

The NimbRo Immersive Telepresence System Winning the ANA Avatar XPRIZE Finals: Human-Centric Evaluation and Lessons Learned

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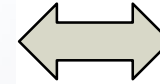
Telepresence Systems

- 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

Operator Station



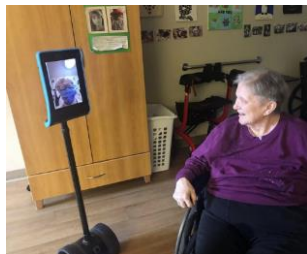
Avatar Robot



[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]



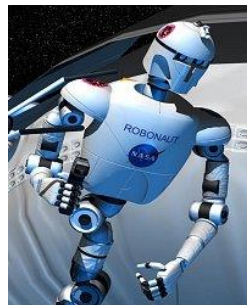
[Pollen Reachy]



[Telexistence]



[KAIST DRC Hubo]



[NASA Robonaut]



[Stanford OceanOneK]



[Fetch]

Experience with Teleoperated Robots

- Multiple domains
- Often motivated by competitions and challenges



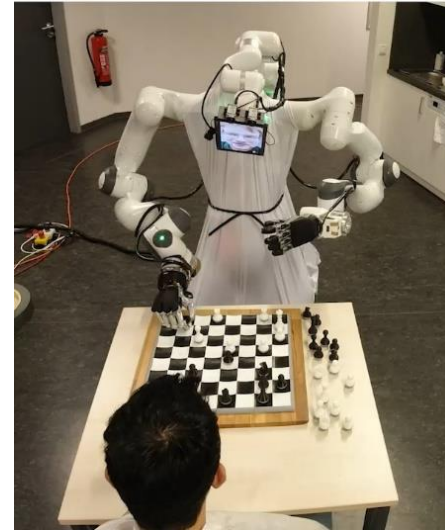
RoboCup@Home



DARPA Robotics Challenge
DLR SpaceBot Cup



CENTAURO



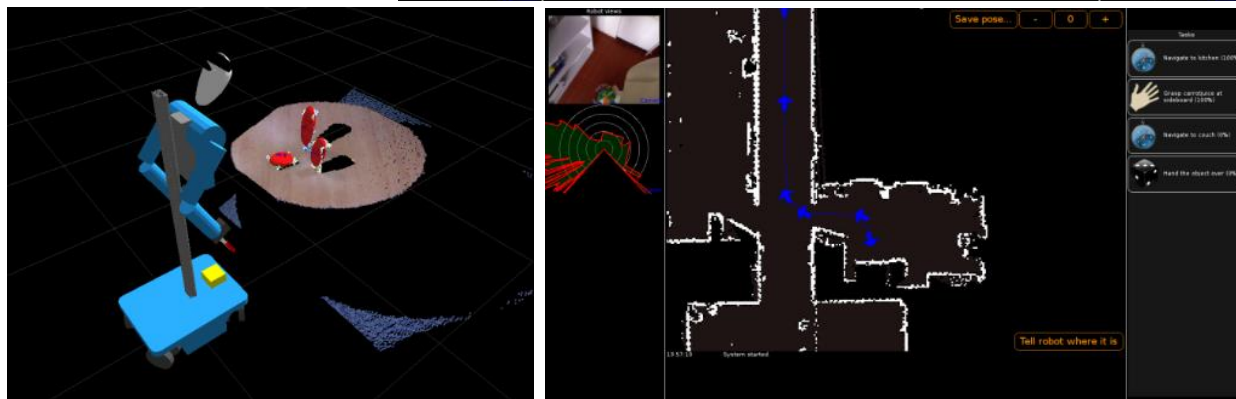
ANA Avatar XPRIZE

Cognitive Service Robot Cosero



Handheld Teleoperation Interface

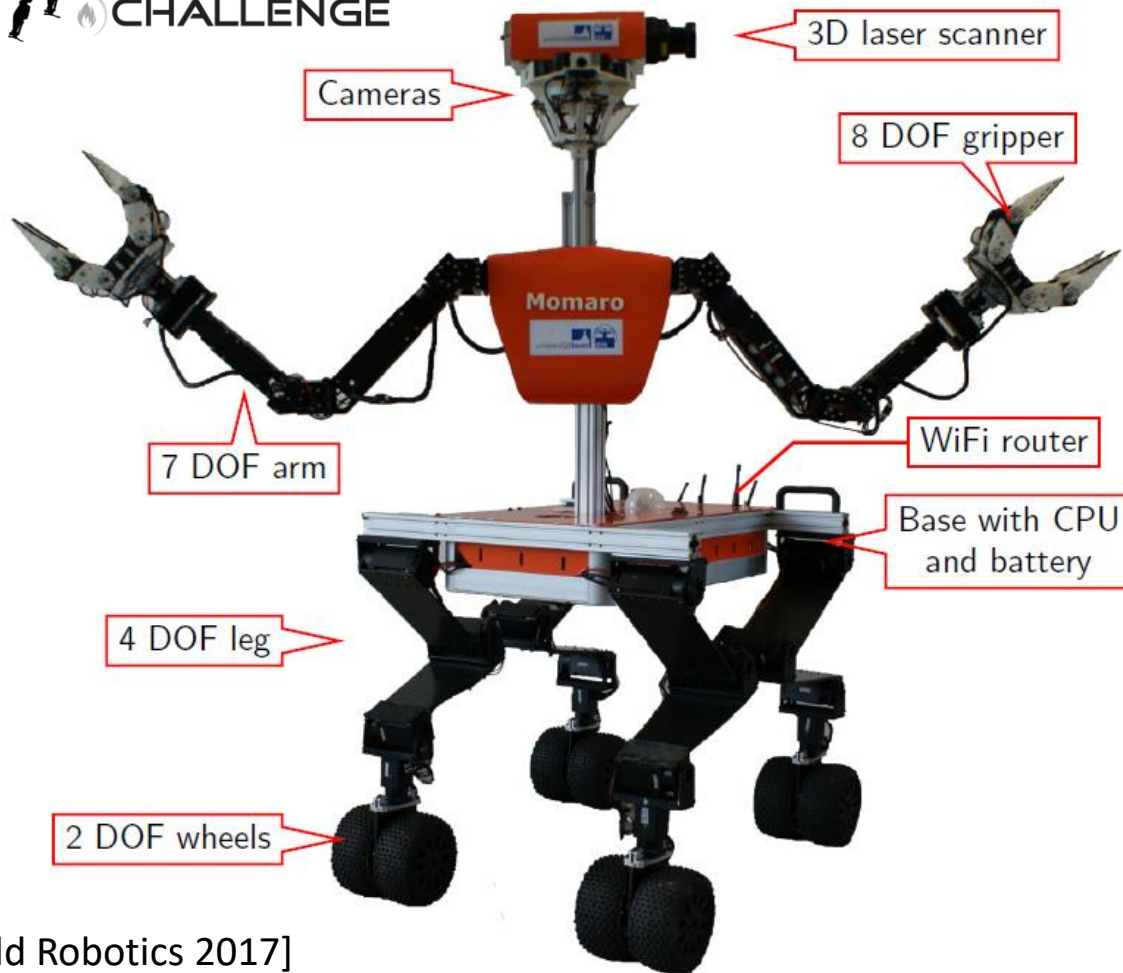
- Three levels of autonomy/control:
 - Task level: Get me a beer!
 - Skill level: Grasp, place, navigate, ...
 - Direct control: Locomotion, manip.



Mobile Manipulation Robot Momaro

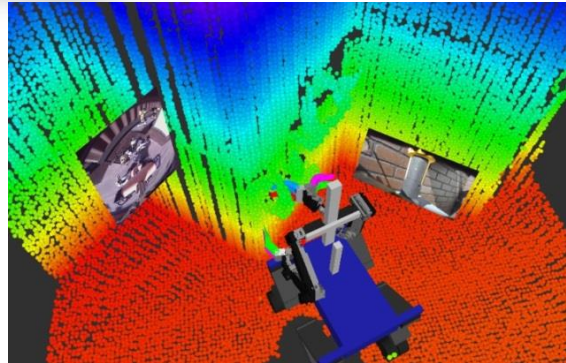


- Four compliant legs ending in pairs of steerable wheels
- Anthropomorphic upper body
- Sensor head
 - 3D laser scanner
 - IMU, cameras



Manipulation Operator Interface

- 3D head-mounted display
- 3D environment model + images
- 6D magnetic tracker



[Rodehutsors et al., Humanoids 2015]

DARPA Robotics Challenge



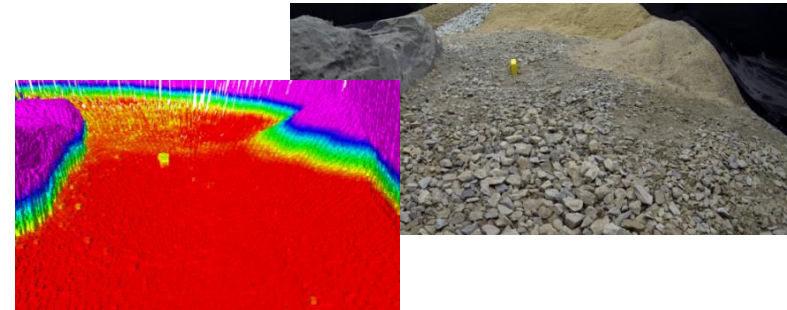
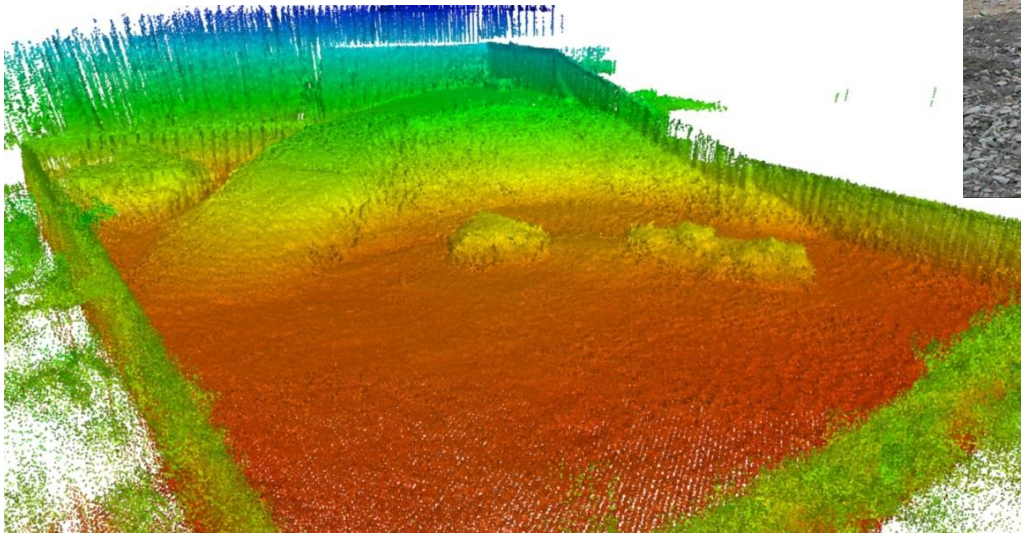
Team NimbRo Rescue



Best European Team (4th place overall),
solved seven of eight tasks in 34 minutes

DLR SpaceBot Cup 2015

- Mobile manipulation in rough terrain





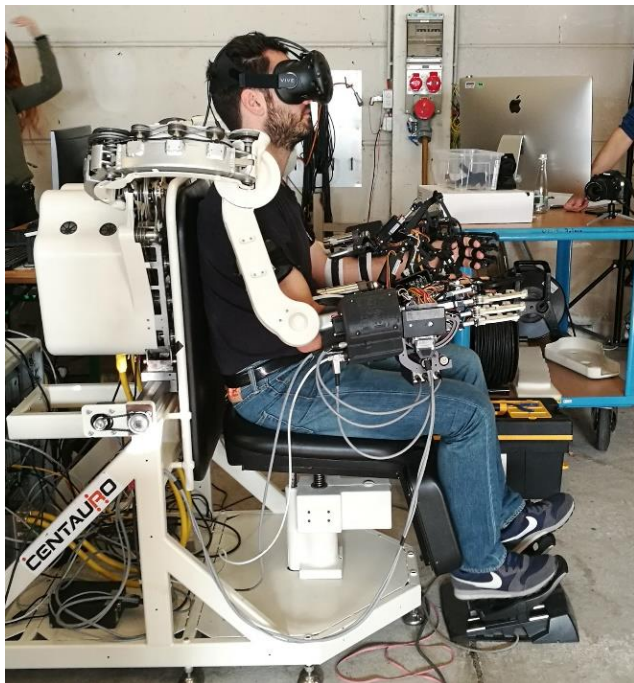
8X

[Schwarz et al., Frontiers on Robotics and AI 2016]

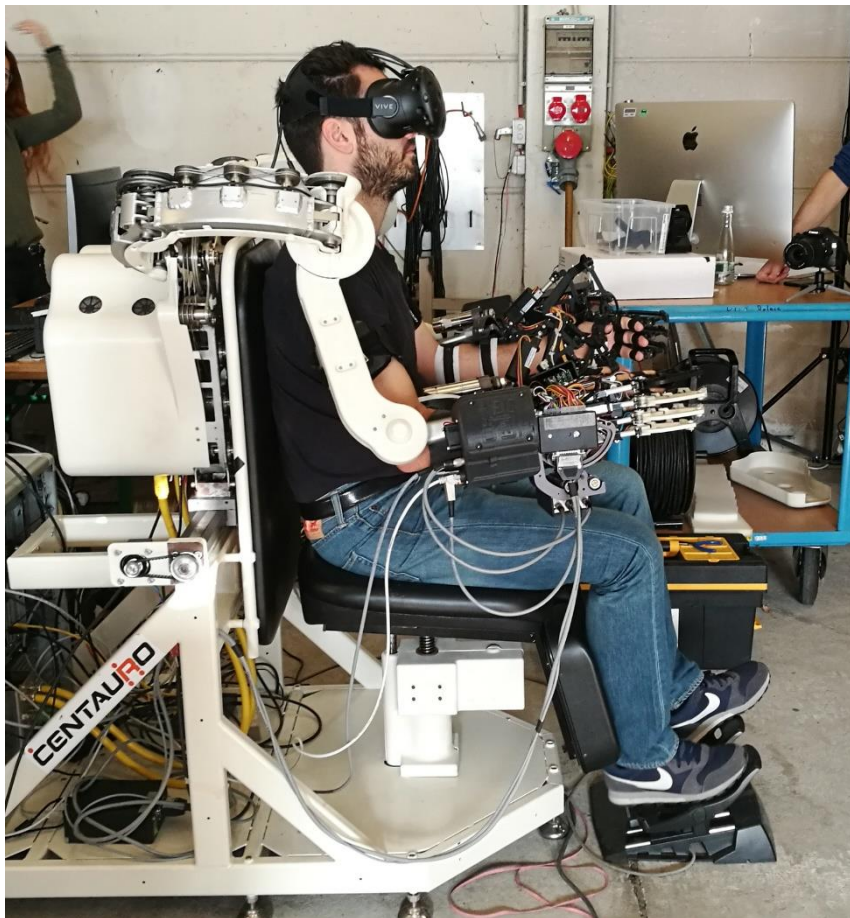
Robust Mobility and Dexterous Manipulation in Disaster Response by Fullbody Telepresence in a Centaur-like Robot

CENTAURRO

- Four-legged robot with steerable wheels and anthropomorphic upper body
- Immersive teleoperation through exoskeleton with HMD



