

# The NimbRo Immersive Telepresence System Winning the ANA Avatar XPRIZE Finals

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# Experience with Teleoperated Robots

- Multiple domains
- Often motivated by competitions and challenges



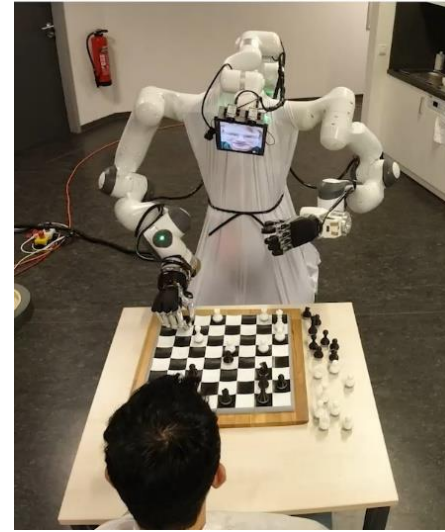
RoboCup@Home



DARPA Robotics Challenge  
DLR SpaceBot Cup



CENTAURO

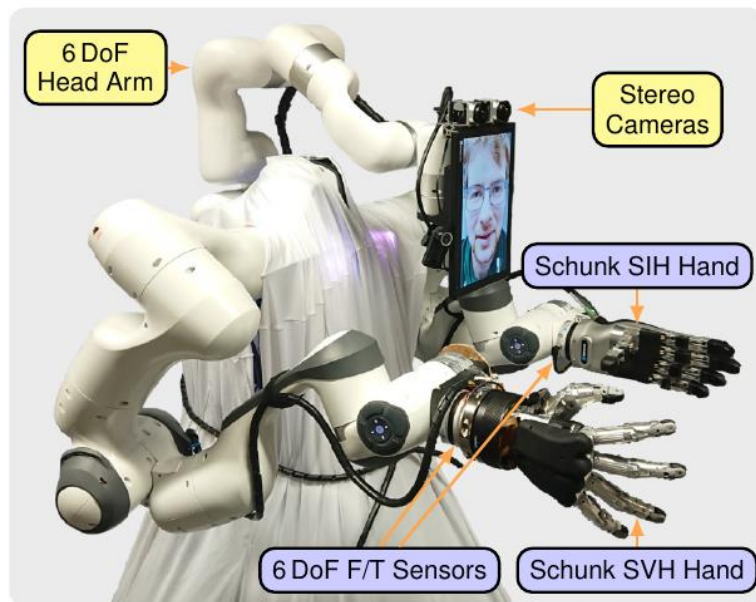
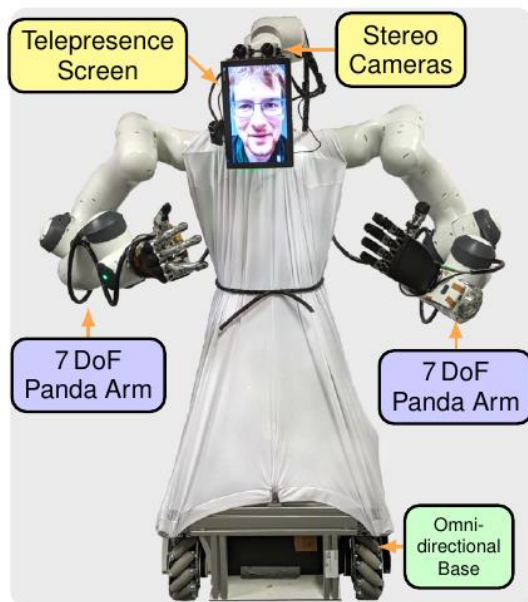


ANA Avatar XPRIZE

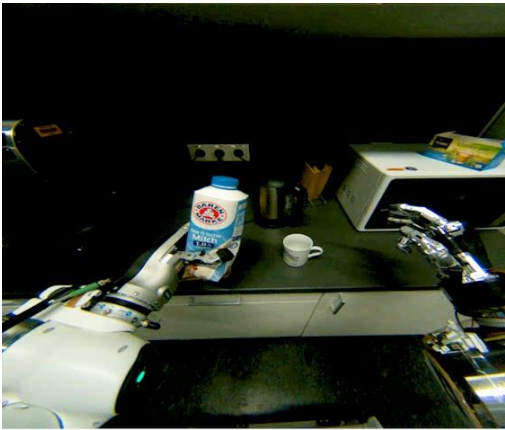
- Requires mobility, manipulation, human-human interaction
- Focuses on the immersion in the remote environment and the presence of the remote operator



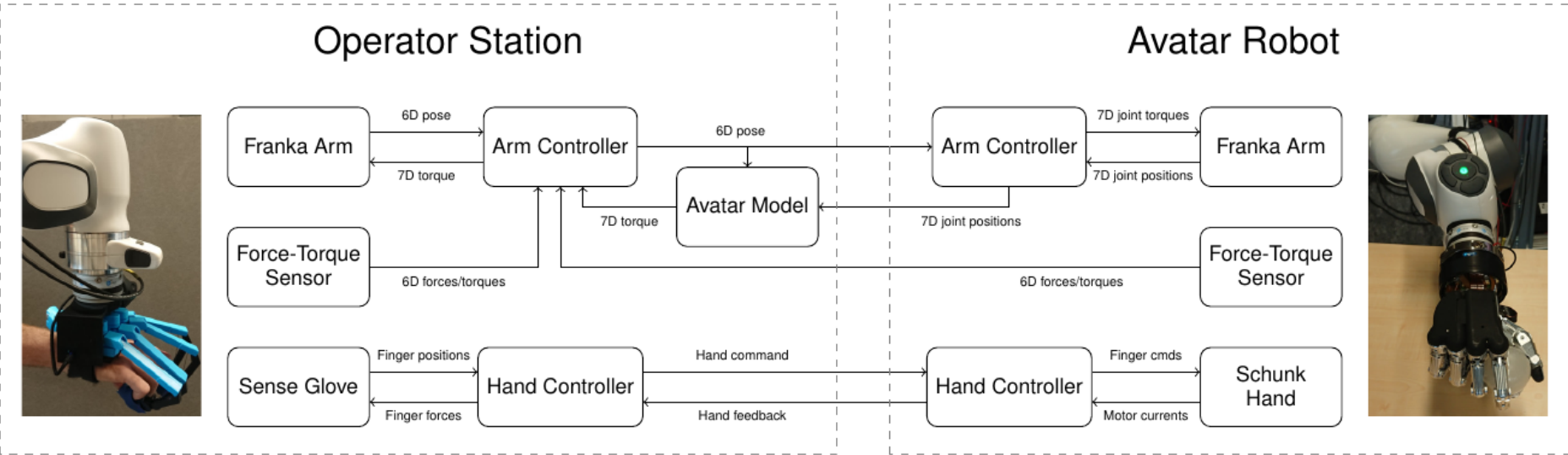
- Two-armed avatar robot designed for teleoperation with immersive visualization & force feedback
- Operator station with HMD, exoskeleton and locomotion interface



# 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 / SIH hand
- Provides force feedback for wrist and haptic feedback for fingers
- Avatar limit avoidance using predictive model to reduce latencies

