PDP-8
https://en.wikipedia.org/wiki/PDP-11
https://en.wikipedia.org/wiki/Apple_II
https://en.wikipedia.org/wiki/IBM_Personal_Computer
https://en.wikipedia.org/wiki/Apple_IIe

Future Applications Look Crazy Today

P.O.O.P. S.C.O.O.P

"Perception Of Offensive Products and Sensorized Control Of Object Pickup"

https://youtu.be/3q4cLRBaDvg

Benjamin Cohen, Daniel Benamy, Anthony Cowley, William McMahan, and Joseph Romano. **"Poop scoop: Perception of offensive products and sensorized control of object pickup."** In The PR2 Workshop at the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). 2011.

Boldness & Creativity Overcome Impracticalities

	Willow Garage PR2	**Digital Equipment Corporation PDP-1**
Price (inflation adjusted)	$540,000	$1,300,000
# of units	~50	~53
Weight	227 kg (500 lb)	730 kg (1,600 lb)
Width	0.67 m	2 m
Date released	2010	1959
Link	https://robotsguide.com/robots/pr2	https://en.wikipedia.org/wiki/PDP-1

Citations for a Variety of PR2 Examples

Examples include assisting people with disabilities [1]–[6], retrieving and delivering objects [7]–[13], cleaning [14]–[16], organizing [17]–[19], laundry [20], [21], exercise [22], and entertainment [23]–[25].

[14] B. Cohen, D. Benamy, A. Cowley, W. McMahan, and J. Romano, "POOP SCOOP: Perception Of Offensive Products and Sensorized Control Of Object Pickup," *The PR2 Workshop at the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, September 2011.

[**excerpt source**] Charles C. Kemp, Aaron Edsinger, Henry M. Clever, and Blaine Matulevich. **The design of stretch: A compact, lightweight mobile manipulator for indoor human environments**. In *2022 International Conference on Robotics and Automation (ICRA)*, pp. 3150-3157. IEEE, 2022.

Applications Look Less Crazy Over Time

PR2

Fetch

PAL Tiago

Stretch

Price

$450,000
$400,000
$350,000
$300,000
$250,000
$200,000
$150,000
$100,000
$50,000
$0

2010
2012
2014
2016
2018
2020

Year

images from:
Willow Garage
https://fetchrobotics.com/fetch-mobile-manipulator/
https://pal-robotics.com/robots/tiago/
https://hello-robot.com

Georgia Tech

Robotic Caregivers

2023 Spring | 2021 Fall | 2021 Spring | 2020 Spring

Search

Robotic Caregivers – Spring 2023

BMED 4833 ROB & BMED 8813 ROB at Georgia Tech

Overview

*Robotic Caregivers is a project-based class in which teams work with real robots to explore the future of robotic caregivers. **

Robotics researchers and futurists have long dreamed of robots that can serve as caregivers. In this project-based course, students learn about future opportunities and present realities for robots that contribute to caregiving. They gain hands-on experience with teleoperation, autonomy, perception, navigation, manipulation, human-robot interaction, and machine learning. They also learn about robot design, healthcare robotics, and entrepreneurship.

Students are Bold and Creative!

Website
https://sites.gatech.edu/robotic-caregivers/

Students Like the Class

Spring Term 2023
2023 Student Recognition of Excellence in Teaching: Spring Semester 2023 CIOS Honor Roll

Fall Term 2021
2021 Student Recognition of Excellence in Teaching: Class of 1934 CIOS Honor Roll