Immersive Operator Interface



Stereo Visual and Audio Feedback

- Head-Mounted Display
- Audio Headset

Arm-Hand Movements

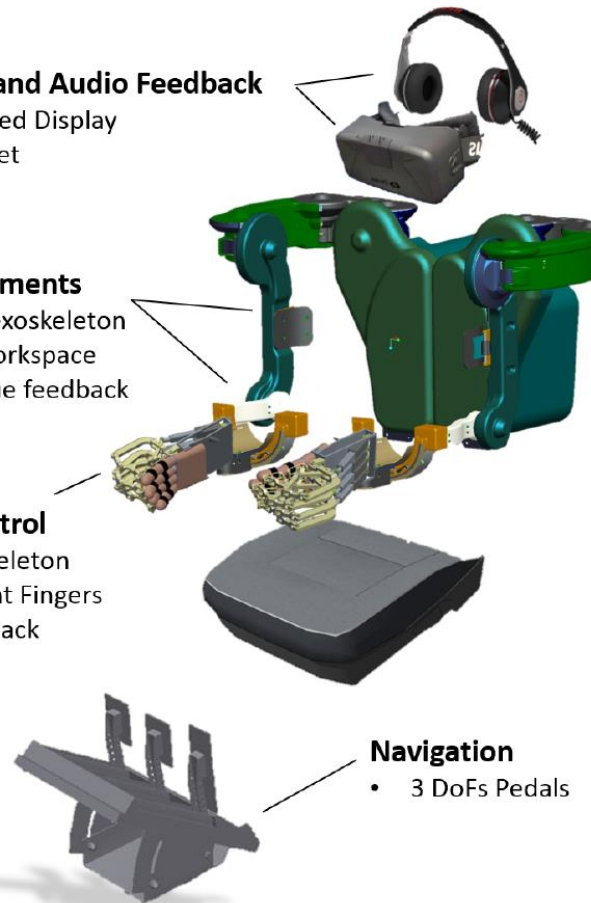
- Arm and wrist exoskeleton
- 7 DoFs, wide workspace
- Force and torque feedback

Grasping Control

- Hand exoskeleton
- Independent Fingers
- Force feedback

Navigation

- 3 DoFs Pedals



Teleoperation with Joystick and Spacemouse

3D VEROSIM
visualization

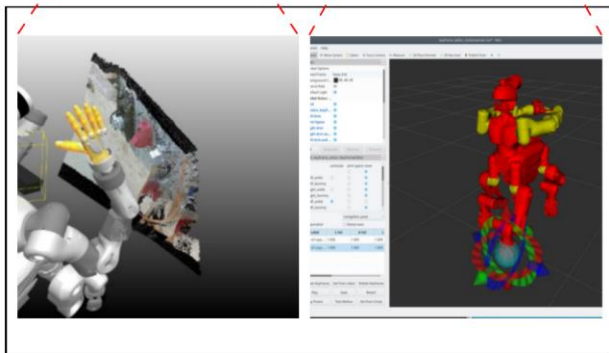
Robot state &
Keyframe editor

Foot
cameras

Panoramic view &
RGB Kinect image

Task specific
GUI

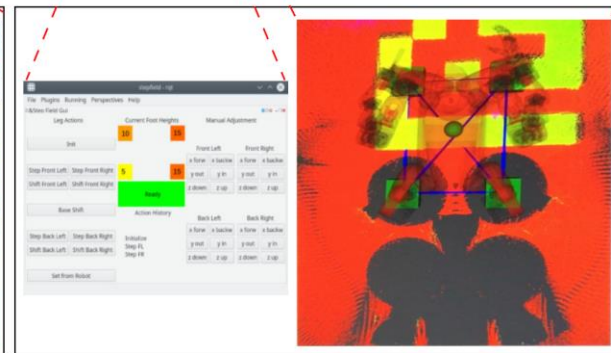
Pointcloud, ground
contact & COM markers



Monitor 1



Monitor 2



Monitor 3

- Flexible user interfaces for locomotion and manipulation tasks
- 3D situation awareness
- Motion editor



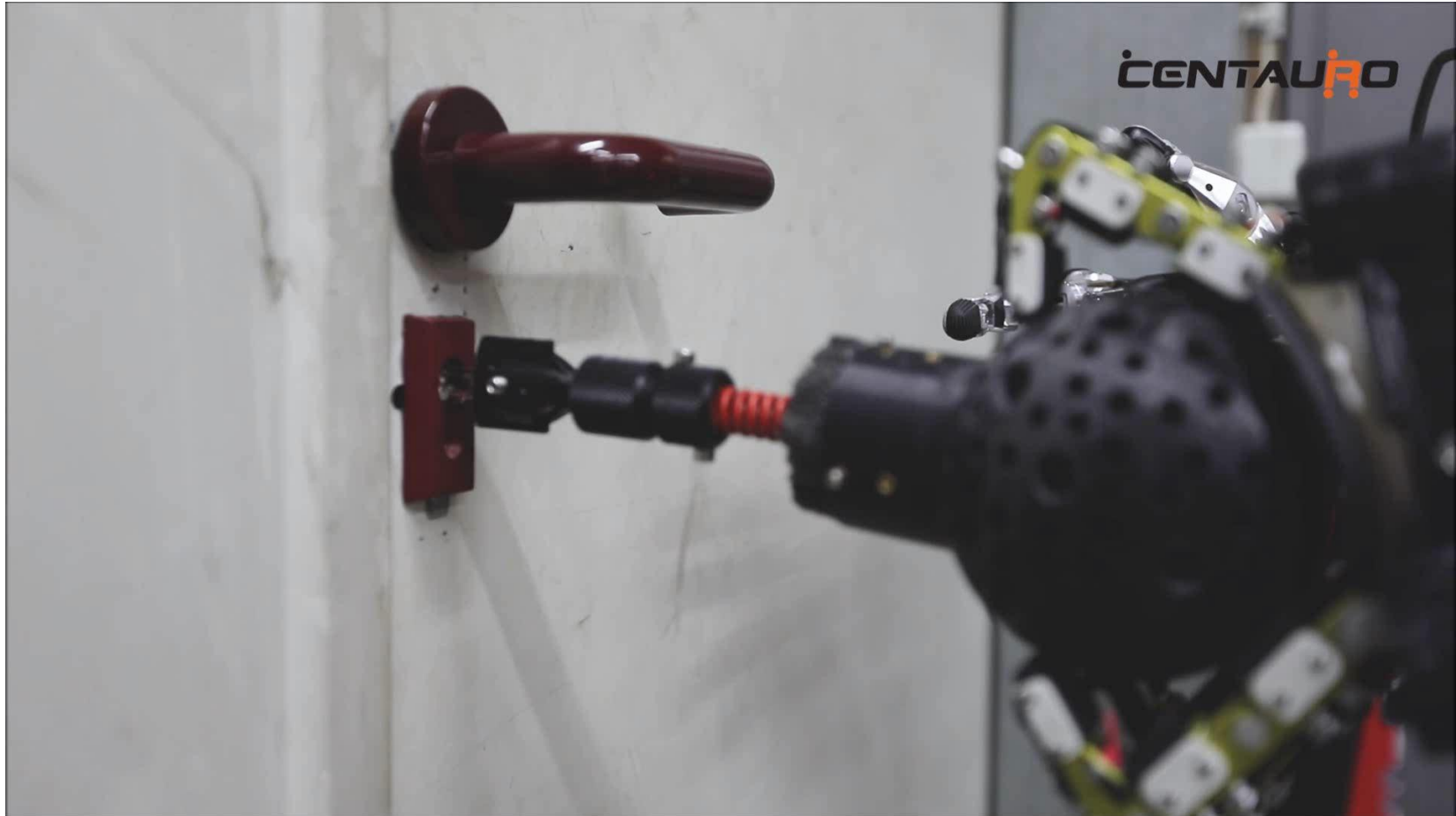
CENTAURO Evaluation @ KHG: Locomotion Tasks



Grasping an Unknown Power Drill and Fastening Screws



CENTAURO: Complex Manipulation Tasks



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

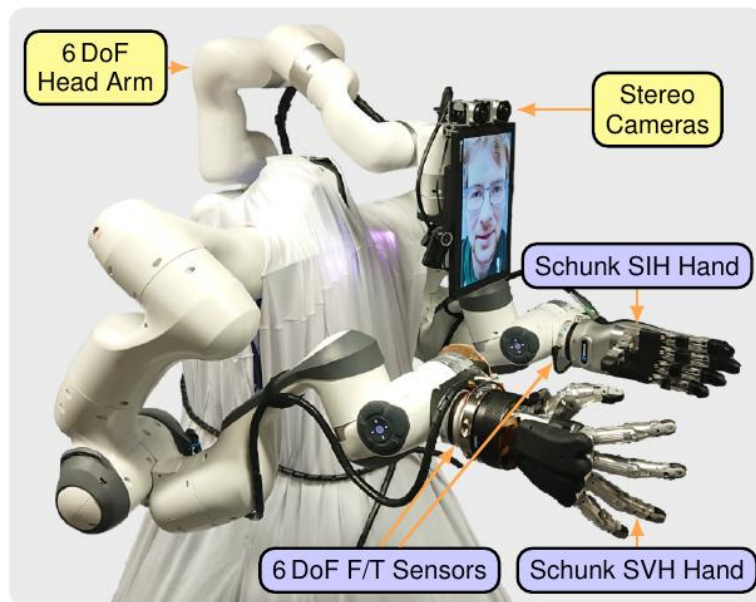
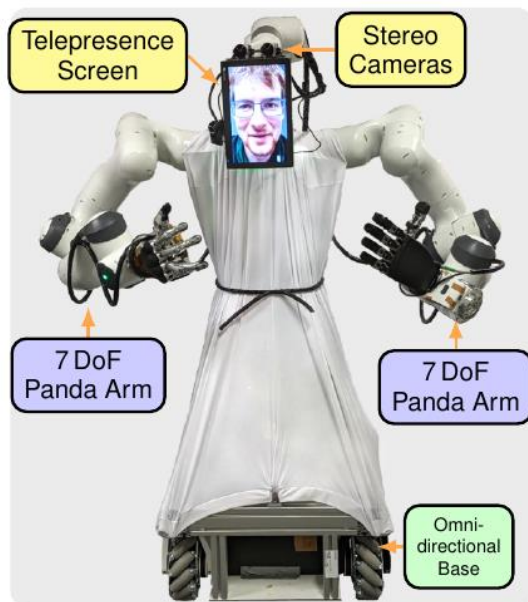


[XPRIZE]

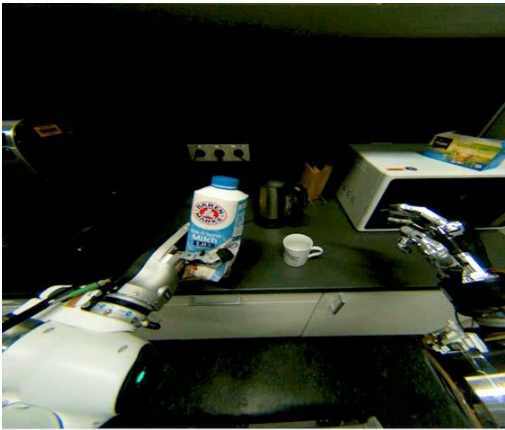
- Required mobility, manipulation, human-human interaction
- Focused on the **immersion** in the remote environment and the **presence** of the remote operator



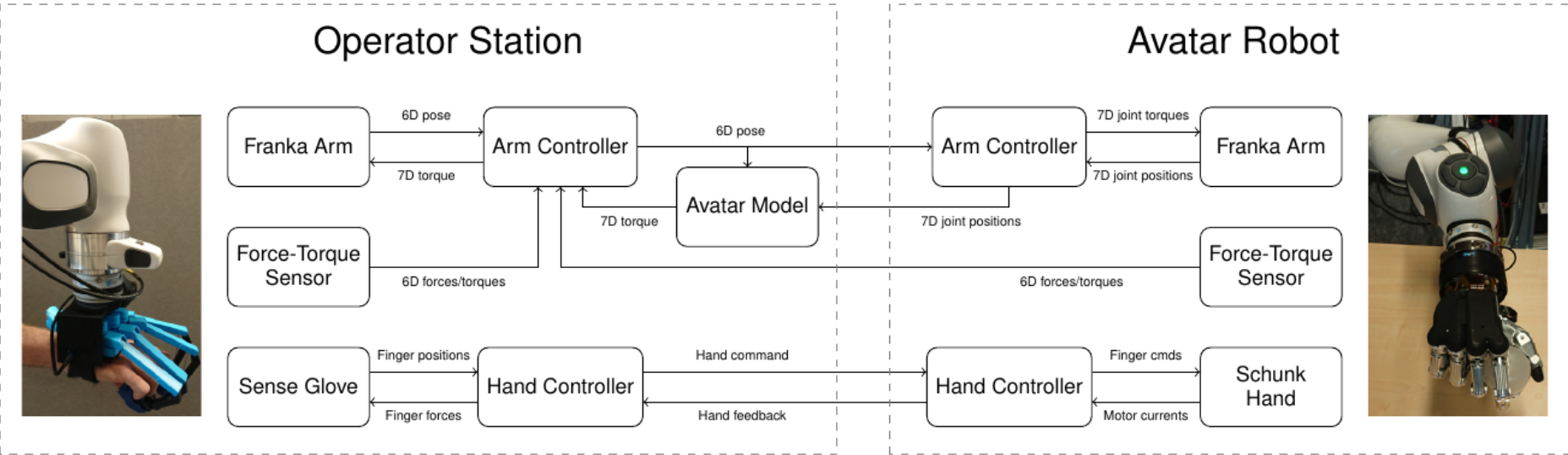
- Two-armed avatar robot designed for teleoperation with immersive visualization & force feedback
- Operator station with HMD, exoskeleton and locomotion interface