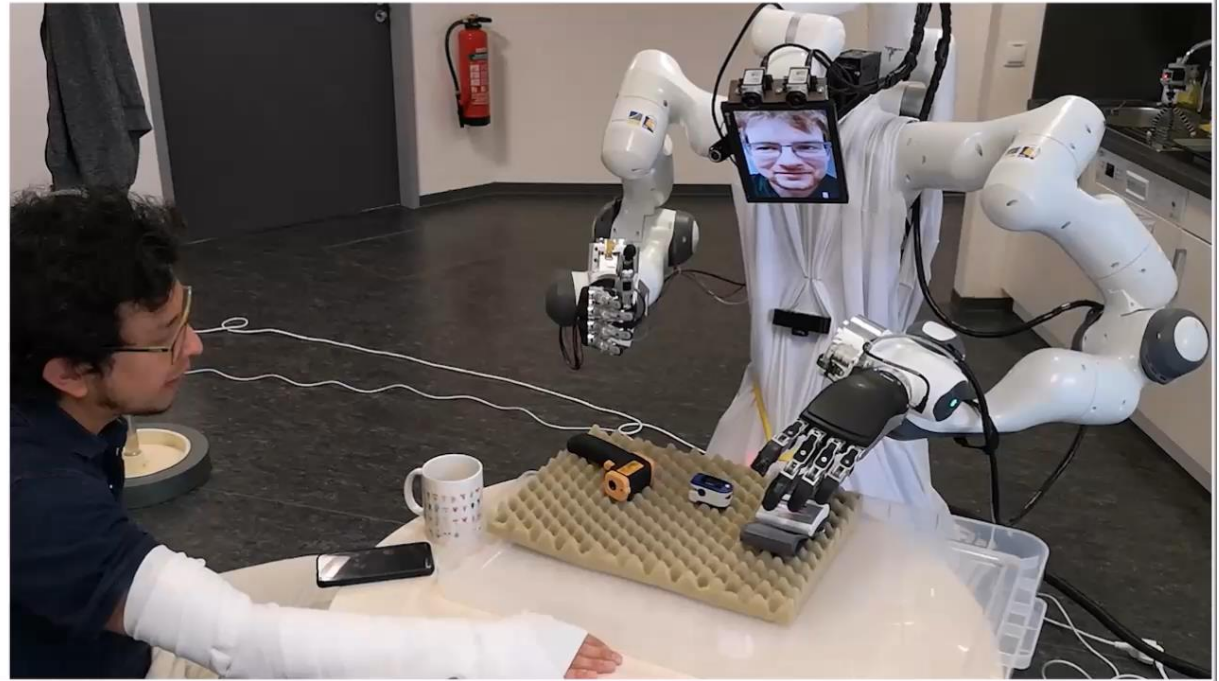
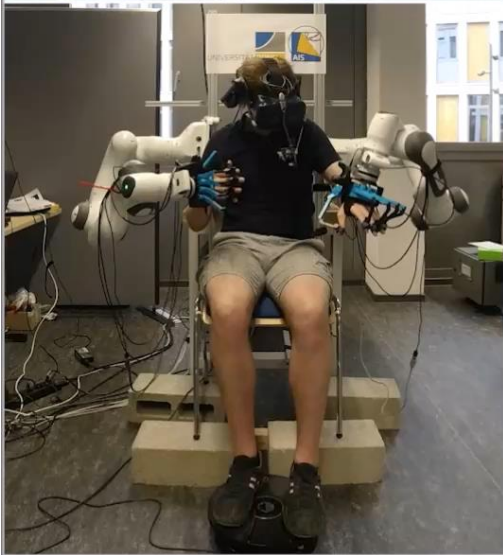
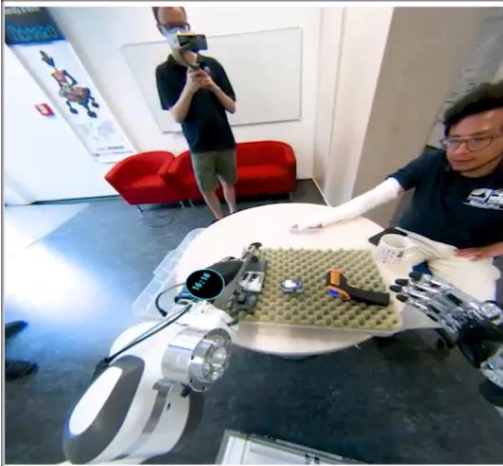
# Team NimbRo

## Semifinal Team Video

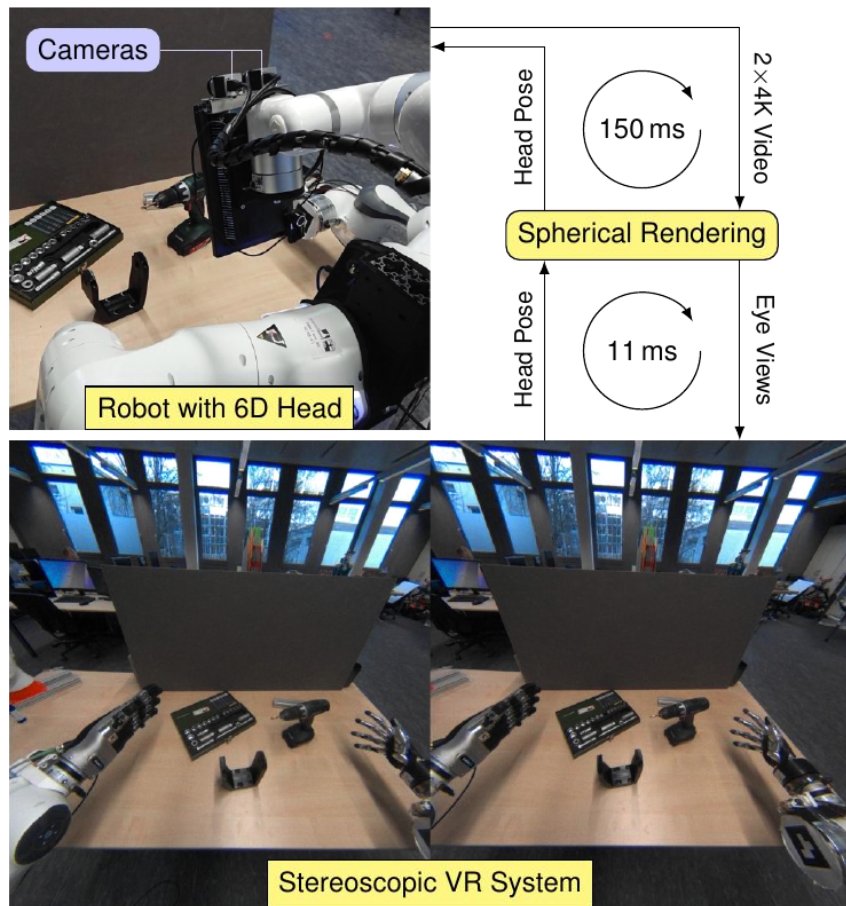


### Tasks

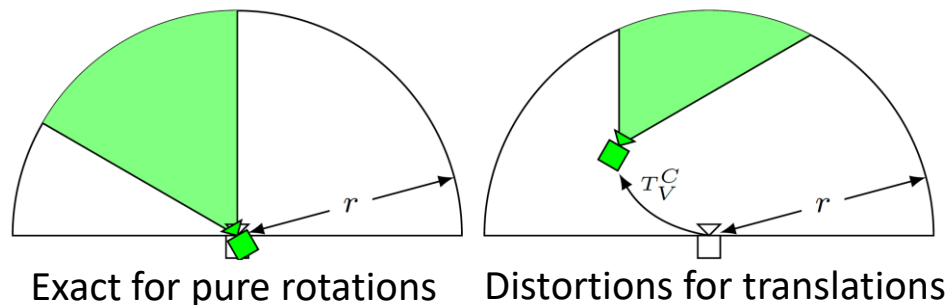
1. Make a coffee
2. Greet the recipient
3. Measure temperature
4. Measure blood pressure
5. Measure oxygen saturation
6. Help recipient with jacket



# NimbRo Avatar: Immersive Visualization



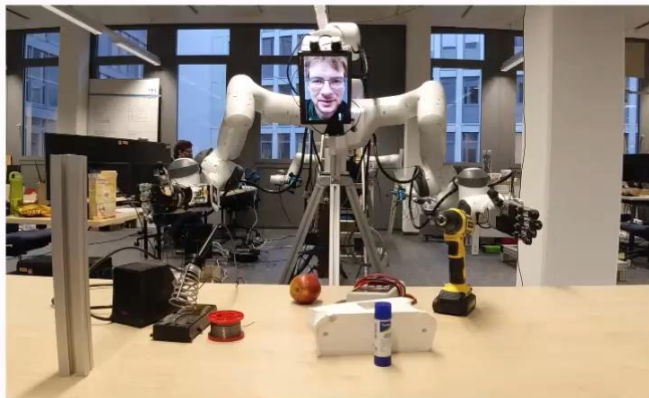
- 4K wide-angle stereo video stream
- 6D neck allows full head movement
  - Very immersive
  - Good hand-eye coordination
- Spherical rendering technique hides movement latencies
  - Assumes constant depth



