

NimbRo Avatar: Intuitive Immersive Telepresence balancing Interaction, Manipulation, and Mobility

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University of Bonn
Computer Science Institute VI
Autonomous Intelligent Systems



Experience with Teleoperated Robots

- Multiple domains
- Often motivated by competitions and challenges



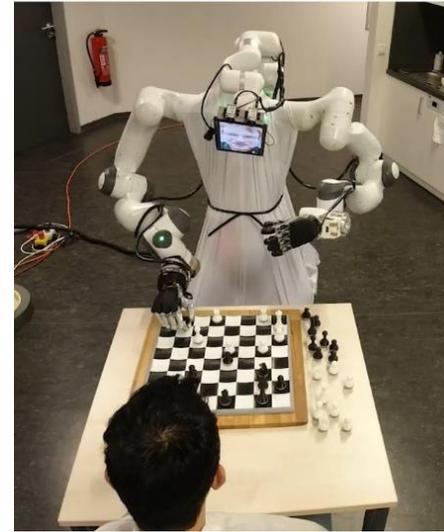
RoboCup@Home



DARPA Robotics Challenge
DLR SpaceBot Cup



CENTAURO



ANA Avatar XPRIZE

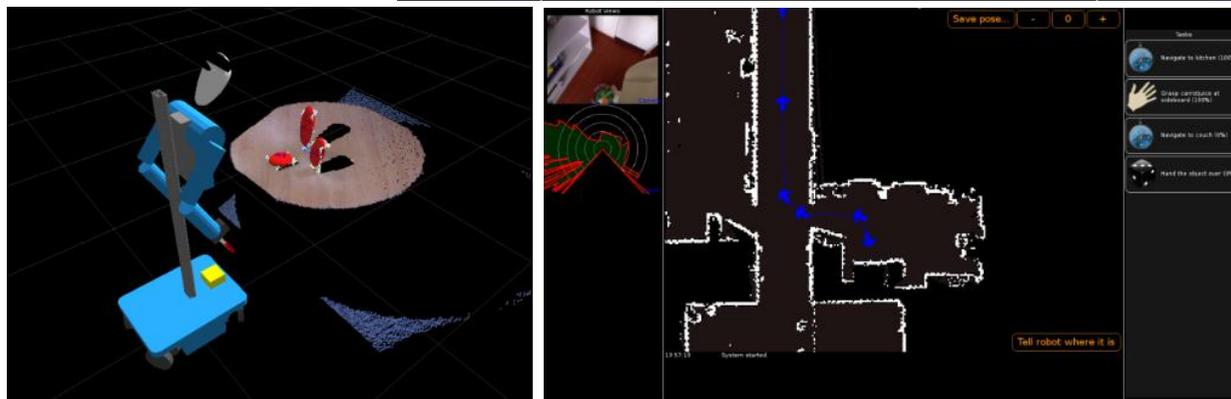
Cognitive Service Robot Cosero



Handheld Teleoperation Interface

■ Three levels of autonomy / control:

