From Intuitive Immersive Telepresence Systems to Conscious Service Robots

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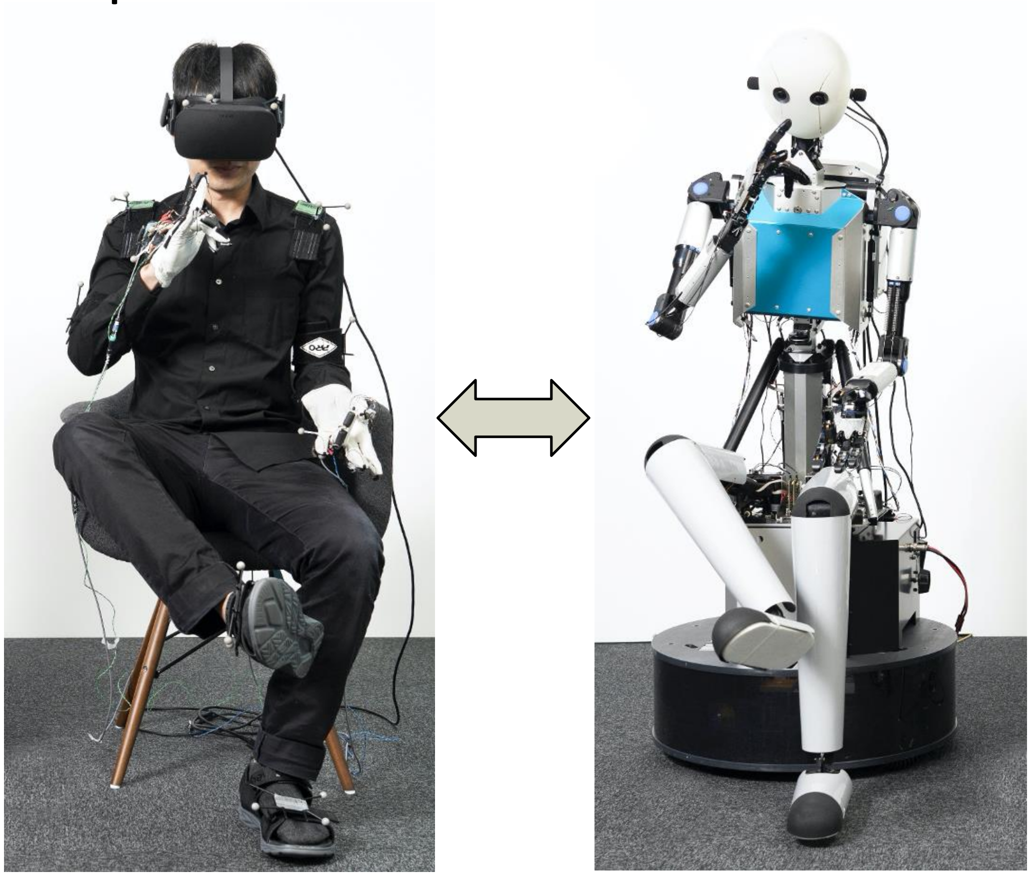
Telepresence Systems

- Enable a human operator to be present at a remote location
- Capture remote location with cameras, microphones, force & haptic sensors, etc.
- Display remote measurements to the operator
- Capture operator movements, speech, and expressions
- Transfer them to avatar robot



[TELESAR VI, Tachi et al. IJHR 2020]

Telepresence Applications

- Remote visits to family and friends
- Business trips
- Health care
- Personal assistance
- Remote work
- Disaster response
- Space
- Underwater
- Remote driving
- Many more …

[Hung et al. 2023]

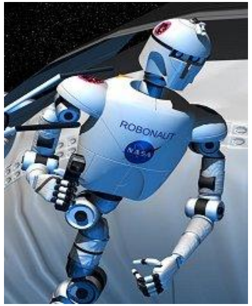
[OhmniLabs Ohmni]

[Intuitive Da Vinci]

[Pollen Reachy]

[Telexistence]

[KAIST DRC Hubo]



[NASA Robonaut]

[Stanford OceanOneK]

[Fetch]

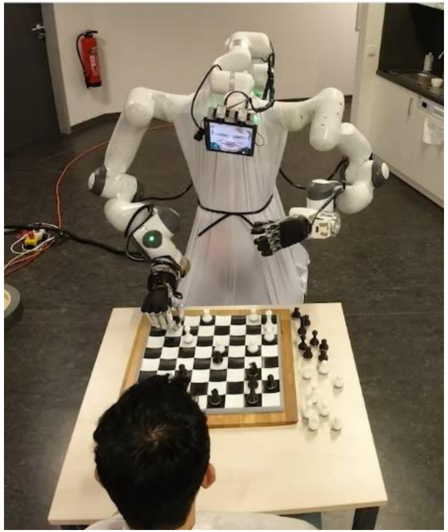
Experience with Teleoperated Robots

- Multiple domains
- Often motivated by competitions and challenges

RoboCup@Home

DARPA Robotics Challenge
DLR SpaceBot Cup

CENTAURO



ANA Avatar XPRIZE

ANA Avatar XPRIZE Competition

- Organized by XPRIZE Foundation
- Sponsored by All Nippon Airways (ANA)
- **Objective**: Create a robotic avatar system that can transport human senses, actions, and presence to a remote location in real time
  - Expanding human connection
  - Transferring skills
  - Exploring dangerous or inaccessible places
- Panel of 22 expert judges
- Launched 03/2018
- **Prize purse of $10M**
- 99 teams registered by 09/2019

[XPRIZE]

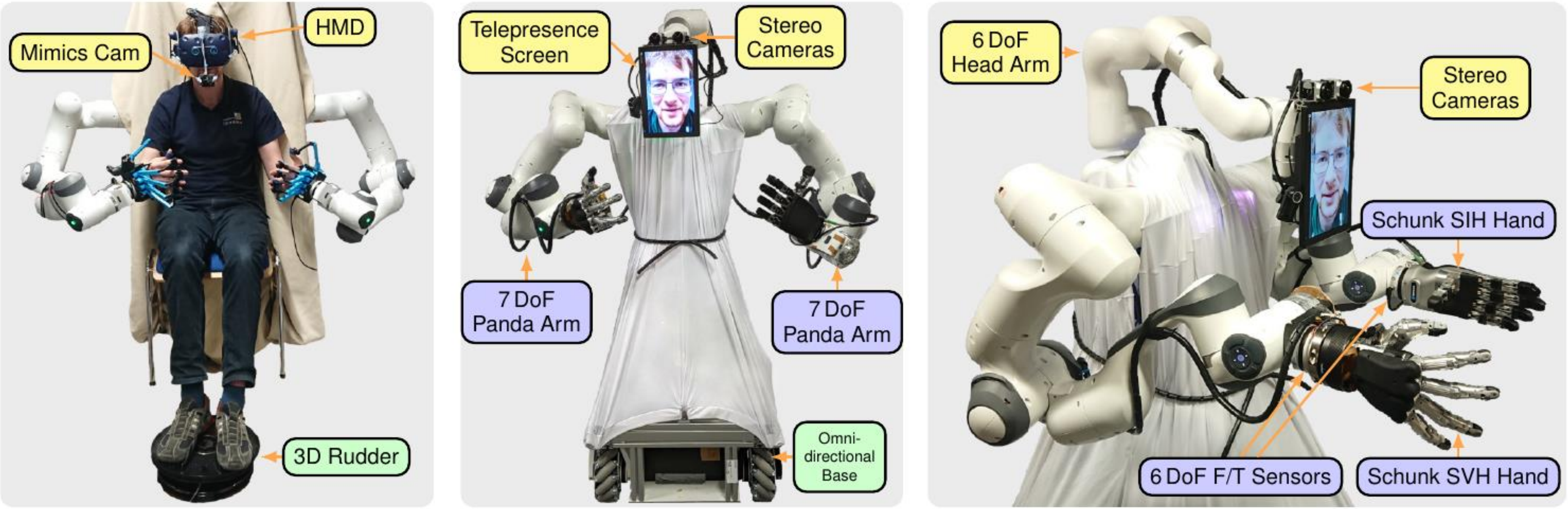
ANA Avatar XPRIZE Competition

- Required mobility, manipulation, human-human interaction
- Focused on the **immersion** in the remote environment and the **presence** of the remote operator

NimbRo Avatar 2021

ANA AVATAR XPRIZE

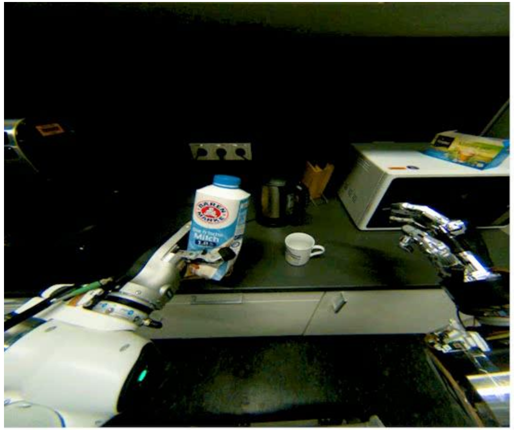
- Two-armed avatar robot designed for teleoperation with immersive visualization & force feedback
- Operator station with HMD, exoskeleton and locomotion interface



[Schwarz et al. IROS 2021]

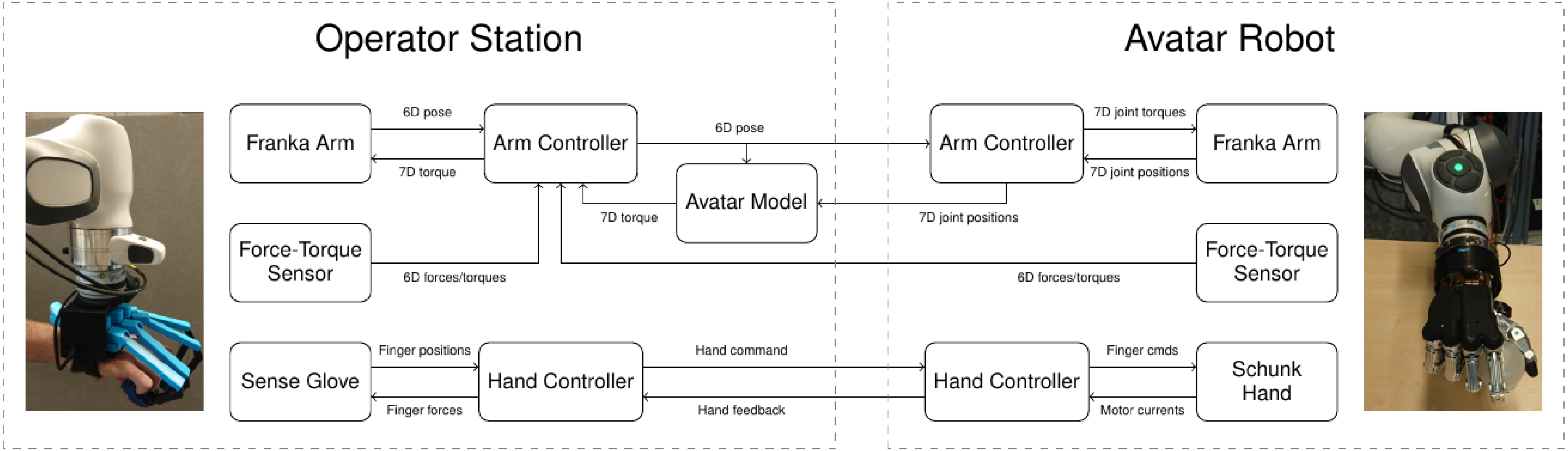
Team NimbRo Semifinal Submission

ANA AVATAR XPRIZE



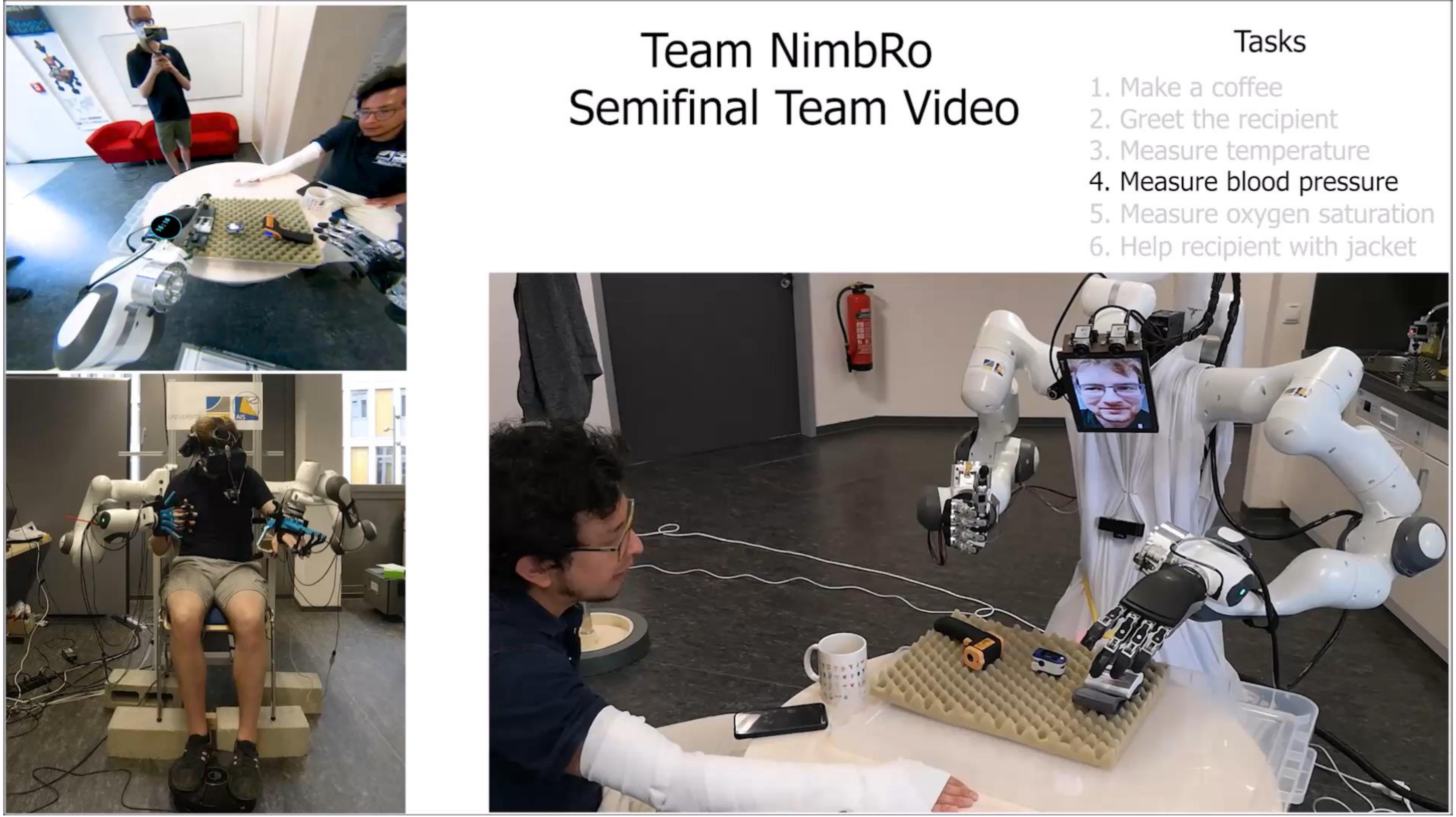
[Schwarz et al. IROS 2021]

Manipulation with Force and Haptic Feedback



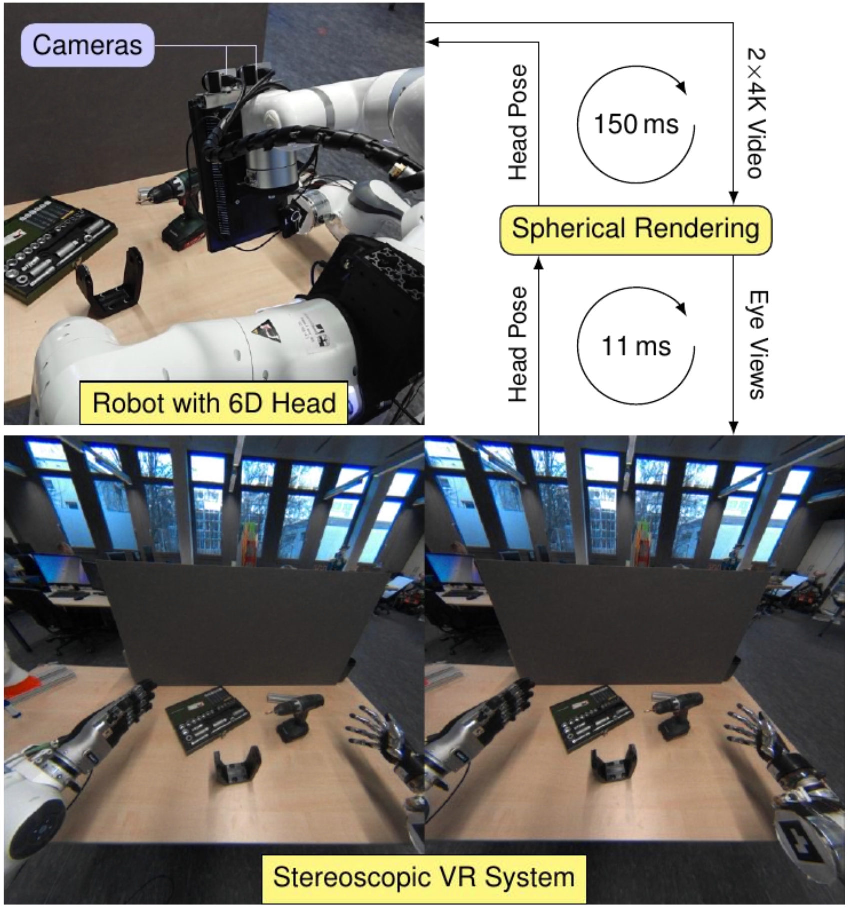
- Arm exoskeleton (Franka Emika Panda), F/T sensor (Nordbo + OnRobot HEX), hand exoskeleton (SenseGlove)
- Avatar side: Arm + F/T sensor + Schunk SVH / SIH hand
- Provides force feedback for wrist and haptic feedback for fingers
- Avatar limit avoidance using predictive model to reduce latencies