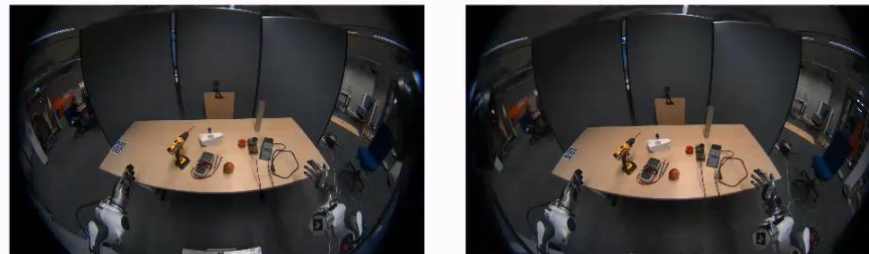


# NimbRo Avatar: Immersive Visualization

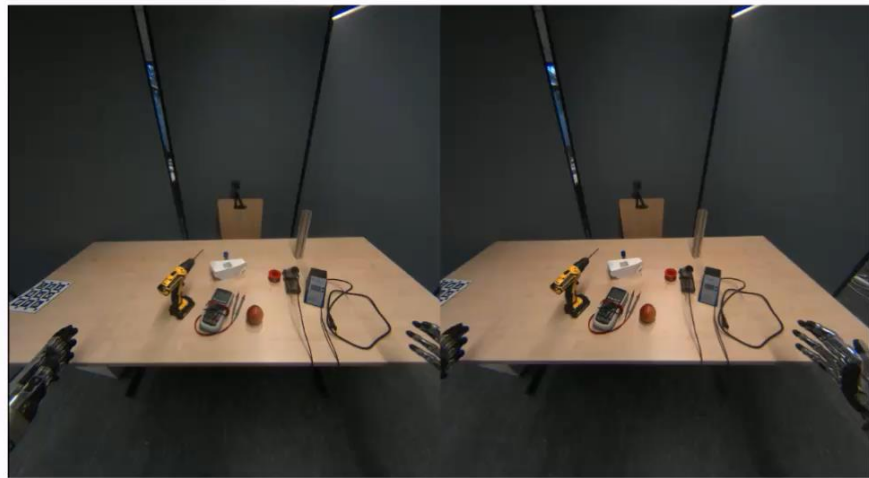
Avatar Robot



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



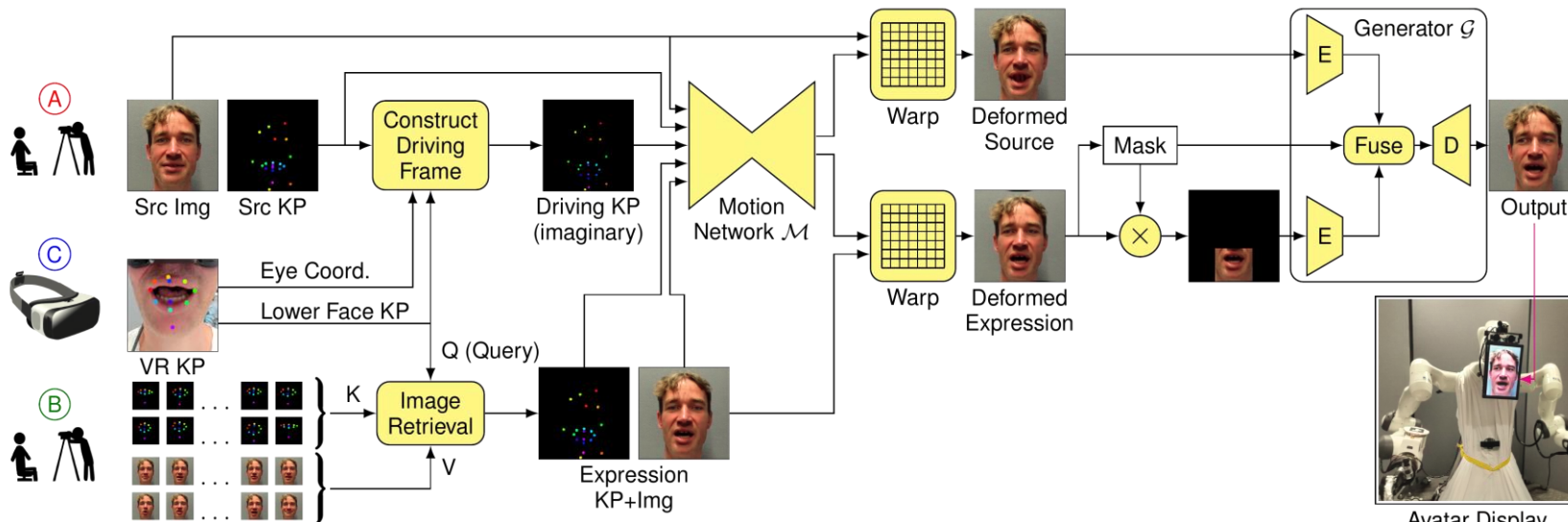
Left Eye



Mouth



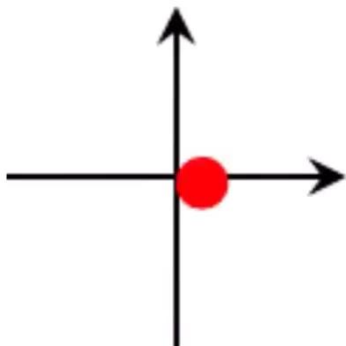
Right Eye



[Rochow et al. IROS 2022]