Team NimbRo Semifinal Submission



Manipulation with Force and Haptic Feedback



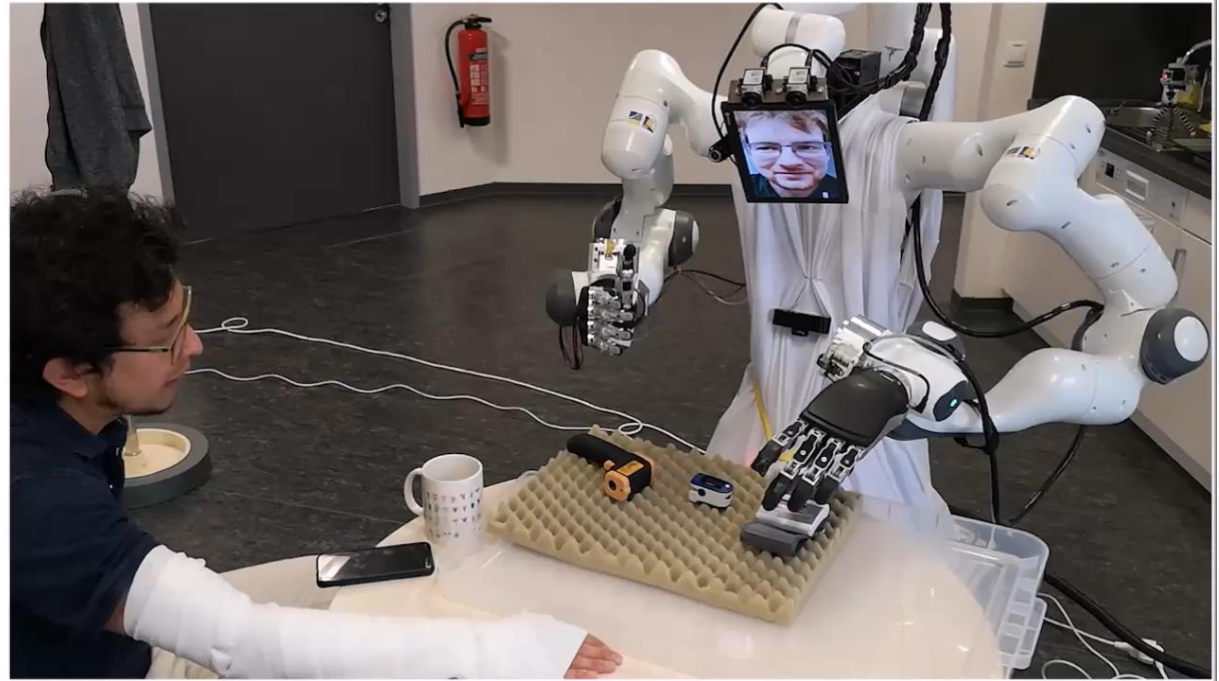
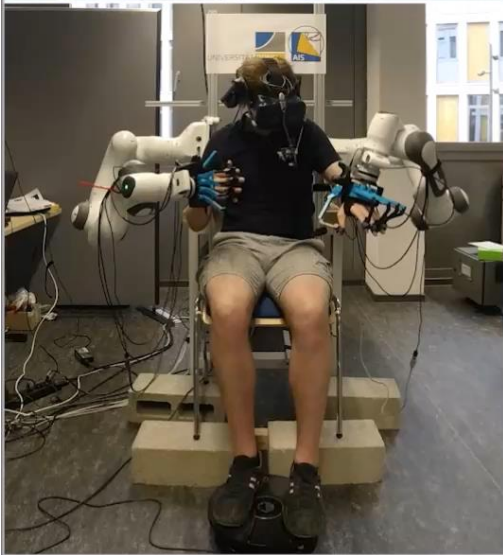
- Arm exoskeleton (Franka Emika Panda), F/T sensor (Nordbo + OnRobot HEX), hand exoskeleton (SenseGlove)
- Avatar side: Arm + F/T sensor + Schunk SVH / SH hand
- Provides force feedback for wrist and haptic feedback for fingers
- Avatar limit avoidance using predictive model to reduce latencies

Team NimbRo

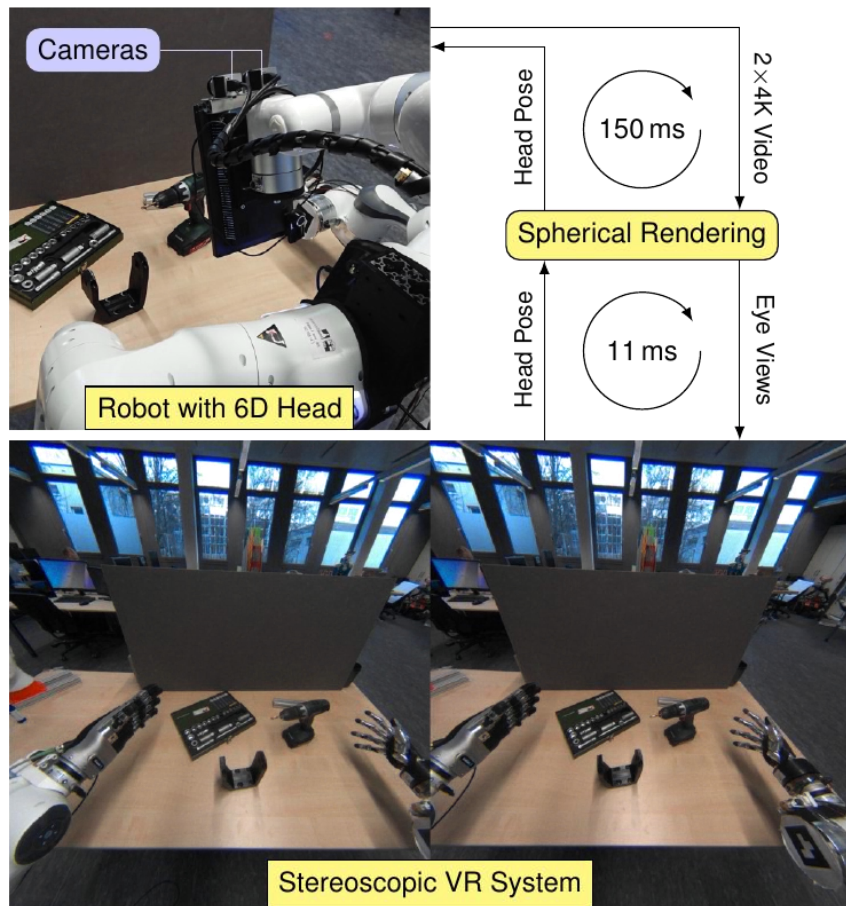
Semifinal Team Video

Tasks

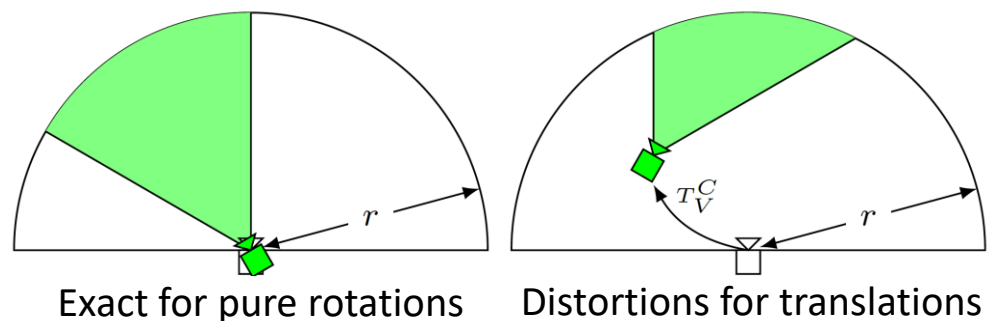
1. Make a coffee
2. Greet the recipient
3. Measure temperature
4. Measure blood pressure
5. Measure oxygen saturation
6. Help recipient with jacket



NimbRo Avatar: Immersive Visualization

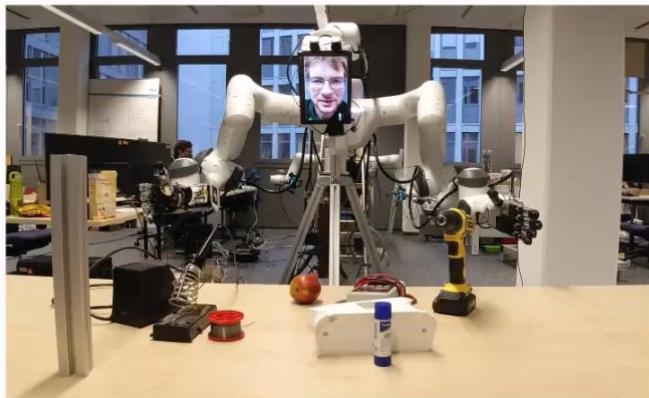


- 4K wide-angle stereo video stream
- 6D neck allows full head movement
 - Very immersive
 - Good hand-eye coordination
- **Spherical rendering** technique hides movement latencies
 - Assumes constant depth

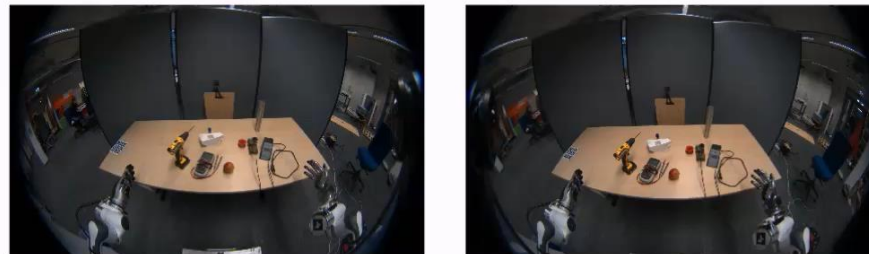


NimbRo Avatar: Immersive Visualization

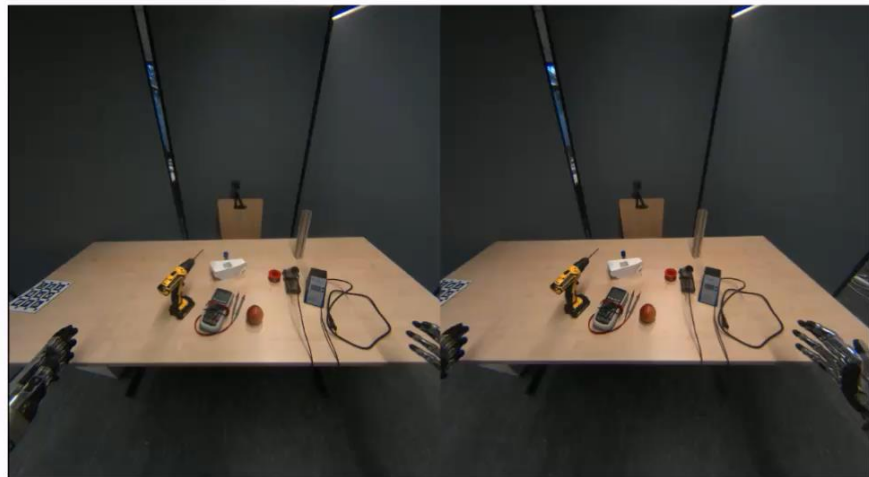
Avatar Robot



Wide-Angle Stereo



HMD View



Operator



NimRo 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



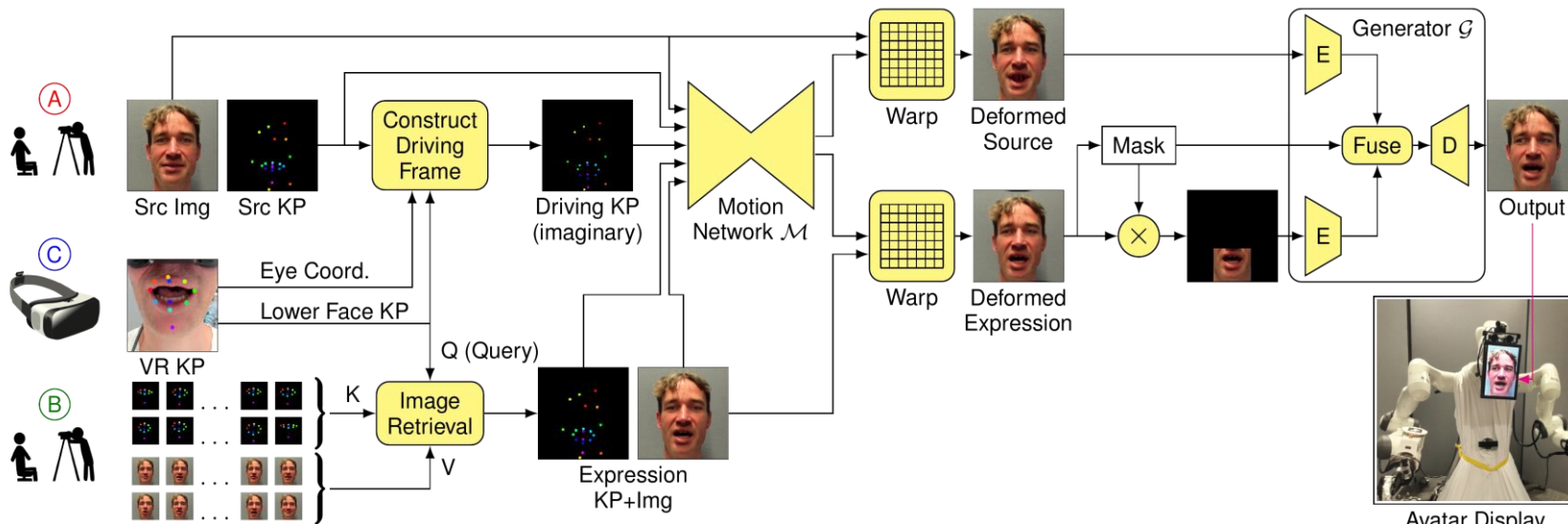
Left Eye



Mouth



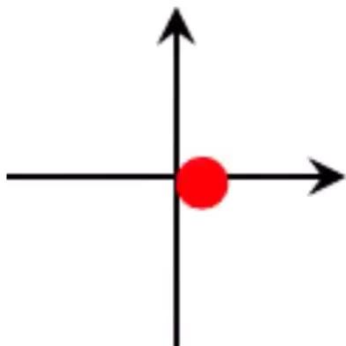
Right Eye



[Rochow et al. IROS 2022]