[Lenz and Behnke ECMR 2021]

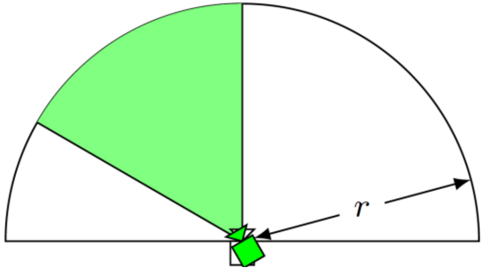


[Schwarz et al. IROS 2021]

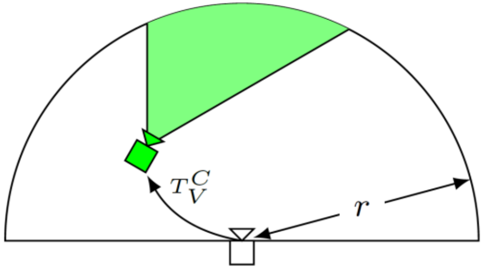
NimbRo Avatar: Immersive Visualization



- 4K wide-angle stereo video stream
- 6D neck allows full head movement
  - Very immersive
  - Good hand-eye coordination
- Spherical rendering technique hides movement latencies
  - Assumes constant depth



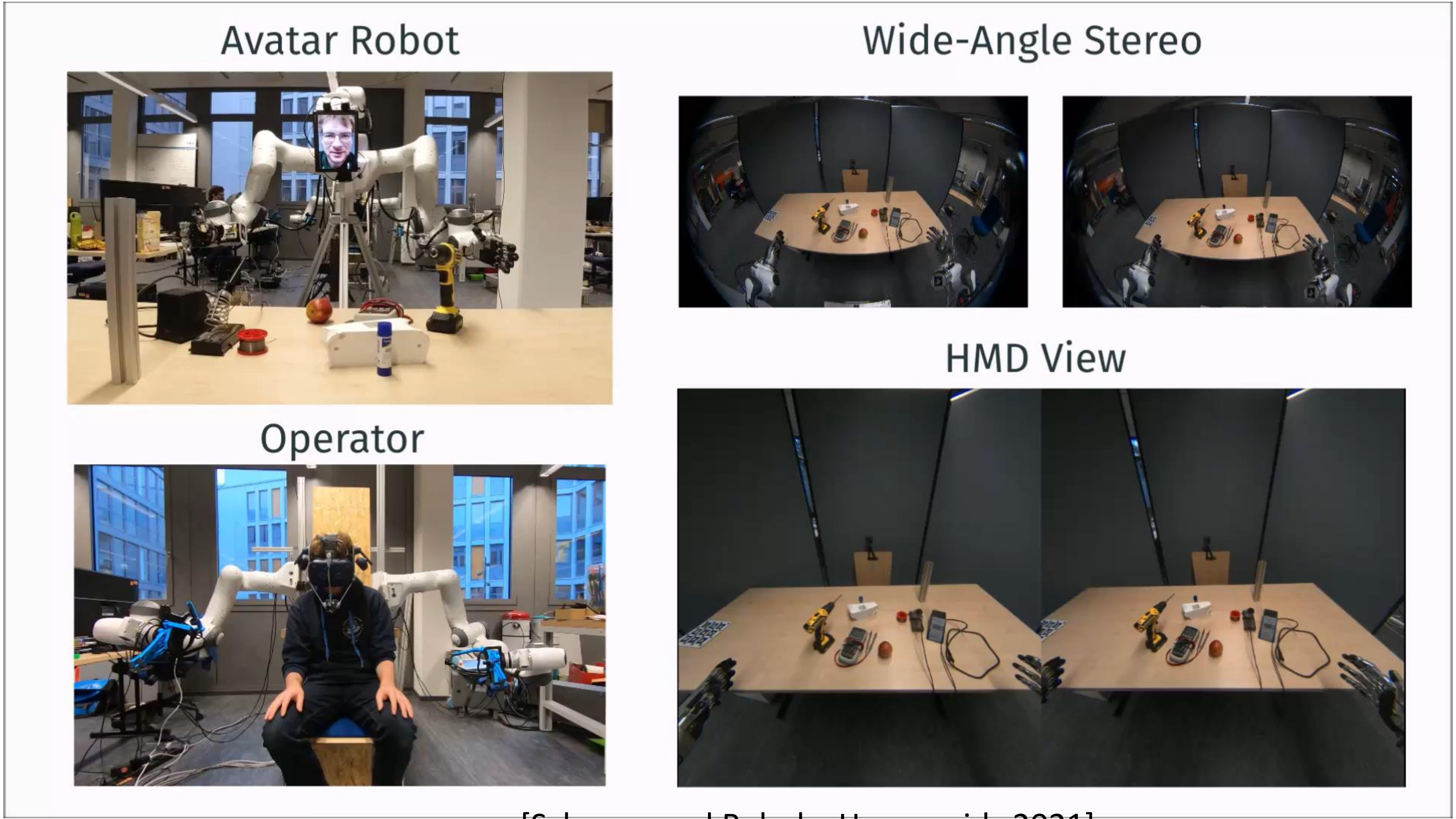
Exact for pure rotations



Distortions for translations

[Schwarz and Behnke Humanoids 2021]

NimbRo Avatar: Immersive Visualization

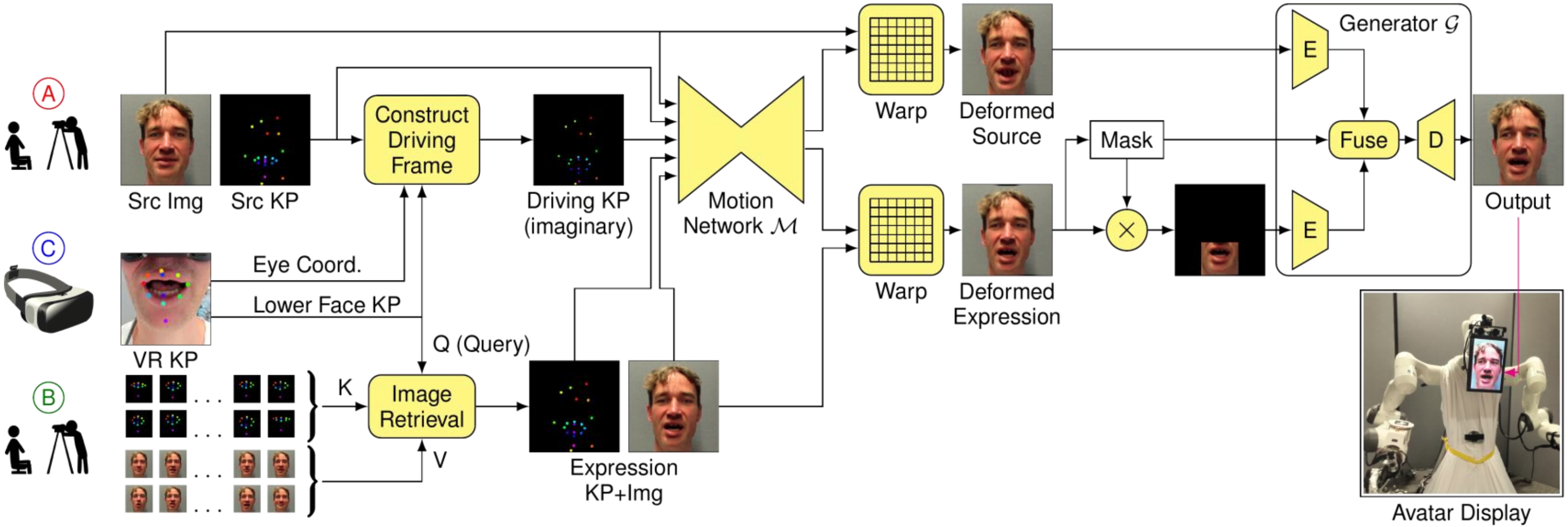


[Schwarz and Behnke Humanoids 2021]

NimbRo Avatar: Operator Face Animation

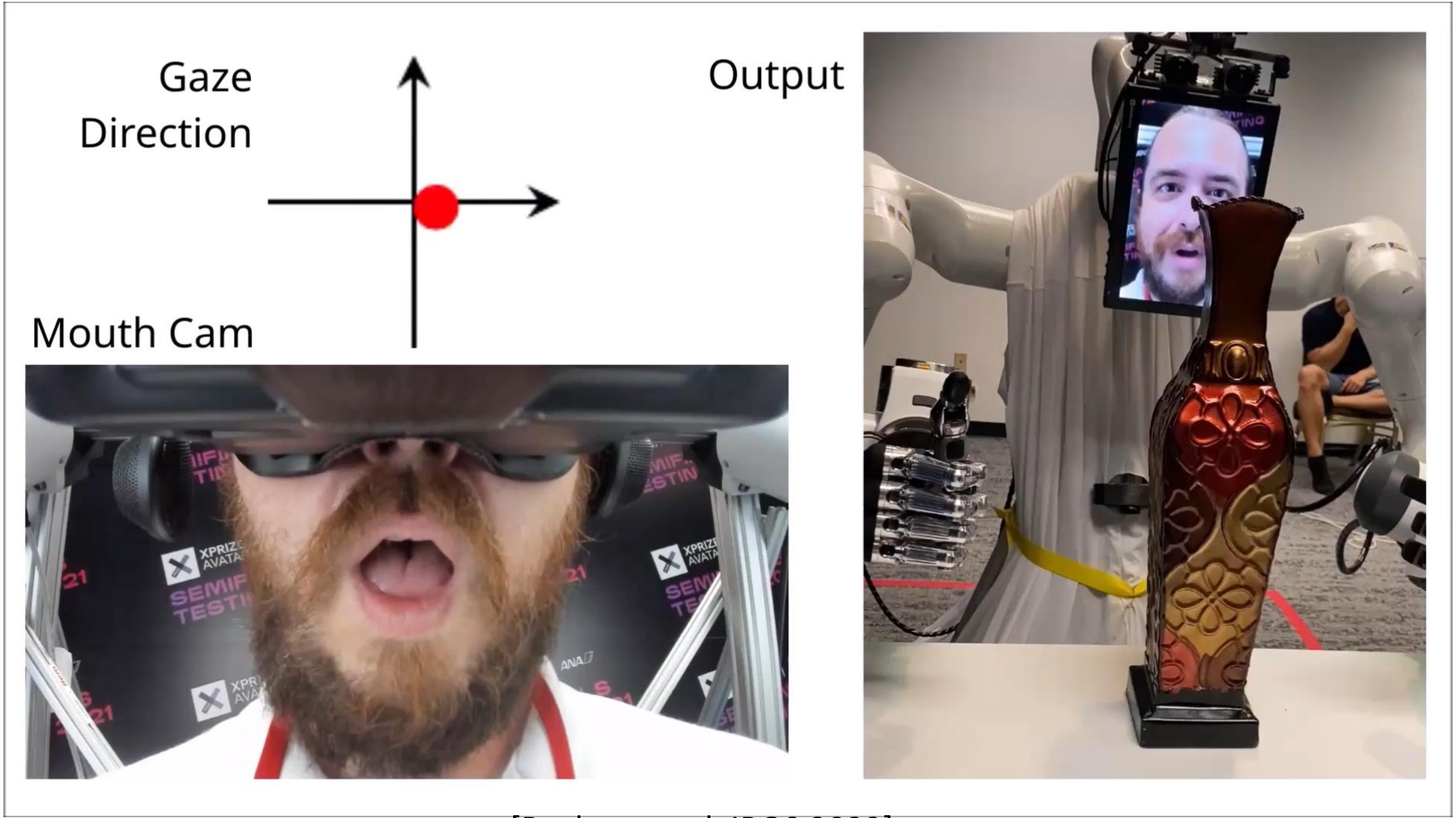
- Operator images without HMD
- Capture mouth and eyes
- Estimate gaze direction and facial keypoints

- Generate animated operator face using a warping neural network



[Rochow et al. IROS 2022]

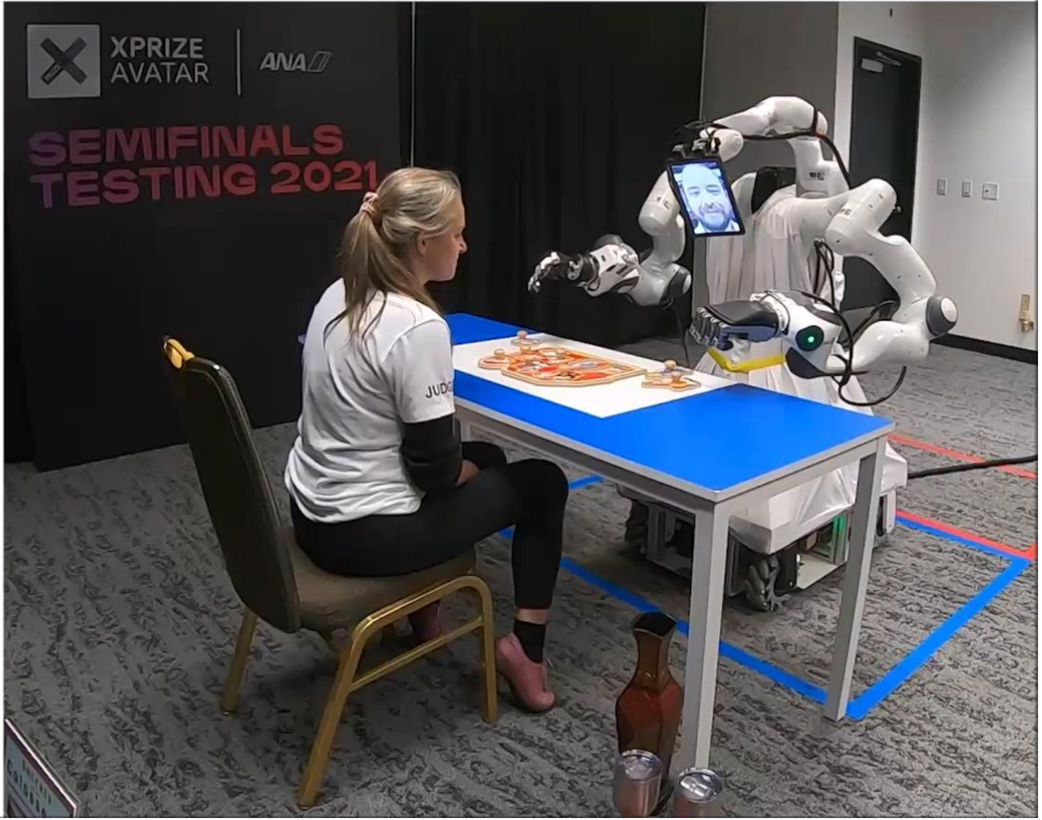
NimbRo Avatar: Operator Face Animation



[Rochow et al. IROS 2022]

NimbRo Avatar

Avatar XPRIZE Semifinals



[Schwarz et al. IROS 2021]

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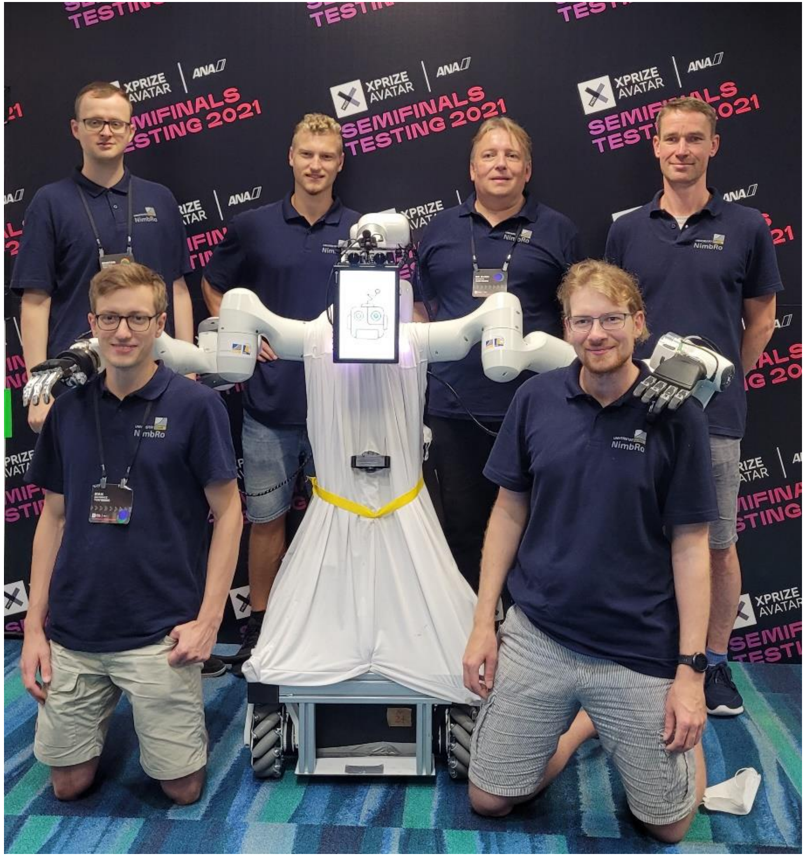
Semifinals Conclusions

ANA AVATAR XPRIZE

- Designed an Avatar system for intuitive immersive telepresence
- Very good immersive visualization
- Operator-Recipient interaction with facial animation
- Bimanual human-like manipulation with force and haptic feedback
- Omnidirectional drive with birds-eye navigation view
- Scored 99/100 points, ranked 1st in the Semifinals
- Judges seemed to enjoy our system