- Task level
- Skill level
- Direct control

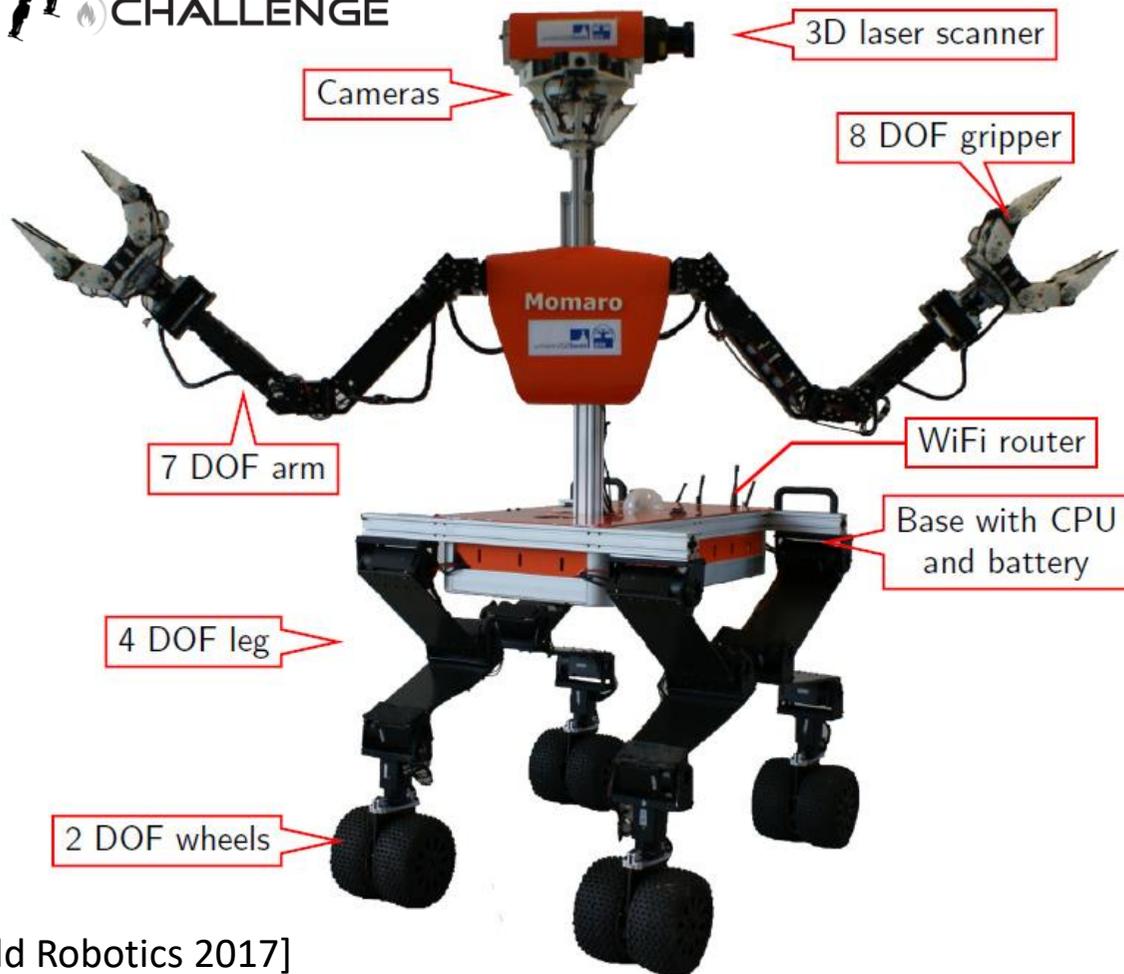


[Schwarz, Stückler, Behnke, HRI 2014]

Mobile Manipulation Robot Momaro

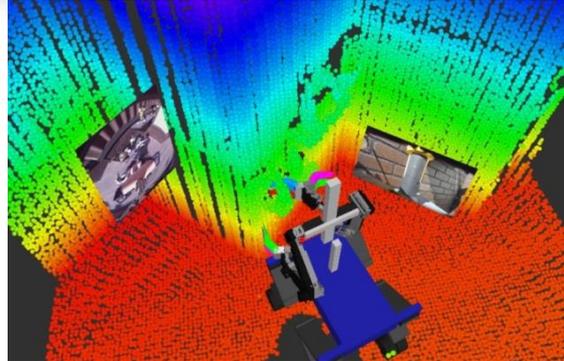


- Four compliant legs ending in pairs of steerable wheels
- Anthropomorphic upper body
- Sensor head
 - 3D laser scanner
 - IMU, cameras



Manipulation Operator Interface

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



[Rodehutsors et al., Humanoids 2015]

