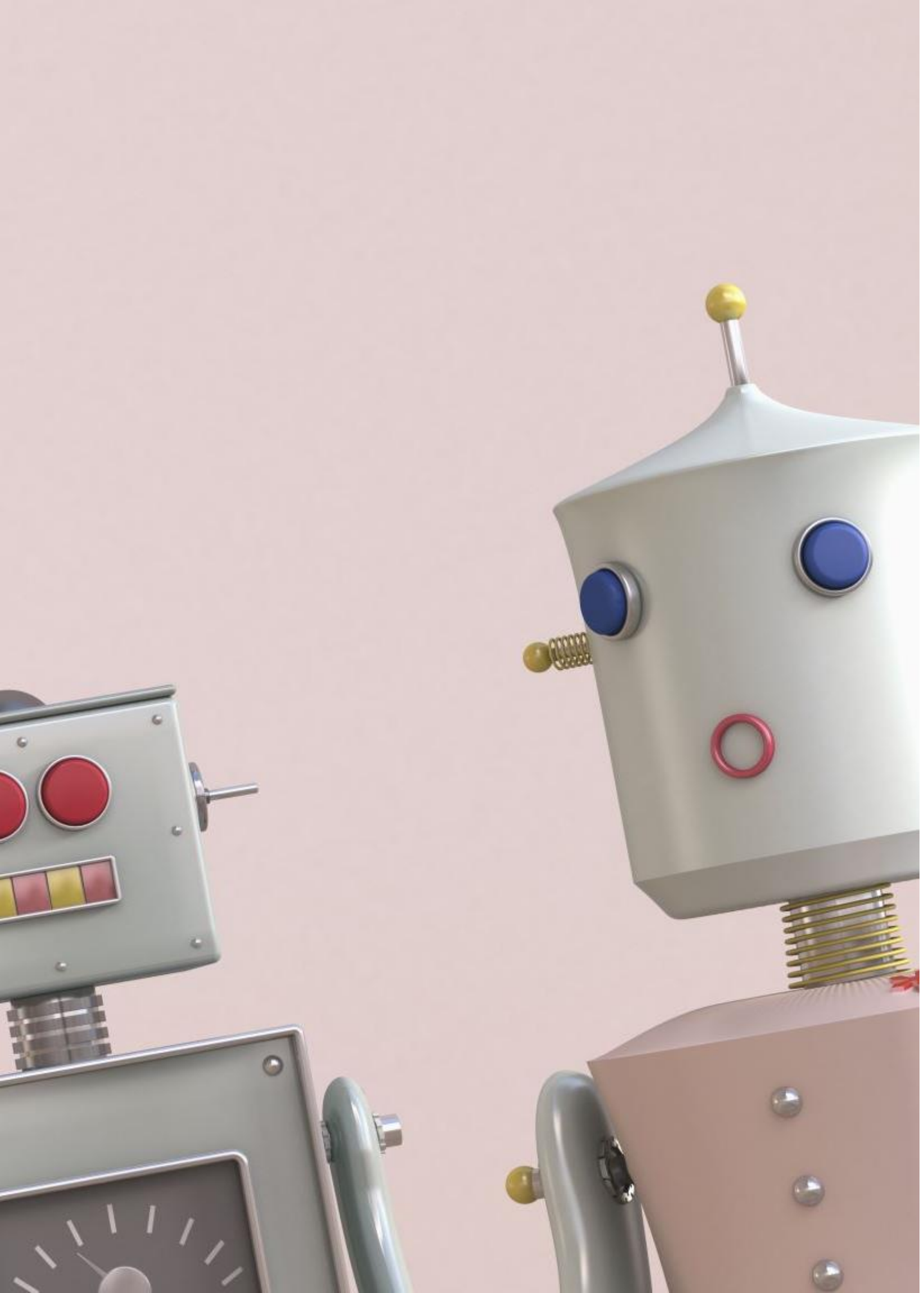


SOCIAL ROBOTS AND HUMAN-ROBOT INTERACTION

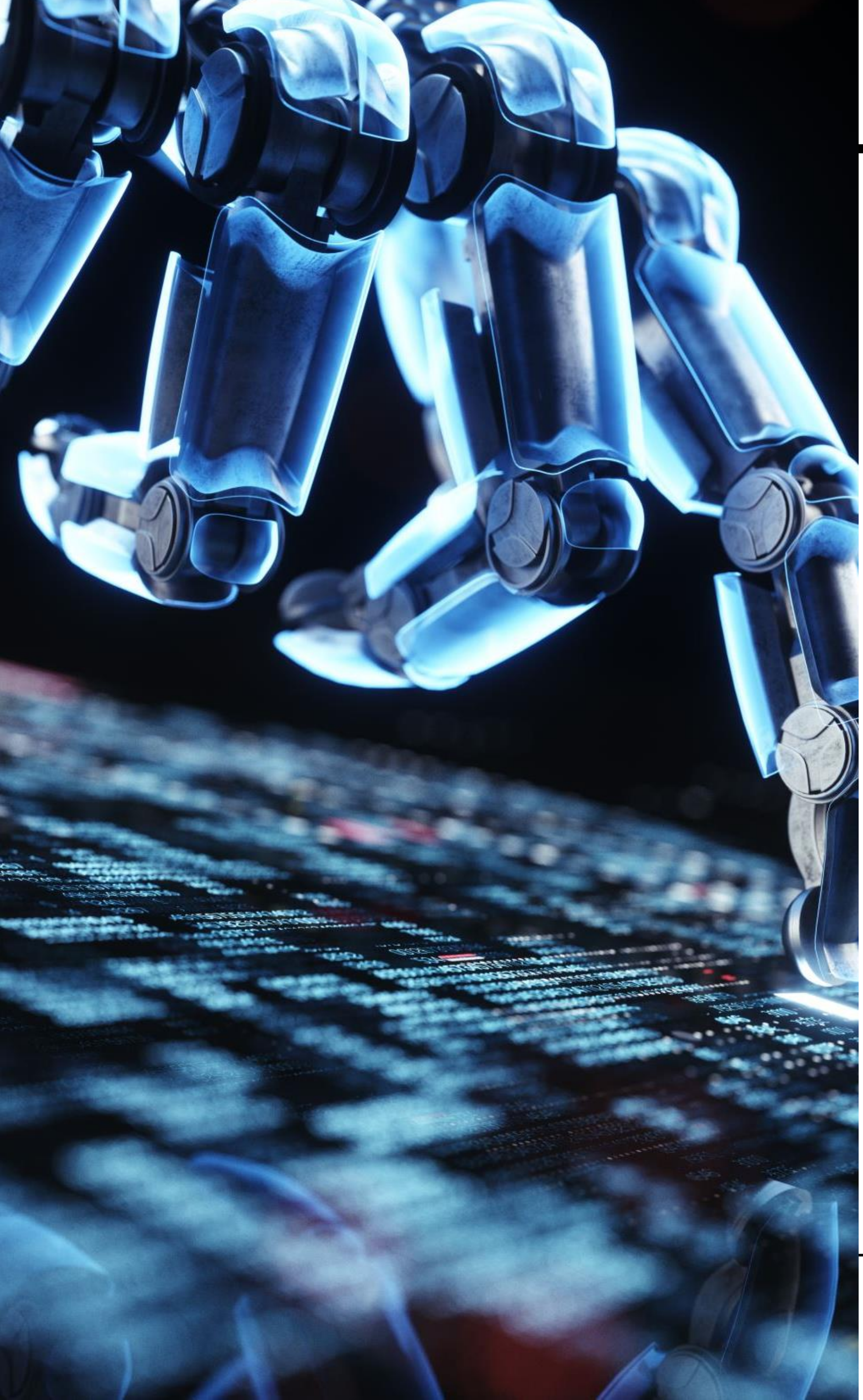
Week 3, Motion and Animation

Ana Paiva

P2
2025/2026

THE PROBLEM

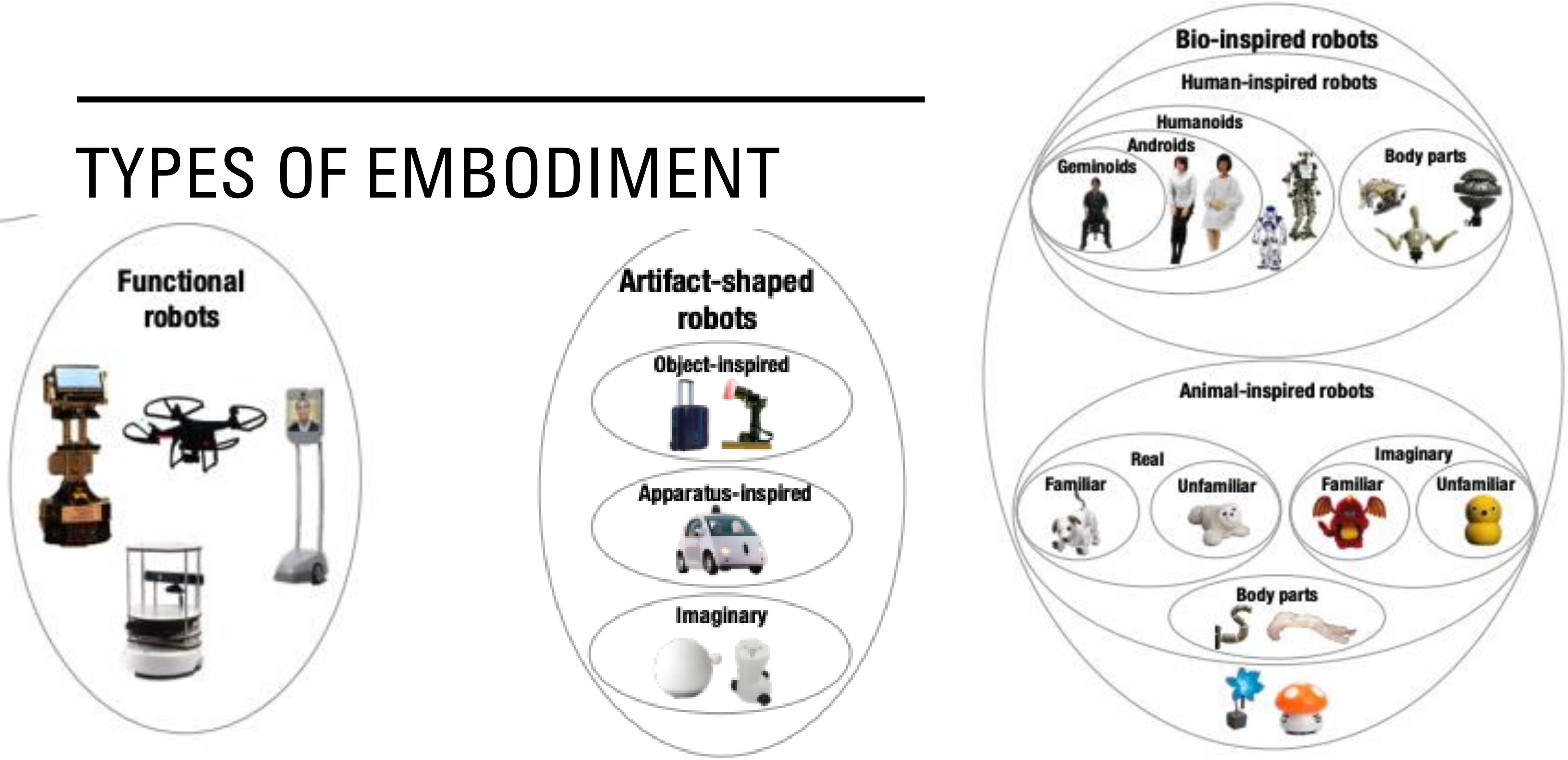
*How to automatically generate physical actions in a robot that are not only **effective at performing** a task but also **expressive enough** to convey intention and social attitudes, be safe and transparent, supporting the social role the robot plays.*



PLAN

- Robots and motion
  - Types of embodiment
  - Properties of motion
- Navigation in social settings
- Designing expressive motion: principles
- Impact of motion (cases)
  - Safety
  - Predictability, Legibility, Intention & Collaboration
  - Intention & Engagement

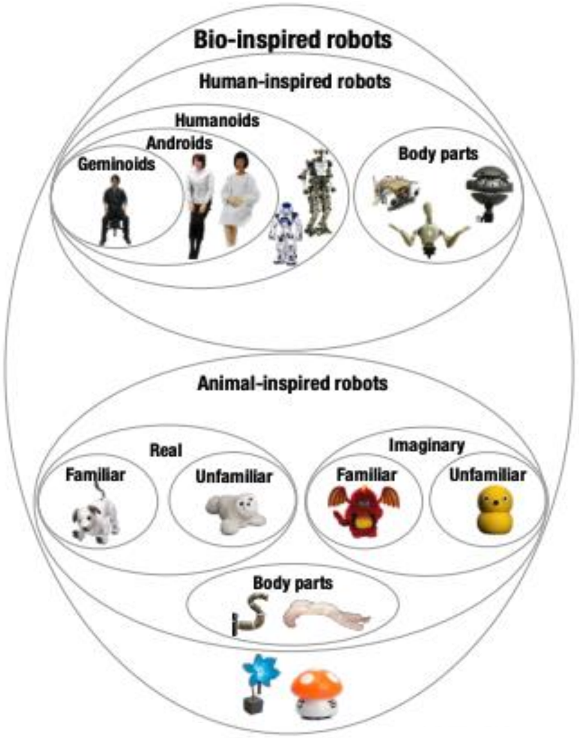
TYPES OF EMBODIMENT



An extended framework for characterizing social robots, by Kim Baraka∗, Patrícia Alves-Oliveira* and Tiago Ribeiro, in Human-robot interaction: evaluation methods and their standardization. Cham: Springer International Publishing, 2020.