# NimbRo Avatar: Operator Face Animation

Gaze  
Direction



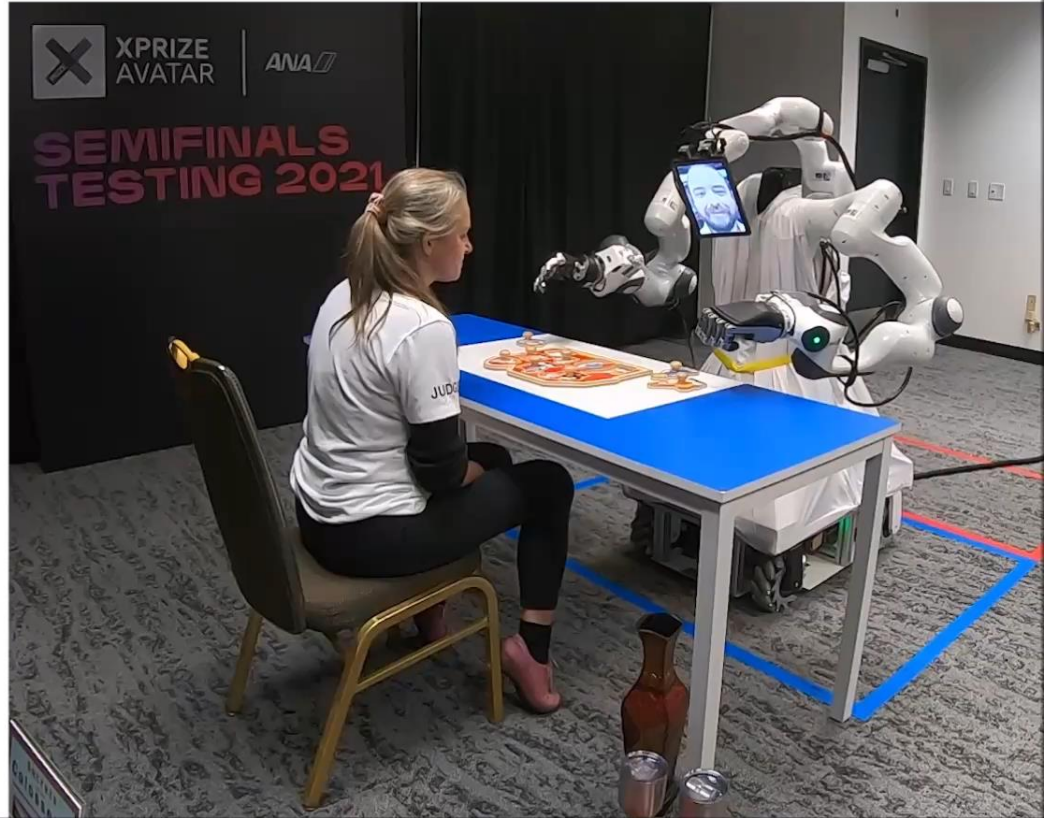
Output

Mouth Cam



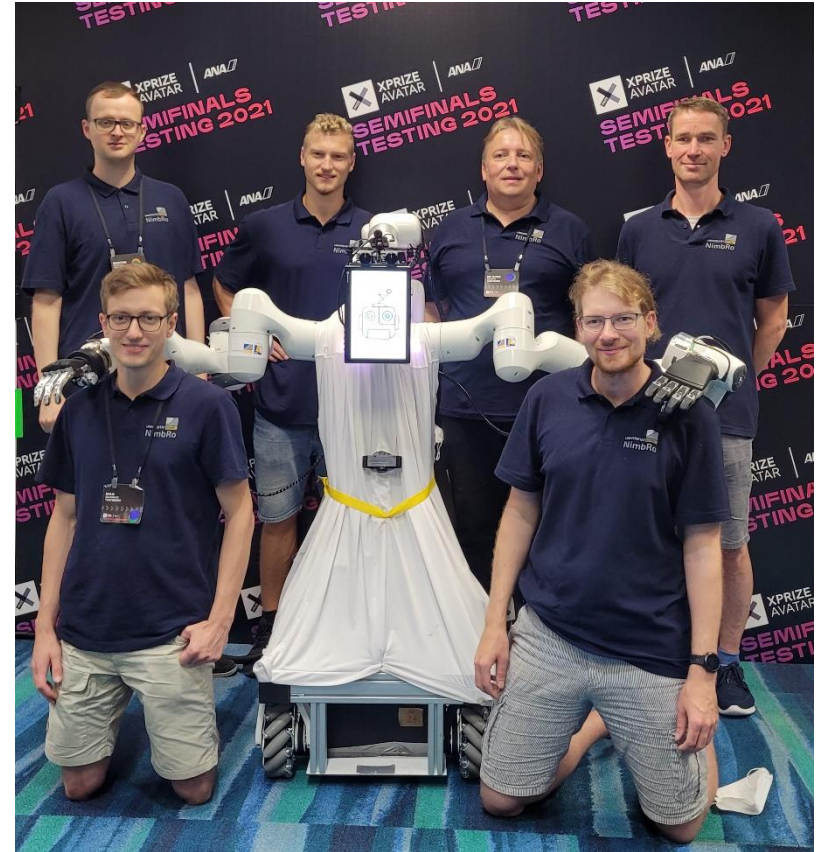
# NimbRo Avatar

## 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

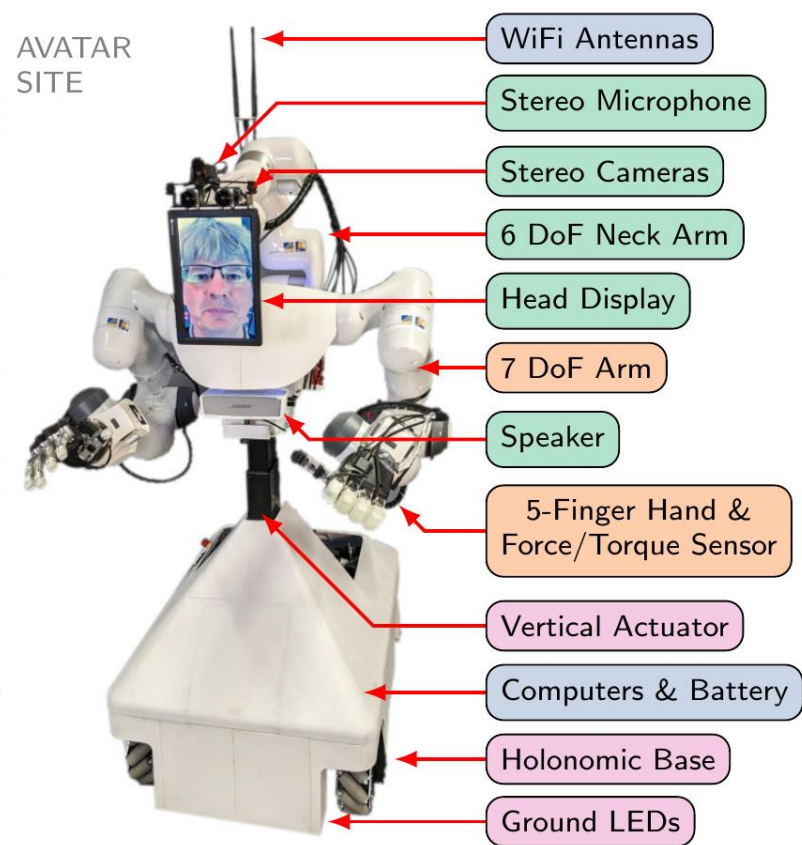
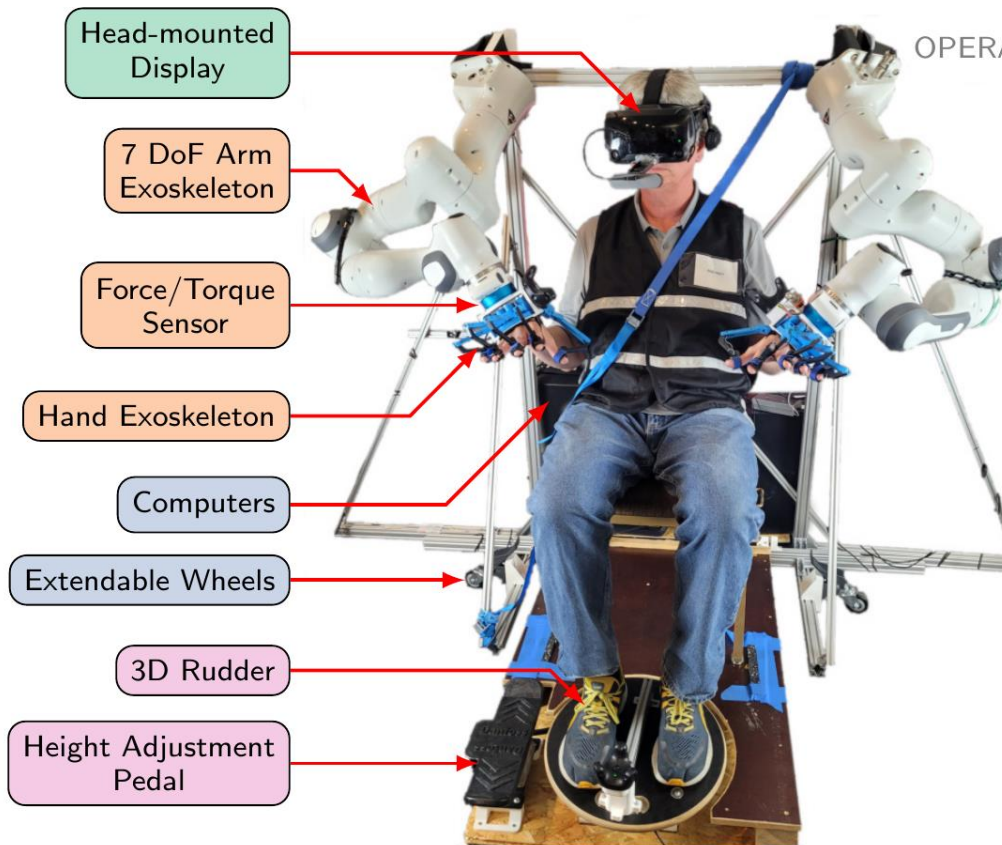