DARPA Robotics Challenge

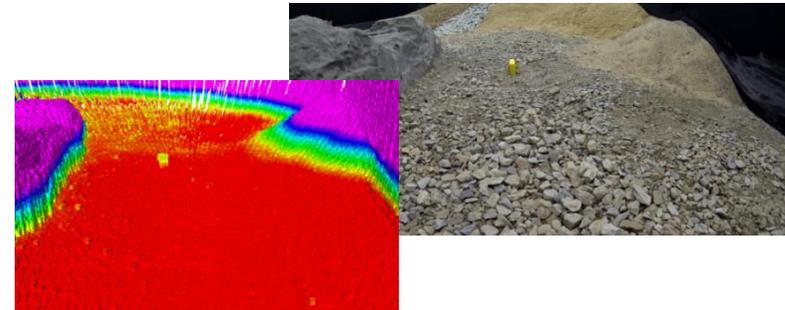
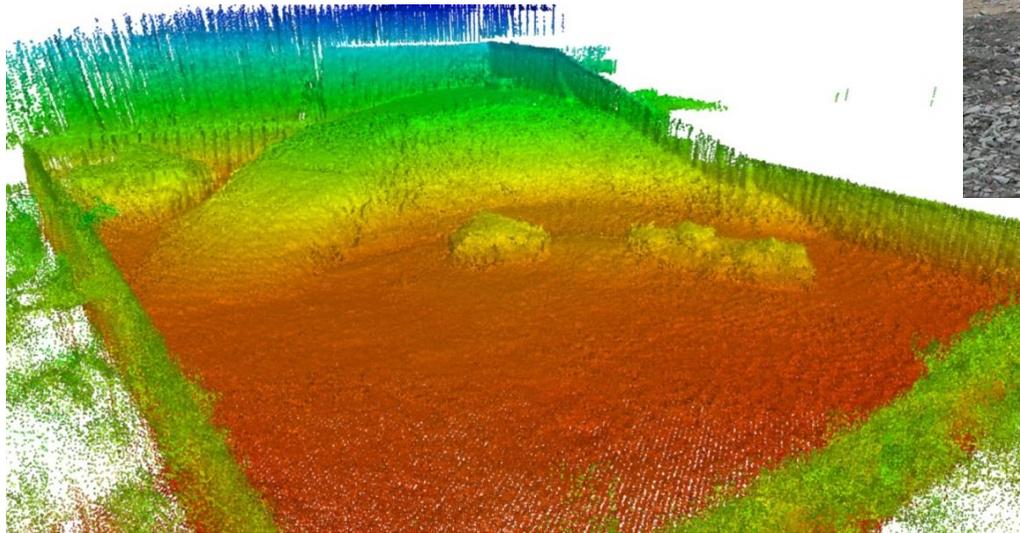


Team NimbRo Rescue



DLR SpaceBot Cup 2015

- Mobile manipulation in rough terrain





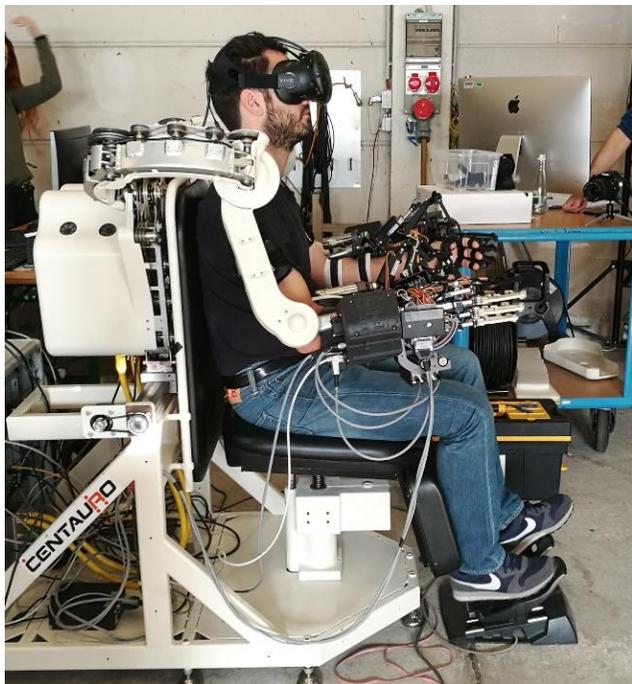
[Schwarz et al., Frontiers on Robotics and AI 2016]