NimbRo Avatar: Operator Face Animation

Gaze
Direction



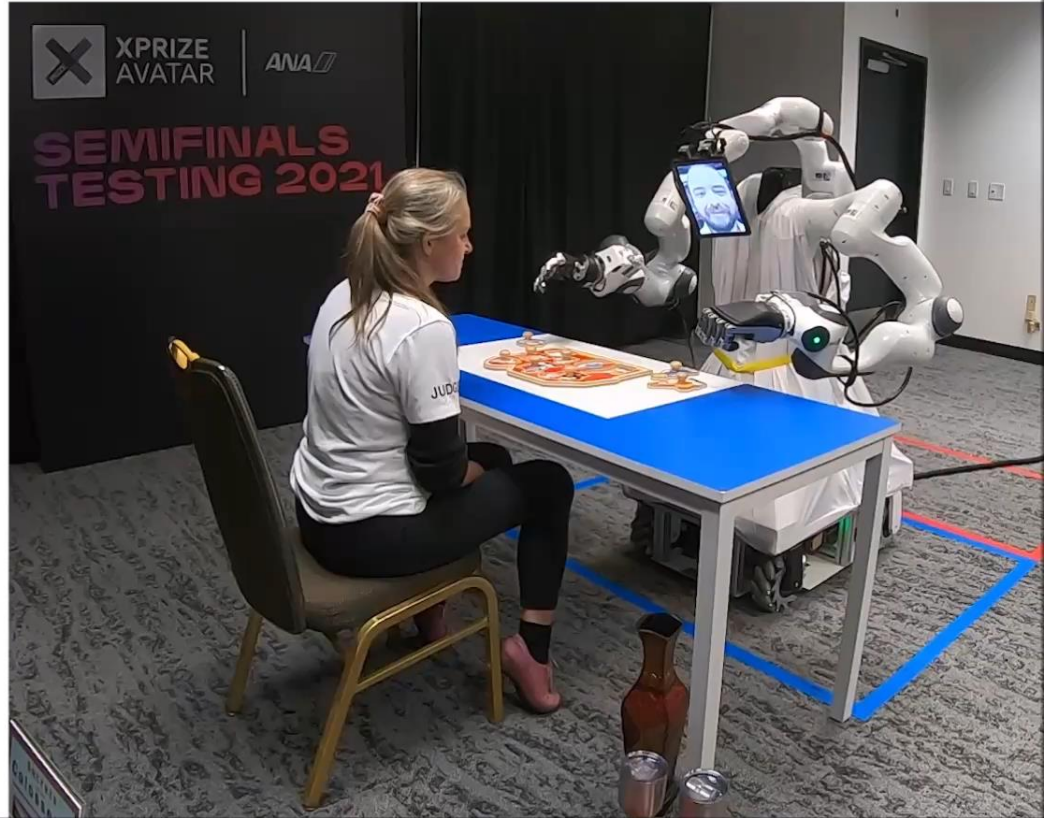
Output

Mouth Cam



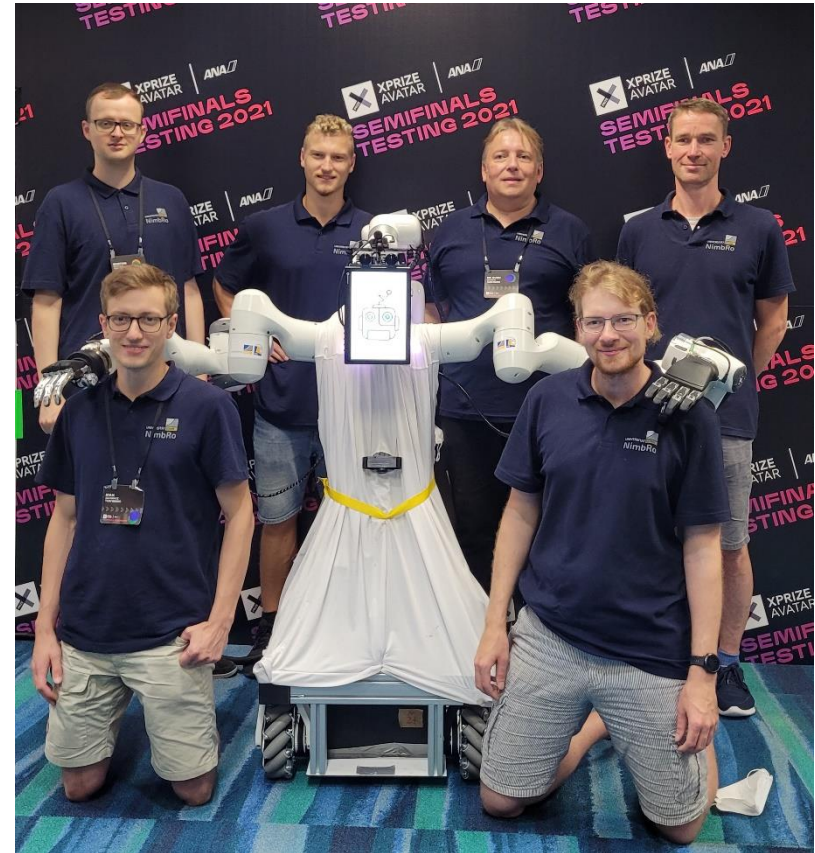
NimbRo Avatar

Avatar XPRIZE Semifinals



Semifinals Conclusions

- 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



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



Inbioidroid Avatar-Hubo AvaDynamics SNU UNIST AlterEgo iCub i-Botics Cyberselves Tangible NimRo AVATRINA Northeastern Pollen Janus Last Mile Dragon Tree Labs

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



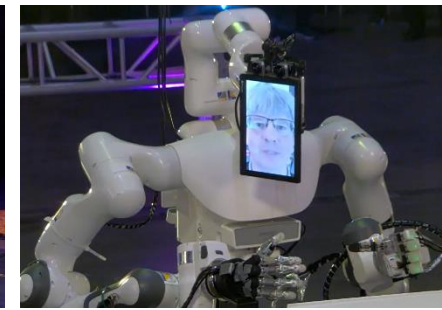
Start



1. Move



2. Introduce



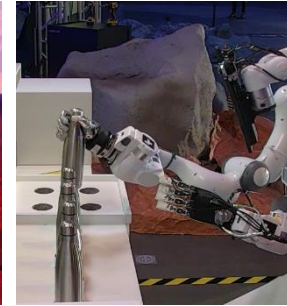
3. Confirm mission



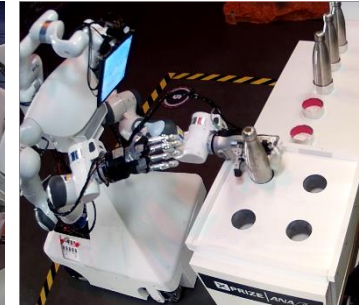
4. Activate switch



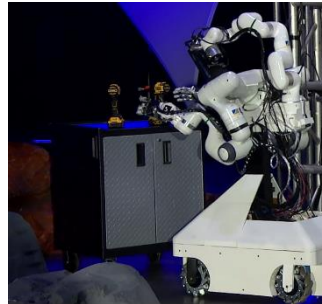
5: Travel planet



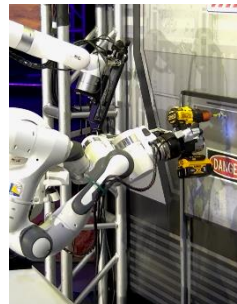
6. Identify full canister



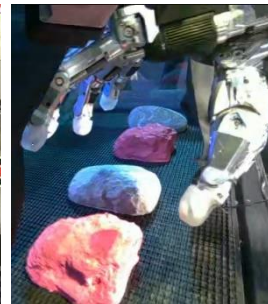
7: Place it



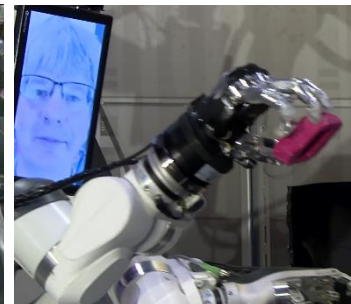
8. Narrow pathway



9: Use drill



10. Feel texture



Finish

[XPRIZE]

Finals Judged Scoring

■ Operator Experience (3 points)

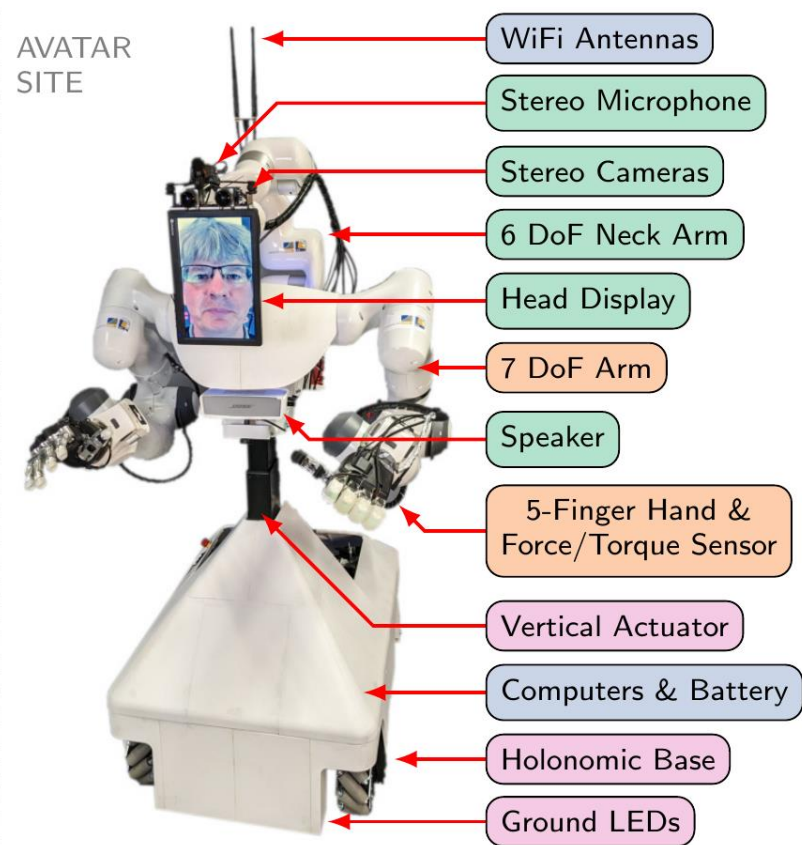
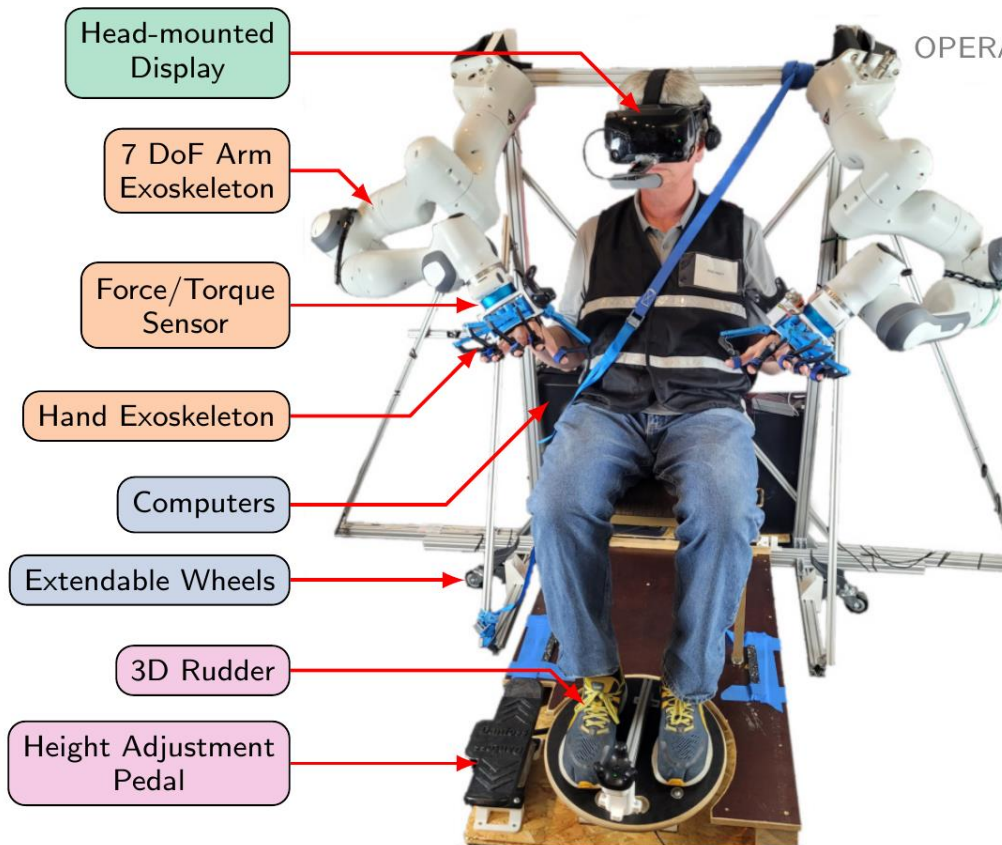
- The avatar system enabled the operator judge to **feel present** in the remote space and conveyed appropriate sensory information.
- The avatar system enabled the operator judge to **clearly understand** (both see and hear) the recipient.
- The avatar system was **easy and comfortable** to use.

■ 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.



NimbRo Avatar Finals System

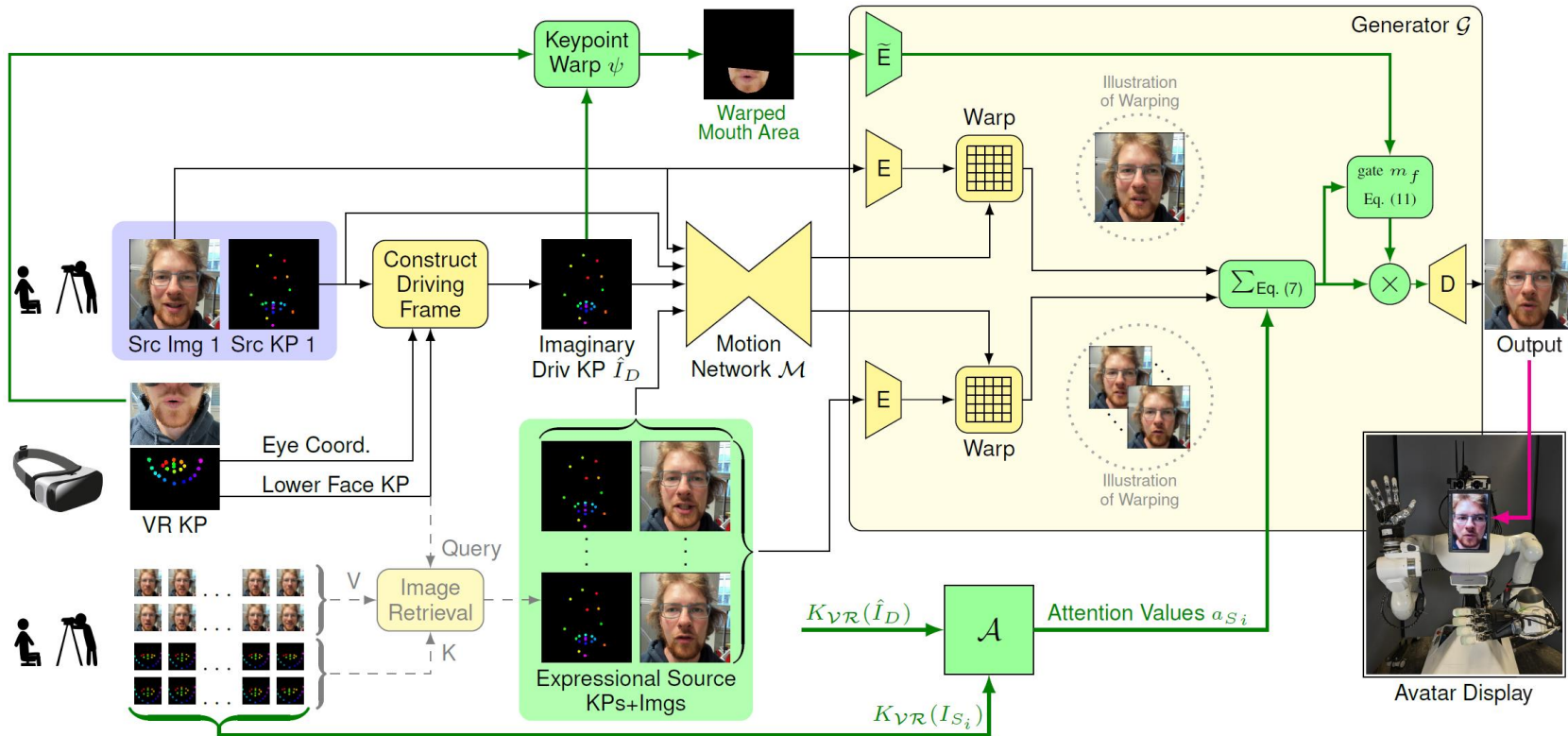


Finals Test Run Day 1



Improved Operator Face Animation

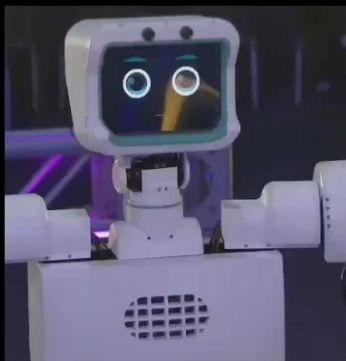
- Direct incorporation of mouth video
- Better temporal continuity



[Rochow et al. IROS 2023]

Face Animation @ Finals

Team UNIST



Ours (NimbRo)



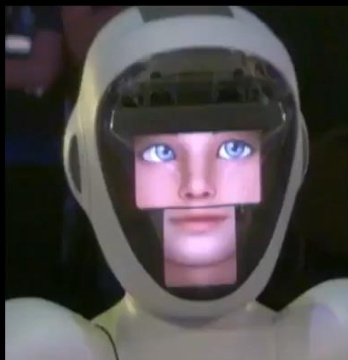
Team AVATRINA [13]



Source: Official XPRIZE Avatar live stream



Northeastern [12]