# New Finals Requirements

- Untethered avatar robot, more mobility
- Movable operator station
- 10 tasks in a sequence, including haptics
- System reliability extremely important
- Tasks fulfillment has highest importance in scoring
- Subjective criteria also important
- Trial time to break ties



# NimbRo Avatar Finals System



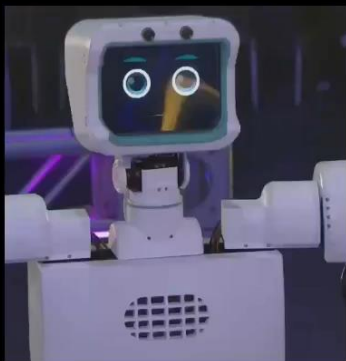
# Finals Test Run Day 1





# Face Animation @ Finals

Team UNIST



Ours (NimbRo)



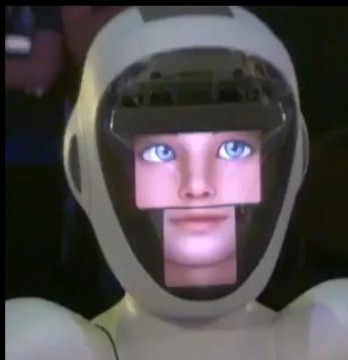
Team AVATRINA [13]



Source: Official XPRIZE Avatar live stream



Northeastern [12]