8X

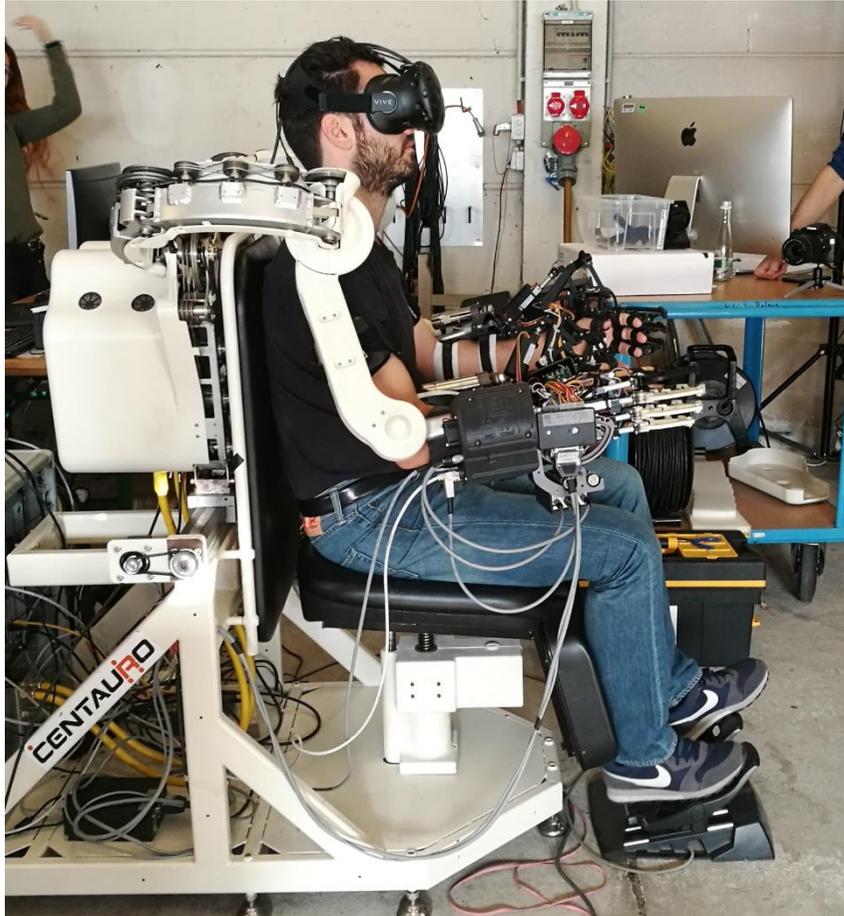
Robust Mobility and Dexterous Manipulation in Disaster Response by Fullbody Telepresence in a Centaur-like Robot

CENTAUR_{RO}

- 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

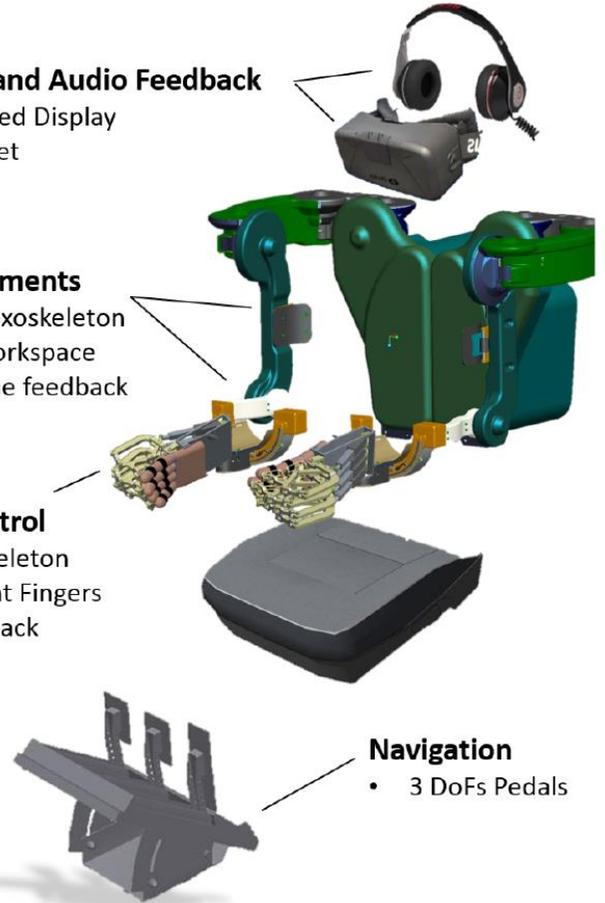
- Arm and wrist exoskeleton
- 7 DoFs, wide workspace
- Force and torque feedback