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Semifinals Results

Rank	Team Name	Country	Tested in	Score
1	NimbRo	Germany	Miami	99
2	iCub	Italy	own lab	95.25
3	i-Botics	Netherlands	own lab	93.75
4	Team Northeastern	Unites States	Miami	93
5	Dragon Tree Labs	Singapore	Miami	93
6	AVATRINA	United States	Miami	92.75
7	Avatar Hubo	United States	Miami	92
8	Tangible	United States	Miami	92
9	AlterEgo	Italy	own lab	91.75
10	Cyberselves	Un. Kingdom	Miami	90.75
11	Team SNU	South Korea	Miami	89.5
12	Pollen Robotics	France	Miami	89.5
13	Last Mile	Japan	Miami	88.5
14	Enzo	Colombia	own lab	87.25
15	Team UNIST	South Korea	Miami	86
16	Inbiodroid	Mexico	Miami	84.5
17	Rezillient	United States	Miami	84
18	Touchlab	Un. Kingdom	Miami	82.5
19	AvaDynamics	United States	Miami	80.5
20	Janus	France/Japan	own lab	80

[XPRIZE]

New Finals Requirements

- Untethered avatar robot, more mobility
- Movable operator station
- Mission on a distant planet
- 10 tasks must be solved in given sequence
- 11/2022: Qualification day, two testing days with daily down-selection of teams

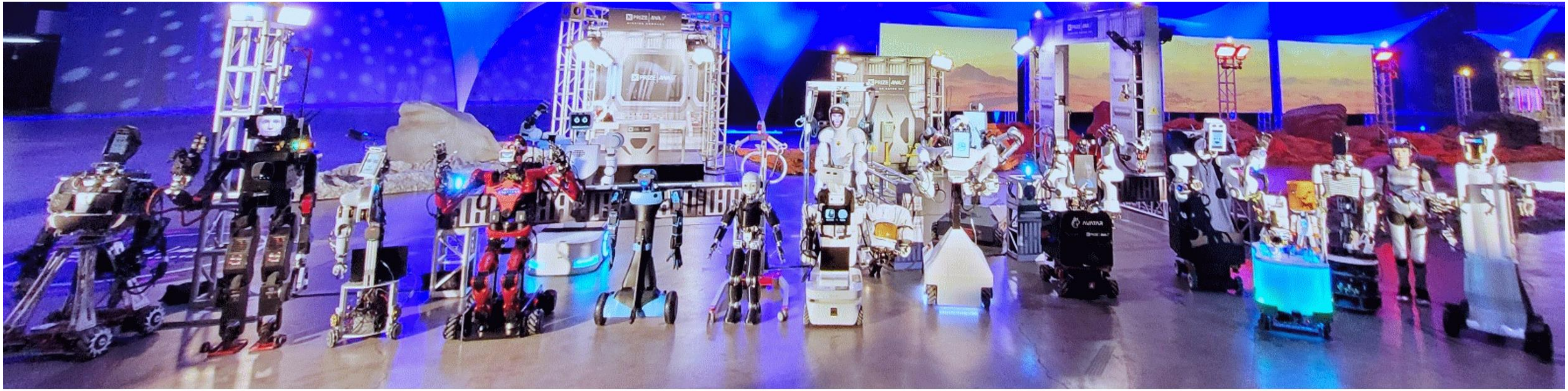
➔ **System reliability extremely important**

Long Beach, CA, USA

Finals Testing Arena

Finals Teams

- 17 teams from 10 countries
- Top research groups and companies



AvaDynamics UNIST i-Botics Tangible AVATRINA Pollen Janus

Inbiodroid Avatar-Hubo SNU AlterEgo iCub Cyberselves NimbRo Northeastern Last Mile Dragon Tree Labs

[Behnke et al. Robotics and Automation Magazine 2023]

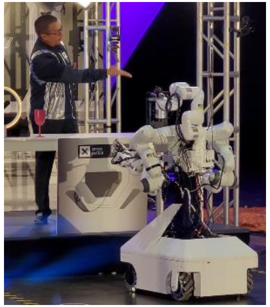
Finals Tasks

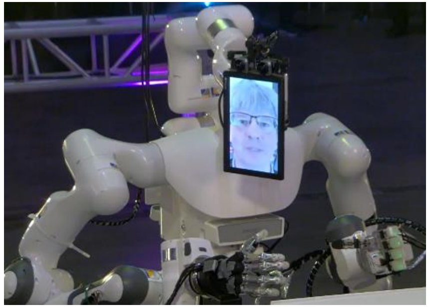
- Three domains:
  - Connectivity
  - Exploration
  - Skill transfer
- Incl. judging object weight and remote feeling of texture
- One point per task
- Tasks fulfillment had highest importance in scoring
- Trial time to break ties

[XPRIZE]


Start

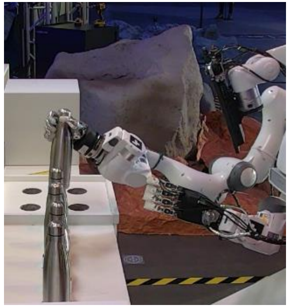

1. Move

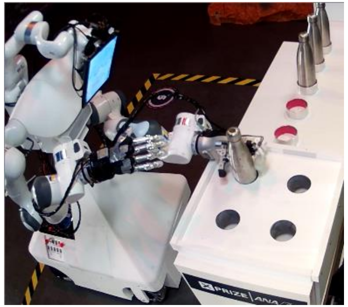

2. Introduce

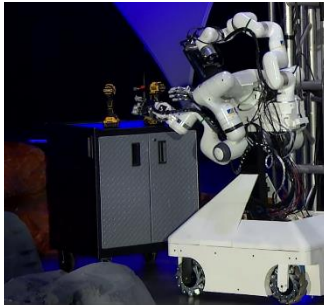

3. Confirm mission


4. Activate switch

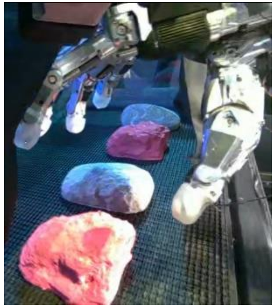

5: Travel planet

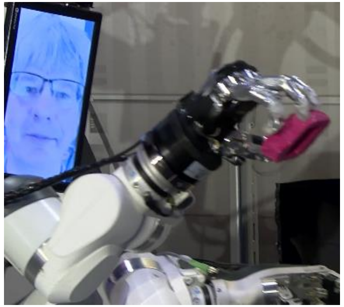

6. Identify full canister


7: Place it


8. Narrow pathway

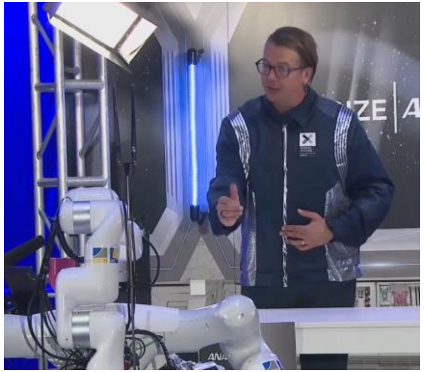
9: Use drill


10. Feel texture


Finish

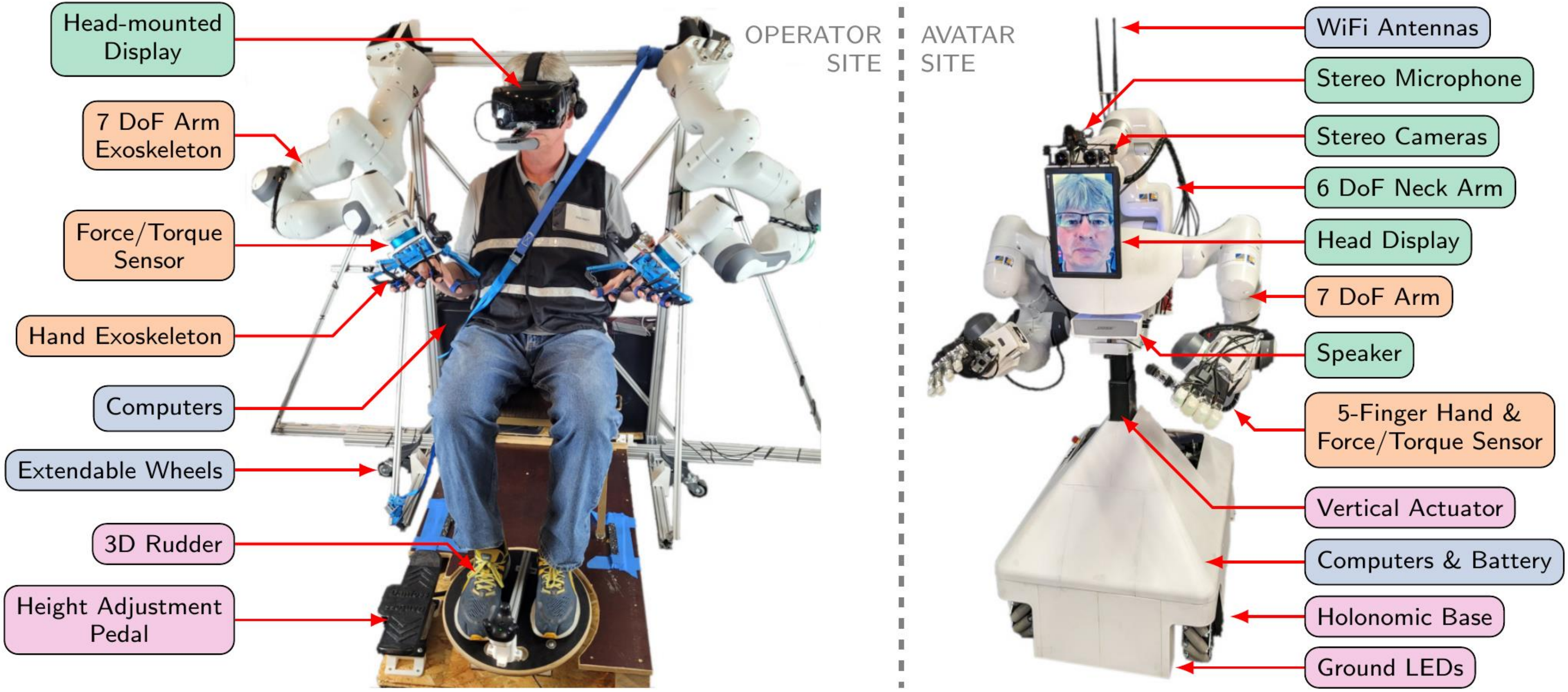
Finals Judged Scoring

- **Operator Experience** (3 points)
  - The avatar system enabled the operator judge to **feel present** in the remote space and conveyed appropriate sensory information.
  - The avatar system enabled the operator judge to **clearly understand** (both see and hear) the recipient.
  - The avatar system was **easy and comfortable** to use.
- **Recipient Experience** (2 points)
  - The avatar robot enabled the recipient judge to feel as though the **remote operator was present** in the space.
  - The avatar robot enabled the recipient judge to **clearly understand** (both see and hear) the operator.



[XPRIZE]

NimbRo Avatar Finals System



[Lenz et al. International Journal of Social Robotics 2023]

Finals Test Run Day 1

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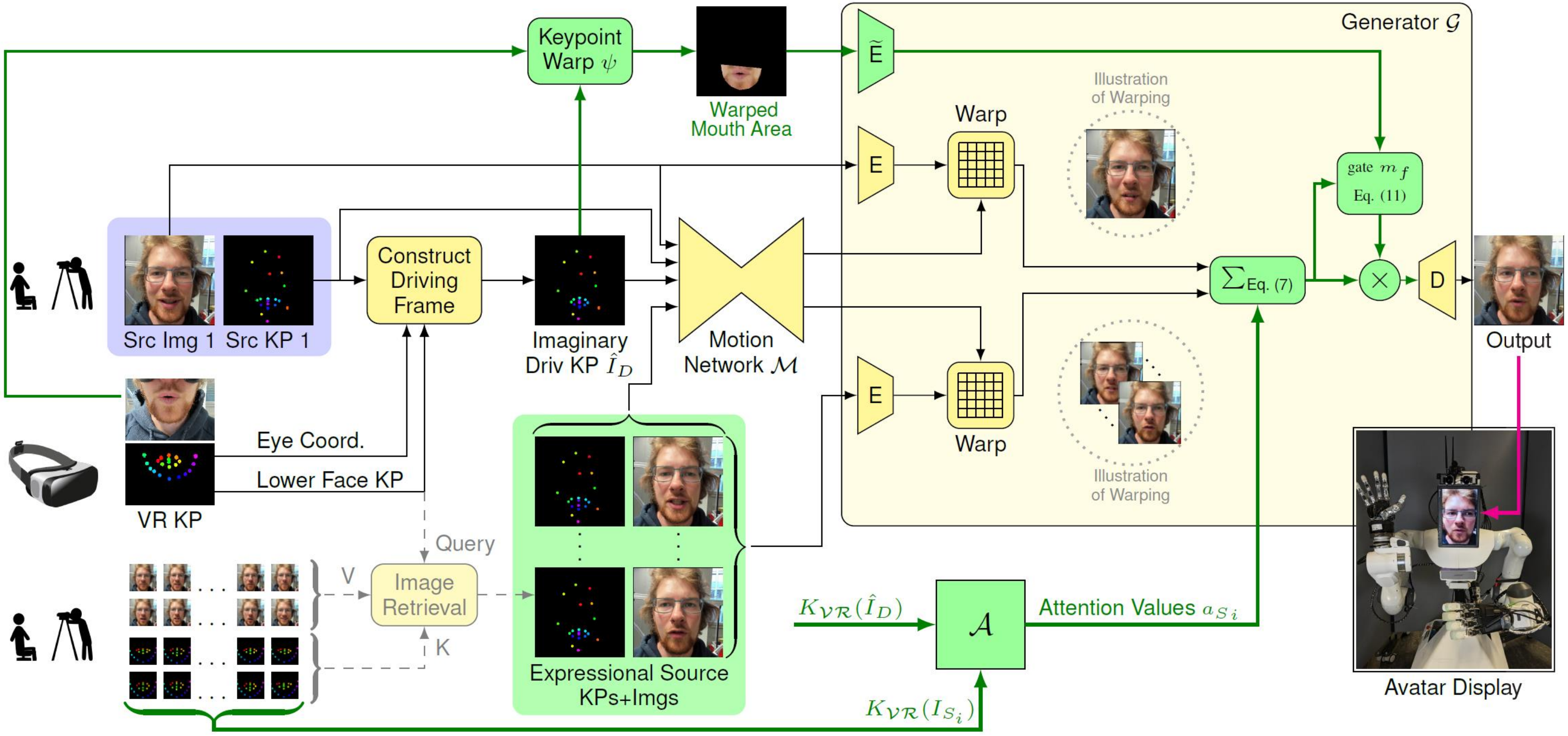
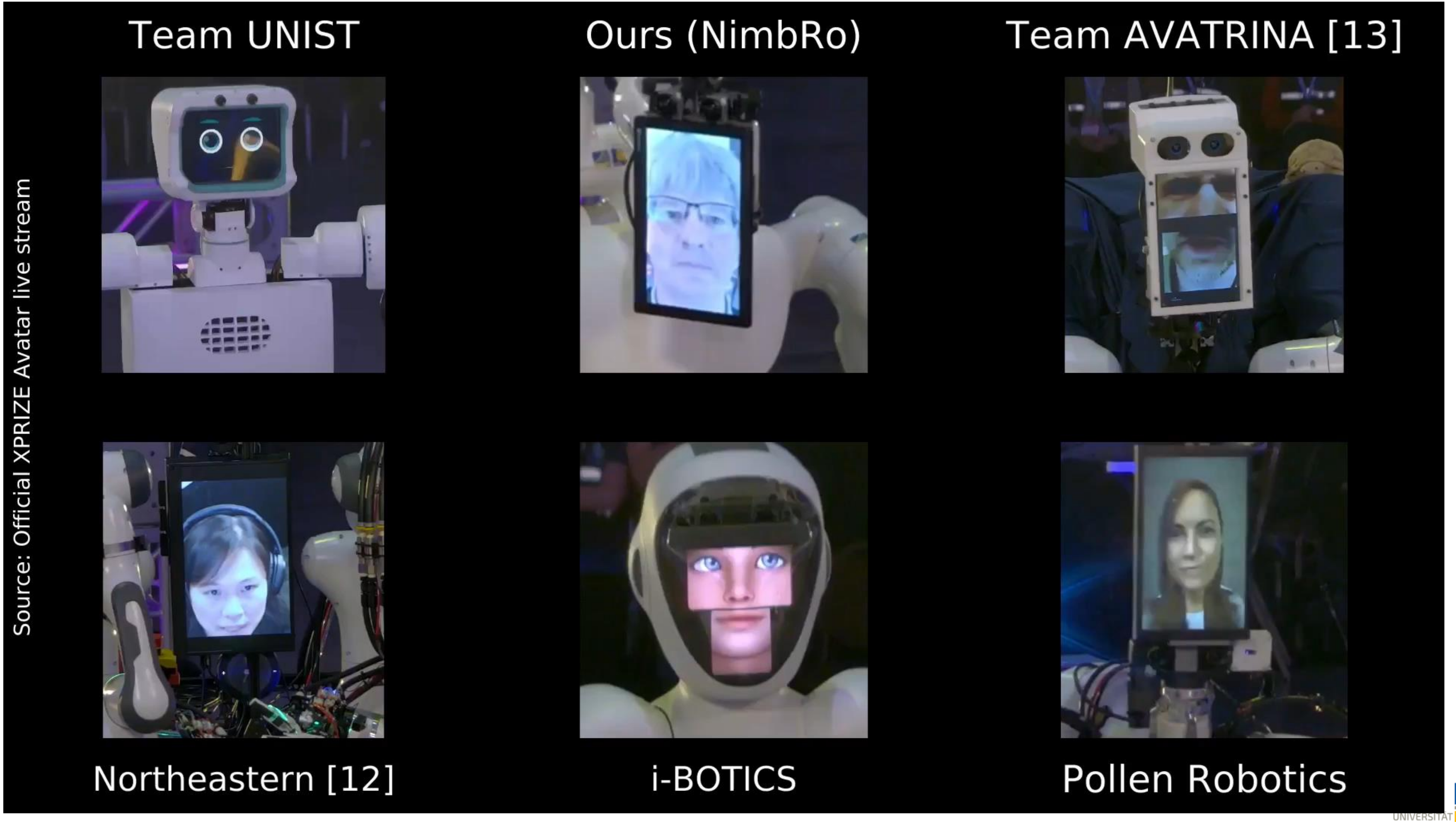
Improved Operator Face Animation