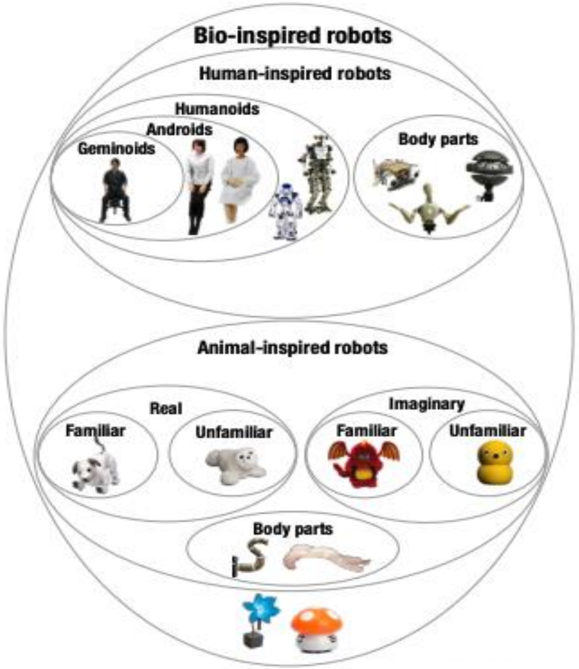
MOTION PROPERTIES SHAPE HOW HUMANS INTERPRET A ROBOT

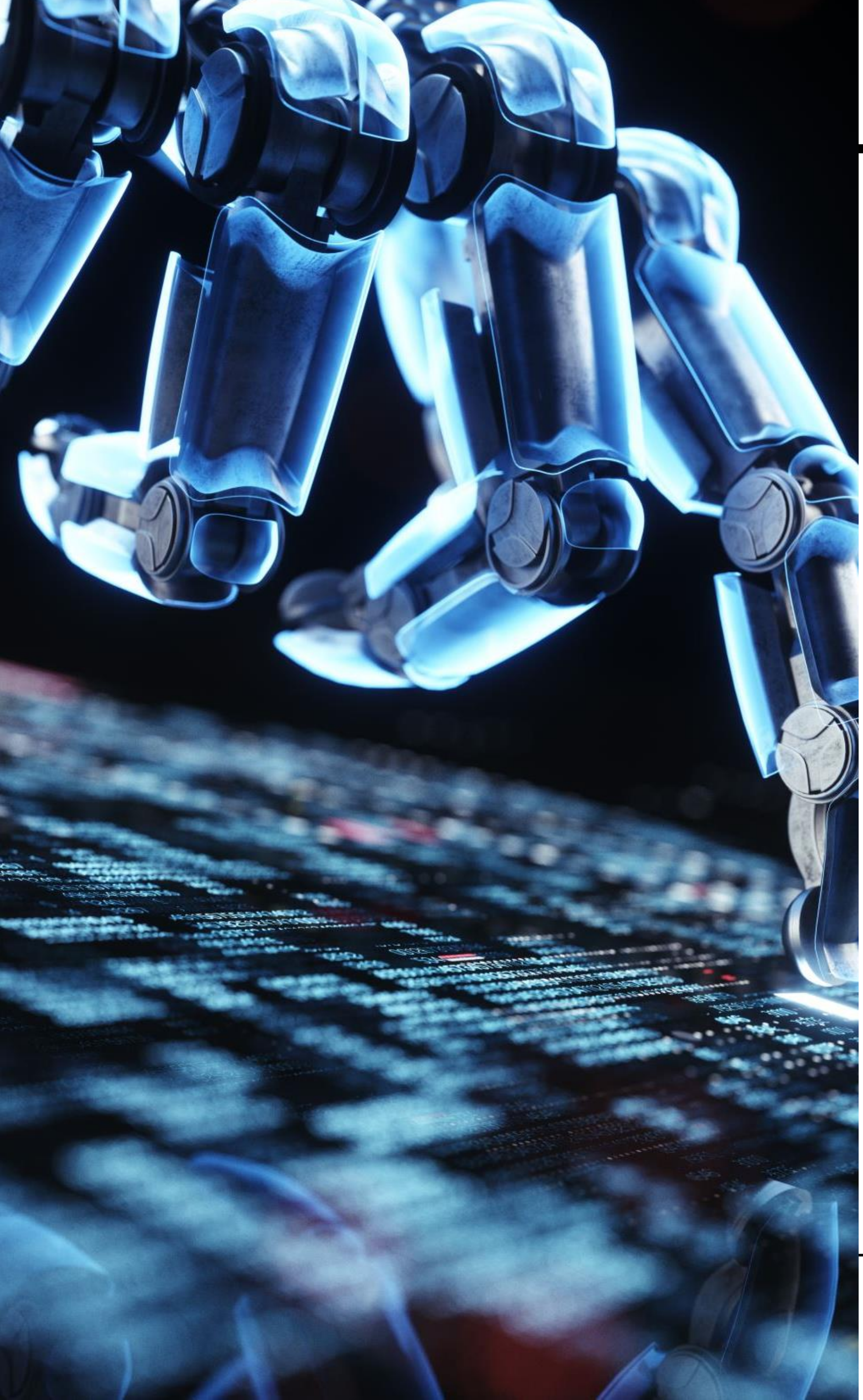
1. Speed – may convey urgency, calmness, confidence,….
2. Acceleration / Deceleration – smooth vs abrupt dynamics influence safety & naturalness
3. Amplitude – large vs small movements can signal dominance, enthusiasm, or shyness
4. Rhythm & Timing – synchrony, pauses, conversational timing affects rapport



MOTION PROPERTIES SHAPE HOW HUMANS INTERPRET A ROBOT

5. Trajectory Shape – arcs = friendly/natural; straight lines = mechanical/efficient
6. Smoothness / Jerk – smoother motion increases trust and perceived competence
7. Posture & Orientation – body/face direction communicates attention & intent
8. Repetition & Variability – small variations create lifelike, non-mechanical behaviour
9. Expressive Modulation – emotional tone through tempo, tension, flow





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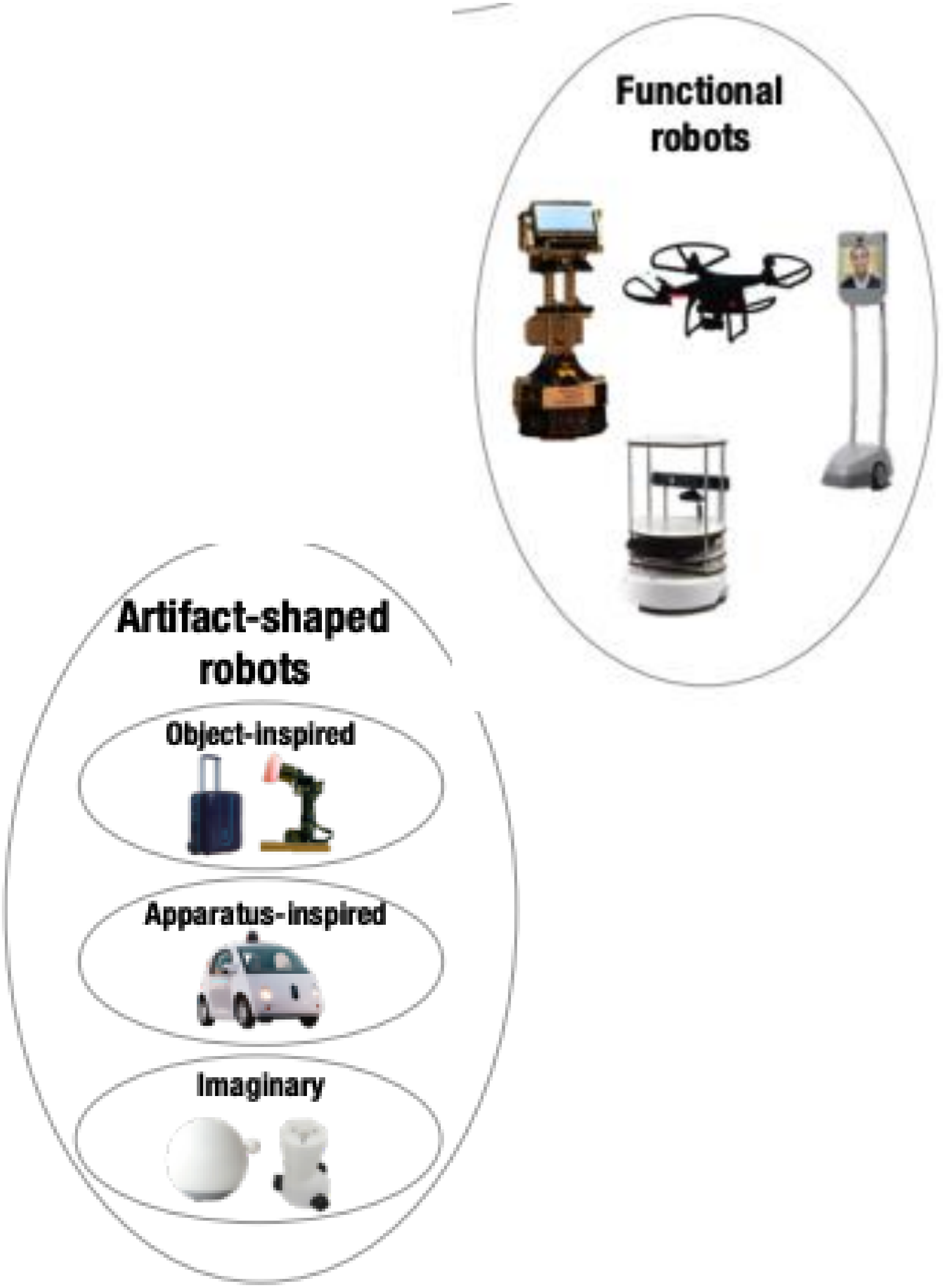
NAVIGATION

Depends on the embodiment…

- Wheels, tracks, legs, hybrid bases
- Control: Kinematics (forward/inverse)
- Control of velocity & acceleration
- Direction control

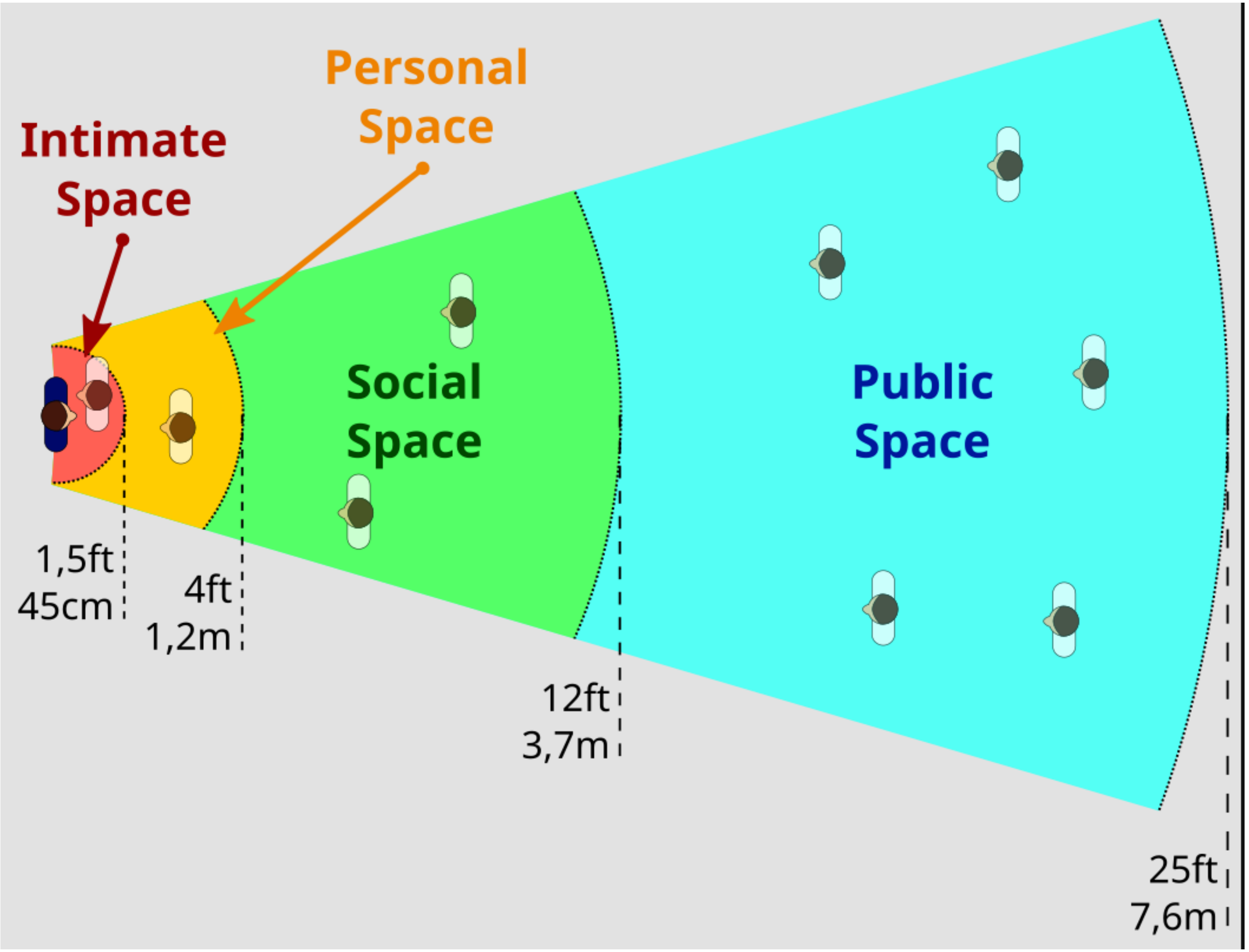
Embodiments to maintain smooth trajectories