Grasping Control

- Hand exoskeleton
- Independent Fingers
- Force feedback

Navigation

- 3 DoFs Pedals



Teleoperation with Joystick and Spacemouse

3D VEROSIM
visualization

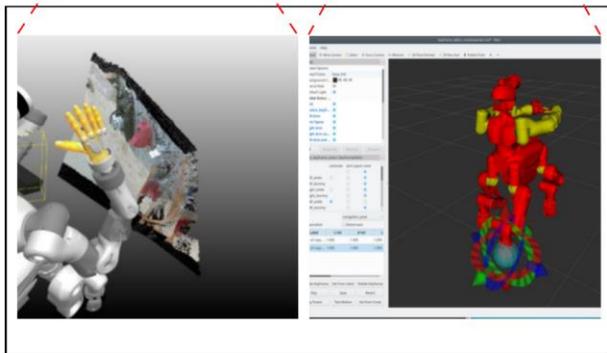
Robot state &
Keyframe editor

Foot
cameras

Panoramic view &
RGB Kinect image

Task specific
GUI

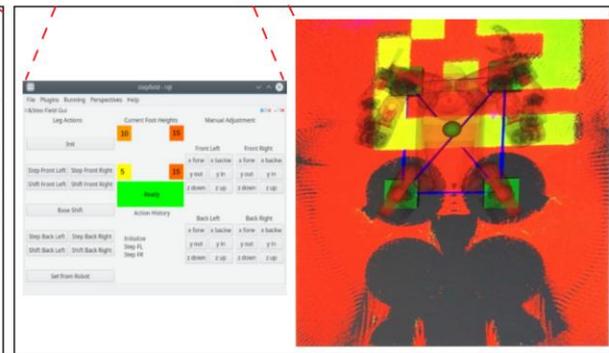
Pointcloud, ground
contact & COM markers



Monitor 1



Monitor 2



Monitor 3

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



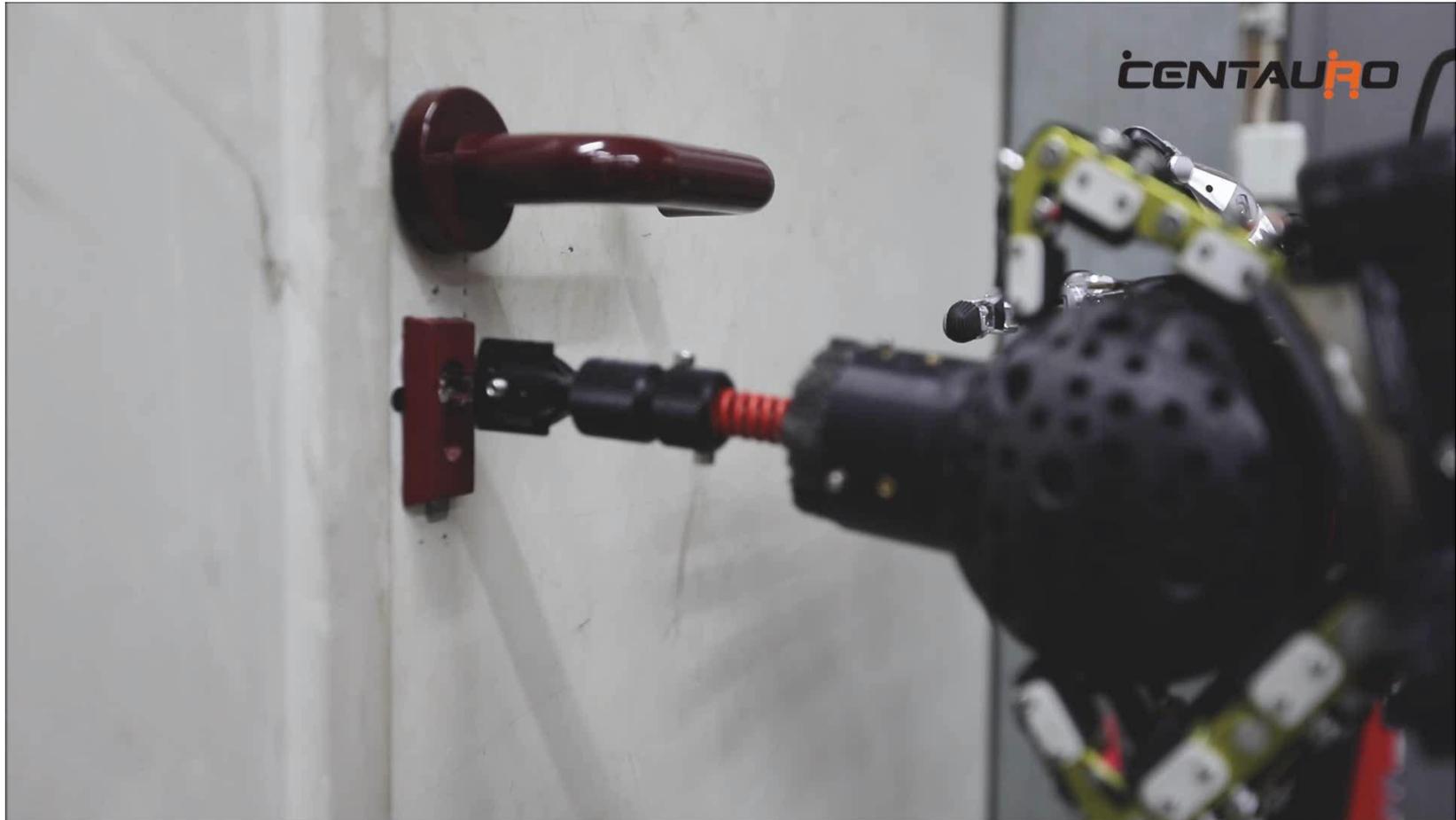
CENTAURO Evaluation @ KHG: Locomotion Tasks