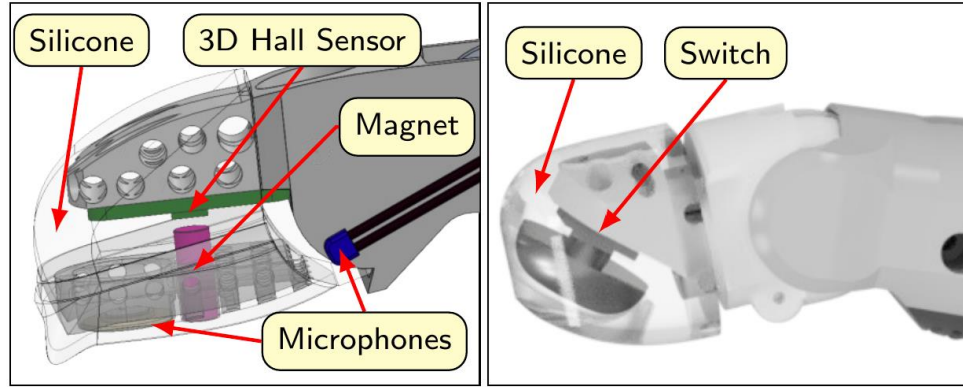
i-BOTICS



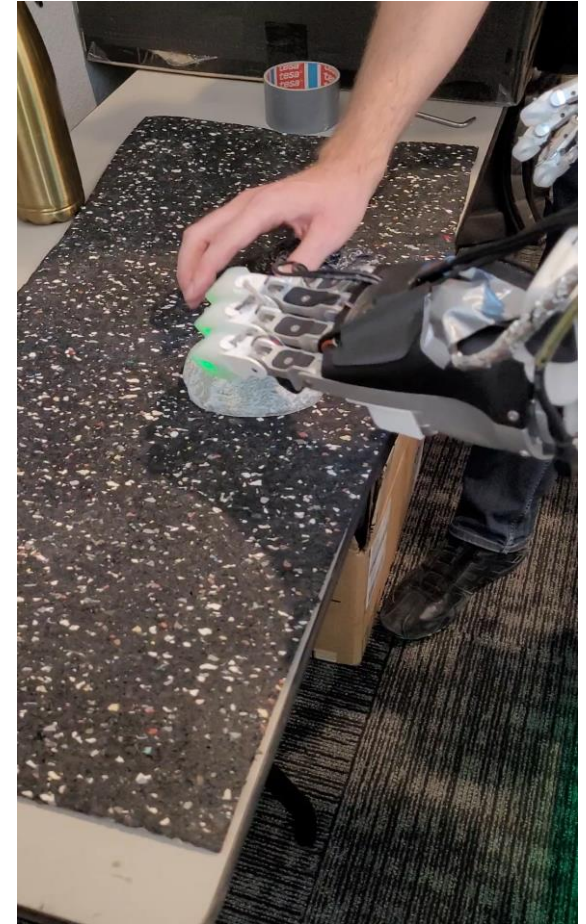
Pollen Robotics

Haptic Perception

■ Sensors in the finger tips

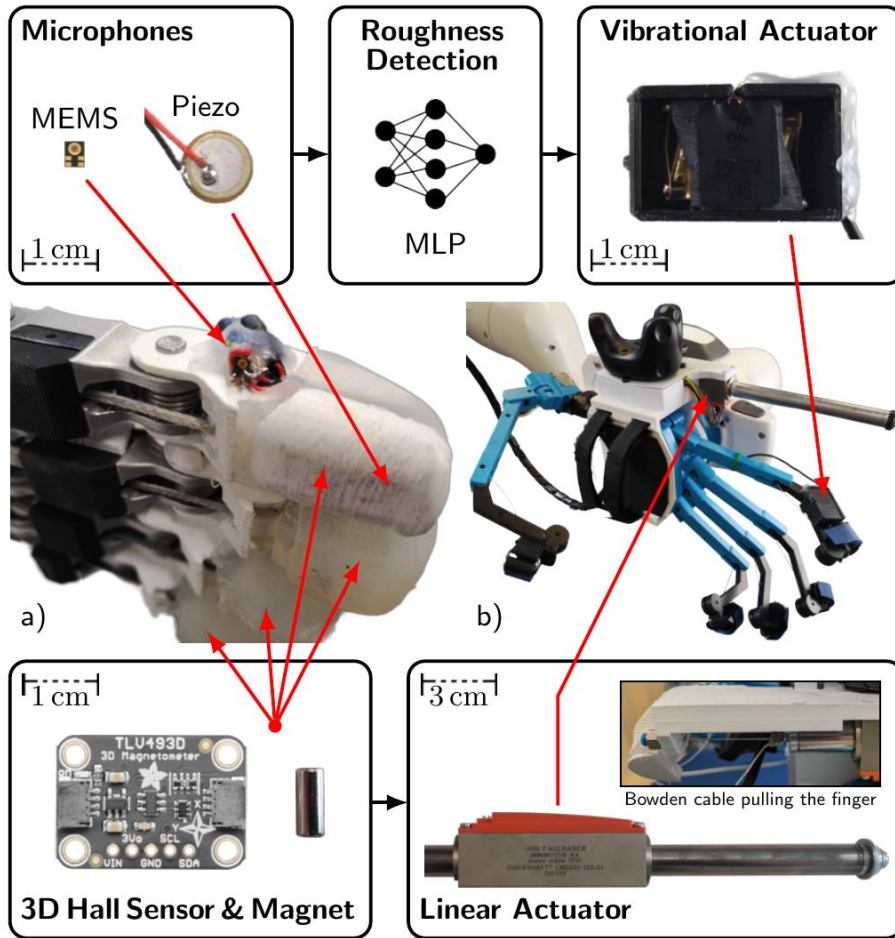


■ Actuators on the hand exoskeleton



[Pätzold et al. SMC 2023]

Roughness Perception



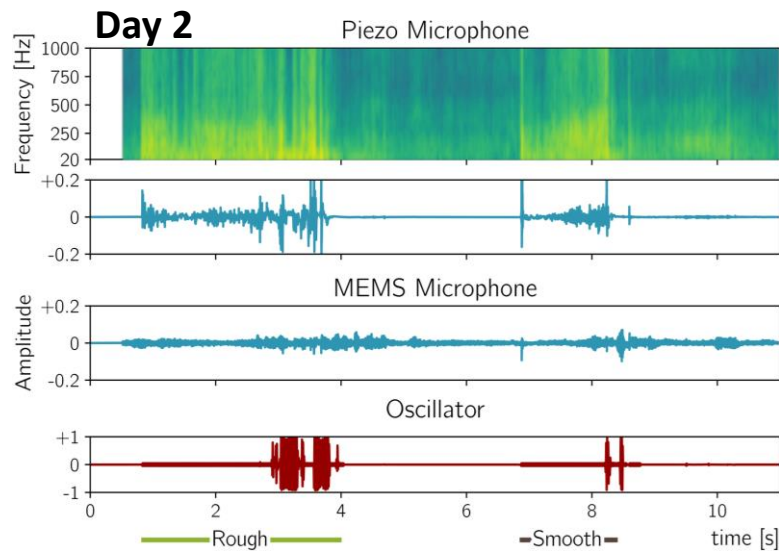
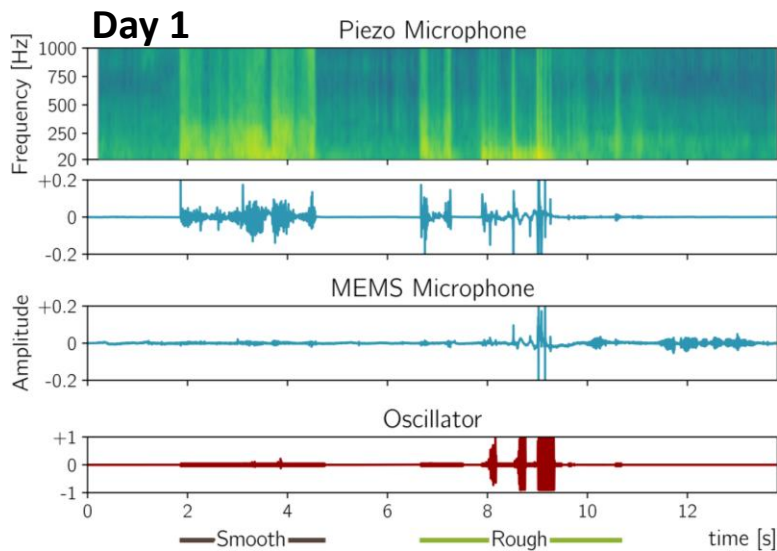
Dataset of Rough and Smooth Objects



[Pätzold et al. SMC 2023]

Finals Task 10: Retrieve a Rough Stone

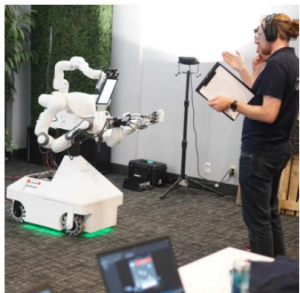
- Vision partially blocked by a curtain
- 5 stones (3 smooth + 2 rough)



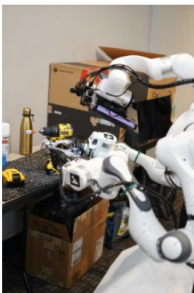
Operator Training



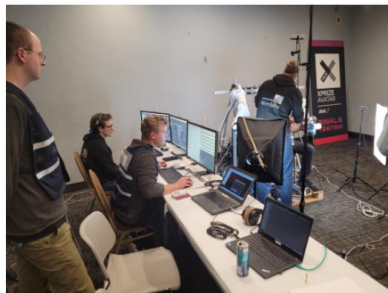
Introduction



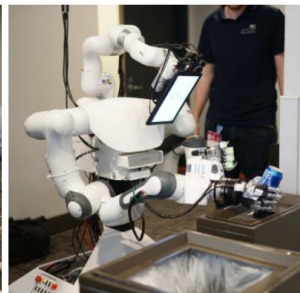
Locomotion



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

Operator Crew GUI

Anna

control_box/Clock: 4:00:37

Battery	Power supply 100%
CPU	Usage 15.11%
Temperature	CPU: 88° PCH: 67° SSD: 44°
HDD	Usage 32% (596G free)
USB	All 11 devices checked
Ping	All 6 connections checked
Network	All 3 connections checked
Basler Left	46.3 Hz (delay 0.09s)
Basler Right	45.8 Hz (delay 0.07s)
Brio Front	19.7 Hz (delay 0.13s)
Brio Rear	15.1 Hz (delay 0.15s)
Hand Cam	15.0 Hz (delay 0.11s)
Hand Left	1: 46°, 2: 48°, 3: 46°, 4: 44°
Hand Right	48.9 Hz (delay 0.04s)
Magnet	3 sensors
SVH Contact	193.2 Hz (delay 0.04s)
Head	Delay: 0.02s
Arm Left	Delay: 0.02s
Arm Right	Delay: 0.02s
FT left	480.2 Hz (delay 0.04s)
FT right	479.9 Hz (delay 0.04s)
Wheels	Delay: 0.05s
Spine	0.30m (57%)
Audio	Human
Face display	Running
E-Stop	OK
Bagfile	Paused

Otto

CPU	Usage 30.51%
HDD	Usage 55% (897G free)
USB	All 9 devices checked
Network	All 4 connections checked
Index cam	52.0 Hz (delay 0.07s)
Mouth cam	56.2 Hz (delay 0.09s)
Eye Left	25.1 Hz (delay 0.12s)
Eye Right	26.0 Hz (delay 0.11s)
Operator Cam	28.7 Hz (delay 0.11s)
Arm Left TF	Delay: 19.86s
Arm Left Comm	No message
Arm Right TF	Delay: 0.00s
Arm Right Comm	0%
Glove Left	96.4 Hz (delay 0.06s)
Glove Right	96.4 Hz (delay 0.06s)
FT left	936.1 Hz (delay 0.05s)
FT right	935.1 Hz (delay 0.06s)
Rudder	Ready
Pedal	47.7 Hz (delay 0.07s)
Eye Tracking	51.0 Hz (delay 0.11s)
VR Calibration	Trackers/Arms not working
Audio	Running
Jamulus Otto	Registered on server
Jamulus Recording	Paused
HDMI	58.2 Hz (delay 0.06s)
Bagfile	Paused

Anna Core

smmon_anna_core/state	On	Off
Head Control	On	Off
Right Hand	On	Off
Left Hand	On	Off
Force / Torque	On	Off
Otto	On	Off
Anna Feedback	On	Off
Anna Limits	On	Off
Atlas	On	Off
Drive	On	Off
Spine	On	Off
Recording	On	Off
Record	On	Off
Run	On	Off
Y Offset	On	Off

Anna Network

System	0.39 MB/s	5GHz	0 p/s	2.4GHz	0 p/s
Feedback	5.32 MB/s	5GHz	0 p/s	2.4GHz	0 p/s
TF	4.16 MB/s	5GHz	0 p/s	2.4GHz	0 p/s
Cam Left	7.16 MB/s	5GHz	0 p/s	2.4GHz	0 p/s
Cam Right	7.33 MB/s	5GHz	0 p/s	2.4GHz	0 p/s
Aux Image	4.25 MB/s	5GHz	0 p/s	2.4GHz	0 p/s

Otto Network

System	0.00 MB/s	5GHz	0 p/s	2.4GHz	0 p/s
Control	0.17 MB/s	5GHz	0 p/s	2.4GHz	0 p/s
TF	1.35 MB/s	5GHz	0 p/s	2.4GHz	0 p/s
Aux Image	1.92 MB/s	5GHz	0 p/s	2.4GHz	0 p/s

Commanders

Reason	EXEC	Lock	Power off
Reason: NOMINAL	[J1] [J2]	[J3] [J4]	[J5] [J6]
Action: inactive	[J1] [J2]	[J3] [J4]	[J5] [J6]
Lock	[J1] [J2]	[J3] [J4]	[J5] [J6]
Power off	[J1] [J2]	[J3] [J4]	[J5] [J6]