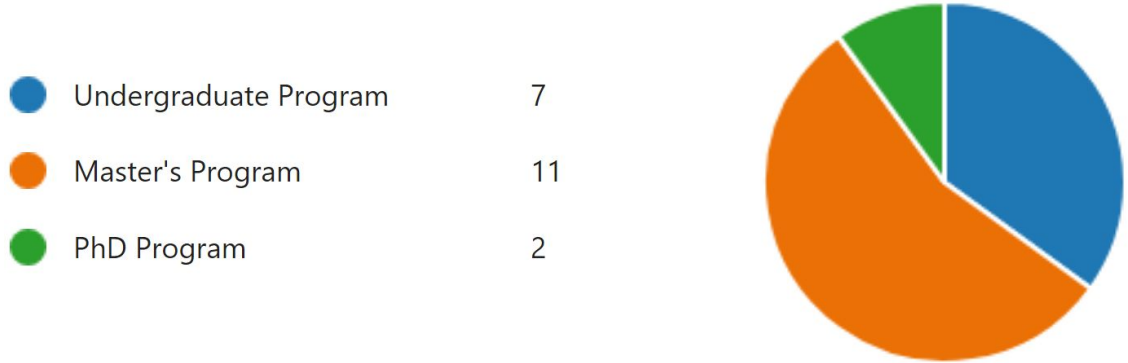
A Project-Based Teaching Community!

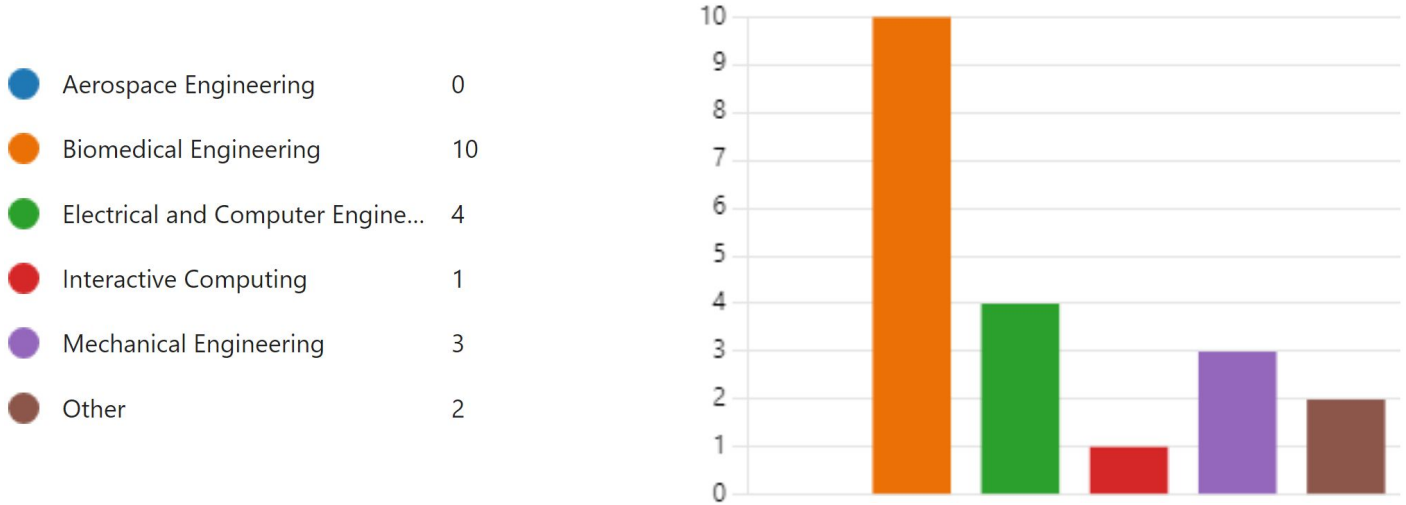
- Prof. Maru Cabrera
  - UMass Lowell
  - Assistive Robotics (COMP.5500)
- Prof. Maya Cakmak
  - University of Washington
  - Robotics Capstone (CSE 481C)
- Prof. Zackory Erickson
  - Carnegie Mellon University
  - Robotic Caregivers and Intelligent Physical Collaboration (16-887)
- Prof. Naomi Fitter
  - Oregon State University
  - Assistive HRI (ROB 599)