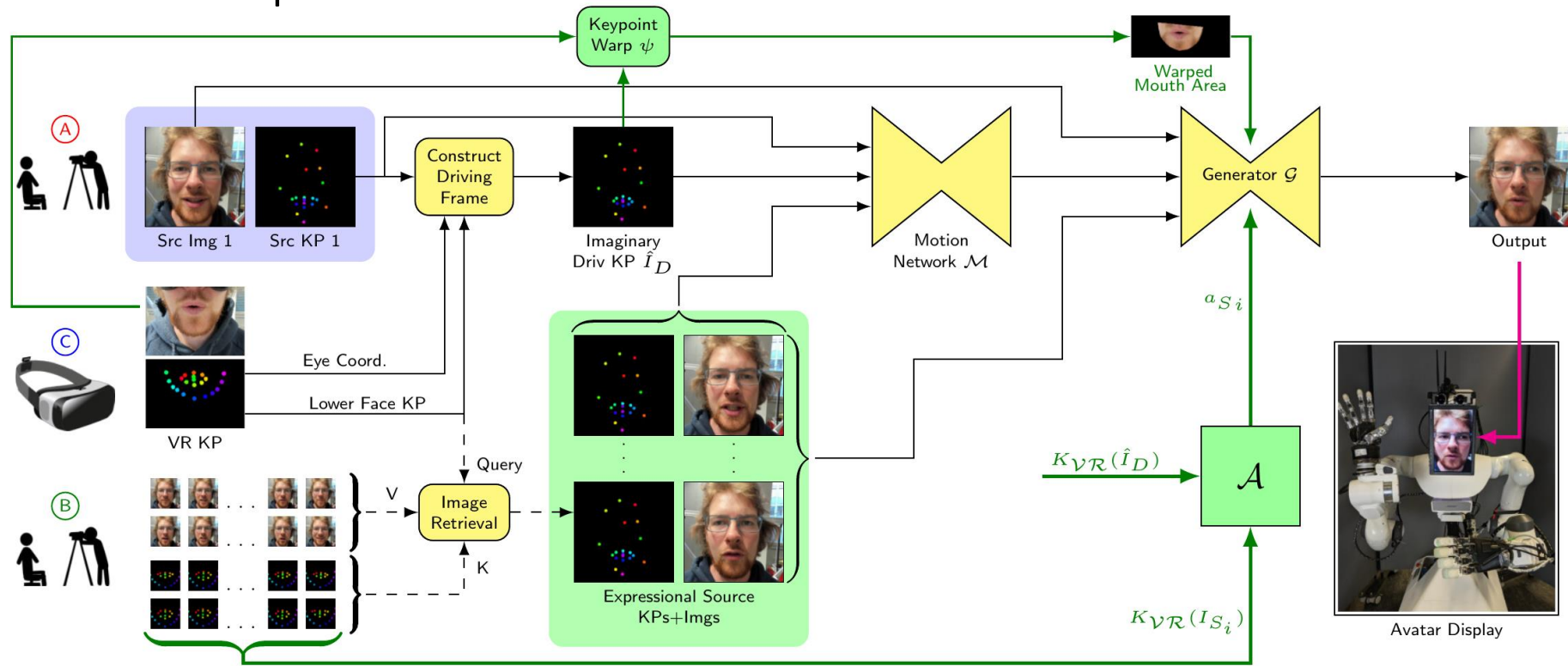
i-BOTICS



Pollen Robotics

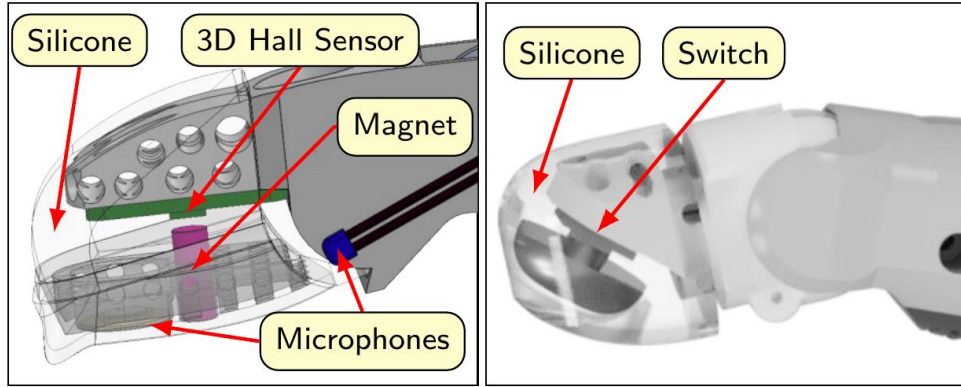
# Improved Operator Face Animation

- Better temporal continuity
- Direct incorporation of mouth video

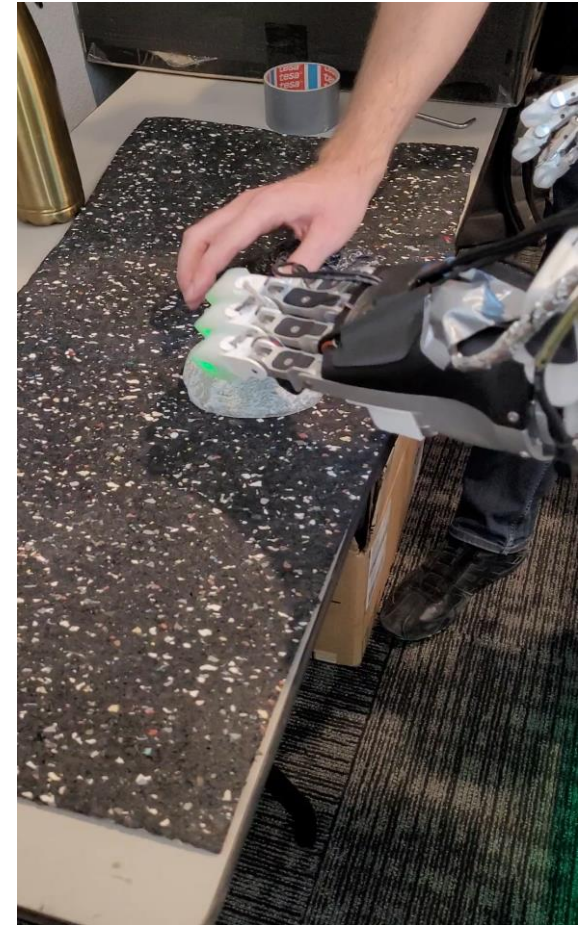


# Haptic Perception

## ■ Sensors in the finger tips

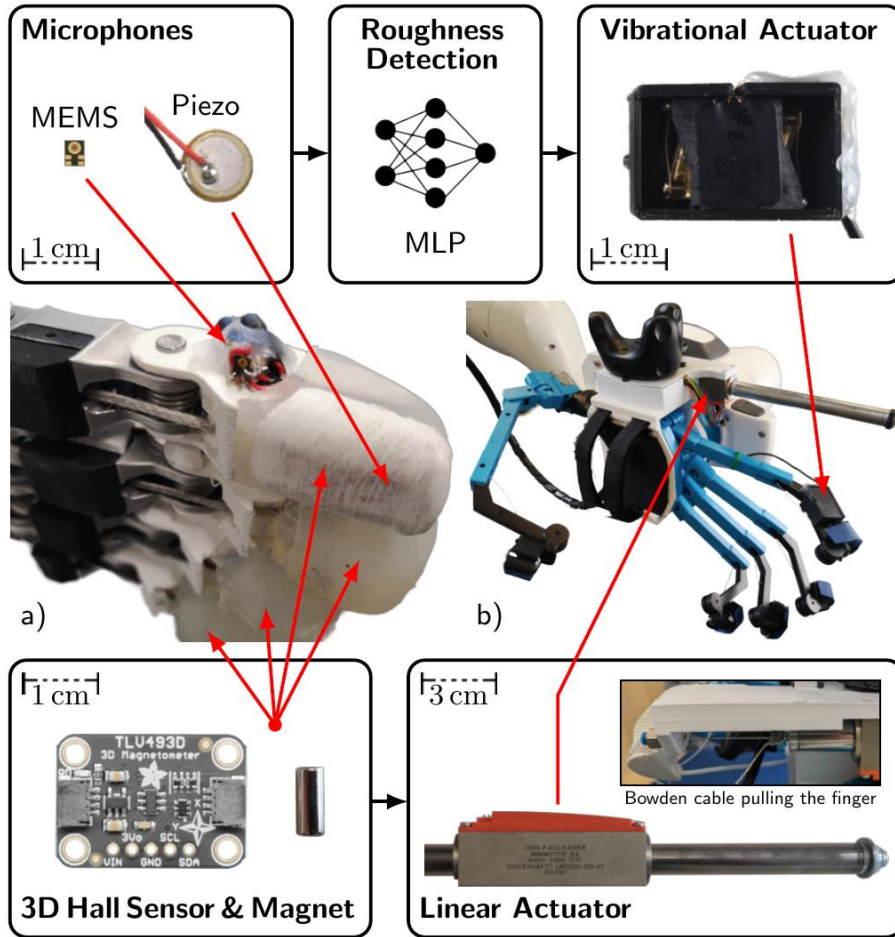


## ■ Actuators on the hand exoskeleton



[Pätzold et al. SMC 2023]

# Roughness Perception



Dataset of rough and smooth objects



[Pätzold et al. SMC 2023]

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

# Operator Training



(a) Introduction

(b) Locomotion

(c) Grasping



(d) Monitoring crew



(e) 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
<b>Total training</b>	<b>45</b>

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

# Moving into the Arena



- Seamless roaming / disconnection handling with UDP data streaming
- No calibration/initialization/button press
- Essential: Operator room crew in the voice loop during setup
- Gamepad control
- To quote Colin: Hydrate to Dominate!

# 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 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

smn_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

### Anna Left/Right Commander

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

### 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

5.88 MB/s  
Ping RTT 0.0ms

XPRIZE  
Ping RTT 0.1ms


28.22 MB/s

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

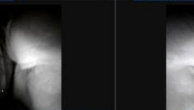
2.4 GHz  
TX: 26 MB/s MCS 0 20M 14000000

5.56 MB/s


### Basler




### Left Eye




### Right Eye



### Mouth



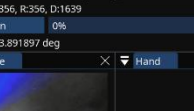
### Reconstruction



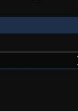
### Eye calibration

Bag:	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



### 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
15:41:15	/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 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	/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)
15:43:19	/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/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

### Otto Config

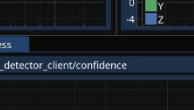
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15:42:22	/avатар_vr	/anna/basler/left/lnage/h264: waiting for transform: Query anna_basler_left_optical_frame <- anna_nominal_head_link: Would require extrapolation
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15:43:23	/otto/left/driver	Robot 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
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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

### Force



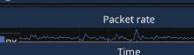
### Torque




### Roughness

/roughness_detector_client/confidence	1.2
0.8	
0.4	
0.0	

### Packet rate



### Packet Loss Concealment



# 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

5 GHz

TX: 390 MB/s MCS 8 20M 1600000


Robot

2.4 GHz


TX: 26 MB/s MCS 2 20M 1600000

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?)
15:42:07	/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 (141.240874364s)
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
15:43:58	/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

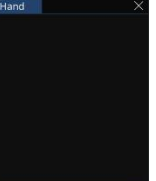
#images: L:356, R:356, D:1639

Train error: 3.891891 deg

### Bird's Eye



### Hand



### Anna/left/commander

Status: EXEC Joints

Reason: NOMINAL

Action: inactive

Lock	J5	J6
Power off	J7	

### Anna/right/commander

Status: EXEC Joints

Reason: NOMINAL

Action: inactive

Lock	J5	J6
Power off	J7	

### otto/left/commander

Status: SS2 Joints

Reason: NOMINAL

Action: inactive

Lock	J5	J6
Power off	J7	

### otto/right/commander


Status: SS2 Joints

Reason: NOMINAL

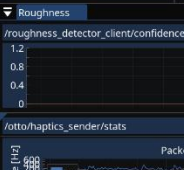
Action: inactive

Lock	J5	J6
Power off	J7	


### Force



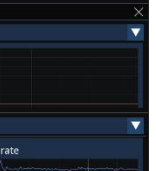
### Torque



### Force

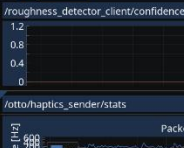


### Torque

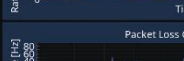


### Roughness

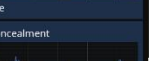
/roughness\_detector\_client/confidence



### Packet rate



### Packet Loss Concealment





# 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 right	479.9 Hz (delay 0.04s)
Wheels	Delay: 0.05s
Spine	0.50m (57%)
Audio	Human
Face display	Human
E-Stop	OK
Bagfile	Paused

Anna Core

/rosmon_anna_core/state	On	Off
Node	CPU...	
/anna/audio/carla	0.00	
/anna/audio/haptics	0.03	
/anna/audio/interface	0.05	
/anna/audio/jack	0.00	
/anna/audio/player	0.01	
/anna/audio/thru_comm	0.26	
/anna/audio/thru_comm02	0.00	
/anna/audio/thru_speak	0.01	
/anna/audio/thru_haptic	0.00	
/anna/audio/thru_speaker	0.02	
/anna/network_control	On	Off
/anna/monitor	0.01	
/anna/network_control	0.00	
/anna/operator_repub	0.02	
/anna/right_commander	0.00	
/anna/service_receiver	0.00	
/anna/sylog	0.00	
/anna/symon	0.10	
/anna/ft_static_agg	0.00	
/anna/ft_transceiver	0.08	
/anna/transceiver	0.04	
/atlas_receiver	0.02	
/atlas_sender	0.00	
/i.config_server	0.00	
/ping_node	0.00	

Anna Network

/anna/network_control/status	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 Left/Right Commander