Network

network_display/network_display

Freq: 5.76 GHz
Associated since: Signal: -64 dBm
RX: 390 MB/s MCS 8 20M 14000000

5 GHz
TX: 390 MB/s MCS 8 20M 14000000

Robot

22.30 MB/s

Ping RTT: 0.0ms

5.88 MB/s

XPRIZE

28.22 MB/s

Ping RTT: 0.1ms

Freq: 2.412 GHz
Associated since: Signal: -53 dBm
RX: 58 MB/s MCS 0 20M 14000000

2.4 GHz

TX: 26 MB/s MCS 0 20M 14000000

5.56 MB/s

Basler

Eye calibration: Waiting, Start, Stop

Bag file: /home/avатар/eye_bags/bag_2022-11-05-23-41-34.bag

#images: L:356, R:356, D:1639

Train: 0%

Train error: 3.891891 deg

Bird's Eye

Hand

Force

Torque

Roughness

roughness_detector_client/confidence

Packet rate

Packet Loss Concealment

Log

Filter

Time	Node	Message
15:41:34	/otto/monitor	Right tracking pose is not valid (tracker turned off?)
15:41:53	/avатар_vr	/anna/basler/right/lnage/h264: waiting for transform: Query anna_basler_right_optical_frame <- anna_nominal_head_link: Would require extrapolation
15:41:15	/avатар_vr	/anna/basler/left/lnage/h264: waiting for transform: Query anna_basler_left_optical_frame <- anna_nominal_head_link: Would require extrapolation
15:41:40	/sense_glove	Could not get Senseglove data. Please check USB connection.
15:41:59	/otto/eye_recorder	Opening bag file: /home/avатар/eye_bags/bag_2022-11-05-23-41-34.bag
15:41:63	/avатар_vr	/anna/basler/right/lnage/h264: waiting for transform: Query anna_basler_right_optical_frame <- anna_nominal_head_link: Would require extrapolation
15:41:25	/otto/eye_recorder	Recording stopped.
15:42:07	/anna/right/driver	Otto right arm command is too old (81.240440935s)
15:42:08	/anna/left/driver	Otto left arm command is too old (81.255314612s)
15:42:46	/otto/monitor	Left tracking pose is not valid (tracker turned off?) (connected=true, valid=true, result=101)
15:42:22	/avатар_vr	/anna/basler/left/lnage/h264: waiting for transform: Query anna_basler_left_optical_frame <- anna_nominal_head_link: Would require extrapolation
15:42:29	/otto/monitor	Right tracking pose is not valid (tracker turned off?)
15:42:07	/otto/monitor	Left tracking pose is not valid (tracker turned off?) (connected=true, valid=true, result=101)
15:42:19	/avатар_vr	long delay in decoder
15:43:07	/anna/right/driver	Otto right arm command is too old (141.240074364s)
15:43:08	/anna/left/driver	Otto left arm command is too old (141.256047258s)
15:43:15	/avатар_vr	/anna/birds_eye/out/compressed: Dropping old frames
15:43:98	/sense_glove	Could not get Senseglove data. Please check USB connection.
15:43:19	/otto/left/driver	E-Stop released (mode 1), back to control
15:43:19	/otto/left/driver	Franka:ControlException: L1bfranka: Move command rejected: command not possible in the current mode
15:43:50	/rosmon_otto_arms	rosmon: /otto/left/driver died from signal 6
15:43:51	/rosmon_otto_arms	rosmon: starting '/otto/left/driver'
15:43:23	/otto/left/driver	Robot is locked, I'm going to unlock it...
15:43:49	/otto/left/driver	Setting brakes to 0
15:43:08	/otto/left/driver	Got error: eResourcePending
15:43:08	/otto/left/driver	Could not lock/unlock brakes: state ABORTED/Got error from Franka: eResourcePending
15:43:71	/otto/left/driver	Checking if operator is present...
15:43:88	/otto/left/driver	Operator is present, not disabling.
15:43:26	/rosmon_otto_arms	rosmon: /otto/left/driver died from signal 6
15:43:27	/rosmon_otto_arms	rosmon: starting '/otto/left/driver'
15:43:24	/otto/left/driver	Waiting for E-Stop release...
15:43:69	/otto/monitor	Could not get kinematic tracker pose: Lookup would require extrapolation 0.09378322s into the past. Requested time 1667680190.18899593 but the earliest data is at time 1667680190.282770025, when looking up transform from frame [otto_arm_left_tracker_link] to frame [vr_link]
15:43:24	/otto/left/driver	Waiting for E-Stop release...
15:43:71	/avатар_vr	/anna/basler/right/lnage/h264: waiting for transform: Query anna_basler_right_optical_frame <- anna_nominal_head_link: Would require extrapolation
15:43:24	/otto/left/driver	Waiting for E-Stop release...
15:43:09	/otto/monitor	Could not get kinematic tracker pose: Lookup would require extrapolation 9.993024202s into the past. Requested time 1667680190.18899593 but the earliest data is at time 1667680200.182815552, when looking up transform from frame [otto_arm_left_tracker_link] to frame [vr_link]
15:43:72	/avатар_vr	/anna/basler/left/lnage/h264: waiting for transform: Query anna_basler_left_optical_frame <- anna_nominal_head_link: Would require extrapolation

Operator Crew GUI

Anna

control_box/Clock: **400:37**

Anna/symon/state

- Battery Power supply 100%
- CPU Usage 15.11%
- Temperature CPU: 88° PCH: 67° SSD: 44°
- HDD Usage 32% (596G free)
- USB All 11 devices checked
- Ping All 6 connections checked
- Network All 3 connections checked
- Basler Left 46.3 Hz (delay 0.09s)
- Basler Right 45.8 Hz (delay 0.07s)
- Brio Front 19.7 Hz (delay 0.13s)
- Brio Rear 15.1 Hz (delay 0.15s)
- Hand Cam 15.0 Hz (delay 0.11s)
- Hand Left 1: 46°, 2: 48°, 3: 46°, 4: 44°
- Hand Right 48.9 Hz (delay 0.04s)
- Magnet 3 sensors
- SVH Contact 193.2 Hz (delay 0.04s)
- Head Delay: 0.02s
- Arm Left Delay: 0.02s
- Arm Right Delay: 0.02s
- FT left 480.2 Hz (delay 0.04s)
- FT right 479.9 Hz (delay 0.04s)
- Wheels Delay: 0.05s
- Spine 0.50m (57%)
- Audio Running
- Face display Human
- E-Stop OK
- Bagfile Paused

Otto

rosmon arms

otto/symon/state

- CPU Usage 30.51%
- HDD Usage 55% (897G free)
- USB All 9 devices checked
- Network All 4 connections checked
- Index cam 52.0 Hz (delay 0.07s)
- Mouth cam 56.2 Hz (delay 0.09s)
- Eye Left 25.1 Hz (delay 0.12s)
- Eye Right 26.0 Hz (delay 0.11s)
- Operator Cam 28.7 Hz (delay 0.11s)
- Arm Left TF Delay: 19.86s
- Arm Left Comm No message
- Arm Right TF Delay: 0.00s
- Arm Right Comm 0%
- Glove Left 96.4 Hz (delay 0.06s)
- Glove Right 96.4 Hz (delay 0.06s)
- FT left 936.1 Hz (delay 0.05s)
- FT right 935.1 Hz (delay 0.06s)
- Rudder Ready
- Pedal 47.7 Hz (delay 0.07s)
- Eye Tracking 51.0 Hz (delay 0.11s)
- VR Calibration Trackers/Arms not working
- Audio Running
- Jamulus Otto Registered on server
- Jamulus Recording Paused
- HDMI 58.2 Hz (delay 0.06s)
- Bagfile Paused

network_display/network_display

Operator

5.88 MB/s

XPRIZE

28.22 MB/s

Router

22.30 MB/s

Robot

5.56 MB/s

5 GHz

TX: 390 MB/s MCS 8

5 GHz

TX: 26 MB/s MCS 2

2.4 GHz

5.56 MB/s

5 GHz

TX: 390 MB/s MCS 8


5 GHz

TX: 26 MB/s MCS 2


2.4 GHz

5.56 MB/s


Basler



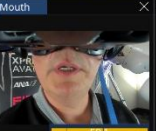
Left Eye




Right Eye



Mouth



Reconstruction



Otto config

Filter

Time	Node	Message
15:41:34	/otto/monitor	Right tracking pose is not valid (tracker turned off?)
15:41:53	/avatar_vr	/anna/basler/right/lnage/h264: waiting for transform: Query anna_basler_right_optical_frame <- anna_nominal_head_link: Would require extrapolation
15:41:15	/avatar_vr	/anna/basler/left/lnage/h264: waiting for transform: Query anna_basler_left_optical_frame <- anna_nominal_head_link: Would require extrapolation
15:41:40	/sense_glove	Could not get Senseglove data. Please check US connection.
15:41:59	/otto/eye_recorder	Opening bag file: /home/avатар/eye_bags/bag_2022-11-05-23-41-34.bag
15:41:63	/avatar_vr	/anna/basler/right/lnage/h264: waiting for transform: Query anna_basler_right_optical_frame <- anna_nominal_head_link: Would require extrapolation
15:41:25	/otto/eye_recorder	Recording stopped.
15:42:07	/anna/right/driver	Otto right arm command is too old (81.240440935s)
15:42:08	/anna/left/driver	Otto left arm command is too old (81.255314612s)
15:42:46	/otto/monitor	Left tracking pose is not valid (tracker turned off?) (connected=true, valid=true, result=101)
15:42:22	/avatar_vr	/anna/basler/left/lnage/h264: waiting for transform: Query anna_basler_left_optical_frame <- anna_nominal_head_link: Would require extrapolation
15:42:29	/otto/monitor	Right tracking pose is not valid (tracker turned off?)
15:42:37	/otto/monitor	Left tracking pose is not valid (tracker turned off?) (connected=true, valid=true, result=101)
15:43:19	/avatar_vr	long delay in decoder
15:43:07	/anna/right/driver	Otto right arm command is too old (141.240074364s)
15:43:08	/anna/left/driver	Otto left arm command is too old (141.256047258s)
15:43:15	/avatar_vr	/anna/birds_eye/out/compressed: Dropping old frames
15:43:98	/sense_glove	Could not get Senseglove data. Please check US connection.
15:43:19	/otto/left/driver	E-Stop released (mode 1), back to control
15:43:19	/otto/left/driver	Franka:ControlException: L2ofranka: Move command rejected: command not possible in the current mode
15:43:50	/rosmon_otto_arms	rosmon: /otto/left/driver died from signal 6
15:43:51	/rosmon_otto_arms	rosmon: starting '/otto/left/driver'
15:43:23	/otto/left/driver	Robot is locked, I'm going to unlock it...
15:43:49	/otto/left/driver	Setting brakes to 0
15:43:08	/otto/left/driver	Getting if @ResourcePending'
15:43:08	/otto/left/driver	Could not lock/unlock brakes: state ABORTED/got error from Franka: eResourcePending
15:43:71	/otto/left/driver	Checking if present to transform...
15:43:88	/otto/left/driver	Operator is present, not disabling.
15:43:26	/rosmon_otto_arms	rosmon: /otto/left/driver died from signal 6
15:43:27	/rosmon_otto_arms	rosmon: starting '/otto/left/driver'
15:43:24	/otto/left/driver	Waiting for E-Stop release...
15:43:69	/otto/monitor	Could not get kinematic tracker pose: Lookup would require extrapolation 0.09378322s into the past. Requested time 1667680190.18899593 but the earliest data is at time 1667680190.282770025, when looking up transform from frame [otto_arm_left_tracker_link] to frame [vr_link]
15:43:24	/otto/left/driver	Waiting for E-Stop release...
15:43:71	/otto/left/driver	/anna/basler/right/lnage/h264: waiting for transform: Query anna_basler_right_optical_frame <- anna_nominal_head_link: Would require extrapolation
15:43:24	/otto/left/driver	Waiting for E-Stop release...
15:43:09	/otto/monitor	Could not get kinematic tracker pose: Lookup would require extrapolation 9.993624202s into the past. Requested time 1667680190.18899593 but the earliest data is at time 1667680200.182815552, when looking up transform from frame [otto_arm_left_tracker_link] to frame [vr_link]
15:43:72	/avatar_vr	/anna/basler/left/lnage/h264: waiting for transform: Query anna_basler_left_optical_frame <- anna_nominal_head_link: Would require extrapolation

Eye calibration

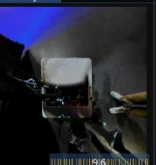
Waiting Start Stop

Bag file: /home/avатар/eye_bags/bag_2022-11-05-23-41-34.bag


#images: L:356, R:356, D:1639

Train error: 3.891891 deg

Bird's Eye



Hand



Anna/left/commander

Status: EXEC Joints

Reason: NOMINAL

Action: inactive

Lock

Power off

Anna/right/commander

Status: EXEC Joints

Reason: NOMINAL

Action: inactive

Lock

Power off

otto/left/commander

Status: SS2 Joints

Reason: NOMINAL

Action: inactive

Lock

Power off

otto/right/commander

Status: SS2 Joints


Reason: NOMINAL

Action: inactive

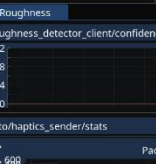
Lock

Power off


Force



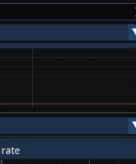
Torque



Force

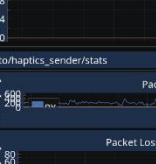


Torque

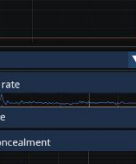


Roughness

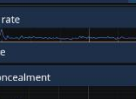
/roughness_detector_client/confidence



Packet rate



Packet Loss Concealment



Operator Crew GUI

Anna

control_box/Clock: 400:37

Anna Core

Movement	On	Off
Send Cmds	Usage	Off
Head Control	Usage	Off
Right Hand	On	Off
Left Hand	On	Off
Force / Torque	On	Off
Otto	On	Off
Anna Feedback	On	Off
Anna Limits	On	Off
Atlas	On	Off
Drive	On	Off
Spine	On	Off
Recording	On	Off
Record	On	Off
Run	On	Off
Y Offset	On	Off

Anna Network

System	0.39 MB/s	5GHz	0 p/s	2.4GHz	0 p/s
Feedback	5.32 MB/s	5GHz	0 p/s	2.4GHz	0 p/s
TF	4.16 MB/s	5GHz	0 p/s	2.4GHz	0 p/s
Cam Left	7.16 MB/s	5GHz	0 p/s	2.4GHz	0 p/s
Cam Right	7.33 MB/s	5GHz	0 p/s	2.4GHz	0 p/s
Aux Image	4.25 MB/s	5GHz	0 p/s	2.4GHz	0 p/s

Anna Network Control Status

System	0.00 MB/s	5GHz	0 p/s	2.4GHz	0 p/s
Control	0.17 MB/s	5GHz	0 p/s	2.4GHz	0 p/s
TF	1.35 MB/s	5GHz	0 p/s	2.4GHz	0 p/s
Aux Image	1.92 MB/s	5GHz	0 p/s	2.4GHz	0 p/s

Anna Left/Right Commander Status

Status: EXEC	Reason: NOMINAL	Action: inactive	Lock	Power off
Status: SS2	Reason: NOMINAL	Action: inactive	Lock	Power off

VR Calibration

VR Calibration	Tracked/Arms not working
Audio	Running
Jamulus Otto	Registered on server
Jamulus	Paused
Recording	Running
HDMI1	58.2 Hz (delay 0.06s)
Bagfile	Paused

network_display/network_display

Freq: 5.76 GHz
Associated since: Signal: -44 dBm
RX: 390 MB/s MCS 8 20M 40M 80M

5 GHz

TX: 390 MB/s MCS 8 20M 40M 80M

Robot

5.88 MB/s

XPRIZE

Ping RTT 0.0ms

28.22 MB/s

22.30 MB/s

Ping RTT 0.1ms

Freq: 2.412 GHz
Associated since: Signal: -53 dBm
RX: 58 MB/s MCS 0 20M 40M 80M

2.4 GHz

TX: 26 MB/s MCS 0 20M 40M 80M

536 MB/s

Basler

Left Eye

Right Eye

Mouth

Reconstruction

Eye calibration

Waiting Start Stop

Bag file: /home/avатар/eye_bags/bag_2022-11-05-23-41-34.bag

#images: L:356, R:356, D:1639

Train 0%

Train error: 3.891891 deg

Bird's Eye

Hand

Force

10 X
0 Y
-10 Z

Torque

4 X
0 Y
-4 Z

Roughness

roughness_detector_client/confidence

1.2
0.8
0.4
0.0

Packet rate

Rate (Hz)

Packet rate

Time

Packet Loss Concealment

Rate (Hz)