- *Eg: to achieve minimum jerk,*
    - *minimum acceleration,*
    - *ease-in/ease-out*



SOCIAL NAVIGATION: PROXEMICS

- Respect personal space (intimate, personal, social zones)
- Do not approach from behind abruptly
- Use “soft” trajectories around humans



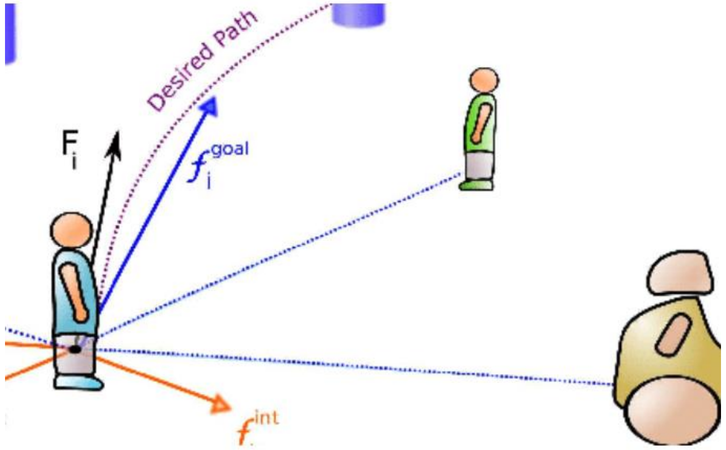
SOCIAL NAVIGATION

Following a Person

- Maintain comfortable distance
- Adjust speed to human walking speed
- Avoid keeping to close to the person (and invading intimate space)

Guiding or Leading

- Keep slow and stable speed
- Frequent orientation toward the human
- Wait when the human stops



iagram of the social forces corresponding to the person p i. The blue arrow represents the force aiming to a estination and the orange arrows represent each of the different kinds of interaction forces: personperson, bject-person and robot-person. The summation of all the forces is represented as the black arrow F i .

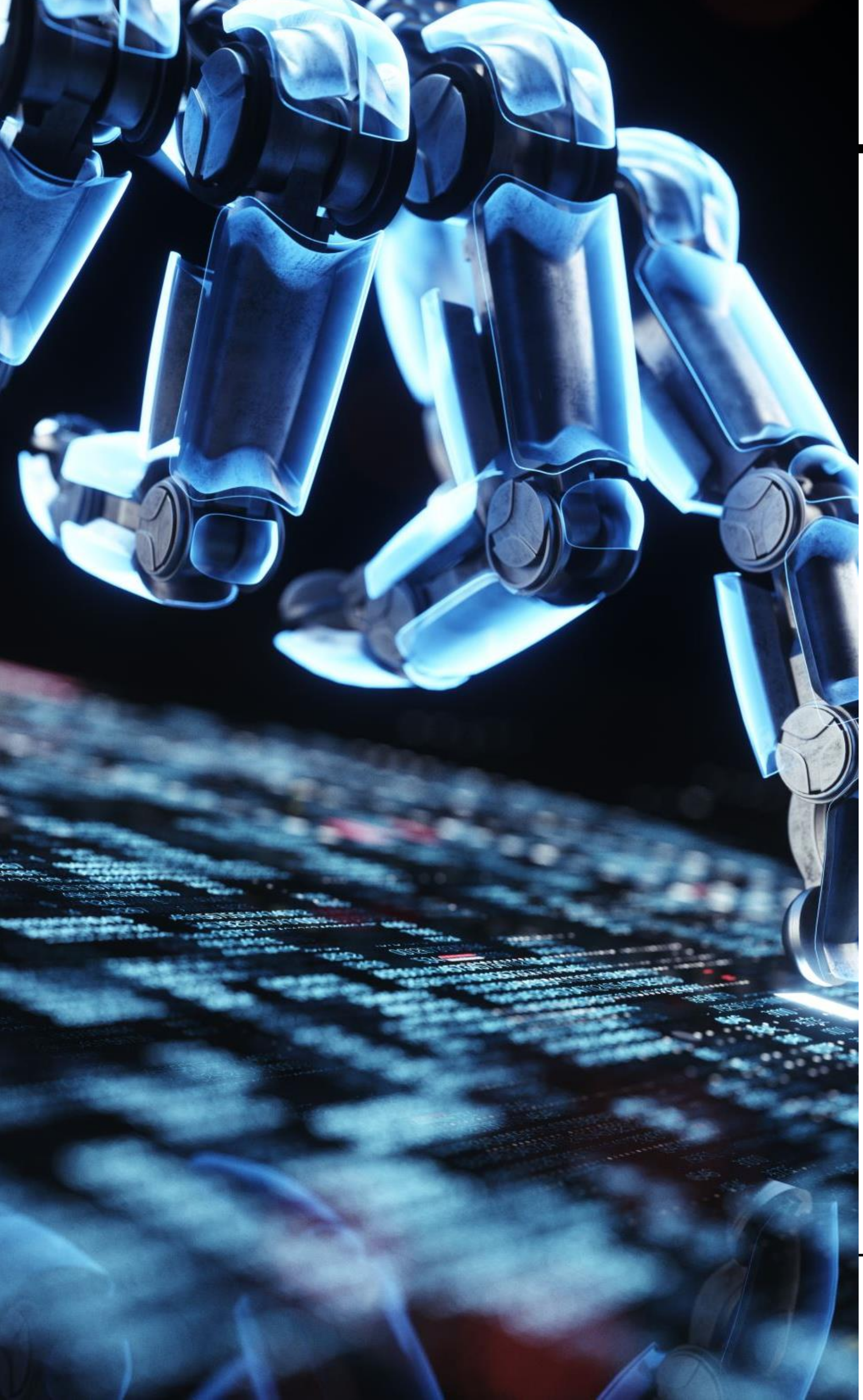
SOCIAL NAVIGATION

Passing & Crossing

- Respecting social conventions
- Make motions broad & predictable
- Slow when passing close to humans

Approaching for Interaction

- Approach angle matters (30 … 45°)
- Stop at social distance
- If possible greet (signal engagement)



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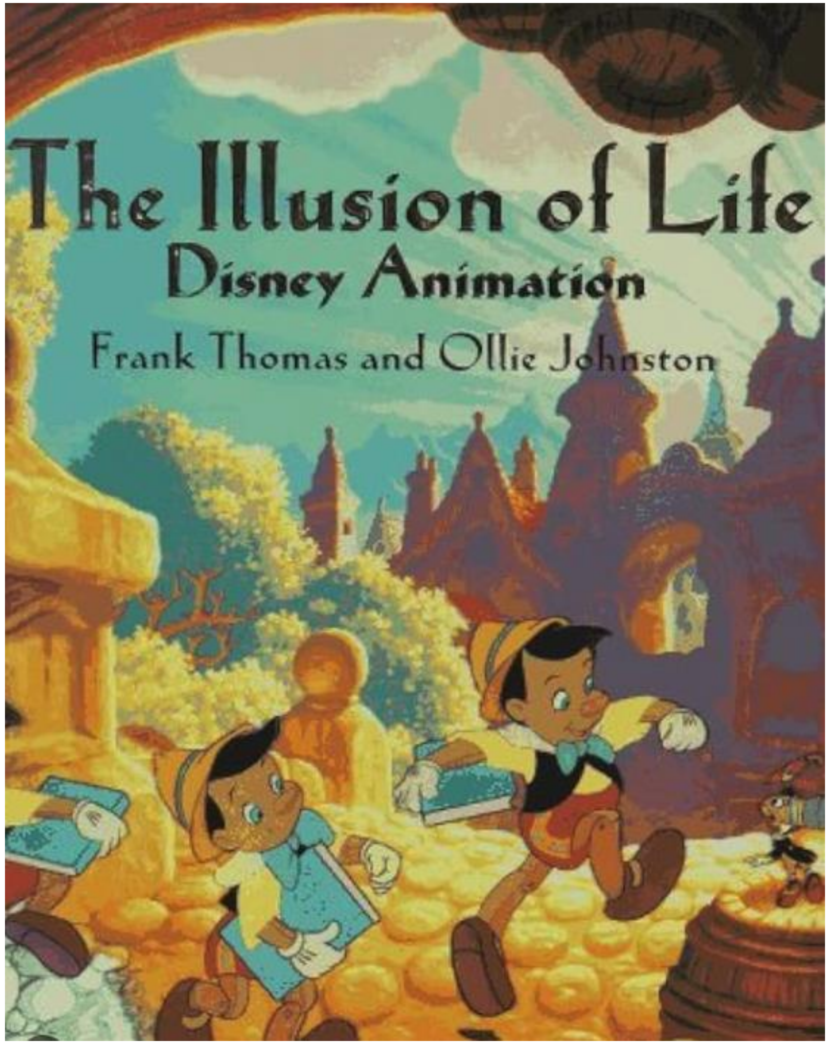
EXPRESSIVE & BELIEVABLE MOTION

"Disney animation makes audiences really believe in… characters, whose adventures and misfortunes make people laugh – and even cry. There is a special ingredient in our type of ANIMATION that produces drawings that appear to think and make decisions and act of their own volition; it is what creates the ILLUSION OF LIFE."

[Thomas&Johnston, 1981]



BELIEVABLE MOTION: DISNEY™ ANIMATION PRINCIPLES

Squash and Stretch
Anticipation
Staging
Straight Ahead and Pose-to-Pose
Follow-Through and Overlapping Animation
Slow In and Slow Out
Arcs
Secondary Action
Timing
Exaggeration
Solid Drawing
Appeal

Ribeiro, T., & Paiva, A. (2012, March). The illusion of robotic life: principles and practices of animation for robots. In Proceedings of the seventh annual ACM/IEEE international conference on Human-Robot Interaction (pp. 383-390). ACM.

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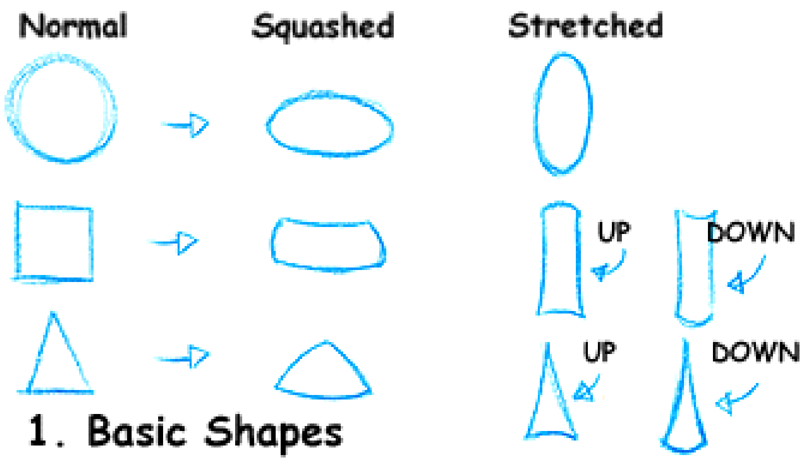
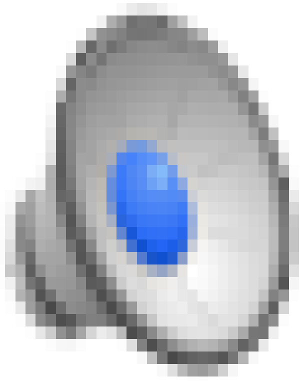
SQUASH AND STRETCH



- The movement and liquidness of an object reflects that the object is alive. One rule of thumb is that despite them changing their form, the objects should keep the same volume while squashing and stretching.

- This principle is hard to apply to robots, because robots are generally composed of rigid parts.



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ANTICIPATION & STAGING

- Anticipating movements and actions helps viewers and

users to understand what a character is going to do (link with the notion of legibility)

- That anticipation helps the user to interpret the character

or robot in a more natural and pleasing way.

. Staging is related to the general set-up in which the

character expresses itself. - This principle is related to

making sure that the expressive intention is clear to the viewer

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ARCS

-This principle states that natural motions occur in arcs, so that should be taken into account when designing motion. When a person looks to the left and the right, it shouldn't just perform a horizontal movement, but also some vertical movement, so that the head will be pointing slightly upwards or downwards than it was while facing straight ahead.