- Direct incorporation of mouth video
- Better temporal continuity



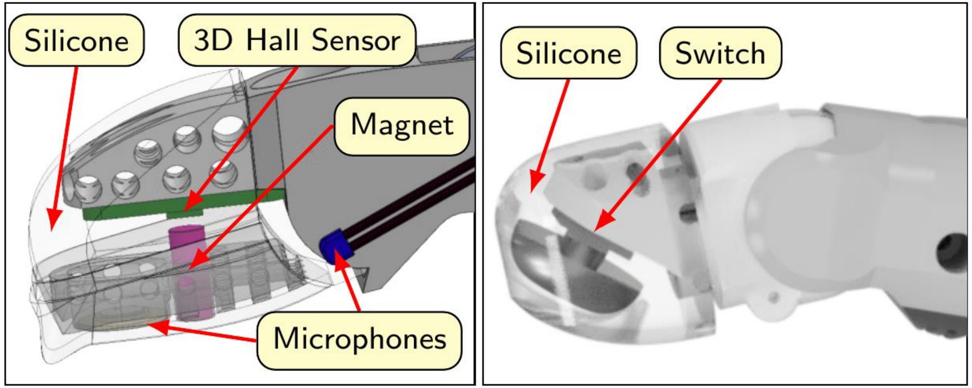
[Rochow et al. IROS 2023]

Face Animation @ Finals

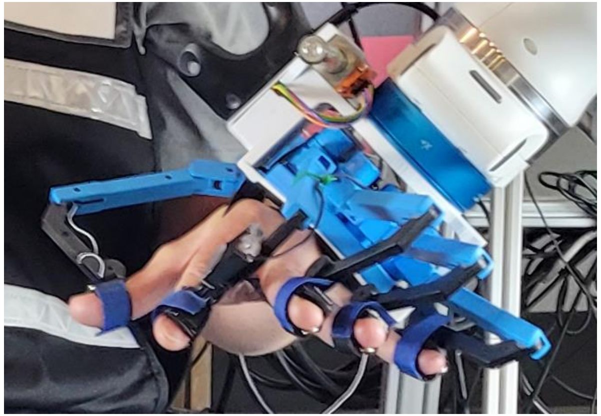


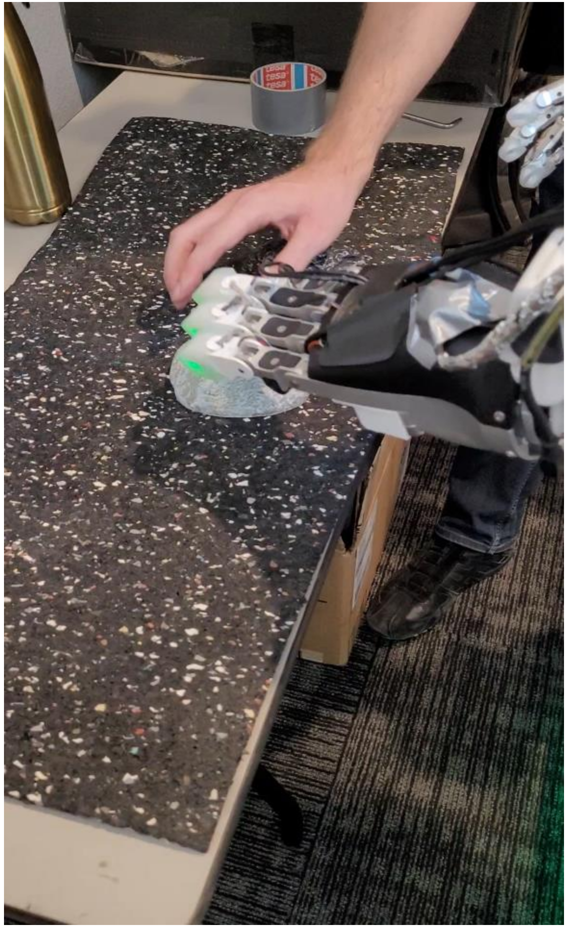
Haptic Perception

- Sensors in the finger tips



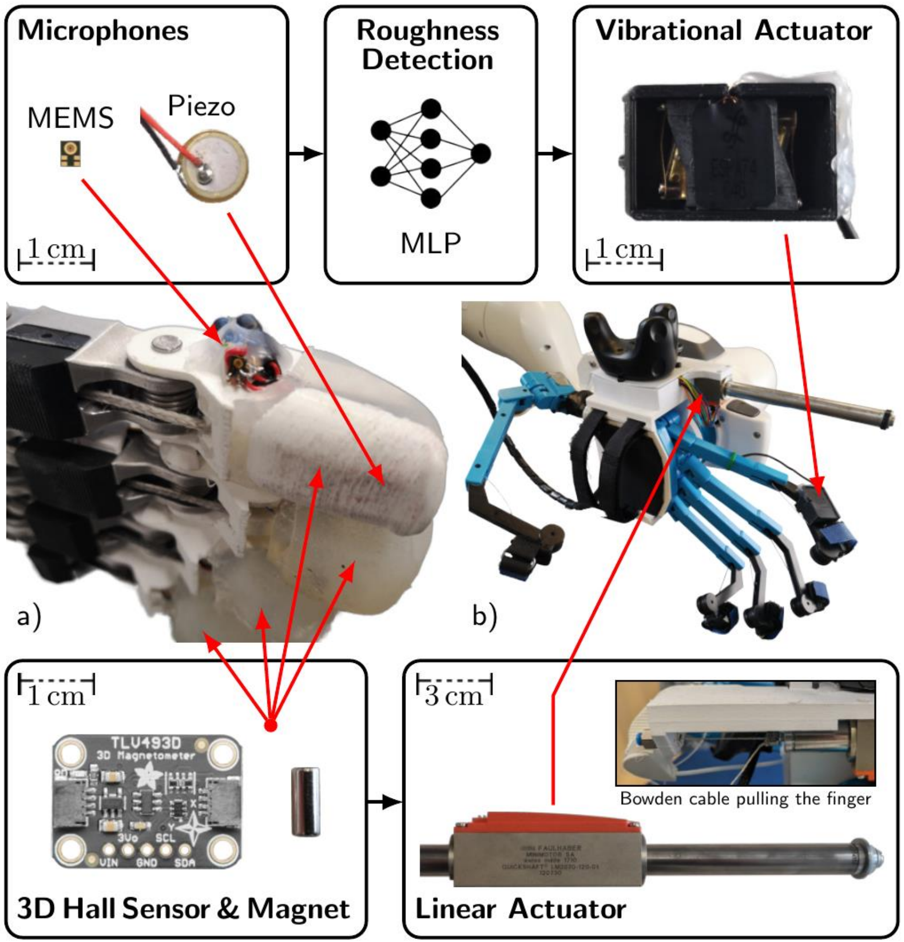
- Actuators on the hand exoskeleton





[Pätzold et al. SMC 2023]

Roughness Perception

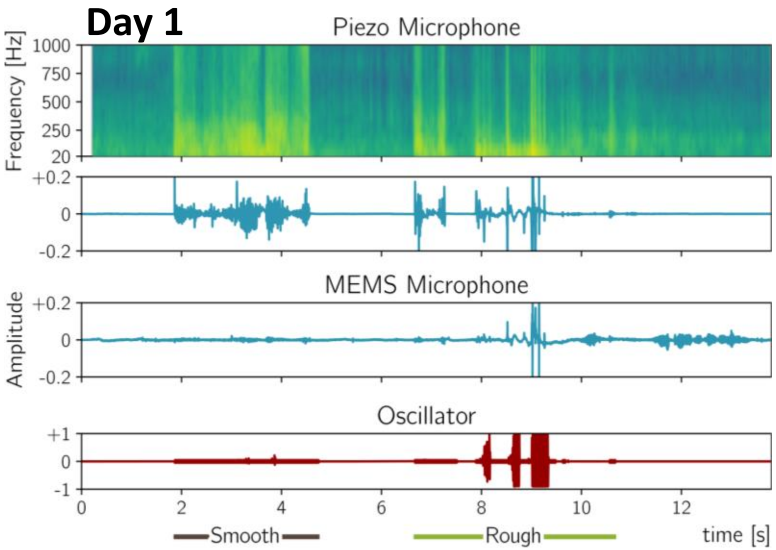


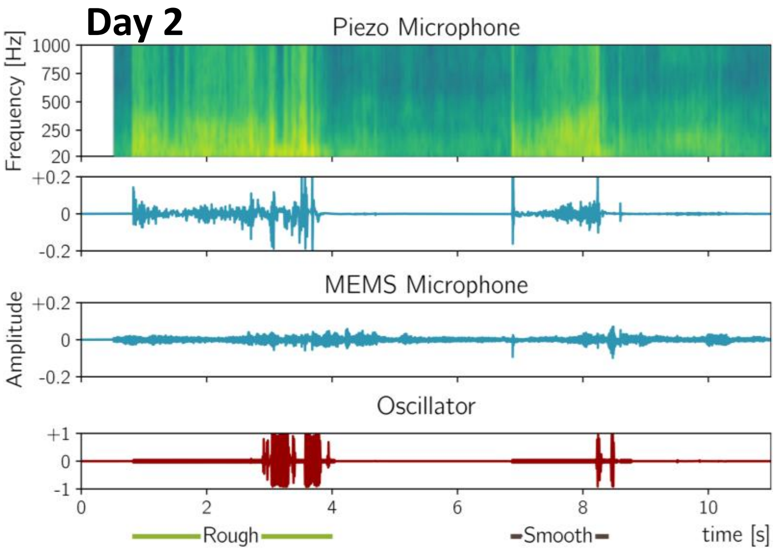
Dataset of Rough and Smooth Objects

[Pätzold et al. SMC 2023]

Finals Task 10: Retrieve a Rough Stone

- Vision partially blocked by a curtain
- 5 stones (3 smooth + 2 rough)



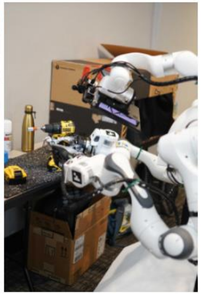


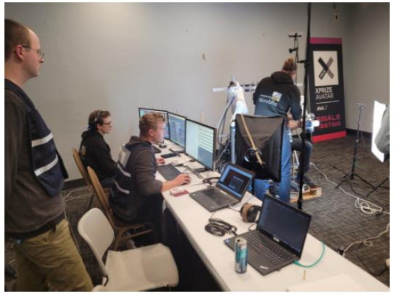
[Pätzold et al. SMC 2023]

Operator Training


Introduction


Locomotion


Grasping


Monitoring crew


Free experiments

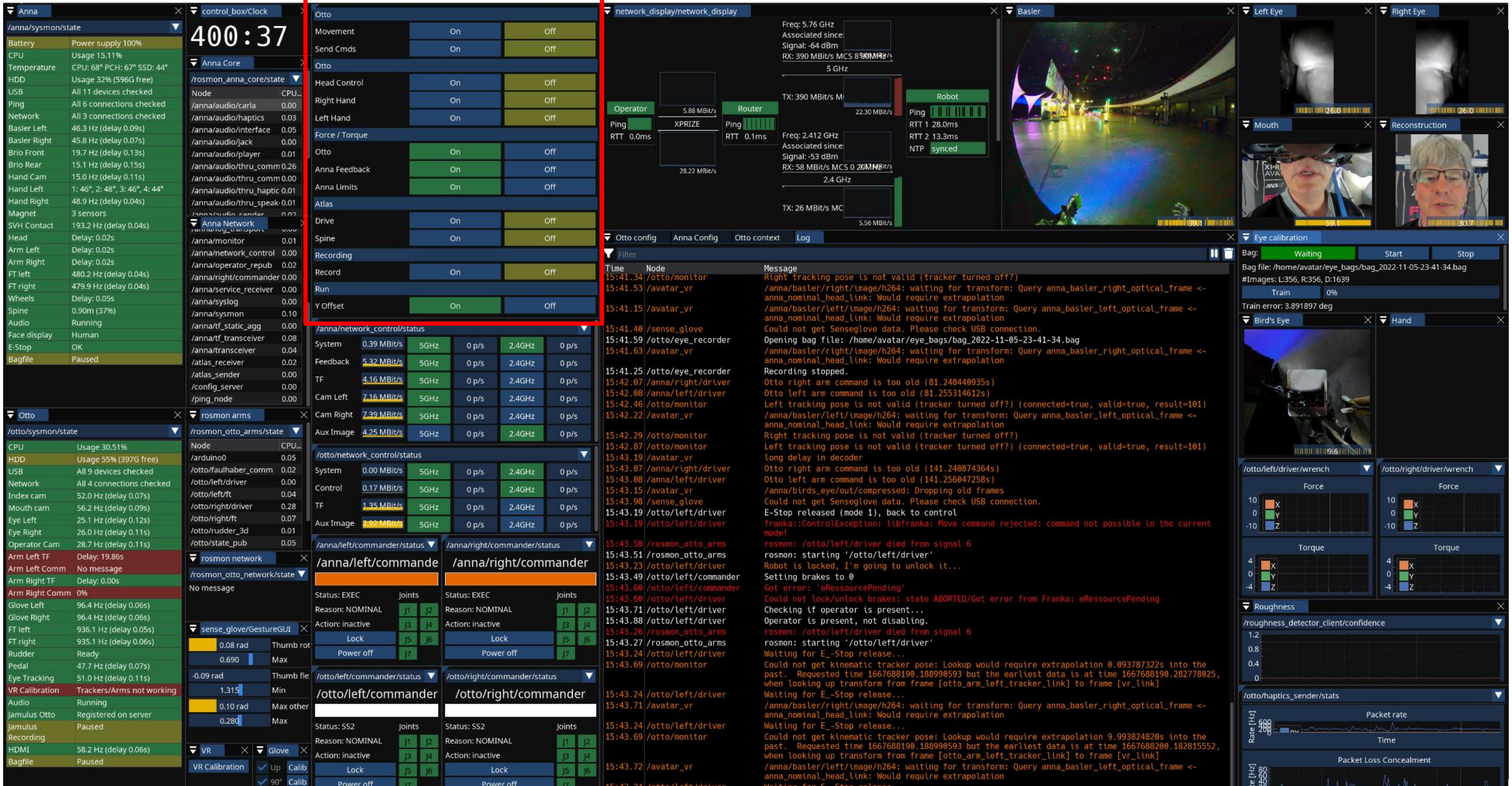
Training	Time [min]
System overview	3
Face animation video w/o HMD	2
Put on HMD	1
Face animation video with HMD	2
Strap in hands	4
Enable arm and hand control	3
Locomotion training (T1, T5, T8)	4
Training switch and canister (T4, T6, T7)	5
Training power drill (T9)	5
Training stones (T10)	10
Enjoy the system	3
System recovery & recap	3
Total training	45

- Dedicated roles: Communication with operator, Software control, Face animation, Hardware support
- Trade-off between learning by own exploration vs. explicit instruction

[Lenz et al. International Journal of Social Robotics 2023]

Operator Crew GUI

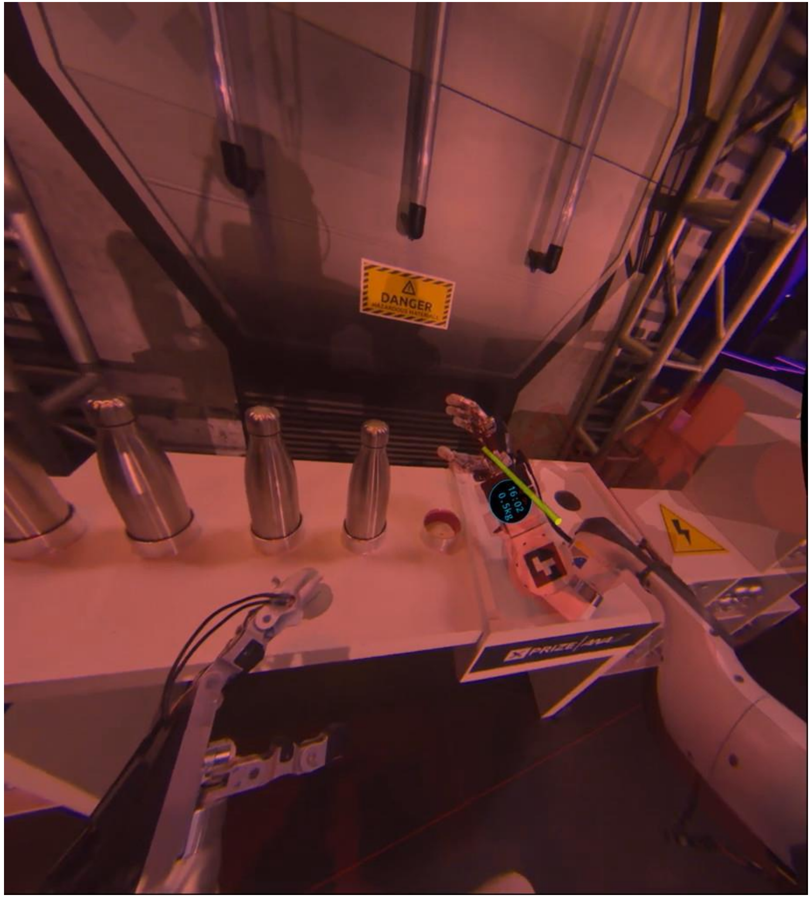
Operator Crew GUI



Operator Crew GUI

Reliability Features

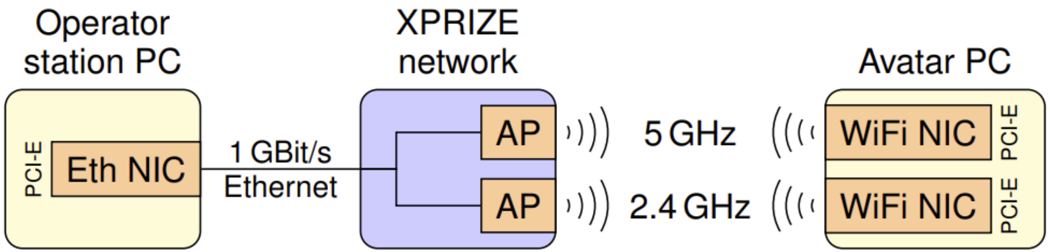
1. Operator crew awareness
2. Automatic arm resets
3. ROS node respawn
4. State- and connectionless network system (pure UDP)
5. Redundant WiFi connections
6. PC watchdog