Packet Loss Concealment

Time

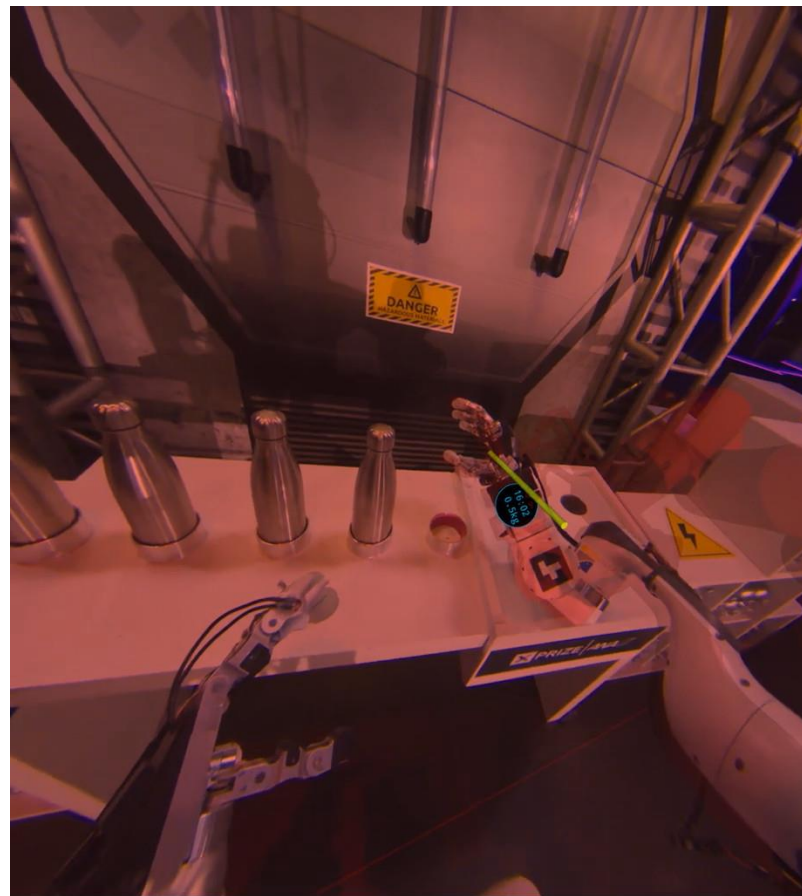
Otto config

Filter

Time	Node	Message
15:41:34	/otto/monitor	Right tracking pose is not valid (tracker turned off?)
15:41:53	/avатар_vr	/anna/basler/right/lnage/h264: waiting for transform: Query anna_basler_right_optical_frame <- anna_nominal_head_link: Would require extrapolation
15:41:53	/avатар_vr	/anna/basler/left/lnage/h264: waiting for transform: Query anna_basler_left_optical_frame <- anna_nominal_head_link: Would require extrapolation
15:41:15	/avатар_vr	Could not get Senseglove data. Please check US connection.
15:41:40	/sense_glove	Opening bag file: /home/avатар/eye_bags/bag_2022-11-05-23-41-34.bag
15:41:59	/otto/eye_recorder	Recording stopped.
15:41:63	/avатар_vr	Recording stopped.
15:41:25	/otto/eye_recorder	Otto right arm command is too old (81.240440935s)
15:42:07	/anna/right/driver	Otto left arm command is too old (81.255314612s)
15:42:08	/anna/left/driver	Left tracking pose is not valid (tracker turned off?) (connected=true, valid=true, result=101)
15:42:46	/otto/monitor	Left tracking pose is not valid (tracker turned off?) (connected=true, valid=true, result=101)
15:42:22	/avатар_vr	/anna/basler/left/lnage/h264: waiting for transform: Query anna_basler_left_optical_frame <- anna_nominal_head_link: Would require extrapolation
15:42:29	/otto/monitor	Right tracking pose is not valid (tracker turned off?) (connected=true, valid=true, result=101)
15:42:07	/otto/monitor	Left tracking pose is not valid (tracker turned off?) (connected=true, valid=true, result=101)
15:43:19	/avатар_vr	long delay in decoder
15:43:07	/anna/right/driver	Otto right arm command is too old (141.240074364s)
15:43:08	/anna/left/driver	Otto left arm command is too old (141.256047258s)
15:43:15	/avатар_vr	/anna/birds_eye/out/compressed: Dropping old frames
15:43:98	/sense_glove	Could not get Senseglove data. Please check US connection.
15:43:19	/otto/left/driver	E-Stop released (mode 1), back to control
15:43:19	/otto/left/driver	Franka:ControlException: L2ofranka: Move command rejected: command not possible in the current mode
15:43:50	/rosmon_otto_arms	rosmon: /otto/left/driver died from signal 6
15:43:51	/rosmon_otto_arms	rosmon: starting '/otto/left/driver'
15:43:23	/otto/left/driver	Robot is locked, I'm going to unlock it...
15:43:49	/otto/left/driver	Setting brakes to 0
15:43:08	/otto/left/commander	Checking if eResource is Pending
15:43:08	/otto/left/driver	Could not lock/unlock brakes: state ABORTED/got error from Franka: eResourcePending
15:43:71	/otto/left/driver	Checking if present to transform...
15:43:88	/otto/left/driver	Operator is present, not disabling.
15:43:26	/rosmon_otto_arms	rosmon: /otto/left/driver died from signal 6
15:43:27	/rosmon_otto_arms	rosmon: starting '/otto/left/driver'
15:43:24	/otto/left/driver	Waiting for E-Stop release...
15:43:69	/otto/monitor	Could not get kinematic tracker pose: Lookup would require extrapolation 0.09378322s into the past. Requested time 1667680190.188998593 but the earliest data is at time 1667680190.282770025, when looking up transform from frame [otto_arm_left_tracker_link] to frame [vr_link]
15:43:24	/otto/left/driver	Waiting for E-Stop release...
15:43:71	/otto/left/driver	/anna/basler/right/lnage/h264: waiting for transform: Query anna_basler_right_optical_frame <- anna_nominal_head_link: Would require extrapolation
15:43:24	/otto/left/driver	Waiting for E-Stop release...
15:43:09	/otto/monitor	Could not get kinematic tracker pose: Lookup would require extrapolation 9.993024202s into the past. Requested time 1667680190.188998593 but the earliest data is at time 1667680200.182815552, when looking up transform from frame [otto_arm_left_tracker_link] to frame [vr_link]
15:43:72	/avатар_vr	/anna/basler/left/lnage/h264: waiting for transform: Query anna_basler_left_optical_frame <- anna_nominal_head_link: Would require extrapolation

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



Network Details

- Separate ROS cores for operator station and avatar
- Pure UDP, no re-connect / initialization

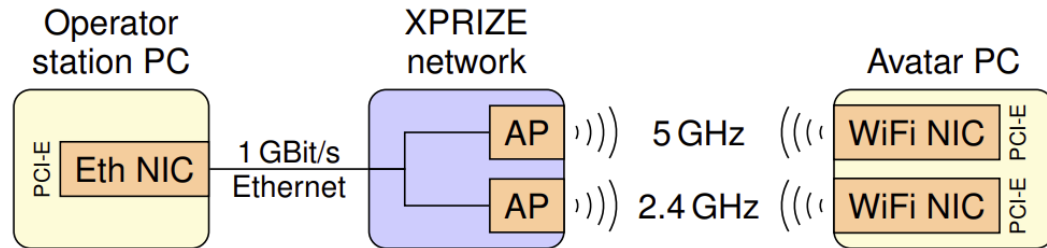
- Main camera stream (stereo 2472×2178 @46 fps) is HEVC-encoded & decoded on GPU (NVENC).

Total bandwidth: ~14 MBit/s

- Control data is sent redundantly
- Monitoring packet loss

- The core software is already open source, more to come:

https://github.com/AIS-Bonn/nimbro_network

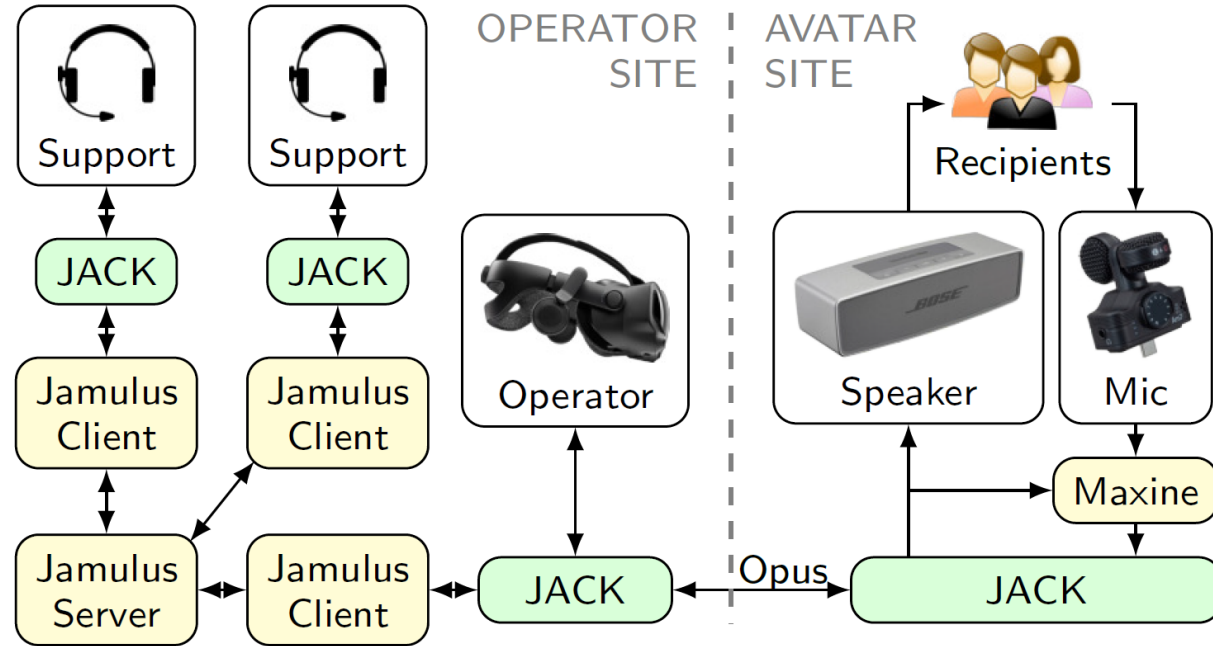


WiFi Bandwidth Requirements

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

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 cancellation*
- *Jamulus* for team communication with operator and recipients



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

Finals Day 2 Testing



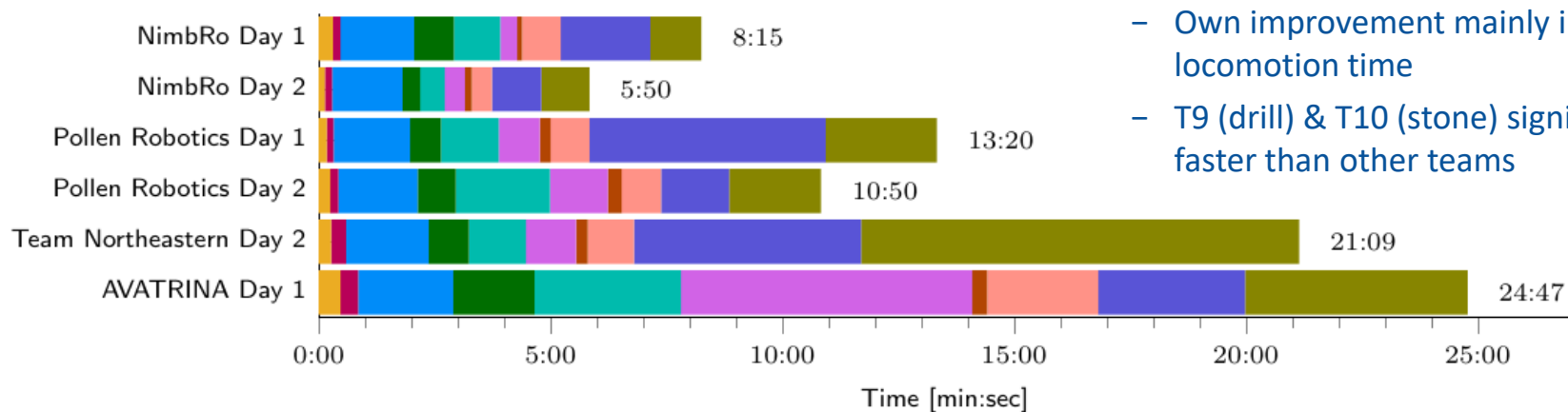
Rank	Team name	Time	Task score	Judged score	Total
1	NimbRo (DE)	5:50	10	5	15
2	Pollen Robotics (FR)	10:50	10	5	15
3	Team Northeastern (US)	21:09	10	4.5	14.5
4	AVATRINA (US)	24:47	10	4.5	14.5
5	i-Botics (NL)	25:00	9	5	14
6	Team UNIST (KR)	25:00	9	4.5	13.5
7	Inbiodroid (MX)	25:00	8	5	13
8	Team SNU (KR)	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

Team NimbRo



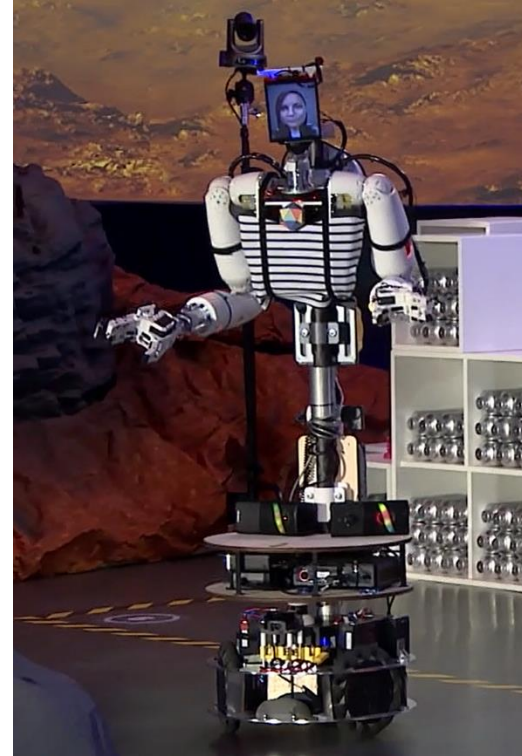
Finals Timings

Team	Day	Time ¹ [mm:ss]											Total
		Start ²	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	
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
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
	2	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



2nd Place: Pollen Robotics

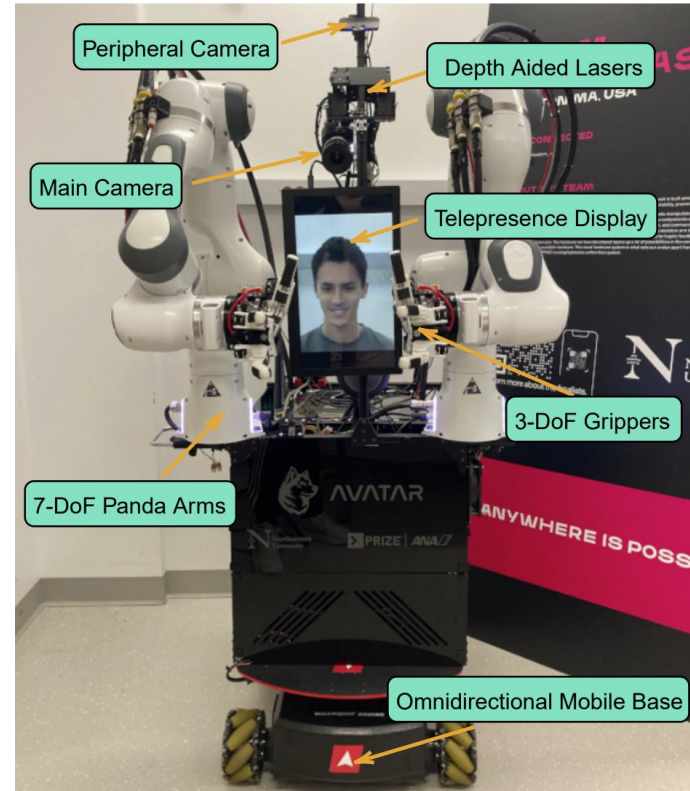
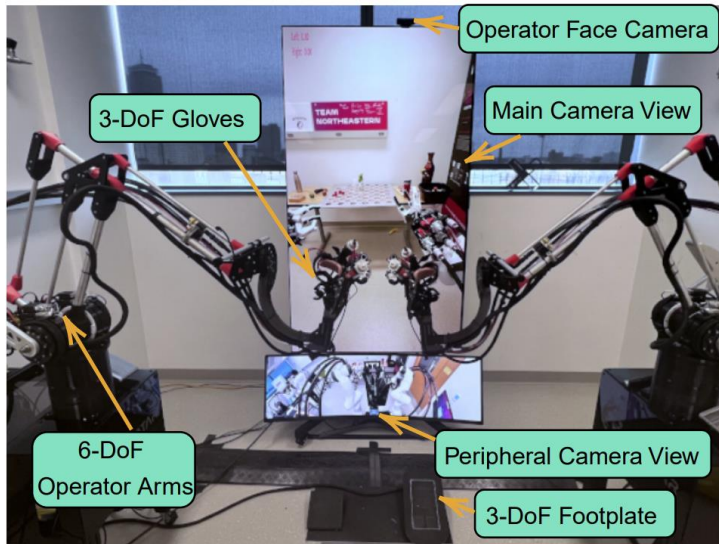
- Cost-effective design of robot and operator station
- Human-like upper body with Orbita 3 DoF actuators in shoulder, wrist, and neck