For robots this principle can be used both for pre-designed animations, and also for procedural ones.

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SECONDARY ACTION

- This kind of action does not directly contribute to the

expression of the character, but aids in making it believable.

When people speak to each other, they often

scratch some part of their body, adjust their hair, or

even look away from the person with who they are interacting with the character

or robot in a more natural and pleasing way.

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EXAGGERATION

-This principle, along with Timing, is one of they key magic features in animation. Animated characters and

objects do not need to follow the rules of our world and our physics.

- Exaggeration can be used to emphasize the robot’s movements, expressions or actions, in order to make them more noticeable and convincing

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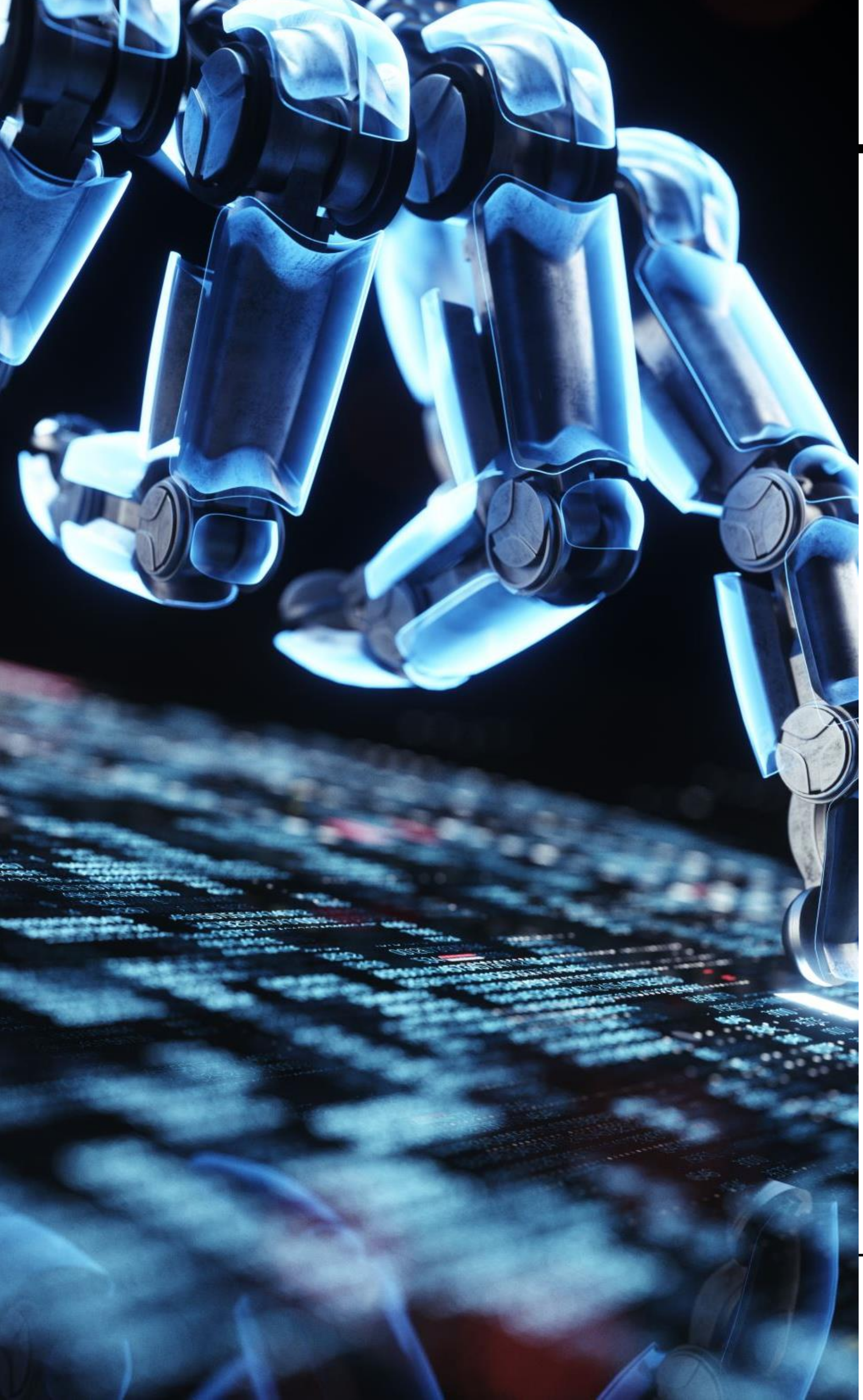

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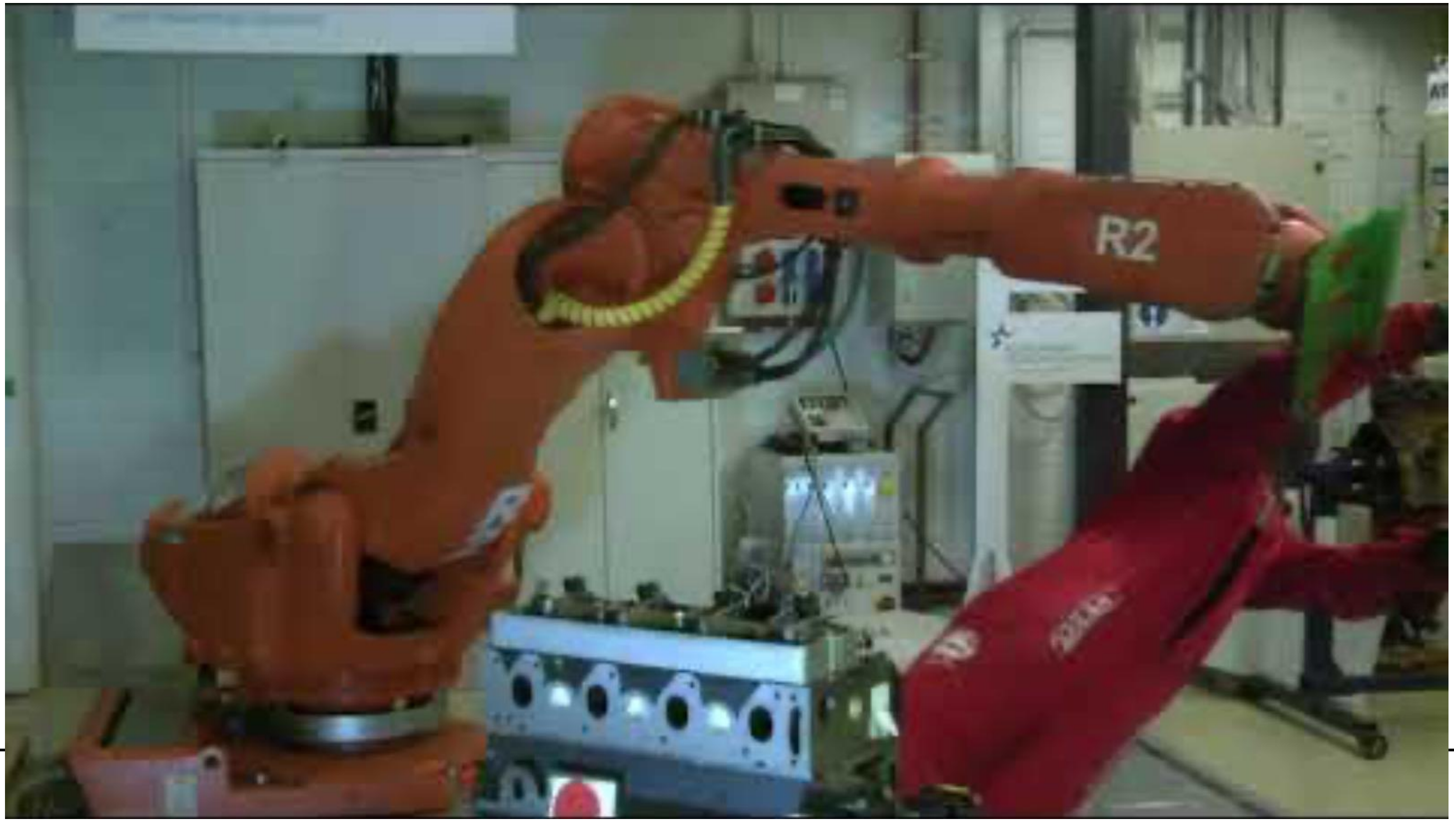
"SAFETY" MOTION IN SOCIAL ROBOTS

Social robots, as they are placed together with humans have the risk of collisions occurring between the robot and its user: too high energy/power may be transferred by the robot, resulting in serious human damages.



SAFE MOTION IN SOCIAL ROBOTS*

To increase a social robot safety, all aspects of manipulator design, including mechanics, electronics, and software, must be considered.

-At the mechanical design, the elimination of sharp edges can reduce the potential for lacerations.

- Also, pursue a mechanical design that reduces manipulator link inertia and weight by using lightweight but stiff materials, complemented by the presence of compliant components in the structure.

- Compliance can be introduced at the contact point by a soft covering of the whole arm with visco-elastic materials or by adopting compliant transmissions at the robot joints.

Alami, R., et al. "Safe and dependable physical human-robot interaction in anthropic domains: State of the art and challenges." Intelligent Robots and Systems, 2006 IEEE/RSJ International Conference on. IEEE, 2006.

SAFE MOTION IN SOCIAL ROBOTS

Improvements for “anticipating and reacting to collisions” can be achieved through the use of combinations of

- external/internal robot sensing,
- software safety procedures, which intelligently monitor, supervise, and control manipulator operation

Alami, R., et al. "Safe and dependable physical human-robot interaction in anthropic domains: State of the art and challenges." Intelligent Robots and Systems, 2006 IEEE/RSJ International Conference on. IEEE, 2006.

ROBOT DESIGN: BAXTER...

Baxter™, is/was a collaborative robot from Rethink Robotics, designed to work effectively directly alongside people in a factory setting

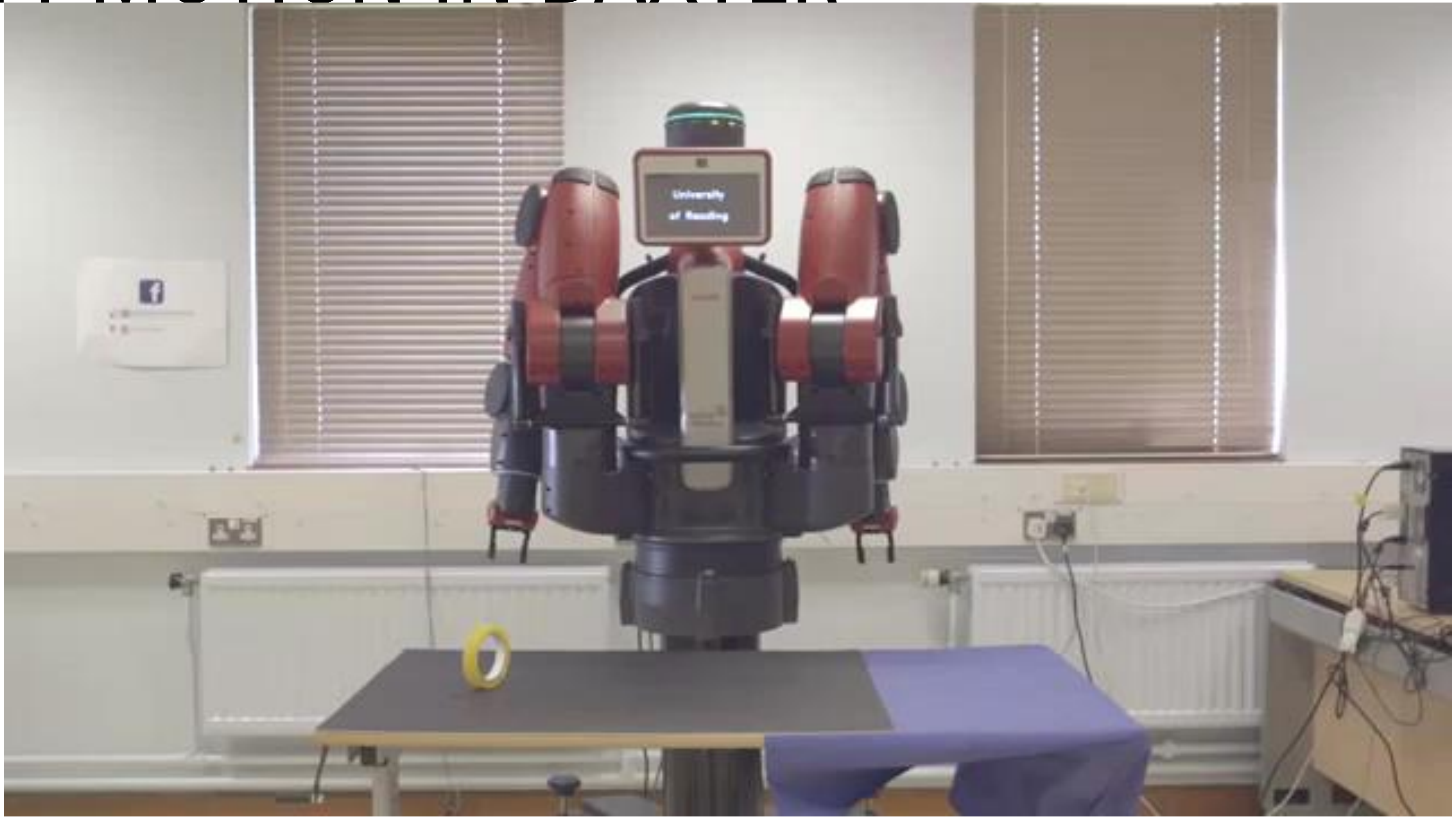
Baxter was designed for:

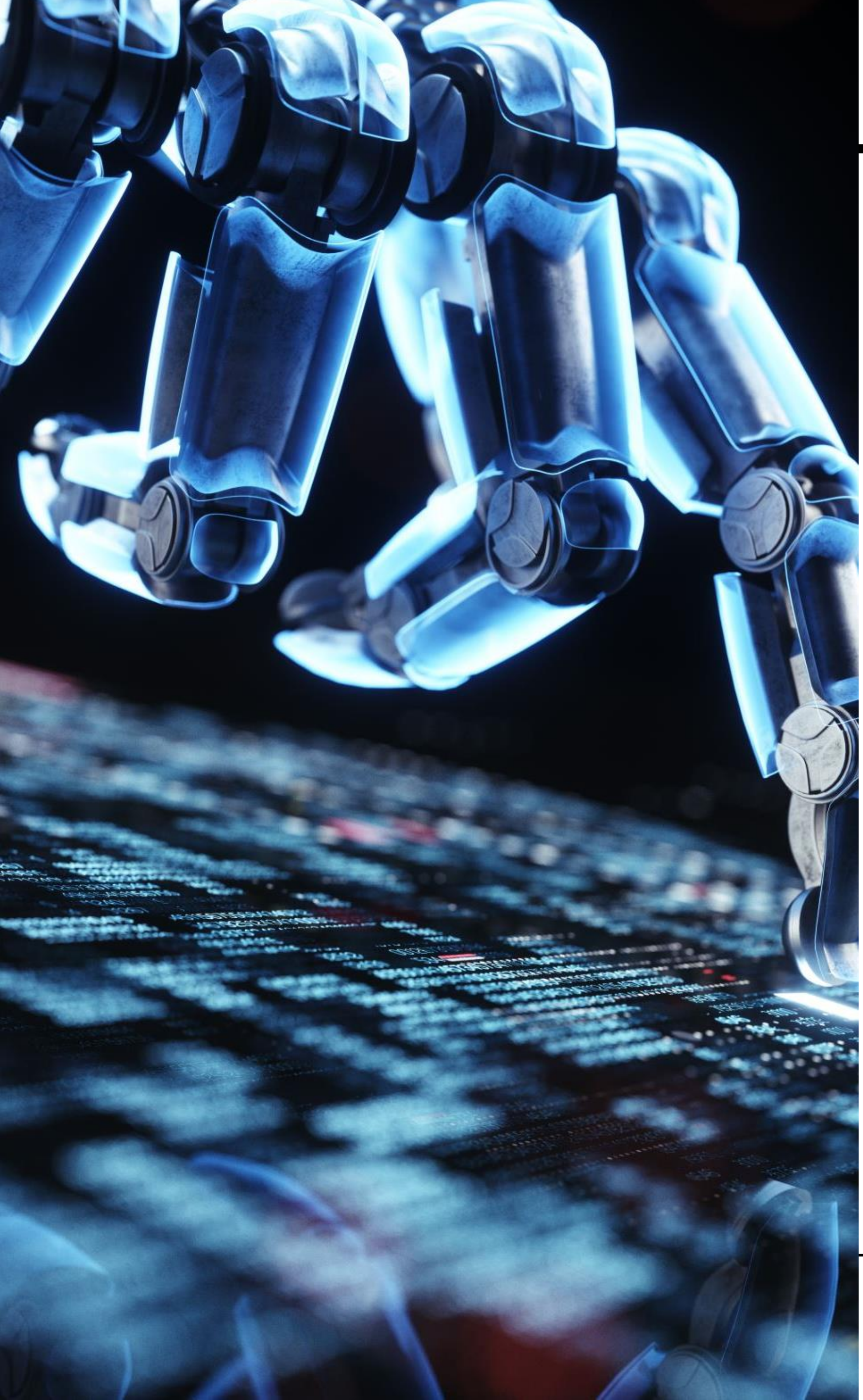
- Physical interaction between a worker and the robot.
- Avoiding accidental contact.
- Minimizing forces and slowing/stopping during human contact.

SAFETY IN BAXTER

- **Software Control**: Baxter is designed to **slow or stop upon inadvertent contact**, allowing it to work collaboratively or to be co-located with an operator in close proximity.
- **Multiple Redundant Systems**: Baxter has a **wide array of innovative sensors** and an emergency stop function to ensure safety.
- **Lightweight, Compliant Materials**: Baxter's arms weigh less than 20 kg, are fully covered in compliant plastic, and use protective foam at key joints.
- **Dynamic Breaking**: Baxter will slowly come to rest in the event of a power loss or an E-stop.
- **Human Awareness**: Baxter can recognize human proximity with its 360° **sonar system**, which signals its awareness of any detected nearby people.

SAFETY MOTION IN BAXTER





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TRANSPARENCY: FUNCTIONAL, PREDICTABLE AND LEGIBLE MOTIONS

Types of Motion:

- **Functional motion,** motion that reaches the goal and avoids collisions.

- **Predictable motion**, is motion performed by the robot that is expected – that is, not surprising to a human.

- **Legible motion-** Legible motion is functional motion that enables the collaborator to quickly and confidently infer the goal.

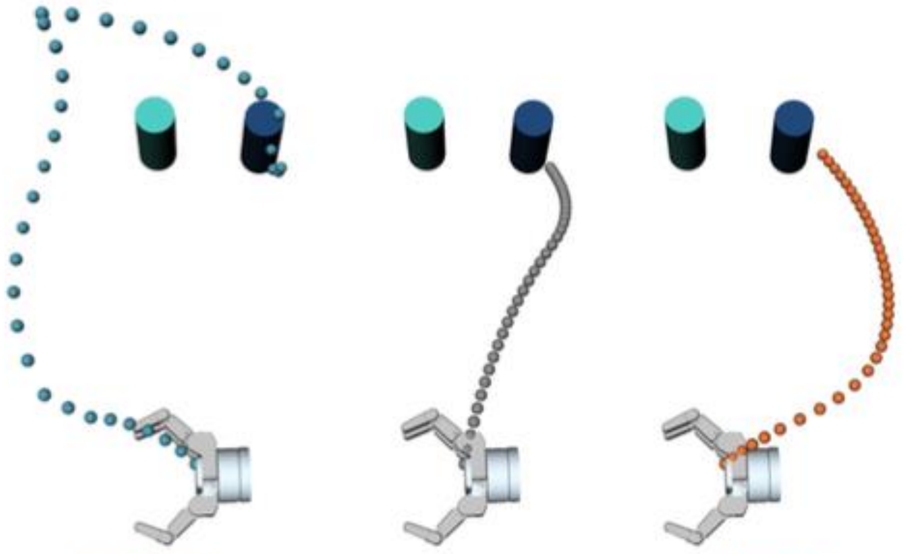

Figure 1: This work manipulates the type of motion the robot plans and studies how this affects physical collaborations between humans and robots.

TÉCNICO LISBOA

Dragan, A. D., Lee, K. C., & Srinivasa, S. S. (2013, March). Legibility and predictability of robot motion. In Human-Robot Interaction (HRI), 2013 8th ACM/IEEE International Conference on (pp. 301-308). IEEE.

PREDICTABLE VERSUS LEGIBLE MOTION

Let’s imagine the following

- There are two bottles and the robot is going to pick up to clean one (the green one).
- Legible motion, that is intent-expressive – enables the inference of intentions, it is “readable”, “anticipatory”, or “understandable”

Predictable Legible

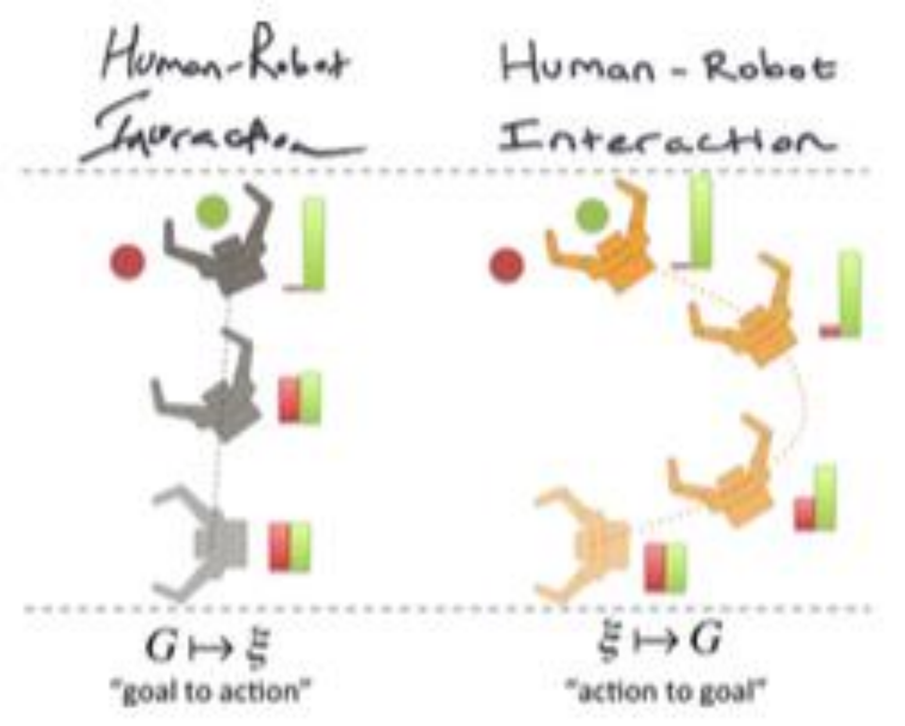

Fig. 1. Above: Predictable, day-to-day, expected handwriting vs. legible handwriting. Center: A predictable and a legible trajectory of a robot's hand for the same task of grasping the green object. Below: Predictability and legibility stem from inferences in opposing directions.

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CASE STUDIED: **PREDICTABILITY** VERSUS **LEGIBILITY** IN ROBOT MOTION

- Predictable: matching expectation means matching the motion inferred by an observer based on knowledge of the goal (an inference from a goal to a trajectory).
- Legible: Expressing intent means enabling an observer to infer the goal of the motion (an inference from a trajectory to a goal),

This opposition lead to the following insight:

- Predictability and legibility are fundamentally different and often contradictory properties of motion.

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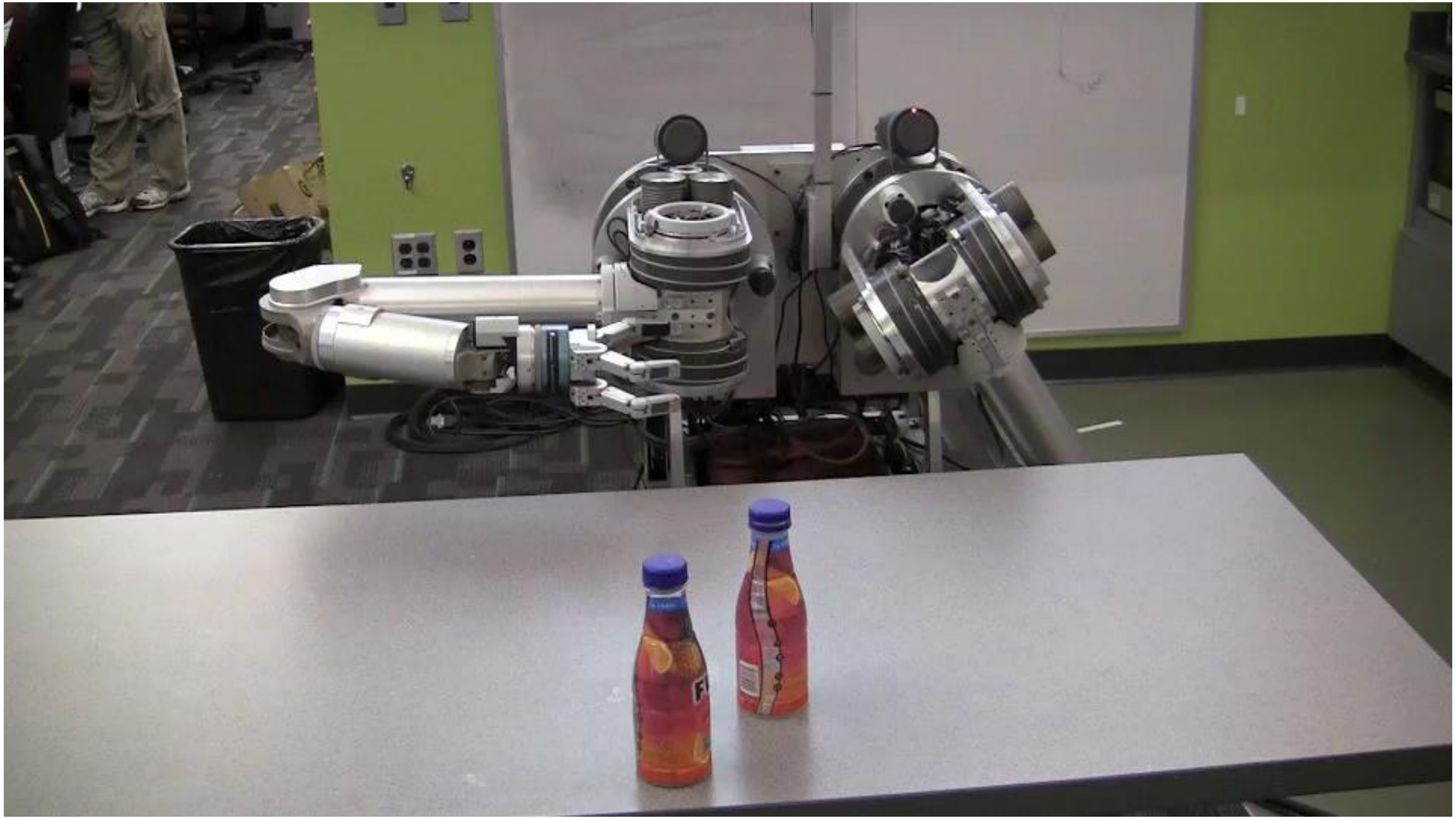
Predictable Motion