Grasping an Unknown Power Drill and Fastening Screws



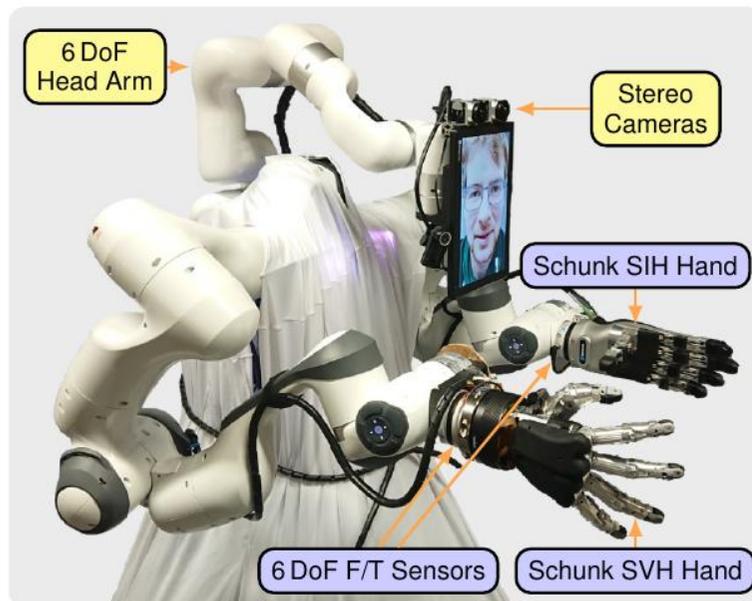
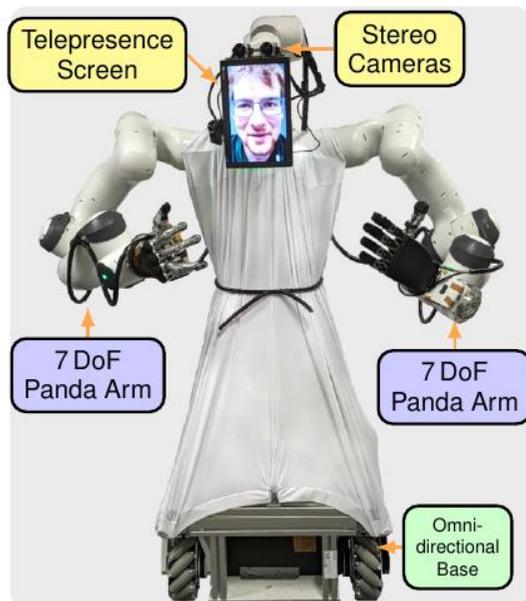
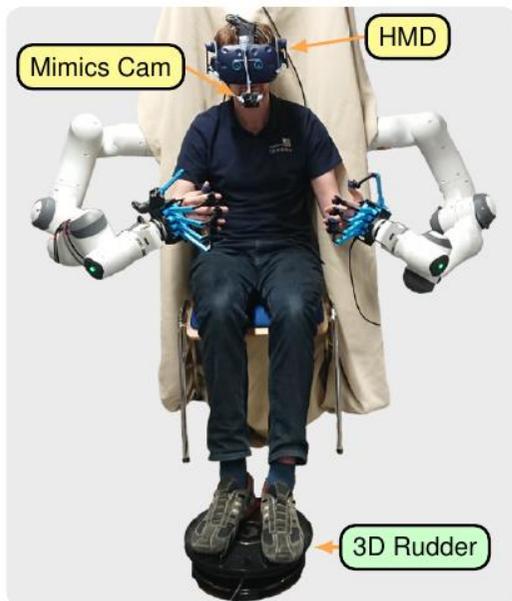
CENTAURO: Complex Manipulation Tasks