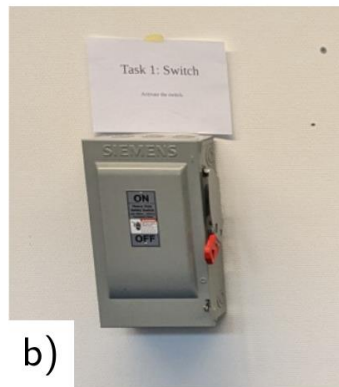
[Pollen Robotics]

3rd Place: Team Northeastern

- Hydraulically actuated glove-gripper pair for haptic force feedback
- Non-immersive visualization with two monitors
- Projected laser lines aid 3D perception



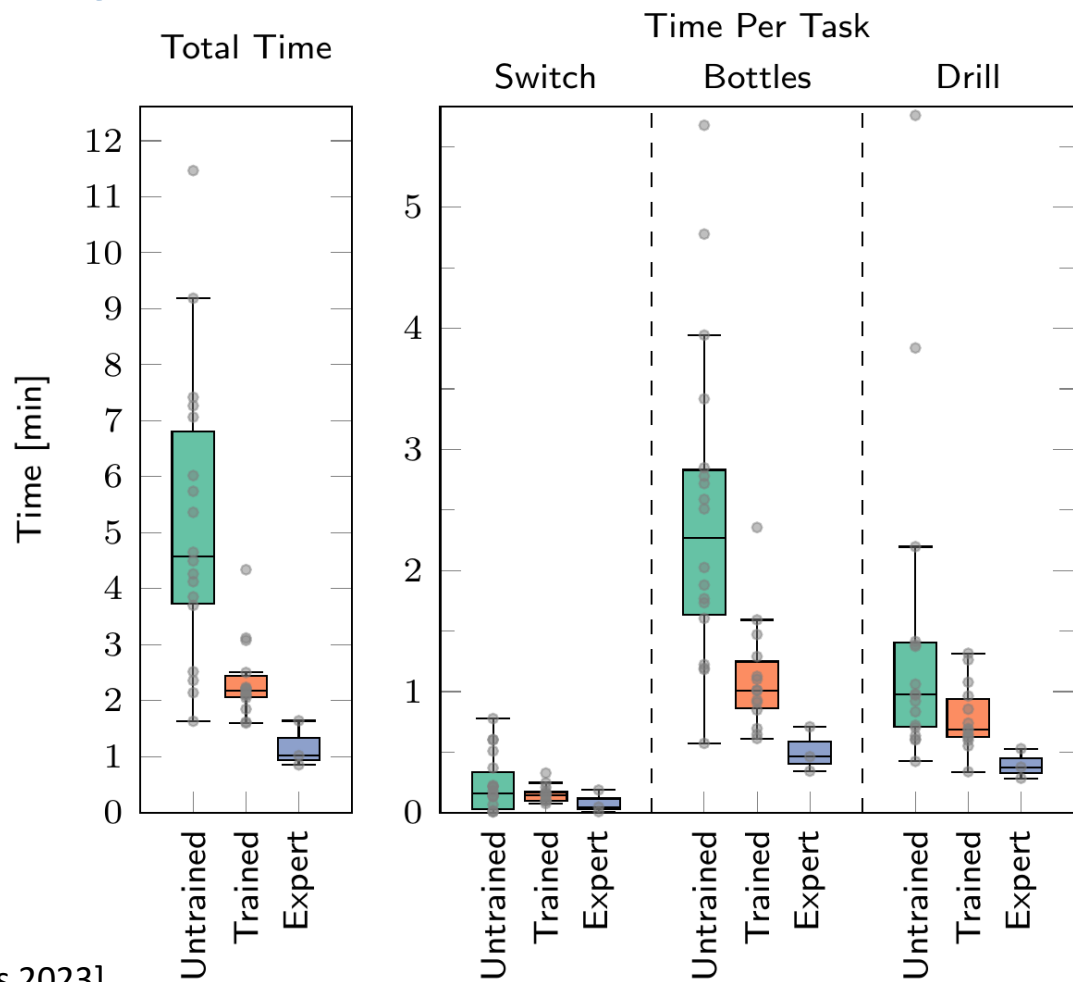
After the Competition: User Study in our Lab



- Three tasks, similar to finals: a), b) Locomotion+Switch, c) Bottles, d) Drill
- 35 participants, 32 with no prior experience of the system
- All participants: 2 min intro video explaining the system (task agnostic)
- Three groups:
 - No training
 - 10 min task training, similar to Finals
 - Expert team members

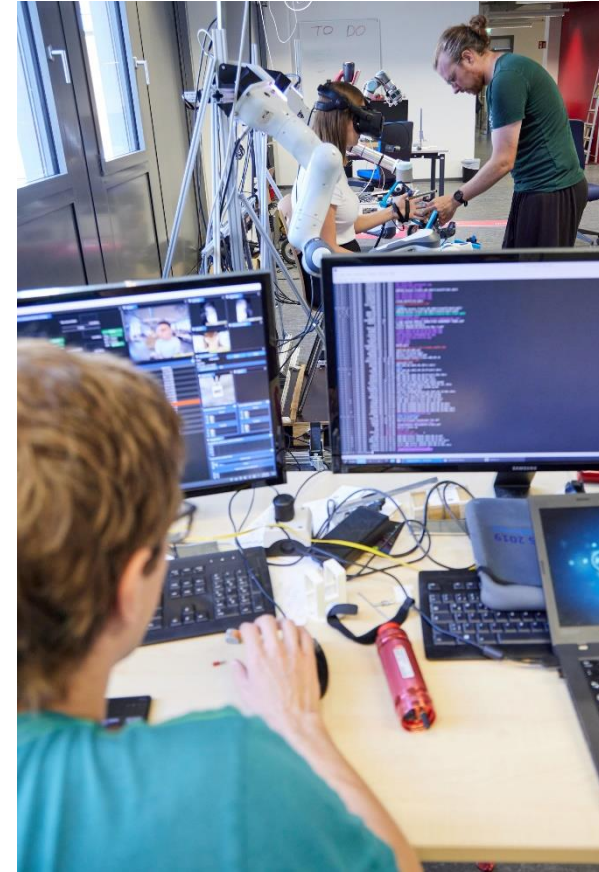
After the Competition: User Study in our Lab

- Unsurprising: Clear advantage of training (2× over untrained)
 - Unsurprising: Expert operators are very fast (2× trained)
 - Untrained operators could still solve all tasks in reasonable time
 - All participants were able to solve the tasks
- ➔ System is very intuitive, but short instruction on tasks improves completion time.



Lessons Learned

- Robustness is key
- Latency is the enemy of direct teleoperation
- Frequent testing under competition conditions is essential: System & team!
- 1:1 correspondence is best
- 6D head motion simplifies manipulation control
- Sparse immersive control overlays – don't break immersion!
- Facial animation and gestures: Head & gaze direction enables shared awareness
- Had to modify components



[Photographer: Volker Lannert]

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

■ **Research questions** include

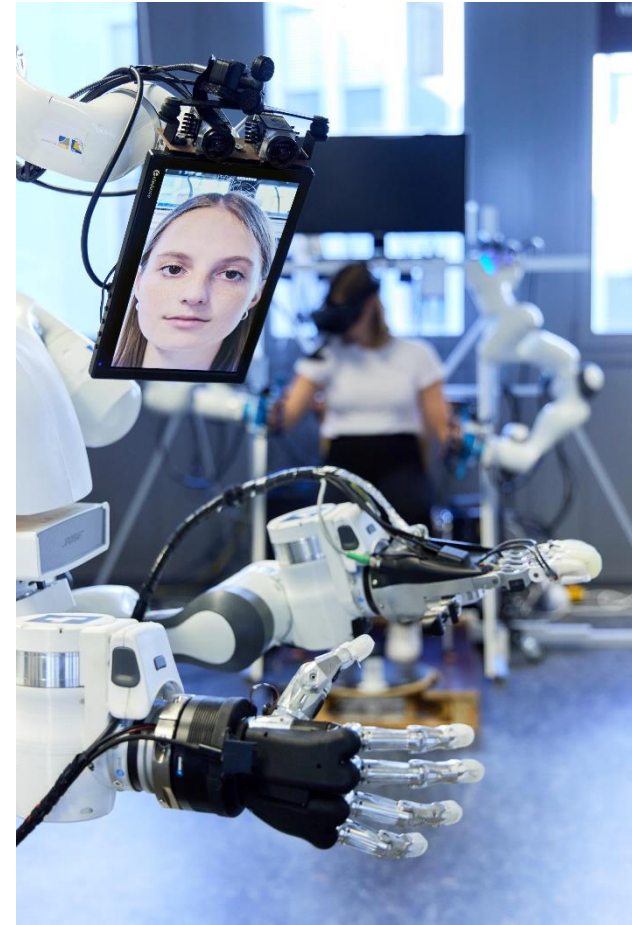
- How much human-likeness avatars should assume?
- How to address latencies and bandwidth limitations?
- How to balance and interface direct control and autonomy?



[Photographer: Volker Lannert]

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

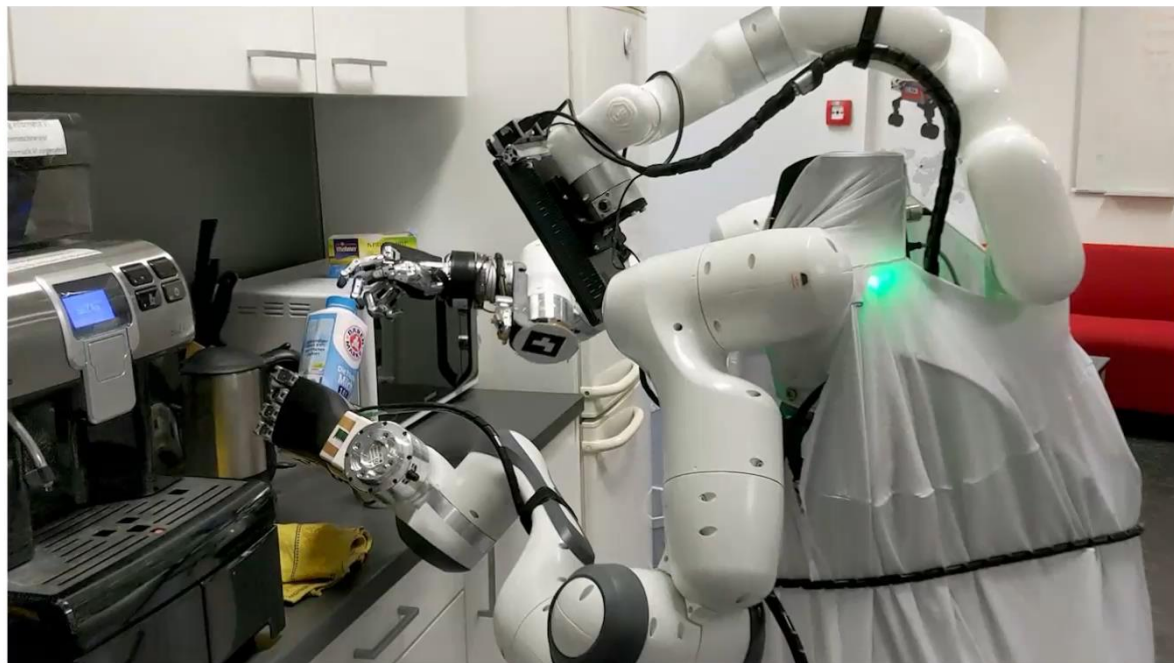


[Photographer: Volker Lannert]

Unmatched Human Operators



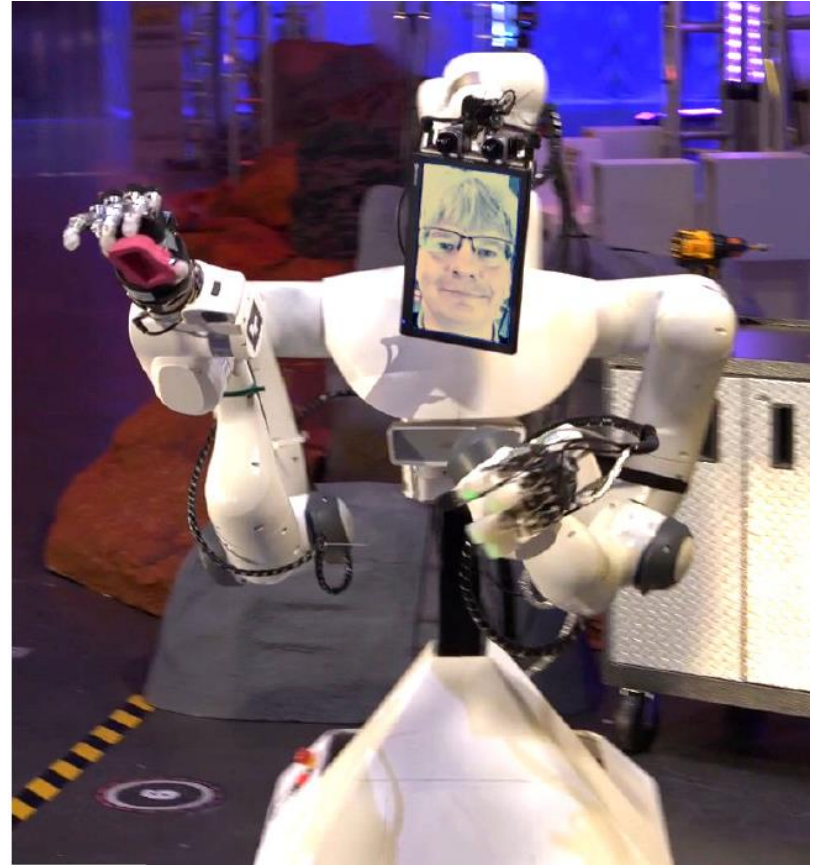
- Humans can solve many tasks by teleoperation
 - Can cope with novel situations, quickly learn new tasks
 - Recognize and mitigate errors
- Far beyond the capabilities of autonomous robots



2x

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



[XPRIZE]

Questions?