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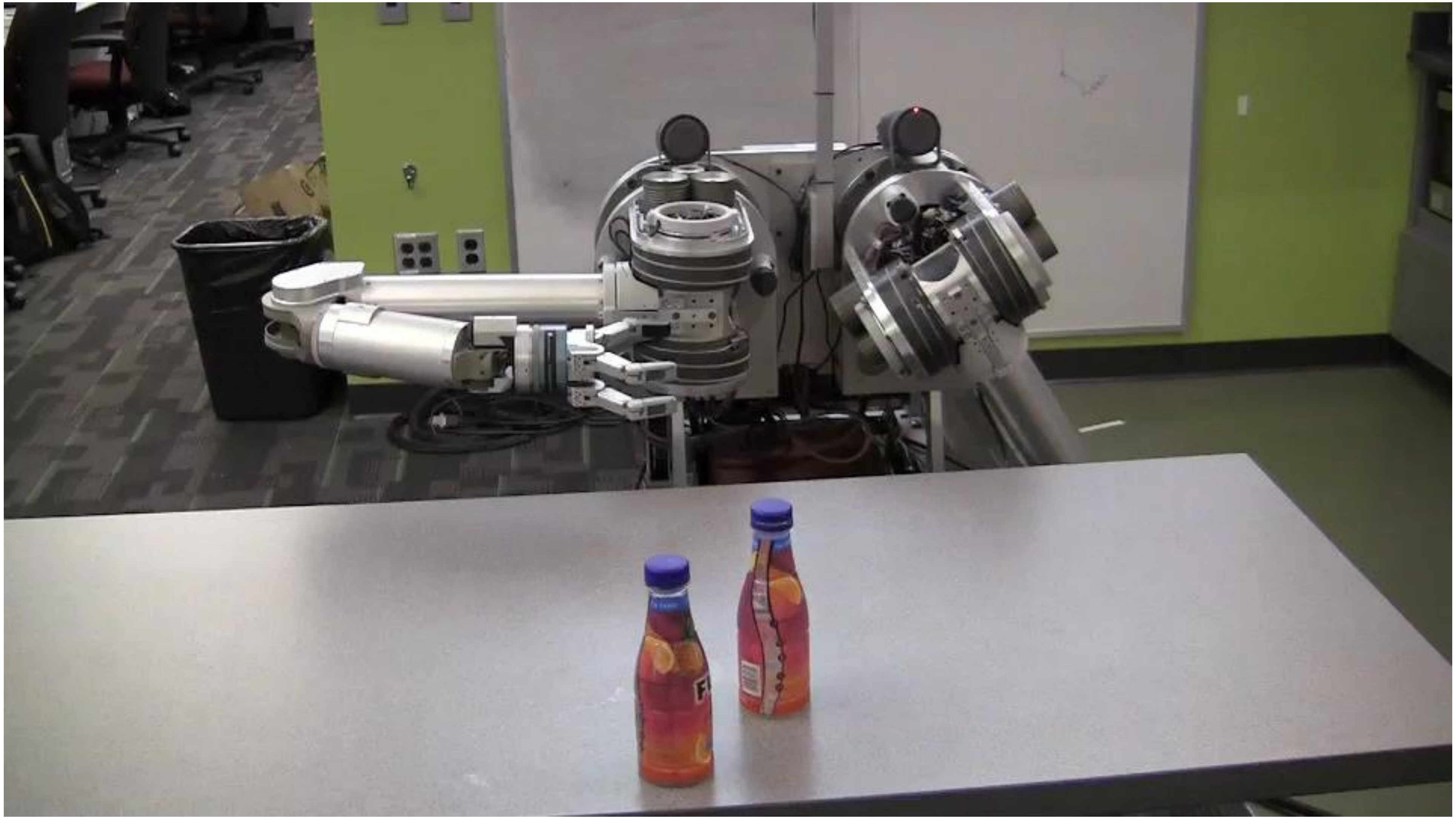
Legible Motion



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STUDY

Hypothesis

- *" There exist two trajectories ξL and ξP for the same task such that ξP is more predictable than ξL and ξL is more legible than ξP"*

- Manipulated Variables:
  - Character: three characters for this task – a simulated point robot, a bi- manual mobile manipulator named HERB, and a human.
  - Trajectory: were hand designed (and recorded videos of) trajectories for each of the characters such that predictability(ξP) > predictability(ξL) according but legibility(ξP) < legibility(ξL)

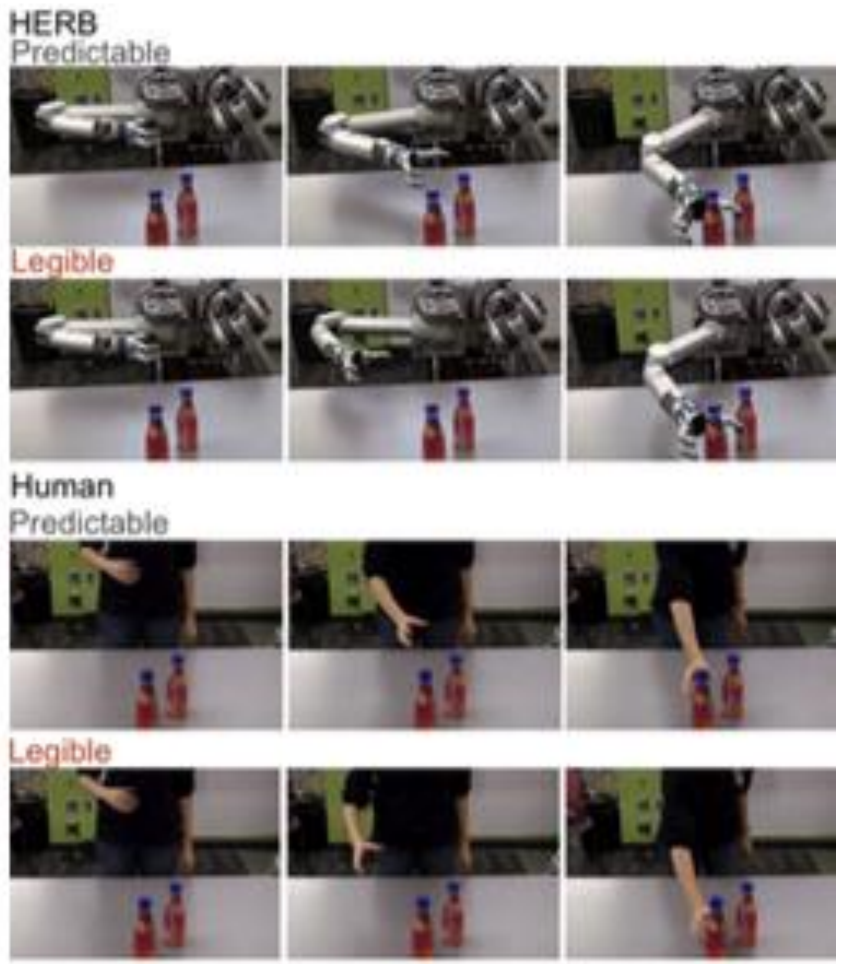

Fig. 4. The trajectories for each character.

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STUDY

Measuring Predictability & Legibility:

A) Predictability: Predictable trajectories match the observer's expectation. To measure how predictable a trajectory is it was used:

1) subjects were shown a video with the character in the initial configuration and were asked to imagine the trajectory they expect the character will take to reach the goal.

2) Then the video of the trajectory was shown and people were asked them to rate how much it matched the one they expected, on a 1-7 Likert scale.

3) People were also asked to draw what they imagined on a two-dimensional representation of the scene before they saw the video and to draw the trajectory they saw in the video as an additional comparison metric.

B) Legibility: Legible trajectories enable quick and confident goal prediction. To measure how legible a trajectory is,

1) subjects were shown a video of the trajectory and told to stop the video as soon as they knew the goal of the character.

2) The time taken and the prediction were recorded.

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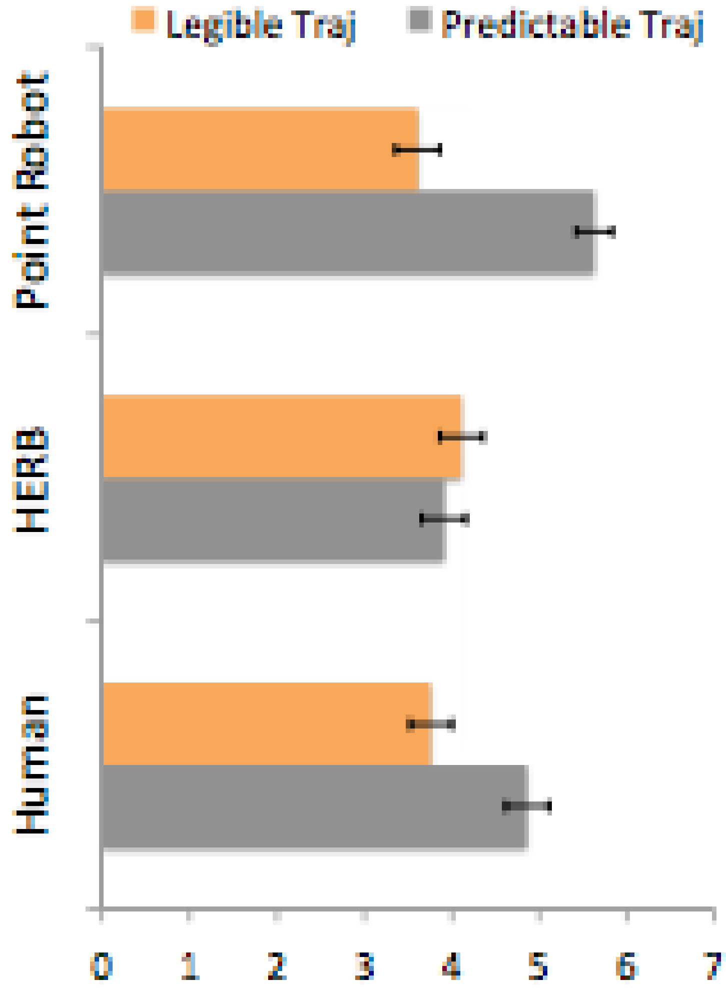
RESULTS

A total of 432 subjects (distributed approximately evenly between groups) through Amazon's Mechanical Turk, all from the United States participated in the study.



(a) Predictability Rating

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STUDY 2: IMPACT ON COLLABORATION

Collaborative task with the bimanual mobile manipulator

- Hypothesis 1 – (Objective Collaboration Metrics).

  Motion type will positively affect the collaboration objectively, with legible motion being the best, and functional motion being the worst.

- Hypothesis 2 – (Perceptions of the Collaboration).

  Motion type will positively affect the participants' perception of the collaboration, with legible motion being the best, and functional motion being the worst.