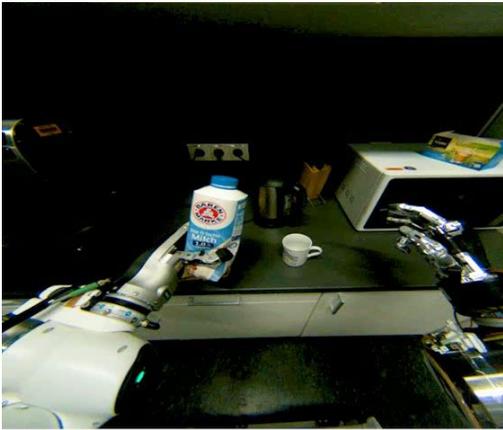
- Requires mobility, manipulation, human-human interaction
- Focuses on the immersion in the remote environment and the presence of the remote operator



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



Team NimbRo Semifinal Submission



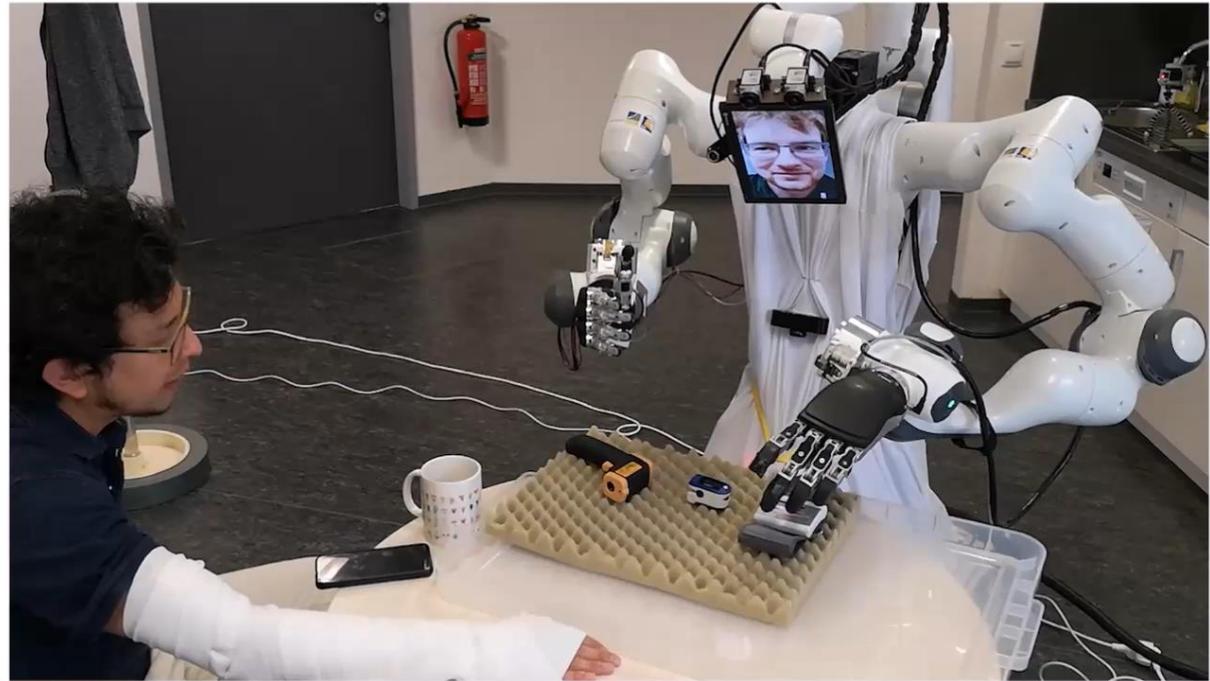
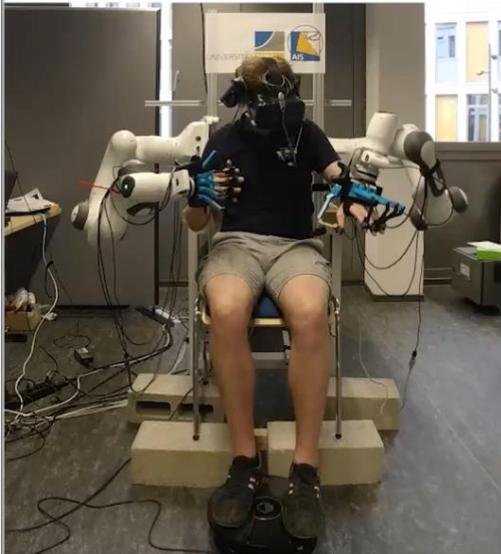
Team NimbRo