[Schwarz et al. Humanoids 2023]

Network Details

- Separate ROS cores for operator station and avatar
- Pure UDP, no re-connect / initialization
- Main camera stream (stereo 2472×2178 @46 fps) is HEVC-encoded & decoded on GPU (NVENC).
  Total bandwidth: ~14 MBit/s
- Control data is sent redundantly
- Monitoring packet loss



WiFi Bandwidth Requirements

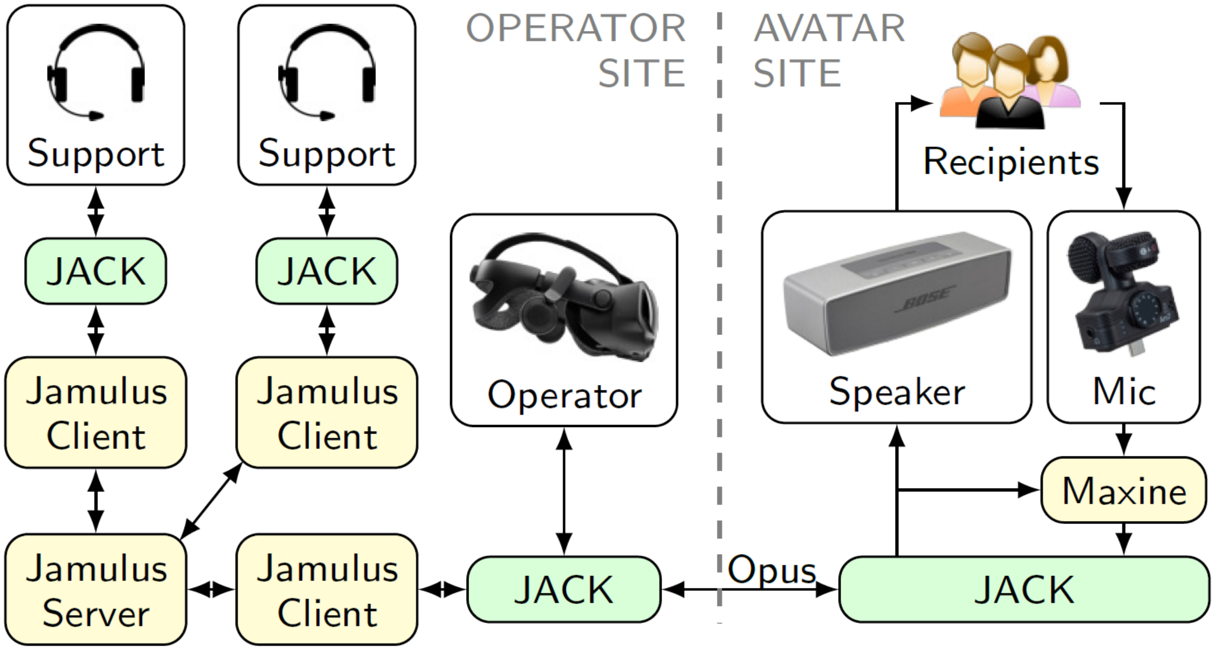
Downlink from avatar				Uplink to avatar			
Channel	MBit/s	5 GHz	2.4 GHz	Channel	MBit/s	5 GHz	2.4 GHz
Arm feedback	8.5	✓	×	Arm control	4.9	✓	✓
Transformations	4.1	✓	×	Transformations	1.4	✓	×
Main cameras	14.7	✓	×	Operator face	5.7	×	✓
Hand camera	5.5	×	✓	Audio	0.4	✓	✓
Diagnostics	0.4	✓	✓				
Audio	0.4	✓	✓				
Total [MBit/s]		28.1	6.3	Total [MBit/s]		6.7	11.0

- The core software is already open source, more to come:
  https://github.com/AIS-Bonn/nimbro_network

[Schwarz et al. Humanoids 2023]

Audio Details

- Low-latency solution utilizing the *JACK Audio Connection Kit*
- Redundant UDP transmission via the *OPUS audio codec*
- *NVIDIA MAXINE* for GPU-accelerated *acoustic echo cancelation*
- *Jamulus* for team communication with operator and recipients



[Lenz et al., International Journal of Social Robotics 2023]

Finals Day 2 Testing

Finals Results

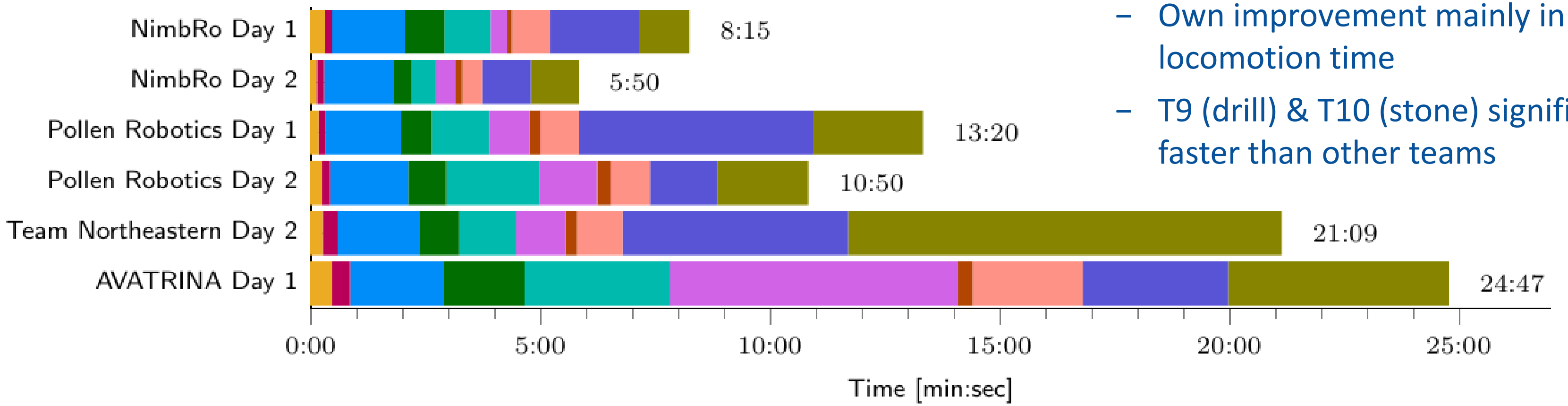
Rank	Team name	Time	Task score	Judged score	Total
1	NimbRo (DE)	5:50	10	5	15
2	Pollen Robotics (FR)	10:50	10	5	15
3	Team Northeastern (US)	21:09	10	4.5	14.5
4	AVATRINA (US)	24:47	10	4.5	14.5
5	i-Botics (NL)	25:00	9	5	14
6	Team UNIST (KR)	25:00	9	4.5	13.5
7	Inbiodroid (MX)	25:00	8	5	13
8	Team SNU (KR)	25:00	8	4.5	12.5
9	AlterEgo (IT)	25:00	8	4.5	12.5
10	Dragon Tree Labs (SG)	25:00	7	4	11
11	Avatar Hubo (US)	25:00	6	3.5	9.5
12	Last Mile (JP)	25:00	5	4	9

[XPRIZE]

Team NimbRo

Finals Timings

Team	Day	Time[1] [mm:ss] Start[2]	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	Total
NimbRo	1	00:00	00:18	00:10	01:35	00:52	01:00	**00:22**	**00:06**	00:50	01:56	01:06	08:15
	2	00:00	**00:08**	**00:09**	01:31	**00:23**	**00:32**	00:26	00:09	**00:26**	**01:04**	**01:02**	**05:50**
	1→2	0:00	-0:10	-0:01	-0:04	-0:29	-0:28	+0:04	+0:03	-0:24	-0:52	-0:04	-2:25
Pollen Robotics	1	00:00	00:10	**00:09**	01:39	00:40	01:15	00:53	00:14	00:50	05:06	02:24	13:20
	2	00:00	00:15	**00:09**	01:43	00:49	02:02	01:15	00:18	00:51	01:28	01:59	10:50
Team Northeastern [25]	1	00:00	00:33	00:24	02:08	01:43	04:03	01:27	00:36	01:56			12:50
		00:00	00:16	00:19	01:47	00:52	01:14	01:05	00:15	01:00	04:54	09:27	21:09
AVATRINA [26]	1	00:00	00:28	00:23	02:03	01:45	03:10	06:17	00:19	02:24	03:10	04:48	24:47
	2	00:00	00:24	00:12	01:39	01:05	02:50	00:48	00:11	01:30	02:43		11:22
i-Botics [51]	1	00:00	00:13	00:26	**01:23**	01:53	01:57	01:52	02:07	02:57	09:47		22:35
	2	00:00	00:19	00:12	01:36	03:25							05:32



- Own improvement mainly in locomotion time
- T9 (drill) & T10 (stone) significantly faster than other teams

[Lenz et al. International Journal of Social Robotics 2023]

What is Next?

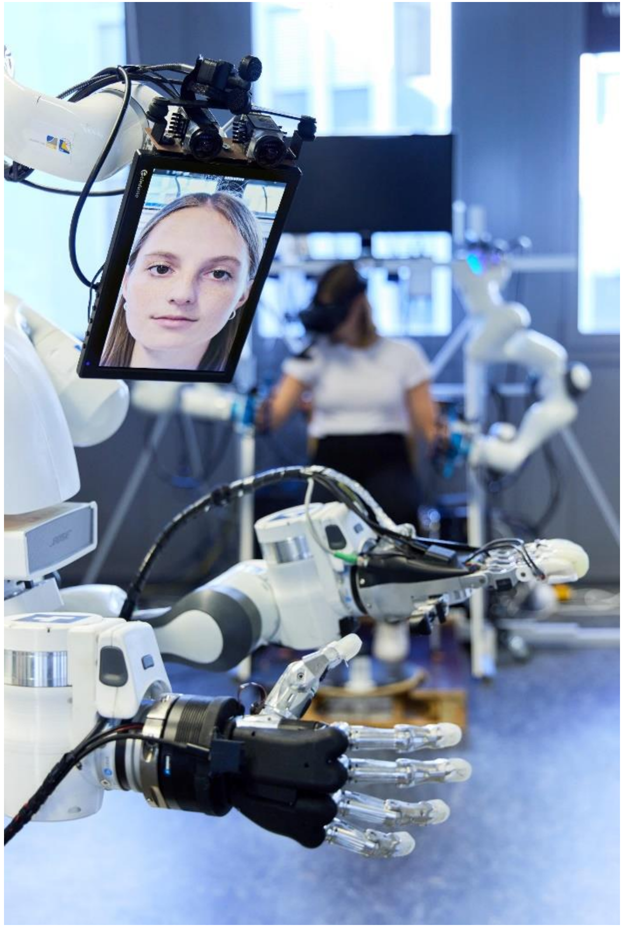
- Transfer to **real applications**
  - Complex avatar systems could be further developed e.g. for
    - Dangerous or hard-to-reach domains,
    - Disaster relief,
    - Medical assistance in isolation wards
  - Everyday virtual travel requires simpler and more affordable systems

[Photographer: Volker Lannert]

- **Research questions** include
  - How much human-likeness avatars should assume?
  - How to address latencies and bandwidth limitations?
  - How to balance and interface direct control and autonomy?

Motivation for Autonomy

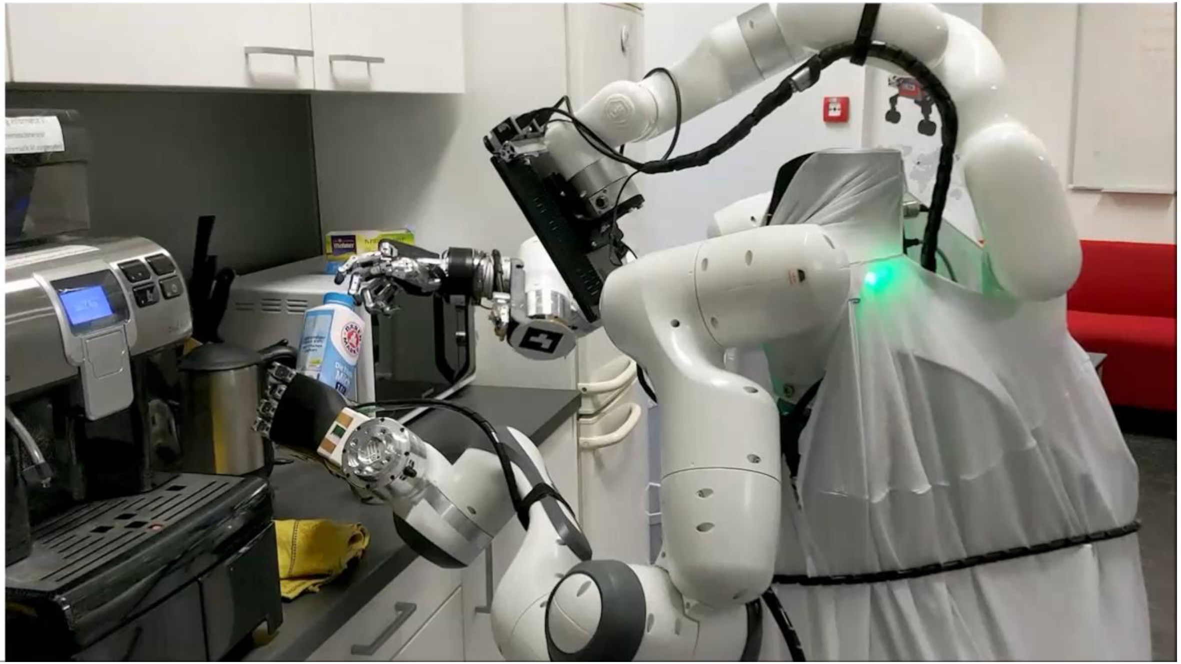
- Longer latencies require less direct control
  - Use autonomous skills, such as grasping an object or navigating to a waypoint
  - Shared autonomy where the operator controls high-level behavior and autonomy fills-in the low-level details (horse metaphor, Flemisch 2003)
- Operator might not always be available
  - 1:1 control often too costly
    => one operator must supervise many robots
  - Issues of privacy and of being in operator‘s dept
- AI: Understanding intelligence by creating intelligent artefacts



[Photographer: Volker Lannert]

Unmatched Human Operators

- Humans can solve many tasks by teleoperation
  - Can cope with novel situations, quickly learn new tasks
  - Recognize and mitigate errors
- Far beyond the capabilities of autonomous robots



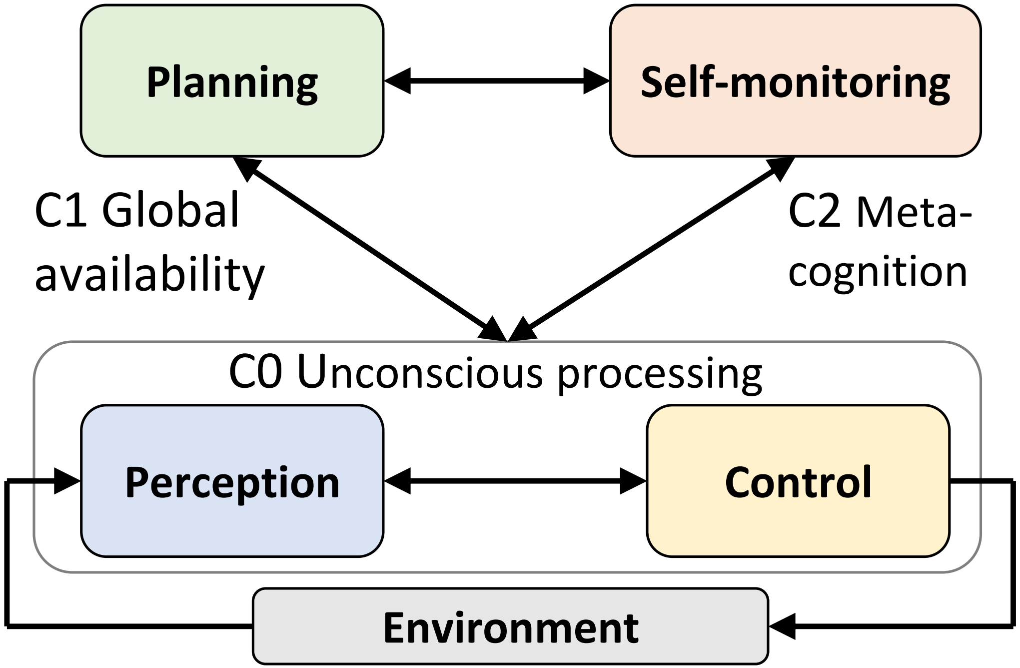
2x

Human Cognitive System

- Cognitive architecture of the human mind has evolved to continuously interact with changing environments and self-monitor

System 2
- slow, serial
- flexible
- **conscious**

System 1
- fast, parallel
- habitual
- unconscious



Cognitive functions according to Kahneman (2011) and Dehaene (2017)