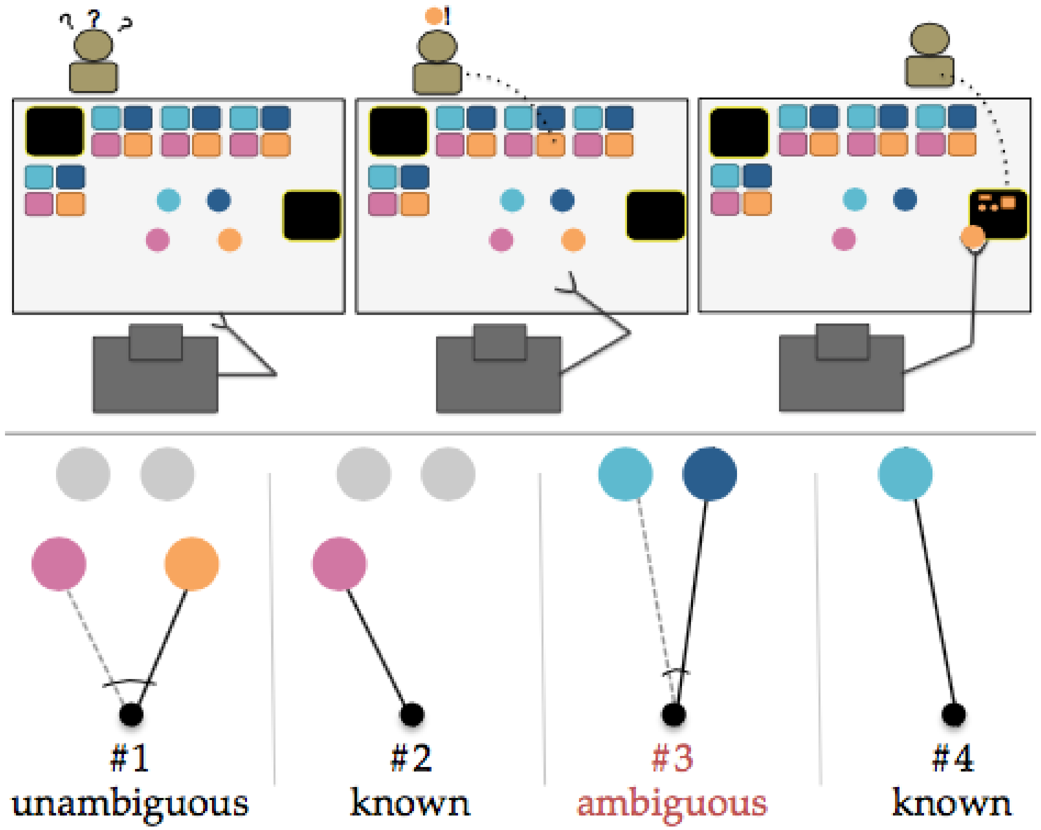


Figure 3: For each tea order, the robot starts reaching for one of the cups. The participant infers the robot's goal and starts gathering the corresponding ingredients. Both place their items on the tray, and move on to the next order. For order #3, the cups are further away from the robot, and closer to each other, making the situation ambiguous.

Dragan, A. D., Bauman, S., Forlizzi, J., & Srinivasa, S. S. (2015, March). Effects of Robot Motion on Human-Robot Collaboration. In Proceedings of the Tenth Annual ACM/IEEE International Conference on Human-Robot Interaction (pp. 51-58). ACM.

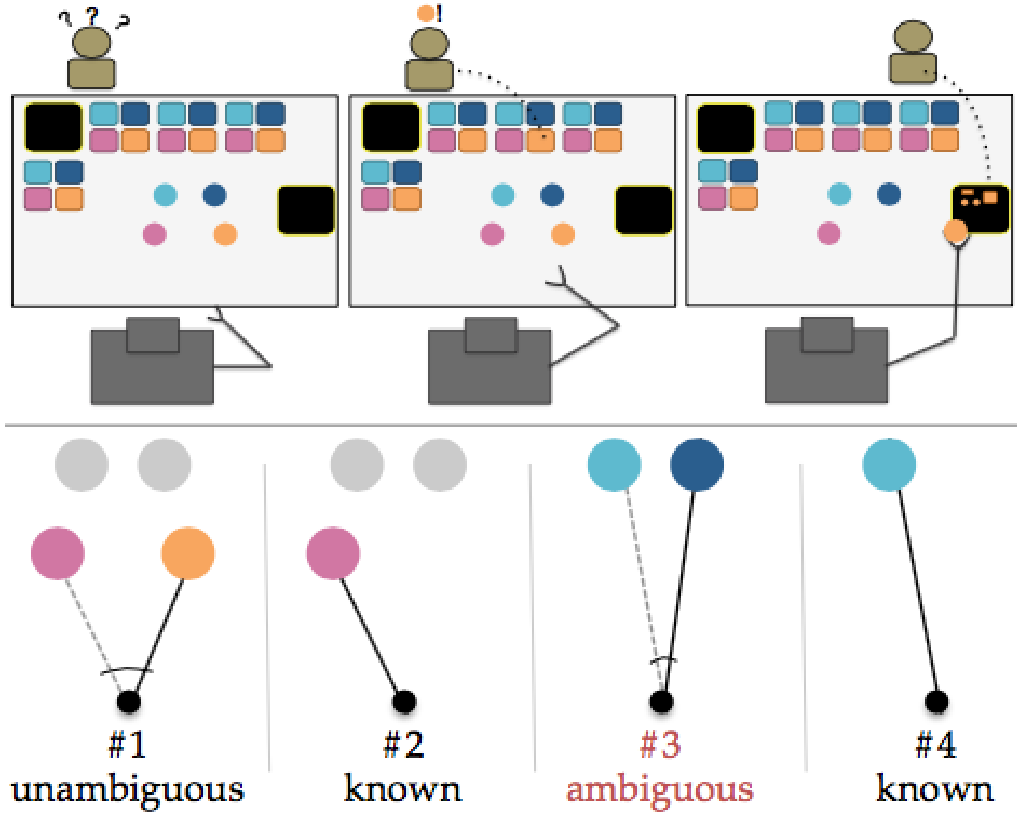
STUDY 2: IMPACT ON COLLABORATION

Task: collaborative task for comparing the impact that different types of motion has in collaboration.

Participants: 18 participants in a counterbalanced within-subjects study

Manipulated Variables: a single variable, motion type, was manipulated to be functional, predictable, legible.

Dependent variables: the success of a collaboration (measured in objective and subjective ways)



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Objective Measures:

- ***coordination time*** is the amount of time from the moment the robot starts moving, until the participant infers the correct goal
- ***total task time*** is the amount of time, from the moment the robot starts moving, until the last ingredient touches the tray.
- ***concurrent motion time*** is the amount of time when both the human and the robot are moving

Subjective measures

TABLE I: SUBJECTIVE MEASURES

Fluency $\alpha = .91$
1.The human-robot team worked fluently together.
2.The robot contributed to the fluency of the team interaction .
Robot Contribution [shortened] $\alpha = .75$
1.I had to carry the weight to make the human-robot team better.(r)
2.The robot contributed equally to the team performance.
3.The robot's performance was an important contribution to the success of the team.
Trust $\alpha = .91$
1.I trusted the robot to do the right thing at the right time.
2.The robot was trustworthy.
3.The robot and I trust each other.
Safety/Comfort [extended] $\alpha = .83$
1.I feel uncomfortable with the robot.(r)
2.I believe the robot likes me.
3.I feel safe working next to the robot. [new]
4.I am confident the robot will not hit me as it is moving. [new]
Capability $\alpha = .72$
1.I am confident in the robot's ability to help me.
2.The robot is intelligent.
Predictability [re-phrased for clarity] $\alpha = .86$
1.If I were told what cup the robot was going to reach for ahead of time, I would be able to correctly anticipate the robot's reaching motion.
2.The robot's reaching motion matched what I would have expected given the cup it was reaching for.
3.The robot's reaching motion was surprising.(r)
Legibility [new] $\alpha = .95$
1.The robot can reason about how to make it easier for me to predict what it is reaching for.
2.It was easy to predict what the robot was reaching for.
3.The robot moved in a manner that made its intention clear.
4.The robot was trying to move in a way that helped me figure out what it was reaching for.
Forced-Choice Questions $\alpha = .91$
1.Which program were you the fastest with?
2.Which program was the easiest?
3.Which program do you prefer?

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TÉCNICO LISBOA

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Results

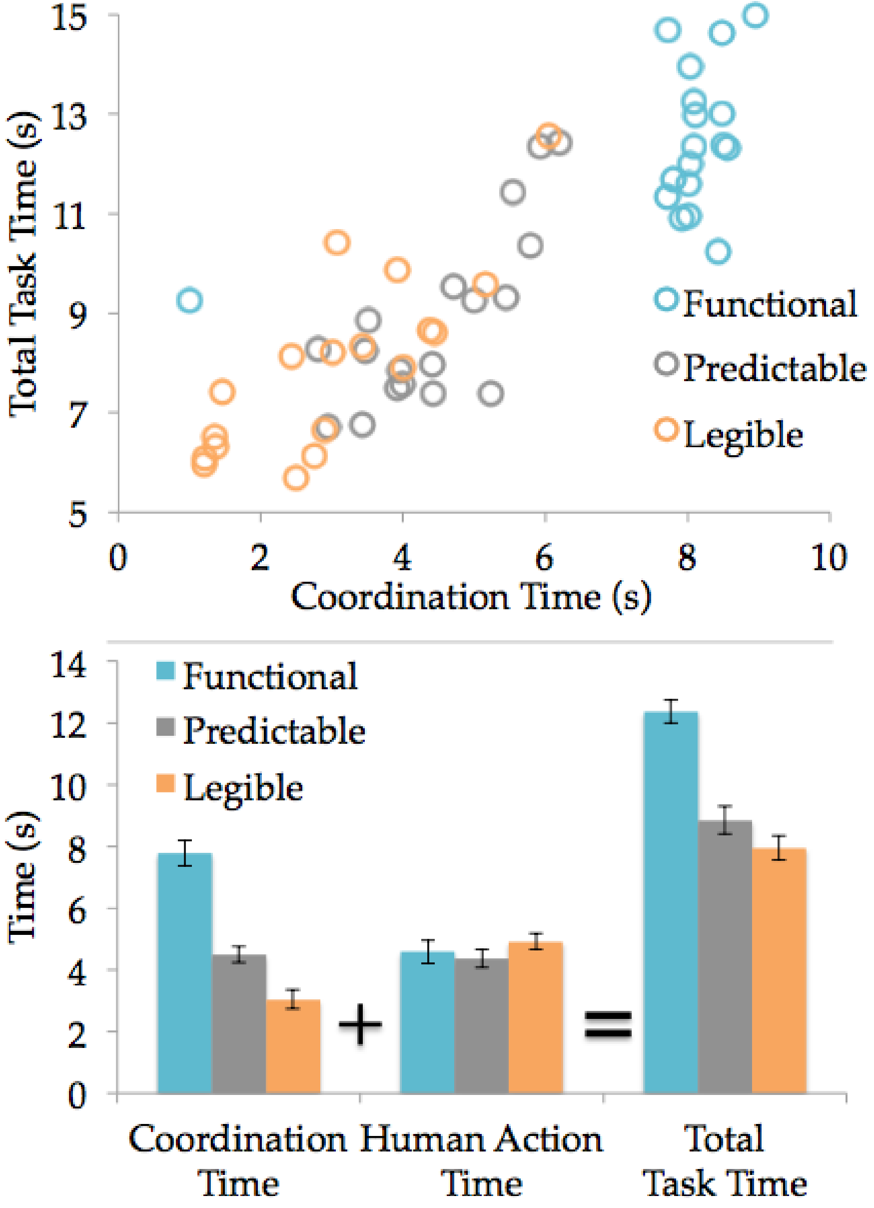

Figure 4: Findings for objective measures.

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Results

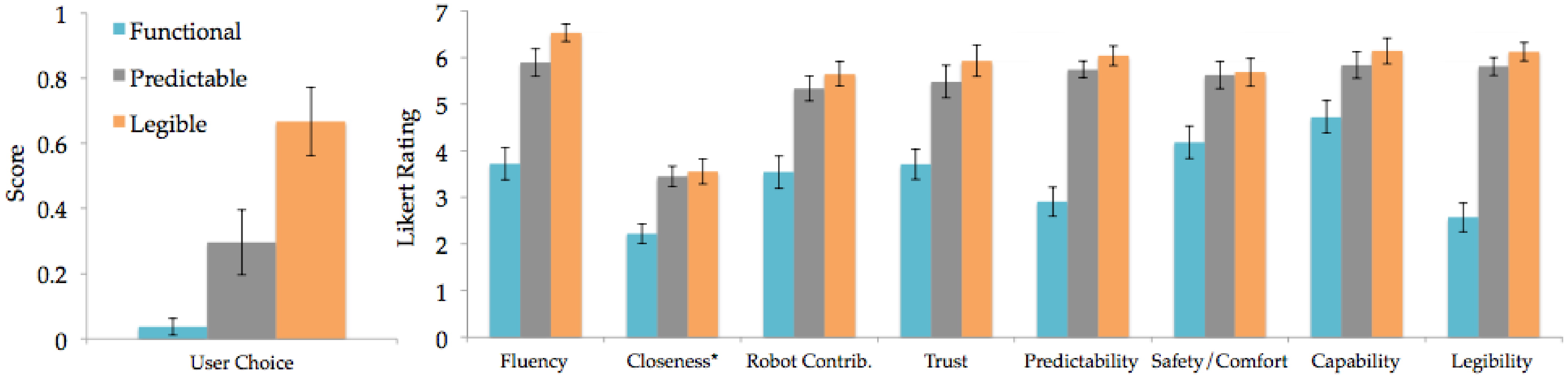

Figure 6: Findings for subjective measures. Closeness was on a 5-point scale.