/anna/left/commander/status	Status: EXEC	Reason: NOMINAL	Action: inactive
/anna/right/commander/status	Status: EXEC	Reason: NOMINAL	Action: inactive

Anna Left/Right Commander

/anna/left/commander	Lock	Power off
/anna/right/commander	Lock	Power off

Anna Left/Right Commander

/anna/left/commander/status	Status: SS2	Reason: NOMINAL	Action: inactive
/anna/right/commander/status	Status: SS2	Reason: NOMINAL	Action: inactive

VR Calibration

VR Calibration	1.315	Min
VR Calibration	0.10 rad	Max other
VR Calibration	0.280	Max

VR Calibration

VR Calibration	Up	Calib
VR Calibration	90°	Calib
VR Calibration	Down	Calib

VR Calibration

VR Calibration	Lock	Power off
VR Calibration	Lock	Power off

### network\_display/network\_display

Freq: 5.76 GHz  
Associated since: Signal: -64 dBm  
RX: 390 MB/s MCS 8 20M 40M 80M 160M 320M 640M 1280M 2560M 5120M

5 GHz

TX: 390 MB/s MCS 8 20M 40M 80M 160M 320M 640M 1280M 2560M 5120M

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 160M 320M 640M 1280M 2560M 5120M

2.4 GHz

TX: 26 MB/s MCS 0 20M 40M 80M 160M 320M 640M 1280M 2560M 5120M

### Basler

### Left Eye

### Right Eye

### Mouth

### Reconstruction

### Eye calibration

Bag: 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

### Left/Right Driver Wrench

Force

Torque

### Roughness

/roughness\_detector\_client/confidence

1.2

0.8

0.4

0.0

Packet rate

Packet Loss Concealment

### Log

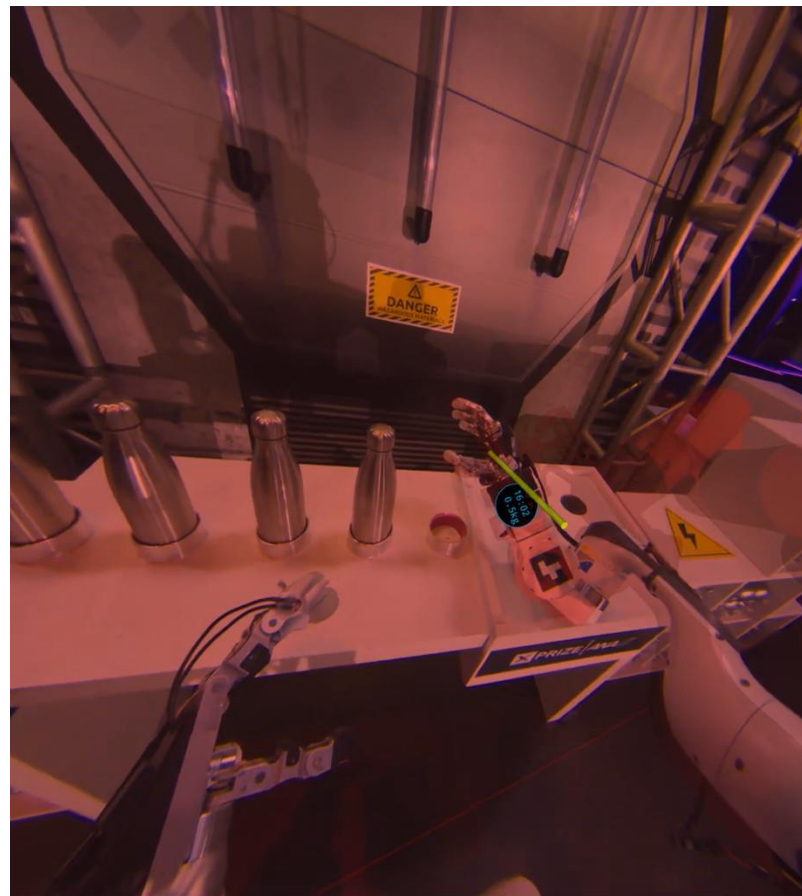
Filter

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
/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 /anna/basler/right/lnage/h264: waiting for transform: Query anna_basler_right_optical_frame <-
anna_nominal_head_link: Would require extrapolation
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 /anna/basler/left/lnage/h264: waiting for transform: Query anna_basler_left_optical_frame <-
anna_nominal_head_link: Would require extrapolation
15:42:22 /avатар_vr Right tracking pose is not valid (tracker turned off?) (connected=true, valid=true, result=101)
15:42:29 /otto/monitor Left tracking pose is not valid (tracker turned off?) (connected=true, valid=true, result=101)
15:42:87 /otto/monitor long delay in decoder
15:43:19 /avатар_vr Otto right arm command is too old (141.240074364s)
15:43:07 /anna/right/driver Otto left arm command is too old (141.256047258s)
15:43:08 /anna/left/driver /anna/birds_eye/out/compressed: Dropping old frames
15:43:15 /avатар_vr Could not get Senseglove data. Please check US connection.
15:43:98 /sense_glove 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
15:43:58 /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 @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 @ResourcePending'
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 9.993624202s 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 /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

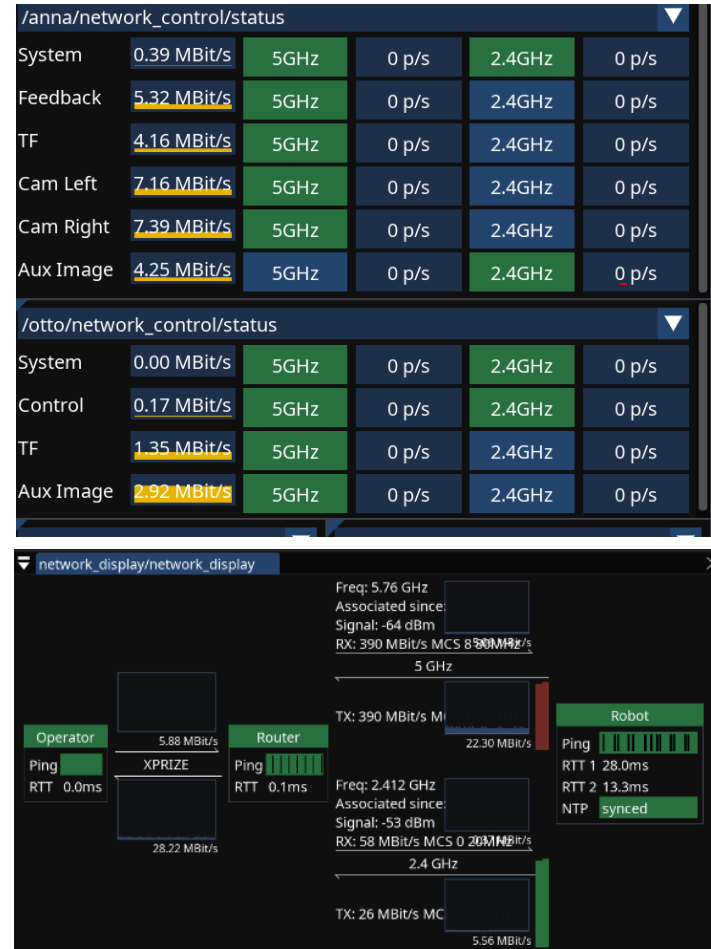
1. Operator crew awareness
2. Automatic arm resets
3. ROS node respawn
4. State- and connectionless network system (pure UDP)
5. Redundant WiFi connections
6. PC Watchdog



# Network Details

- Separate ROS cores operator / 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
- Monitor packet loss due to congestion
- The core software is already open source,

[https://github.com/AIS-Bonn/nimbro\\_network](https://github.com/AIS-Bonn/nimbro_network)