My Objective

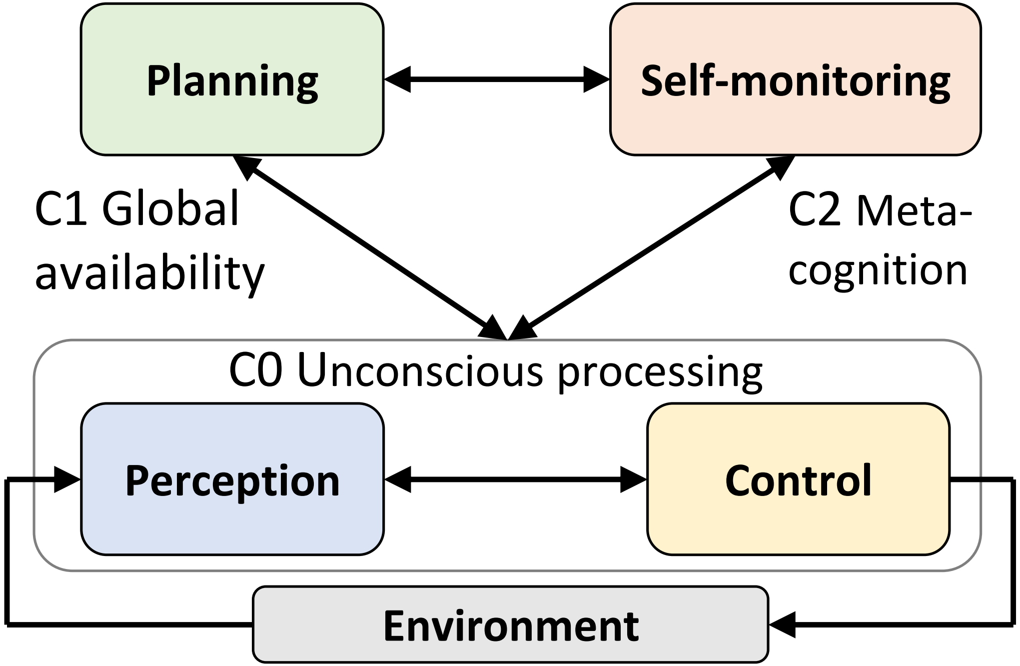
- Develop methods for learning perception and planning for service robots, which go beyond unconscious routine tasks by incorporating **conscious processing** to cope with novel situations and self-monitor

Overall Approach

- Equip service robots with key elements of human cognitive architecture
- **Bottom-up** approach ensures **grounding** of conscious processing

System 2
- slow, serial
- flexible
- conscious

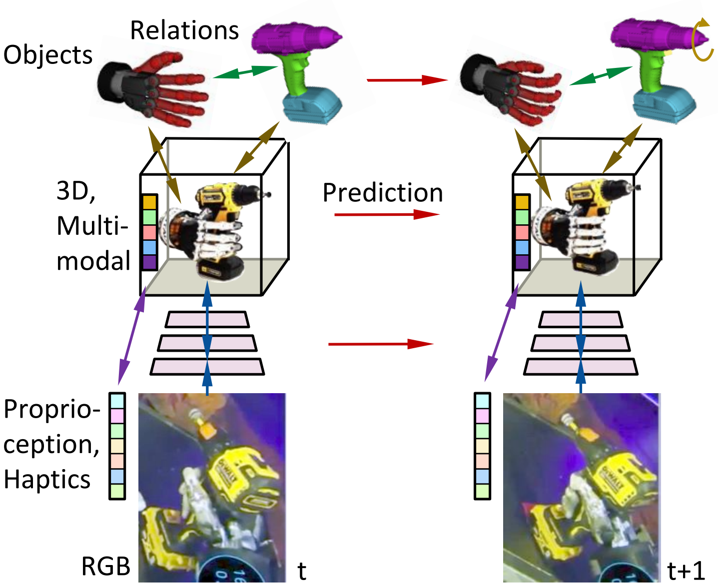
System 1
- fast, parallel
- habitual
- unconscious



Cognitive functions according to Kahneman (2011) and Dehaene (2017)

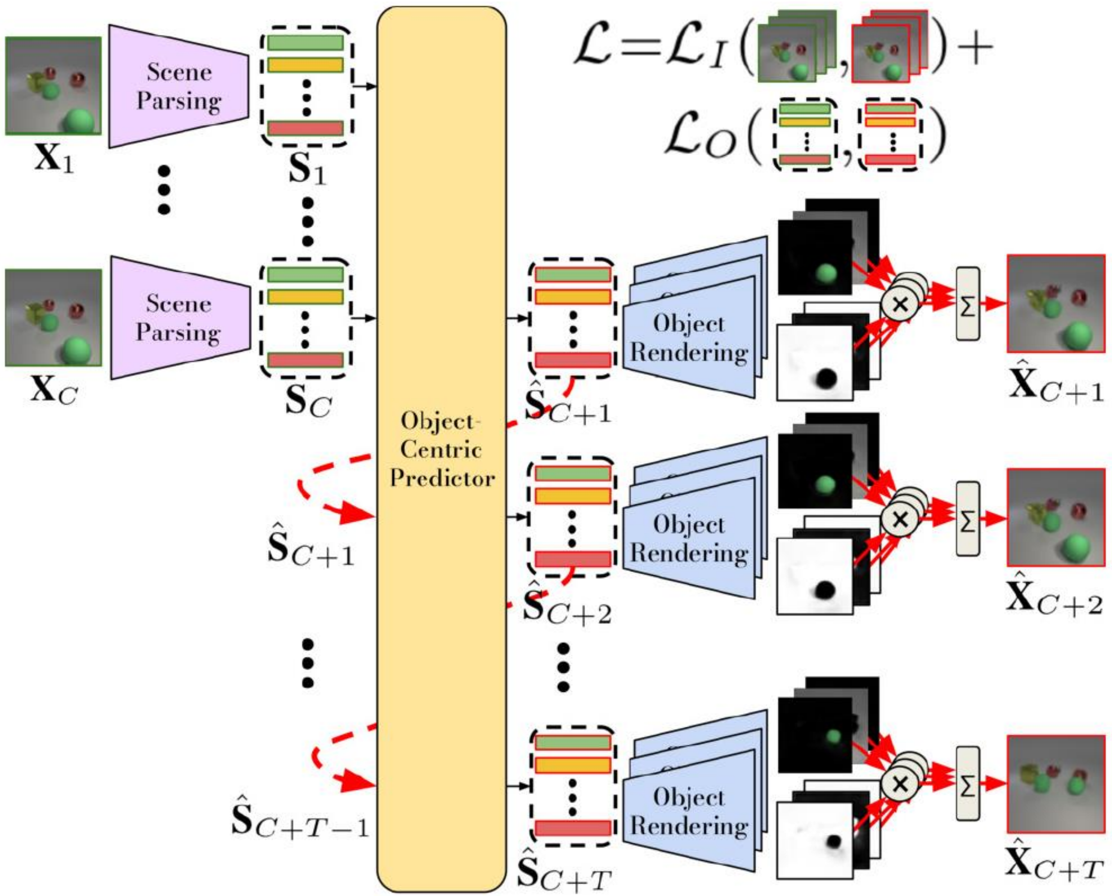
Unconscious Perception & Tracking

1. Learning hierarchical representations
2. Learning 3D multimodal scene models
3. Learning object models & relations
4. Learning prediction and tracking

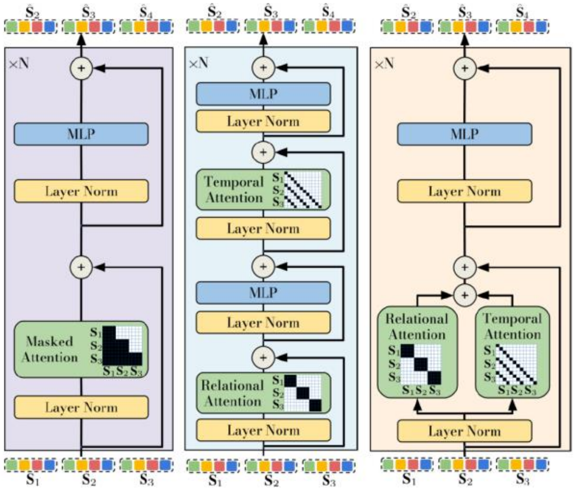


- **Scene compositionality**
  - Objects and scenes described by their constituent parts and their relations
  - Infinite variants from a finite set of building blocks
- Exploit inductive biases like canonical frames, 3D projective geometry, camera motion, object relations, compositional structure, hierarchical categorization, …

Object-centric Video Prediction Decoupling Dynamics and Interaction



- Scene parsing into object slots
- Video synthesis from objects and masks
- Predictor decouples temporal and relational attention



[Villar-Corrales et al. ICIP 2023]

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Object-centric Video Prediction Data Sets

Obj3D

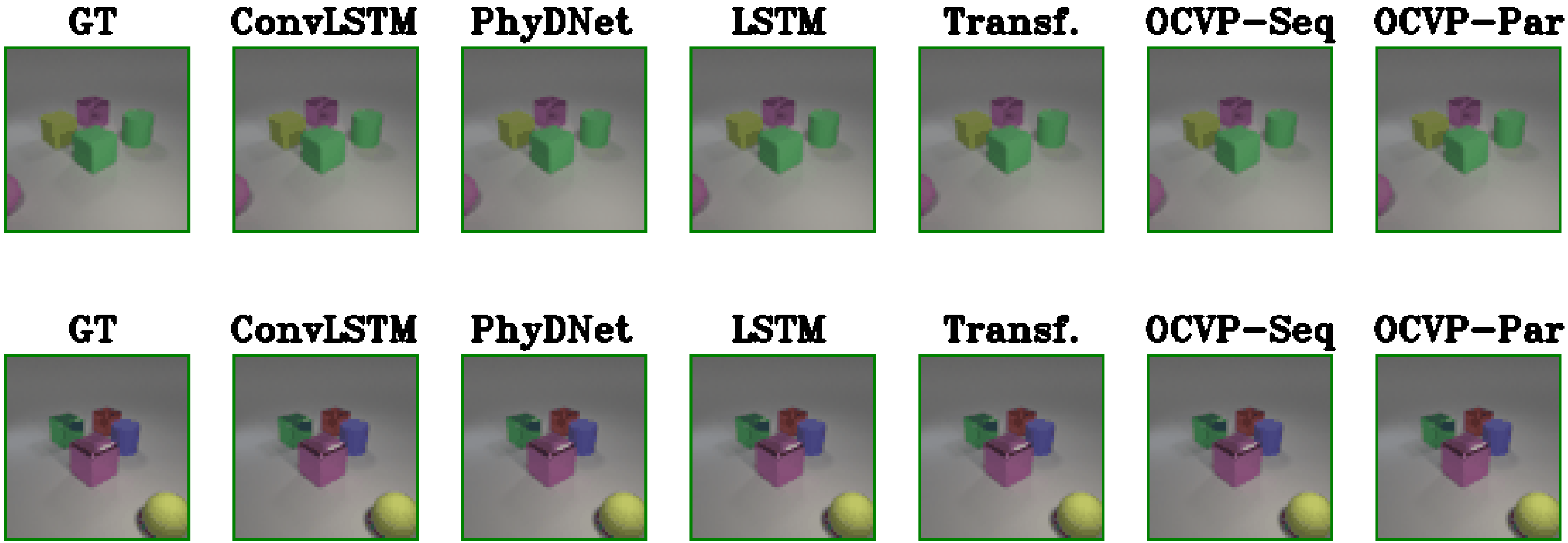
- Synthetic 3D objects
- Ball colliding with static objects
- Given 5 frames, predict next 5

MOVi-A

- Synthetic 3D objects
- Complex dynamics and occlusions
- Given 6 frames, predict next 8

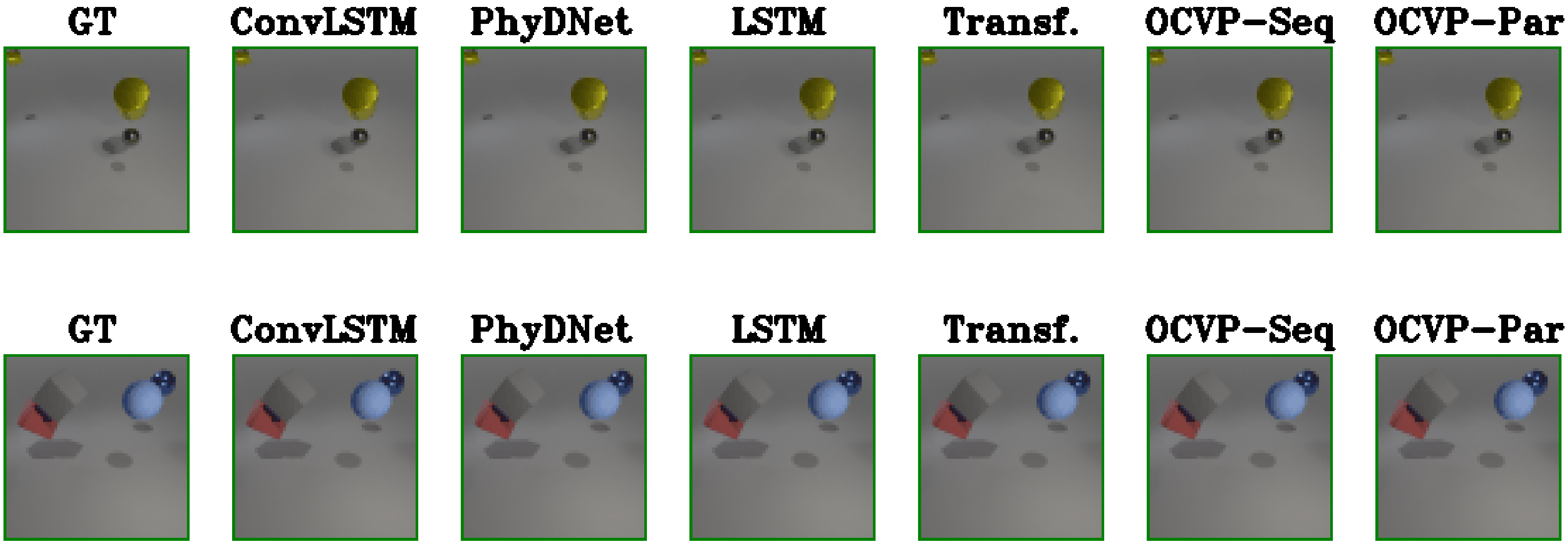
[Villar-Corrales et al. ICIP 2023]

Object-centric Video Prediction: Obj3D



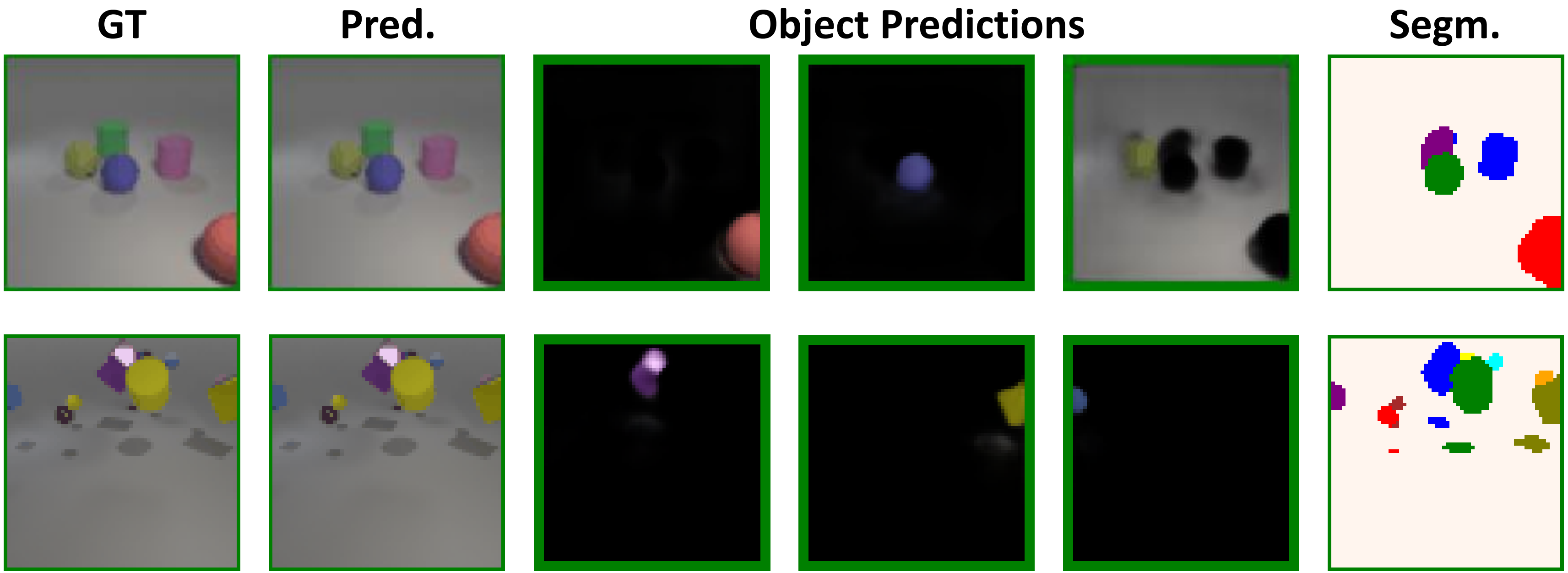
[Villar-Corrales et al. ICIP 2023]