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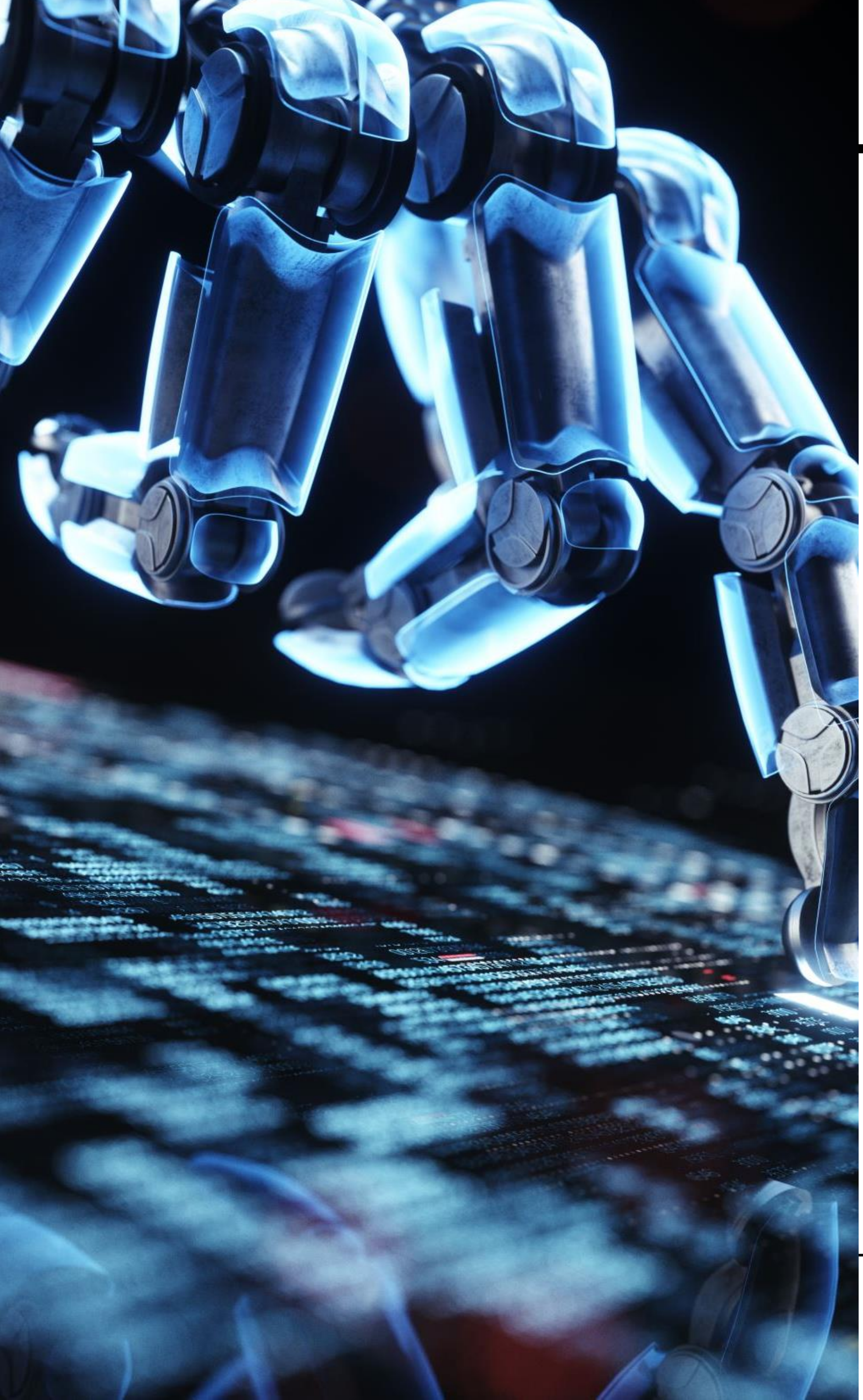


PLAN

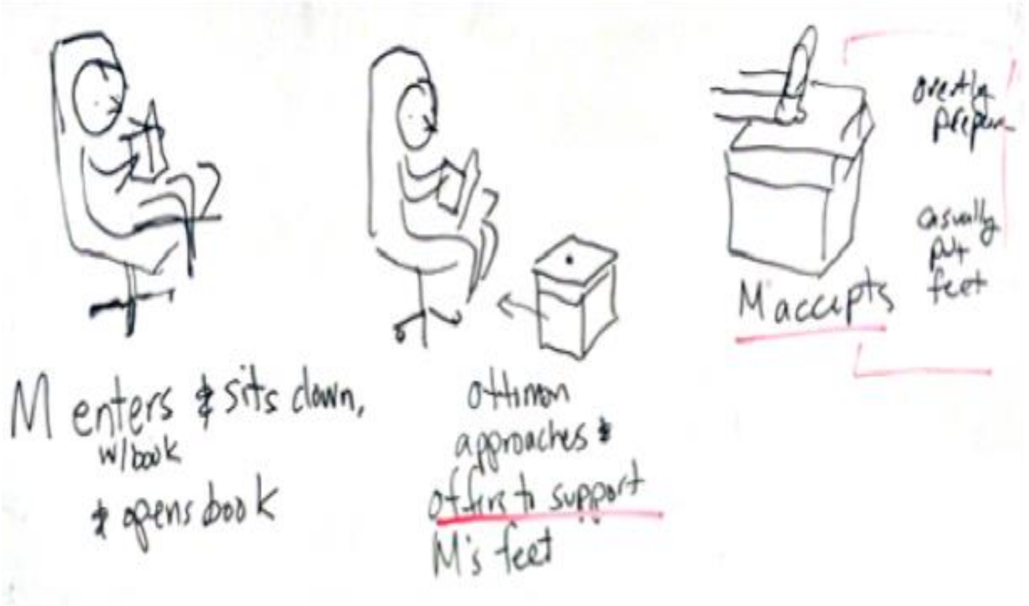
- Robots and motion
  - Types of embodiment
  - Properties of motion
- Navigation in social settings
- Designing expressive motion: principles
- Impact of motion (cases)
  - Safety
  - Predictability, Legibility, Intention & Collaboration
  - Intention & Engagement

MOVEMENT IN ROBOTIC FURNITURE

Designing for intention recognition

Initial storyboarding a few settings and interaction scenarios,

- Aim: to develop intuition about how a moving ottoman might initiate, or respond to, requests to interact with someone.



Sirkin, D., Mok, B., Yang, S., & Ju, W. (2015, March). Mechanical ottoman: how robotic furniture offers and withdraws support. In Proceedings of the Tenth Annual ACM/IEEE International Conference on Human-Robot Interaction (pp. 11-18).

PROTOTYPE

- Based on the sketches, a low-resolution functional prototype was built.
- The prototype used an inexpensive store-bought ottoman, which we set atop casters, and steered around the floor by hand using two-meter long wooden dowels.
- Participants were placed in various individual seating arrangements, and the ottoman was *puppeted* by a researcher **simulating the movements**.
- The sessions tried to explored ways by which someone could beckon or dismiss the ottoman, gestures or angles of approach and departure projected, and appropriate social distance .

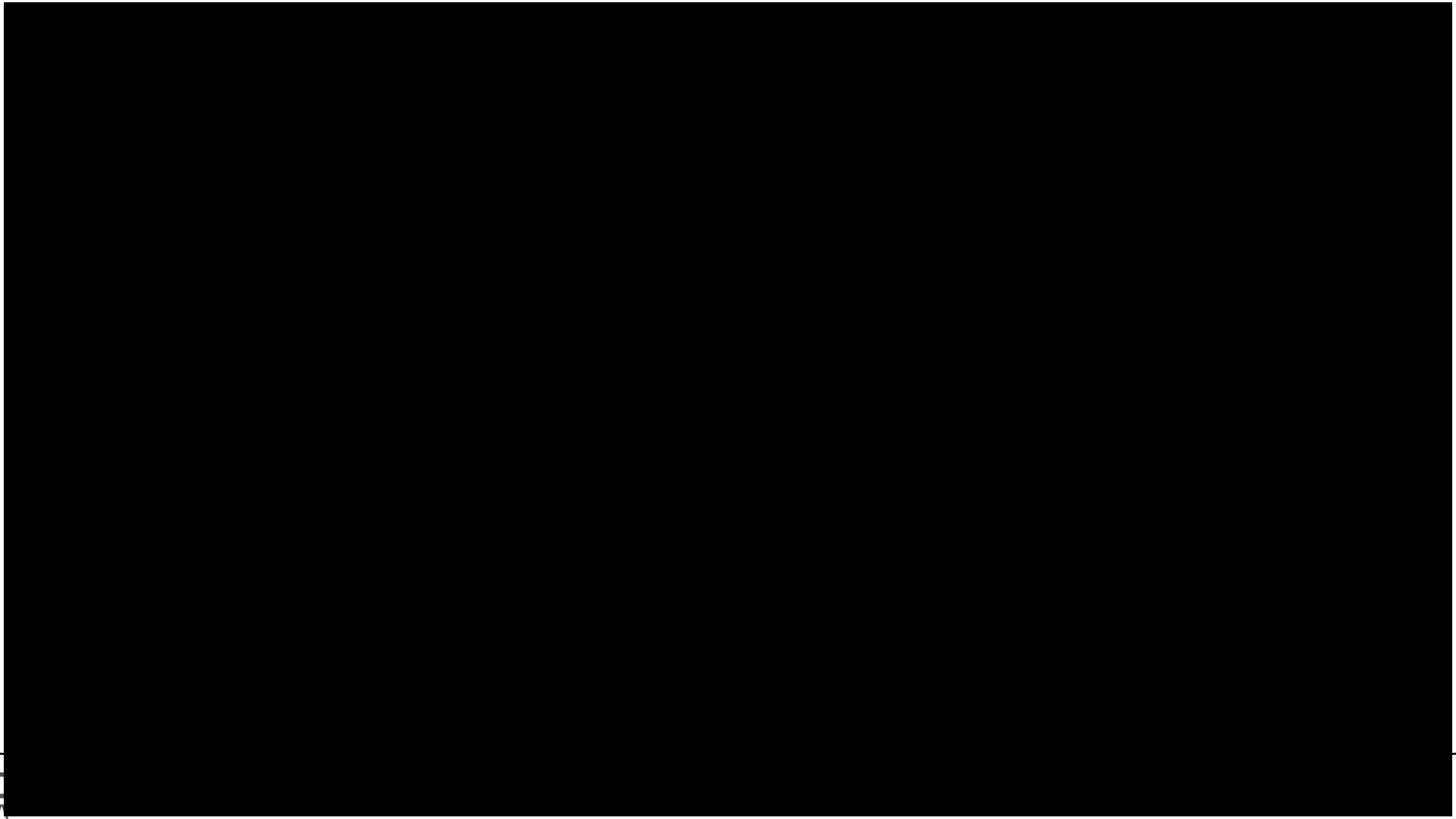
DESIGNING MOTION: PROTOTYPE OF A TELEOPERATED OTTOMAN

- Prototype: teleoperated ottoman, as a way to practice and confirm the approaches and expressive movements that we were fashioning by hand. The ottoman was built on top of a Willow Garage Turtlebot, which is based, in turn, on the iRobot Create robotic base.
- Given the base's architecture, the ottoman could move forward or backward, rotate in place, or follow a curved path, but it could not move immediately sideways.

DESIGNING MOTION: A WOZ STUDY

- Twenty undergraduate and graduate students participated in the study (12 females, 8 males, age M=20.8, SD=3.1 years).
- Participants first completed the prior robotic furniture activity, and then were asked them to sit in the lounge chair to complete a ten-minute questionnaire about their preceding experience. After 1 minute of the start of the video, the ottoman drove to the participant, or to a position about one meter away.

DESIGNING MOTION: A WOZ STUDY



DESIGNING MOTION: WOZ STUDY, RESULTS

Table 1. Participants' responses to the ottoman's approach.

	Direct approach	*Pause on the way*
Starting near front	5 lifted, 0 did not	3 lifted, 2 did not
Opposite side wall	3 lifted, 2 did not	3 lifted, 2 did not

"The ottoman used nothing more than movement to interact with participants, yet their reflections are overflowing with references that ascribe intentionality to it: *"I thought it wanted to leave." "It realized someone was coming through the door and its attention moved there."* and *"It wanted to interact with me in the way that ottomans do." "*

FROM MOVEMENT TO PERSONALITY.... CREATING RELATABLE CHARACTERS

BELIEVABLE MOTION

https://www.ted.com/speakers/guy_hoffman

FURTHER READING

- Sirkin, D., Mok, B., Yang, S., & Ju, W. (2015, March). Mechanical ottoman: how robotic furniture offers and withdraws support. In Proceedings of the Tenth Annual ACM/IEEE International Conference on Human-Robot Interaction (pp. 11-18).
- Dragan, A. D., Bauman, S., Forlizzi, J., & Srinivasa, S. S. (2015, March). Effects of Robot Motion on Human-Robot Collaboration. In Proceedings of the Tenth Annual ACM/IEEE International Conference on Human-Robot Interaction (pp. 51-58). ACM.
- Dragan, A. D., Lee, K. C., & Srinivasa, S. S. (2013, March). Legibility and predictability of robot motion. In Human-Robot Interaction (HRI), 2013 8th ACM/IEEE International Conference on (pp. 301-308). IEEE.
- Ribeiro, T., & Paiva, A. (2012, March). The illusion of robotic life: principles and practices of animation for robots. In Proceedings of the seventh annual ACM/IEEE international conference on Human-Robot Interaction (pp. 383-390). ACM.