AI CARING

Three Teams - Each with a Dedicated Robot

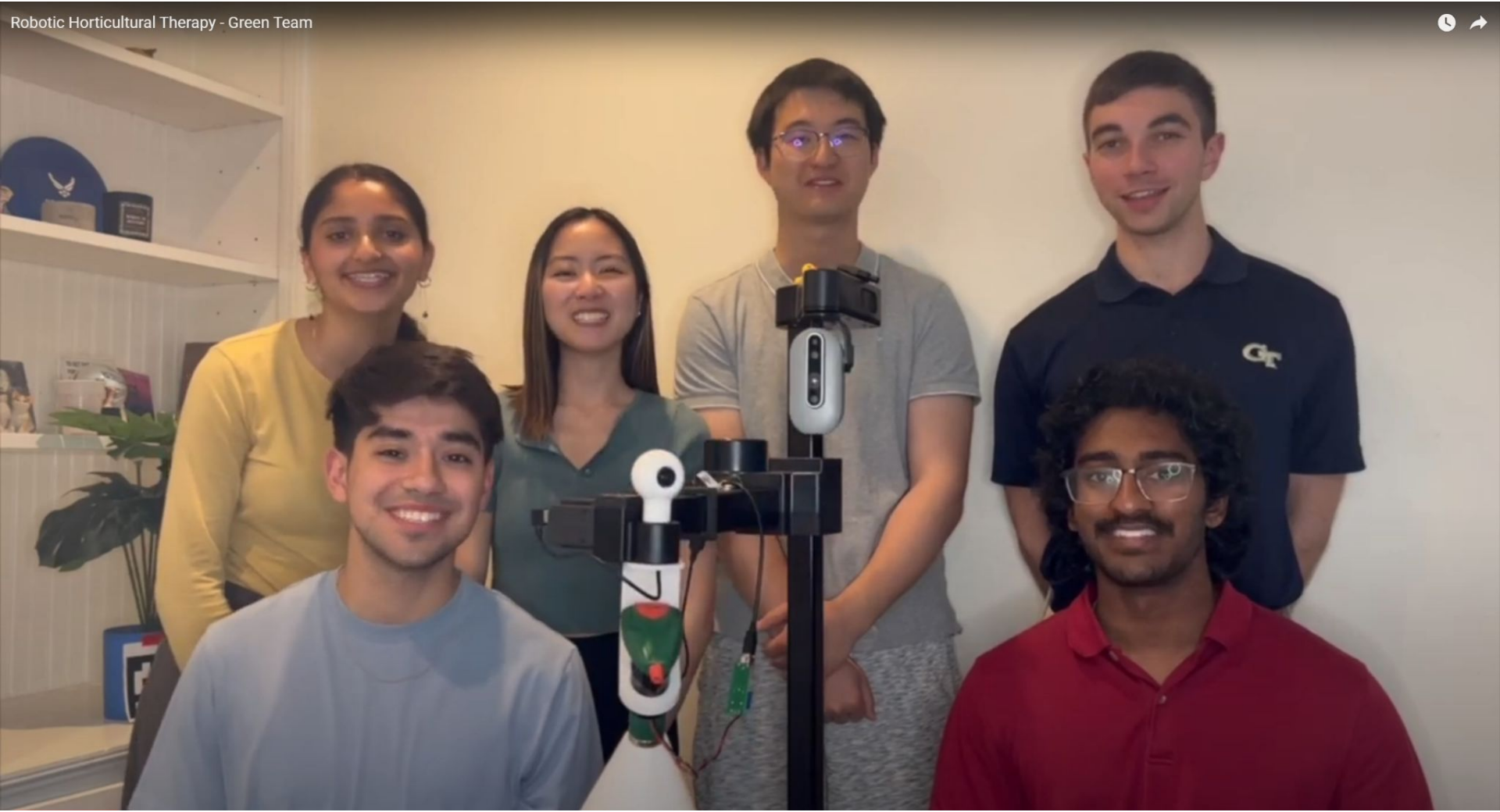




“Other” responses are School of Computer Science and the School of Physics.