Object-centric Video Prediction: MOVi-A



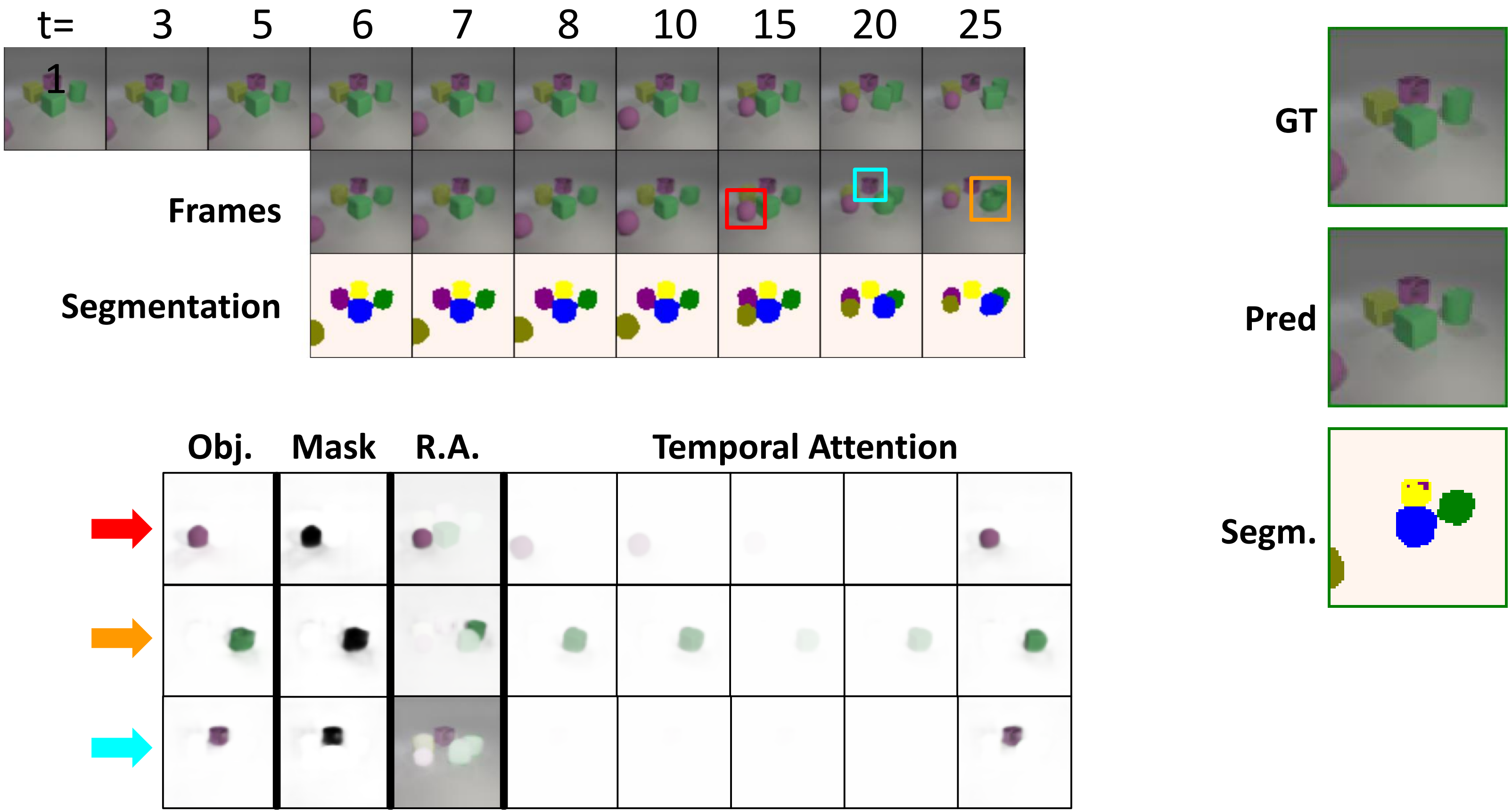
[Villar-Corrales et al. ICIP 2023]

Object-centric Video Prediction: Object Predictions



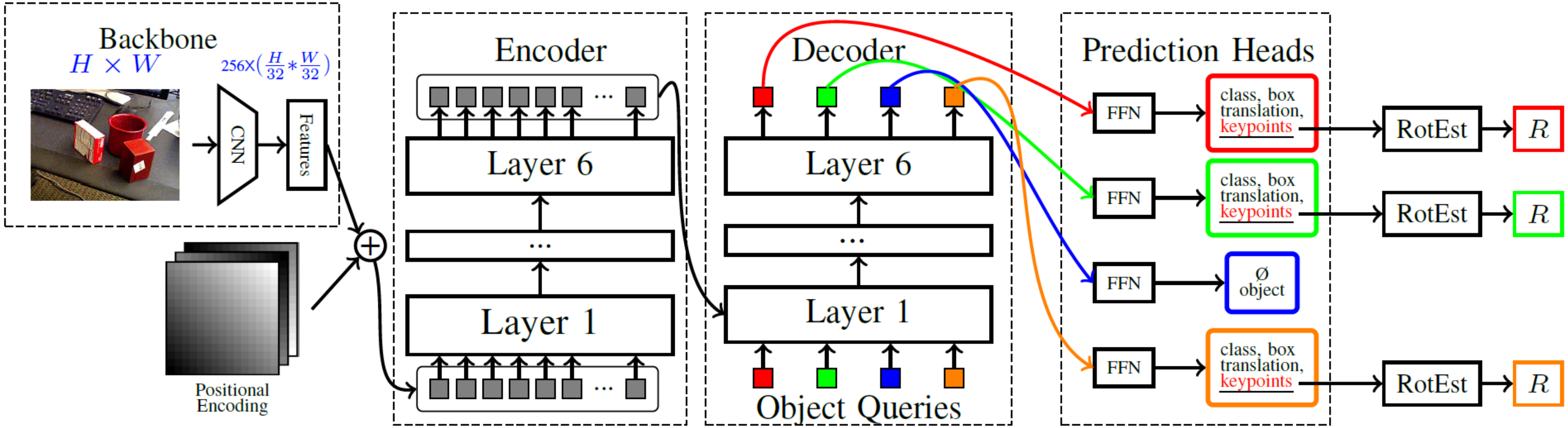
[Villar-Corrales et al. ICIP 2023]

Object-centric Video Prediction: Model Interpretability



[Villar-Corrales et al. ICIP 2023]

YOLOPose: Multi-Object 6D Pose Estimation using Keypoint Regression



[Amini et al. IAS 2022, Best Paper Award]

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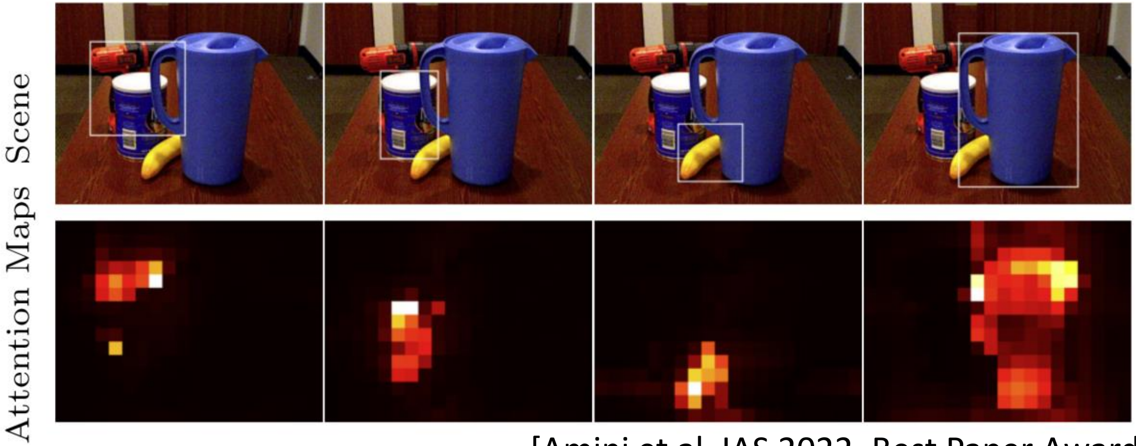
YOLOPose: Multi-Object 6D Pose Estimation using Keypoint Regression

- Encoder self-attention

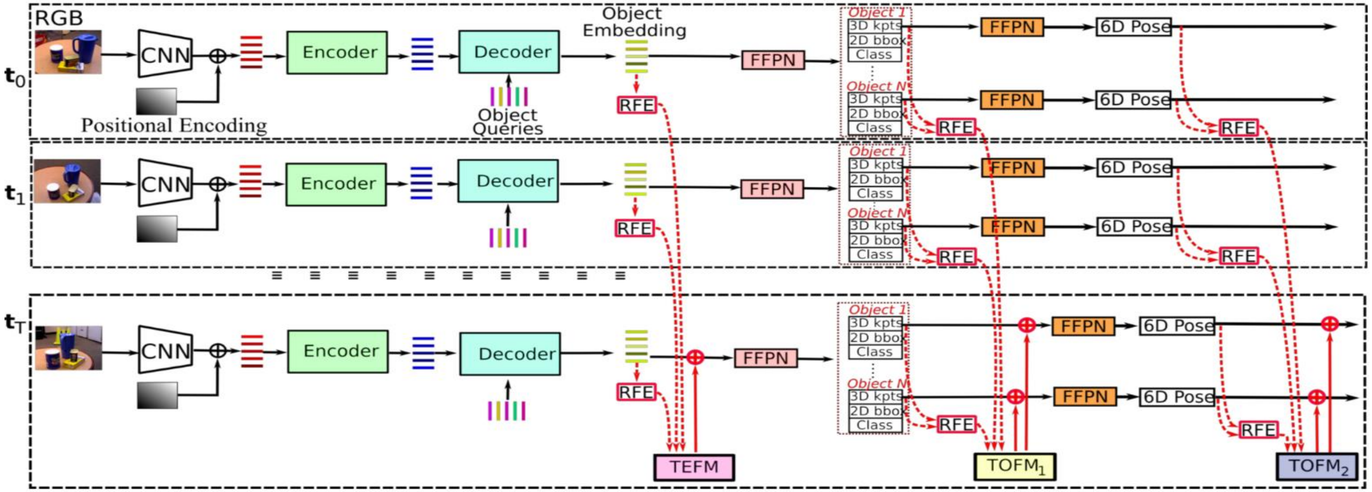
- Object detections and decoder cross-attention

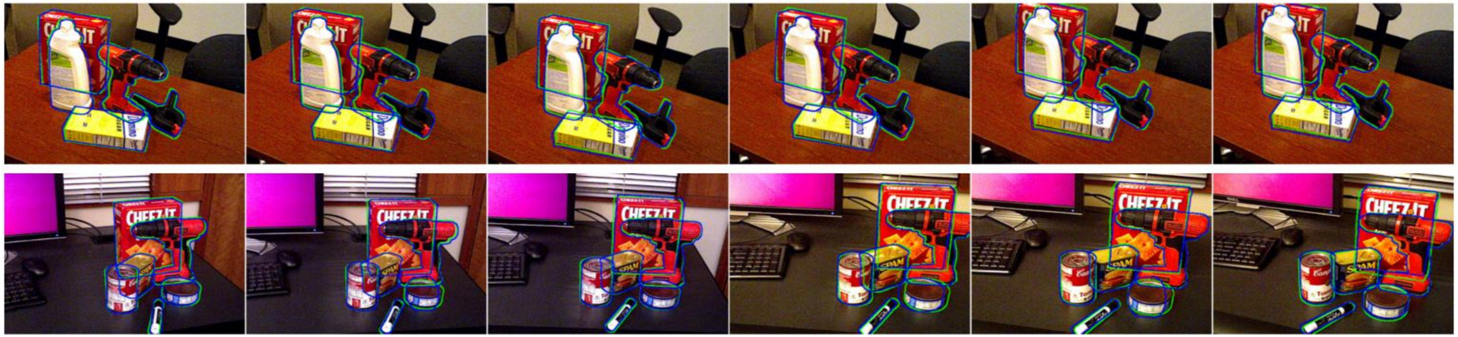


[Amini et al. IAS 2022, Best Paper Award]

MOTPose: Attention-based Temporal Fusion for Multi-object 6D Pose Estimation

- Propagating object embeddings, object descriptors, and poses

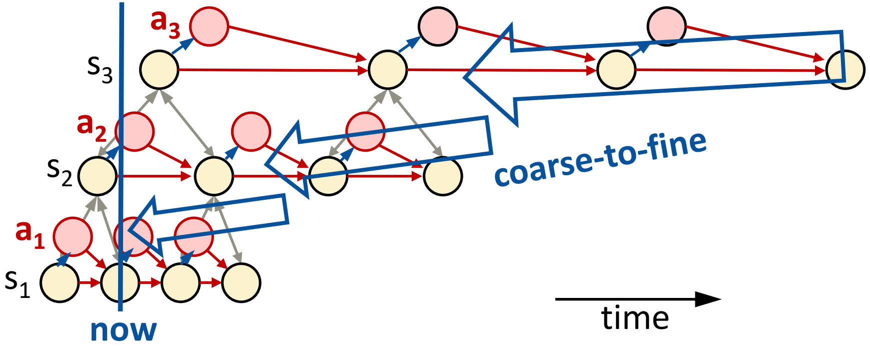




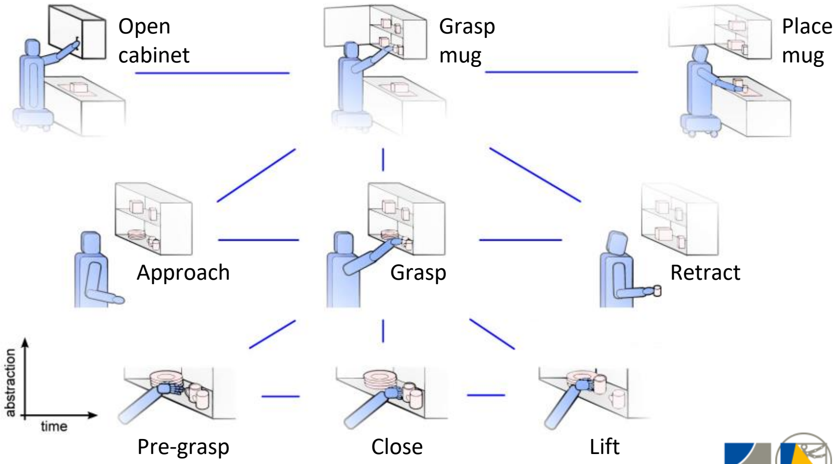
[Periyasamy, ICRA 2024]

Unconscious Prediction and Control

1. Learning action-conditioned prediction
2. Learning to control in the now
3. Learning reusable skills
4. Learning from imitation and real-robot experience

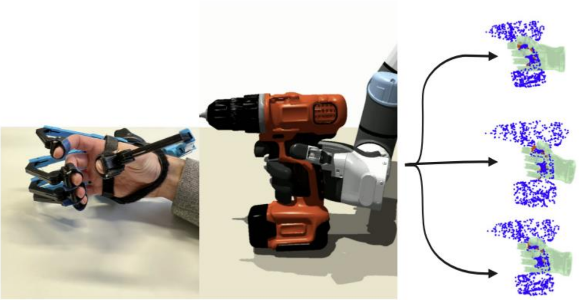


- **Action compositionality**
  - Activities consists of sequence of actions, which can be decomposed into movement primitives
- Exploiting inductive biases like hierarchical structure, object binding, planning in the now, …

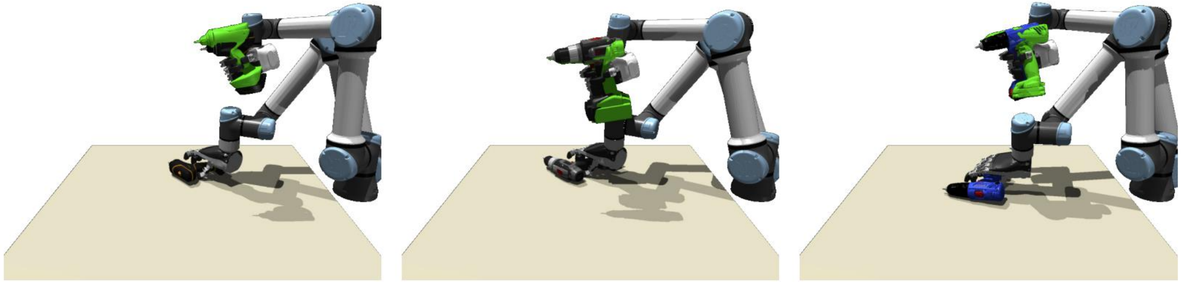


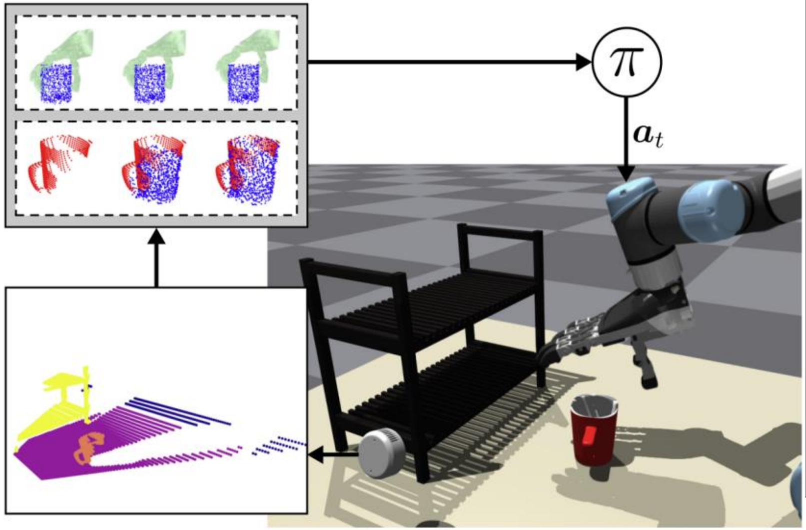
Learning Interactive Functional Grasping