# 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

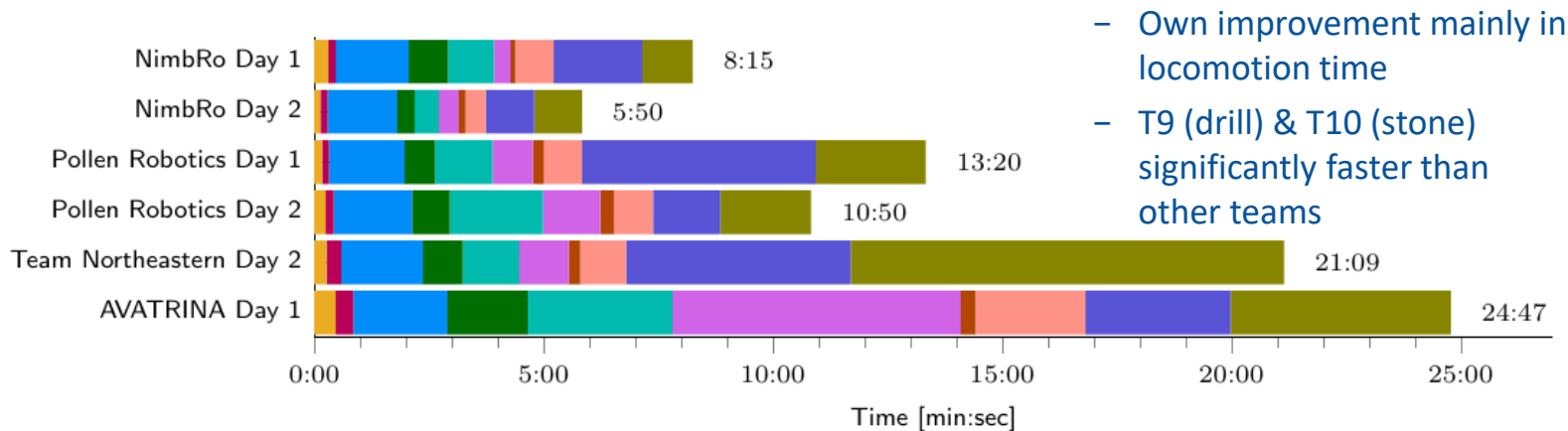


# Finals Day 2 Testing



# Finals Timings

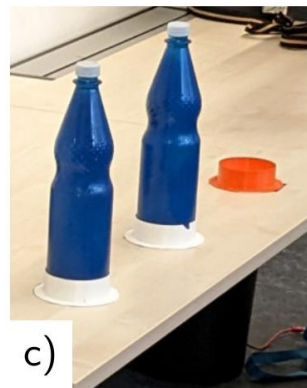
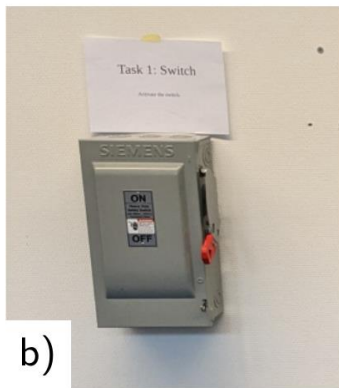
Team	Day	Time [mm:ss]											Total
		Start	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	
NimbRo	1	00:00	00:18	00:10	01:35	00:52	01:00	<b>00:22</b>	<b>00:06</b>	00:50	01:56	01:06	08:15
	2	00:00	<b>00:08</b>	<b>00:09</b>	01:31	<b>00:23</b>	<b>00:32</b>	00:26	00:09	<b>00:26</b>	<b>01:04</b>	<b>01:02</b>	<b>05:50</b>
	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	<b>00:09</b>	01:39	00:40	01:15	00:53	00:14	00:50	05:06	02:24	13:20
	2	00:00	00:15	<b>00:09</b>	01:43	00:49	02:02	01:15	00:18	00:51	01:28	01:59	10:50
Team Northeastern	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	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	1	00:00	00:13	00:26	<b>01:23</b>	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



# Team NimbRo



# User Study



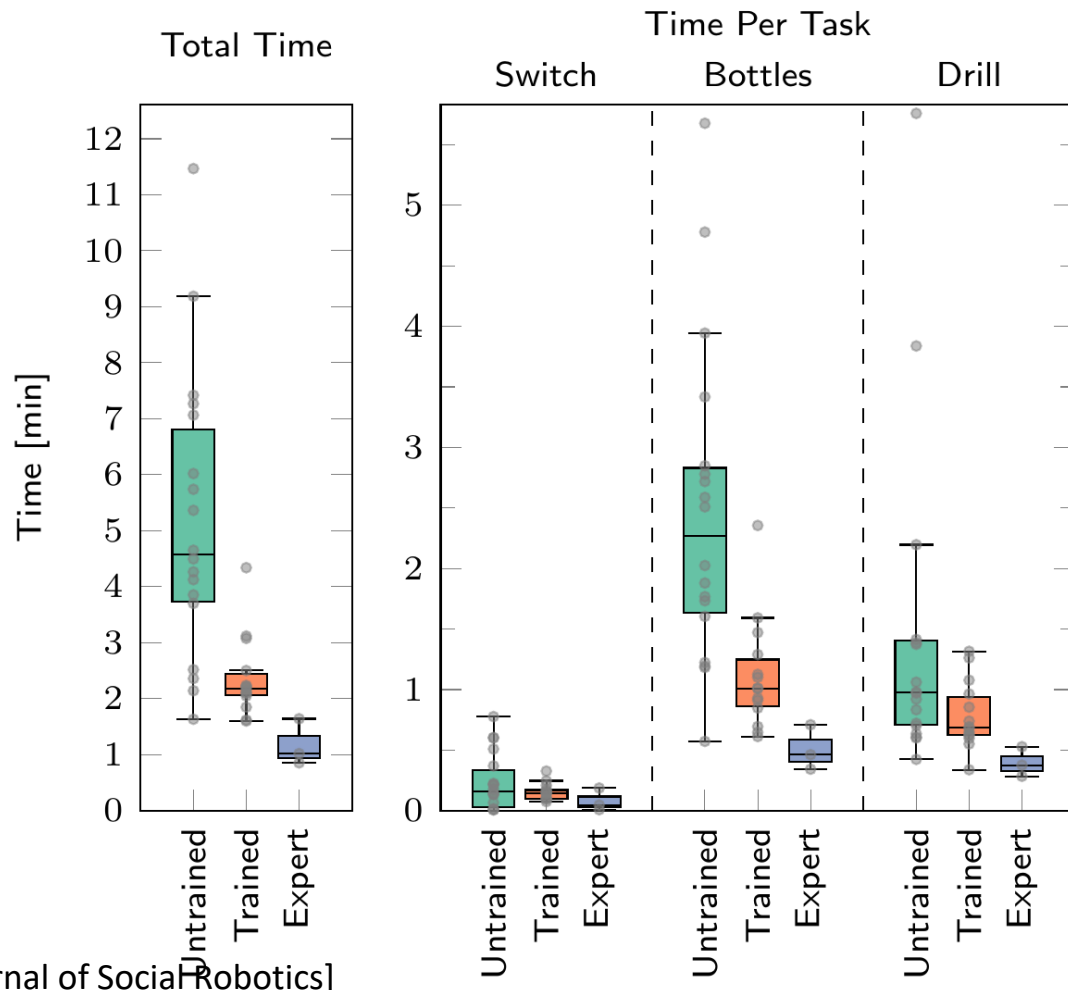
- Three tasks, similar to finals (Locomotion+Switch, Bottles, Drill)
- 35 participants, 32 with no prior experience of the system
- All participants: 2 min intro video explaining the system (task agnostic)
- Three groups: No further training, 10 min task training, expert team members  
similar to Finals



# User Study

- Unsurprising: Clear advantage of training (2x)
- Unsurprising: Expert operators are very fast (2x)
- 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
- Frequent testing under competition conditions: system & people!
- 1:1 correspondence is best
- 6D head motion actually simplifies manipulation control
- Immersive control overlays – don't break immersion!
- Facial animation and gestures: Head & gaze direction enables shared awareness
- Modified components

# Questions?

## Join the Winning Team!

## We are hiring.