Sprout – Robot-Assisted Horticultural Therapy for People with Mobility Impairments

https://youtu.be/0LqbrnJNvPA


Robotic Horticultural Therapy - Green Team


Robotic Horticultural Therapy - Green Team
Time Speed: 1x

localhost:3000

Ok I will go home

Getting plant time lapse video...

Check plant

Plant time lapse

Water plant

Ask question

Cancel action

Call for help

Bye Sprout


Robotic Horticultural Therapy - Green Team
POPCORN
POPCORN


Robotic Horticultural Therapy - Green Team


Robotic Horticultural Therapy - Green Team
Kirk W. Hines, HTR
Director of Horticultural Therapy

Helping People with Mild Cognitive Impairment (MCI) Find Misplaced Objects

https://youtu.be/QUB79UTbwvE

Robotic Assistant for Finding Misplaced Objects


Kanishk .


Oluwatofunmi Sodimu


Nikhil Chittaluru

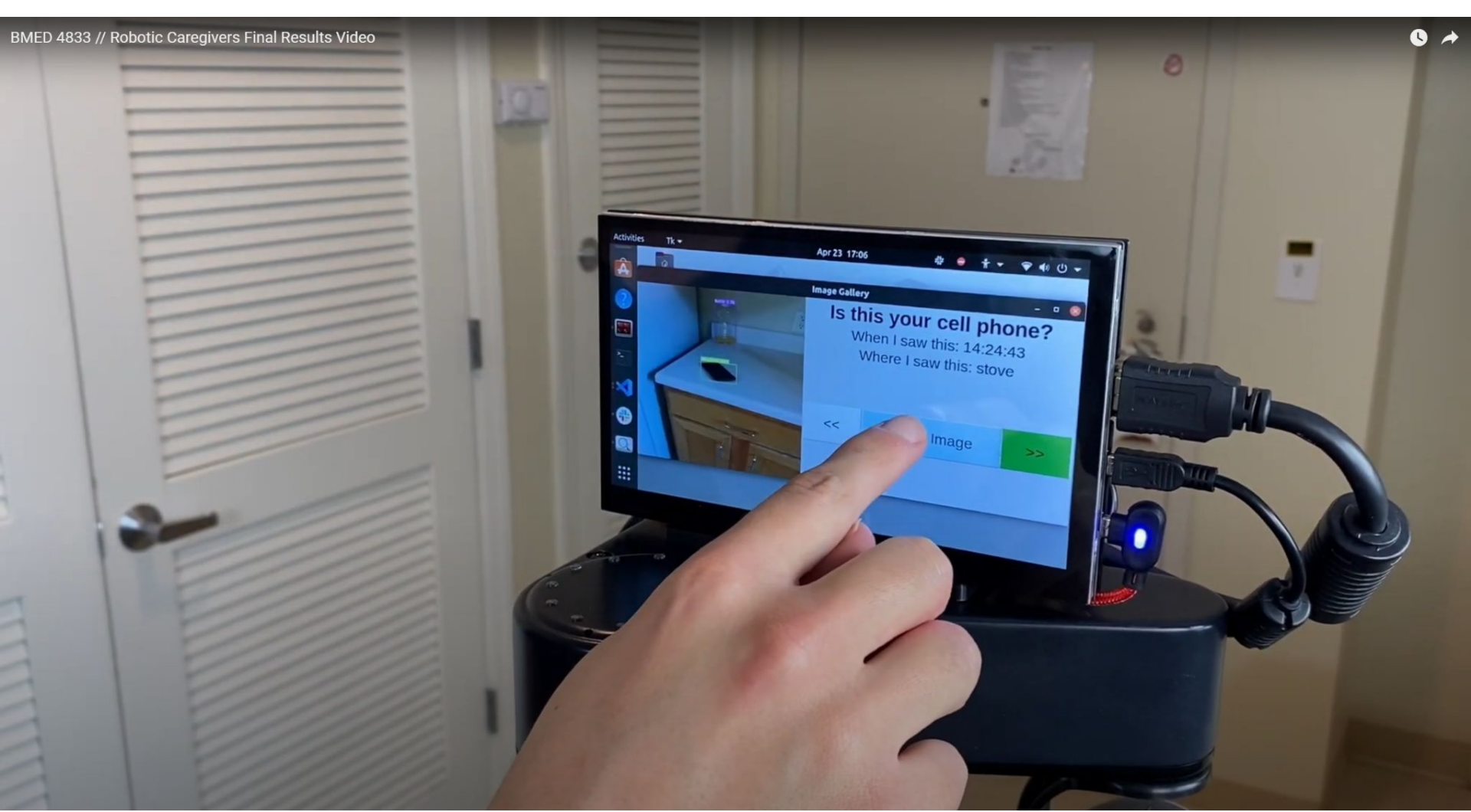

Thanapol Tantagunninat


Erin Kelly


Daniel Lewis


Juan Antonio Robledo


BMED 4833 // Robotic Caregivers Final Results Video
4x speed


BMED 4833 // Robotic Caregivers Final Results Video
Activities
Tk
Apr 23 17:06
Image Gallery
Is this your cell phone?
When I saw this: 14:24:43
Where I saw this: stove
<<
Image
>>


BMED 4833 // Robotic Caregivers Final Results Video
here is where I took the photo

Stretch with Stretch: Robot-led Physical Therapy for Individuals with Parkinson's Disease

https://youtu.be/33iy9St0hBw


Stretch with Stretch: Robot-led Physical Therapy for Individuals with Parkinson's Disease


2x

fyzical_chastain Last week, we had the awesome opportunity to meet with a research group from @georgiatech and discuss the future of technology in physical therapy - and test out this cute little robot named "Stretch"! For people who have Parkinson's Disease (PD), physical