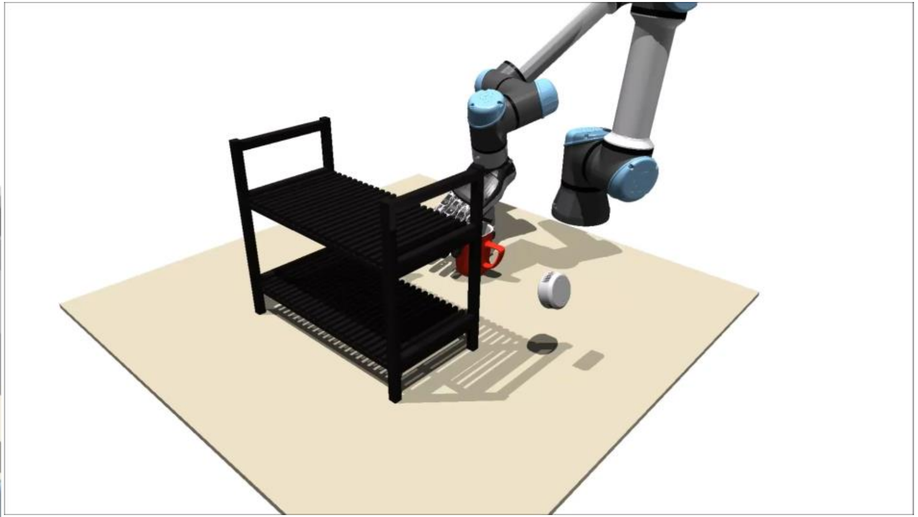
Generalization of a single demonstration



Interactive operation of unseen tools

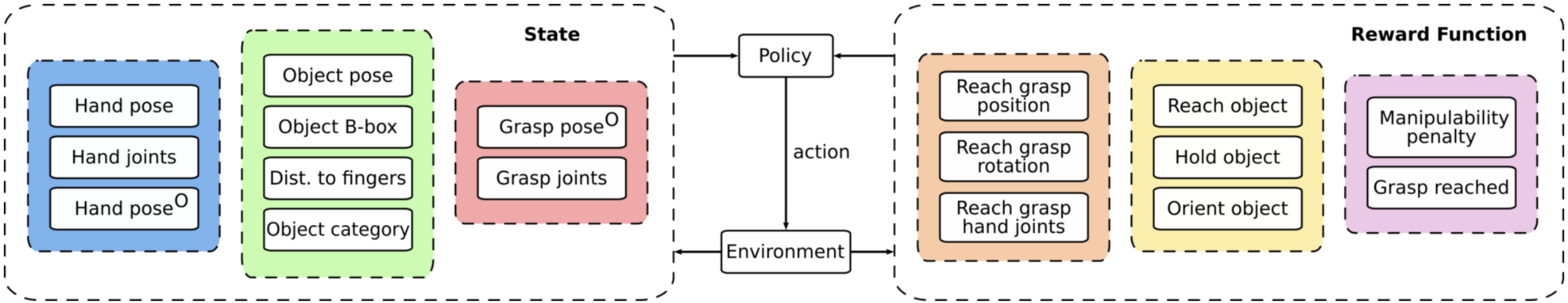




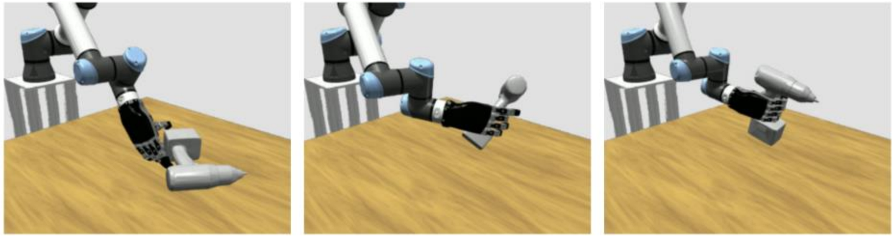


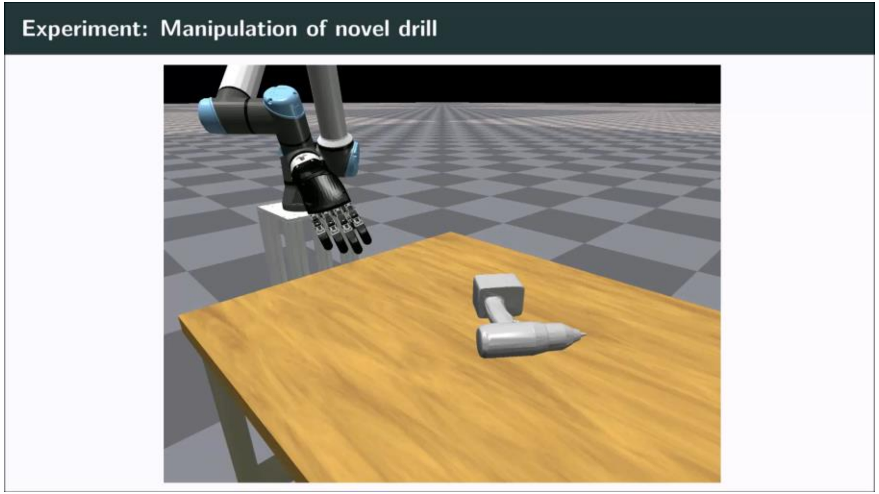
[Mosbach and Behnke CASE 2023, Best Paper Award]

Learning Pre-grasp Manipulation for Human-like Functional Grasping



- Dense multi-component reward function encodes desired functional grasp



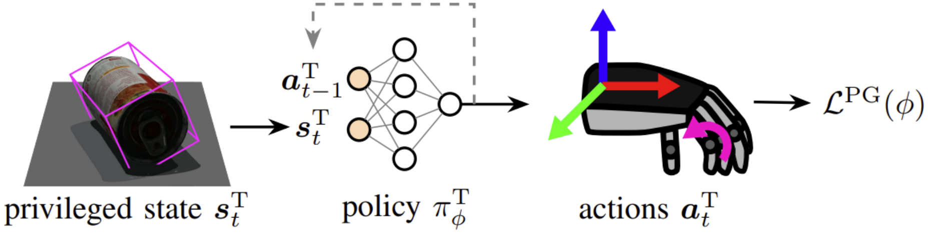


- Learns to reposition and reorient objects to achieve functional grasps

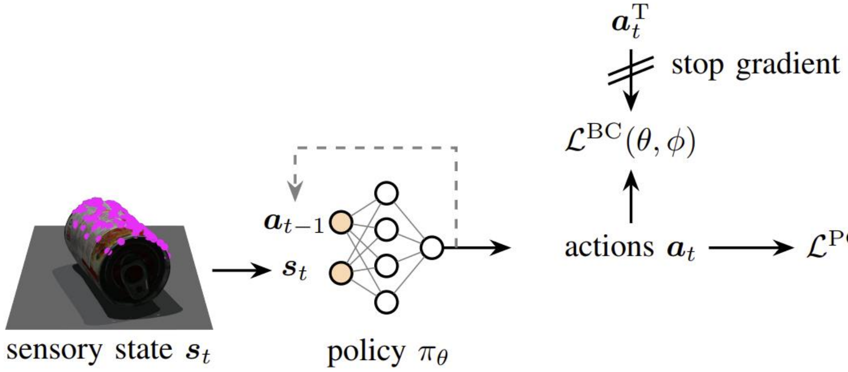
[Pavlichenko and Behnke CASE 2023]

Grasp Anything: Augmenting Reinforcement Learning with Instance Segmentation to Grasp Arbitrary Objects

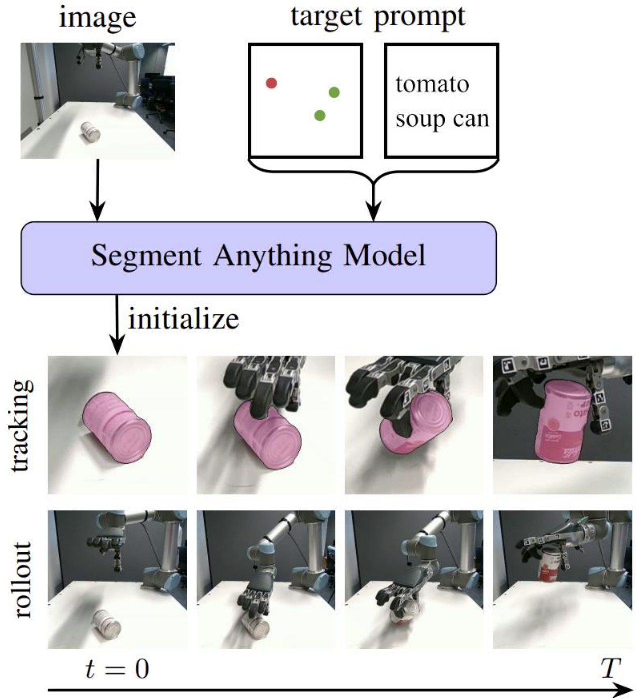
- Teacher training



- Teacher-guided sensorimotor learning



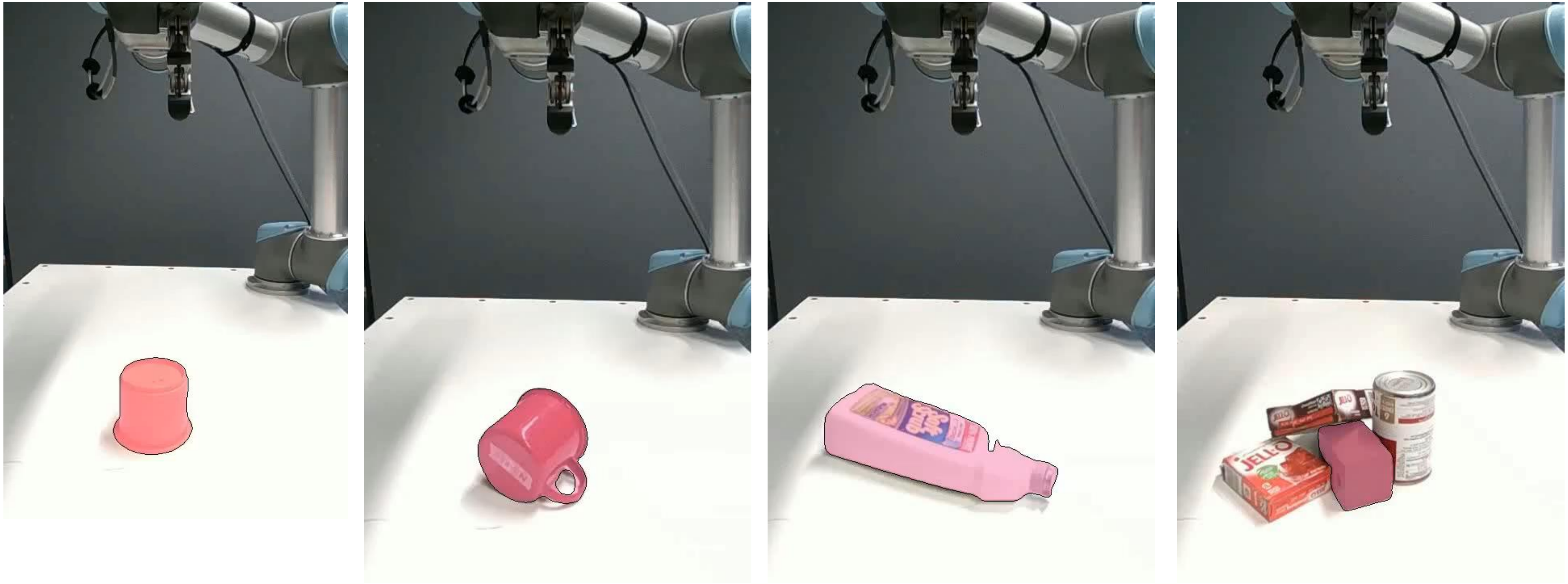
- Real-world deployment of promptable grasping policy



[Mosbach and Behnke ICRA 2024]

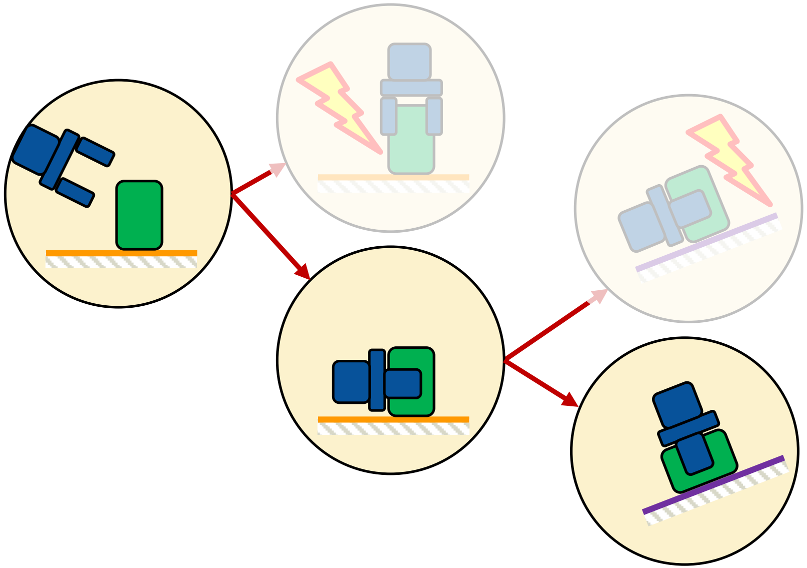
Grasp Anything: Augmenting Reinforcement Learning with Instance Segmentation to Grasp Arbitrary Objects

- Learned policy with improved object visibility is real-world deployable



[Mosbach and Behnke ICRA 2024]

Conscious Prediction and Planning

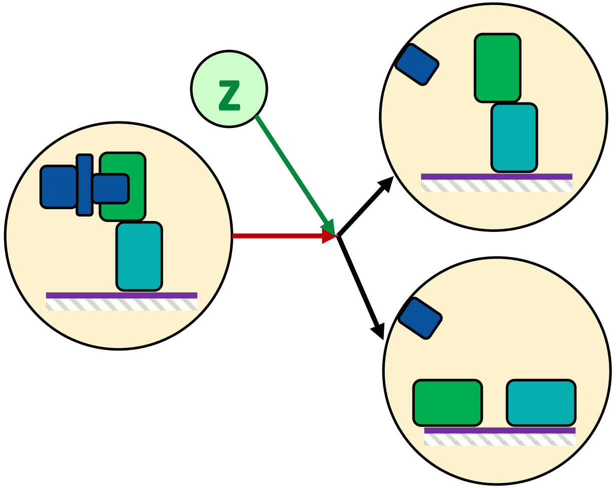


1. Learning a working memory
2. Learning working memory predictions
3. Learning conscious planning
4. Learning new conscious concepts

- **Systematic generalization**
  - Reuse task knowledge in infinitely many novel situations in which irrelevant items change
- Working memory as communication bottleneck
  - Focus on few items, ignore all others which are irrelevant for the task
  - Must combine multiple lower-level items to larger, composite items

Conscious Self-monitoring

1. Representing uncertainty
2. Predicting multiple plausible futures
3. Error detection and mitigation
4. Interactive learning



- **Self-aware**
  - Being aware of own capabilities and limitations, dangers, etc.
- Systematically model and use uncertainty
  - Collect more information when needed
  - Avoid dangerous situations
  - Detect System 1 errors and mitigate them

Potential Impact

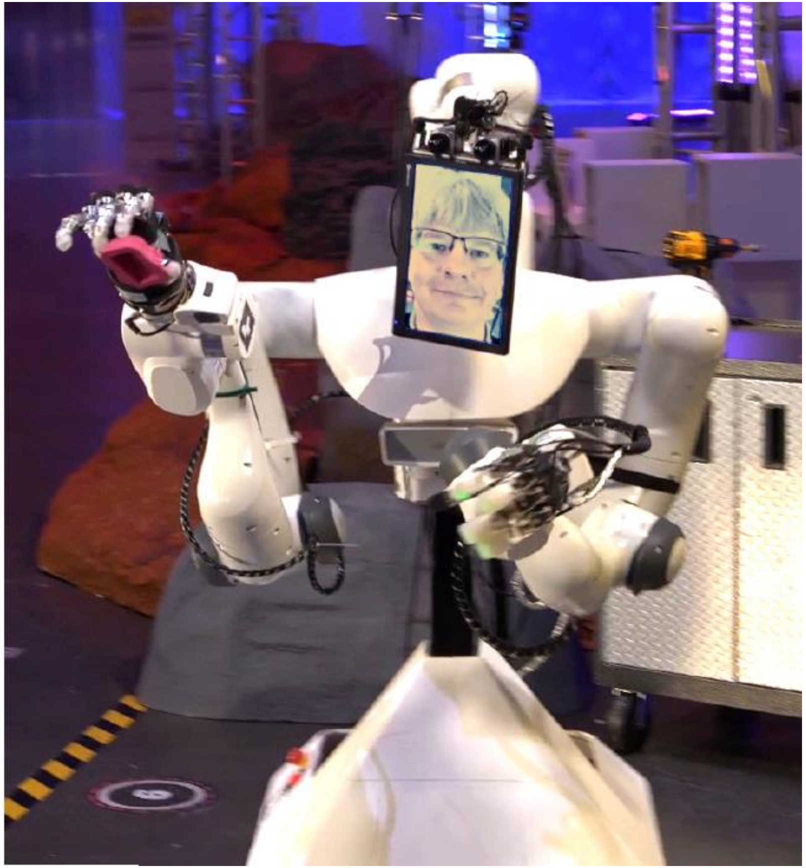
Consciousness is not a bug, but a feature!

©DALL·E 2

- Will bring service robots to the next level
  - **Systematically generalize** skills and cope with novel situations
  - **Self-monitor** perceptions and actions: obtain more information when needed, avoid risks, detect errors, and mitigate them
- Consciousness-inspired robots will have a high impact on economy and society since they will be **applicable to a large variety of open-ended domains**
- Will enable the creation of **personal service robots** which have the potential to change our society to the same degree personal and mobile computers changed it in the last decades

Conclusions

- The ANA Avatar XPRIZE competition advanced immersive telepresence systems
- Potential follow-up could raise the bar
  - Bandwidth restrictions and latencies
  - Locomotion on more difficult terrain
  - More complex manipulation (e.g., bimanual tasks)
  - Additional interaction modalities (e.g., temperature or smell)
  - Deeper interactions between avatars and recipients including interpretation of subtle communication cues and direct physical contact
- More autonomy is needed
- Need to match human cognitive functions
- Demonstrations can guide RL
- Consciousness needed for systematic generalization and self-monitoring



[XPRIZE]

Questions?