therapy involves retraining the brain to correctly perceive the amplitude of the body's movements. External targets provide feedback - did you reach/ lean/ kick far enough or not? This team is working on optimizing a robot to generate an external target, measure outcomes, and provide consistent repetitions. We are looking forward to seeing their progress! Thanks guys!

*

*

*

The Team Grew After the Class

Prof. Madeleine Hackney
Neurokinesiology Lab
Emory School of Medicine
Department of Medicine
Division of Geriatrics and Gerontology
Atlanta VA

Dr. Meredith Wells, PhD
Post-doctoral Research Fellow
Emory School of Medicine
Division of Geriatrics and Gerontology

Emory Master's Students

Zoe Walsh
Nneka Ezeanya

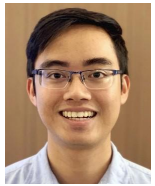
Emory Undergraduates

Elizabeth Nguyen
Arielle Wallenstein

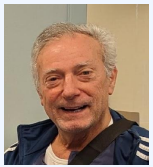
Prof. Charlie Kemp
Georgia Institute of Technology
Department of Biomedical Engineering

Matt Lamsey
Robotics PhD student
Georgia Tech

You Liang Tan
Computer Science
MS student
Georgia Tech



Louis Nguyen
Computer Science and Engineering
MS student
Georgia Tech



Jerry Feldman
Patient Stakeholder Adviser

Dr. Naveen Kuppuswamy, PhD
Senior Research Scientist
Toyota Research Institute

Team that developed the original concept
Robotic Caregivers, Fall 2021

Opportunities for Robot-assisted Physical Therapy

- Reduce caregiver burden in clinics and homes
- Increase frequency and quality of exercise [1]
- Quantitatively track progress and adherence
- Collect clinically-relevant functional measurements

[1] Mak, M. *et. al.* “Long-term effects of exercise and physical therapy in people with Parkinson’s Disease.” *Nature Reviews Neurology 13*, 689-703 (2017).

Fig. 4: We performed a user study with 10 people with PD. (**A-C**) Participants performing seated reaching, kicking, and calf raise exercises. (**D-F**) Participants performing standing reach across, reach down, and high knees exercises. Chairs were placed near the participant as safety devices for the standing exercises.

Preliminary Results

10 people with Parkinson's disease (PD)

1 hour with 6 different exercises

7 participants had increased forward standing reach

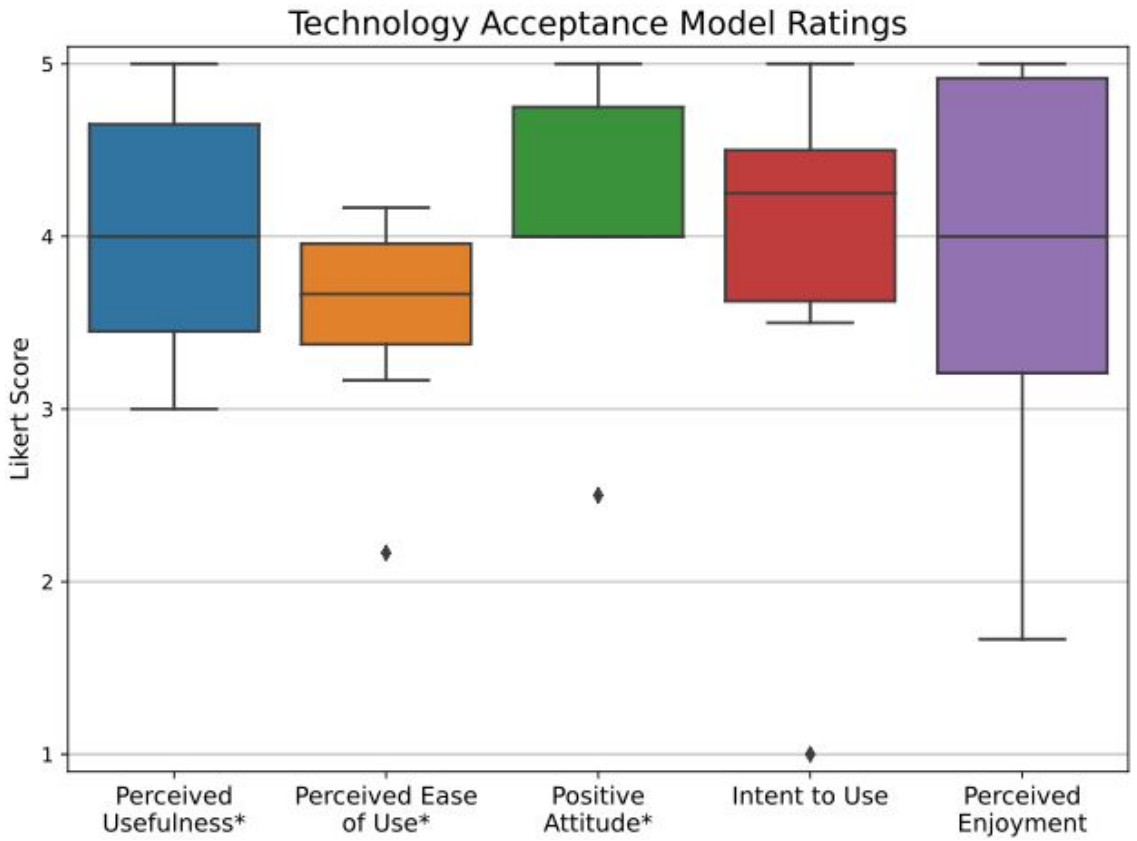
average increase: 0.040±0.046 m

all participants had increased heart rate (HR)

average of 108±13 bpm at the end

all had increased perceived exertion (RPE)

1.6 pre to 6.6 post averages on 0 to 10 scale



Personal Favorites from Explorations at My Home

Two of My Favorite Experiences from the Early Days of Hello Robot

Thanksgiving 2017

Taking care of my family's cat in Atlanta from rural Tennessee using my laptop tethered to my phone.

January 28, 2018

Playing hide-and-seek with my young kids at a time when they ignored video calls. The robot leveled the playing field. I didn't have to pretend I didn't see them!


Hello Robot Inc., February 6, 2018, x8 speedup


remotely teleoperated 32x speed


Hello Robot Inc., January 28, 2018

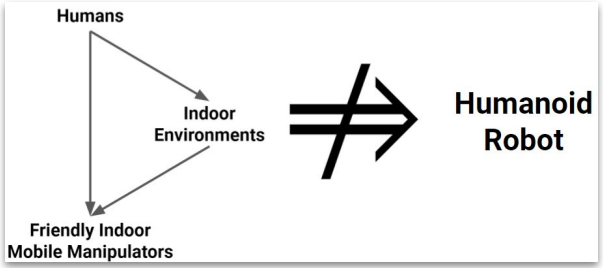
The Future of Friendly Mobile Manipulation

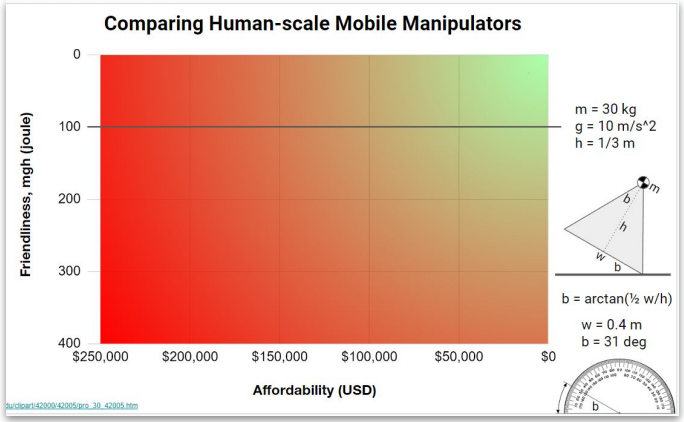
The robot's body depends on our bodies

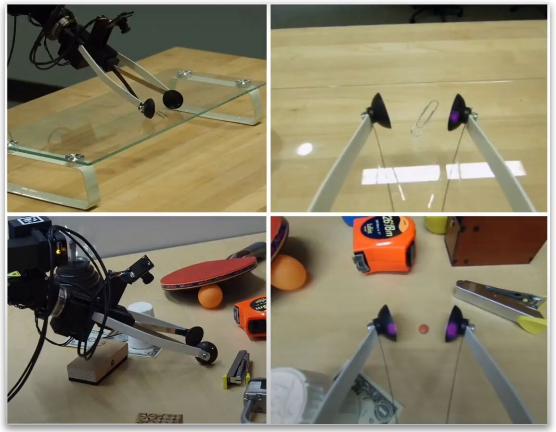
Comparing designs with gravitational potential energy

Haptic intelligence will be increasingly useful

Future applications look crazy today







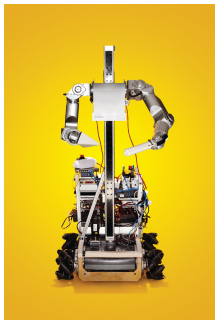
The Future Depends on Us

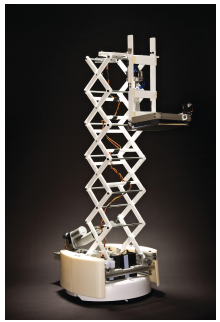
If you don’t create the future, someone will create it for you.

Goodbye and Hello

- Goodbye
  - I'm starting at Hello Robot full-time on Sept 1
  - Giving up tenure
  - Thank you for 17 excellent years at Georgia Tech!
- Hello
  - Working from Atlanta
  - Adjunct appointment expected
  - Happy to facilitate Hello Robot collaborations
  - Are you a faculty member interested in teaching Robotic Caregivers? Let me know!


EL-E (2008)


Cody (2009)


Dusty (2010)


Stretch (2020)