Semifinal Team Video

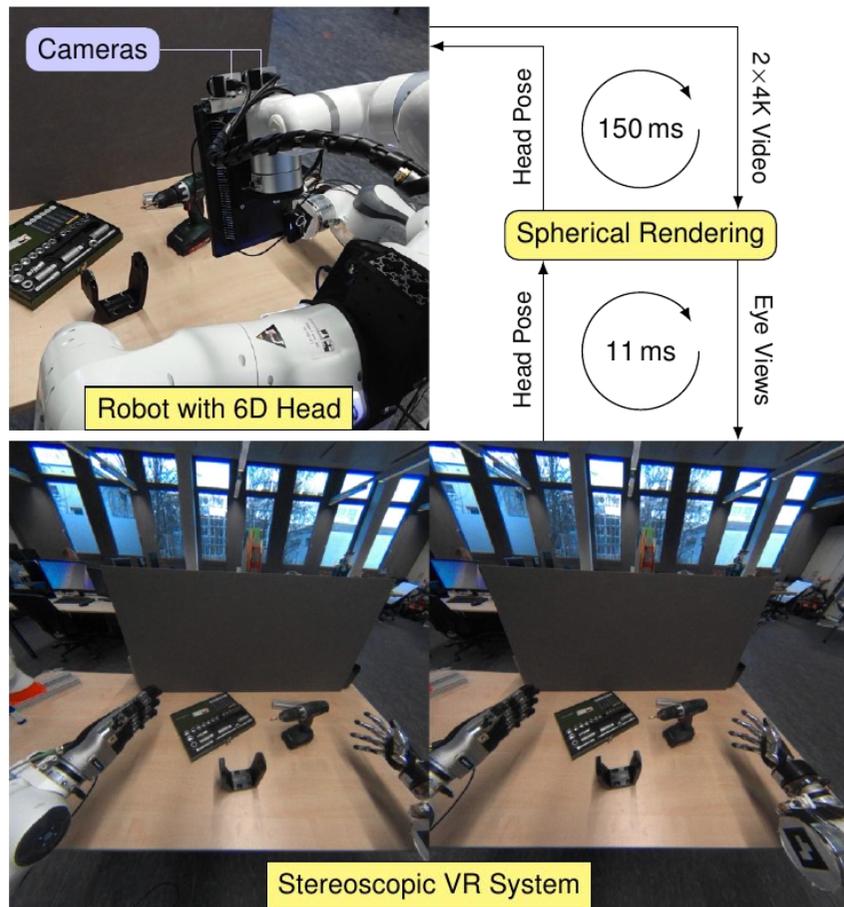


Tasks

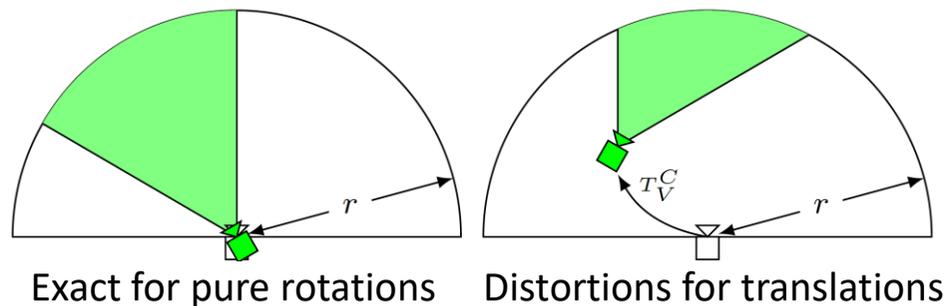
1. Make a coffee
2. Greet the recipient
3. Measure temperature
4. Measure blood pressure
5. Measure oxygen saturation
6. Help recipient with jacket



NimbRo Avatar: Immersive Visualization

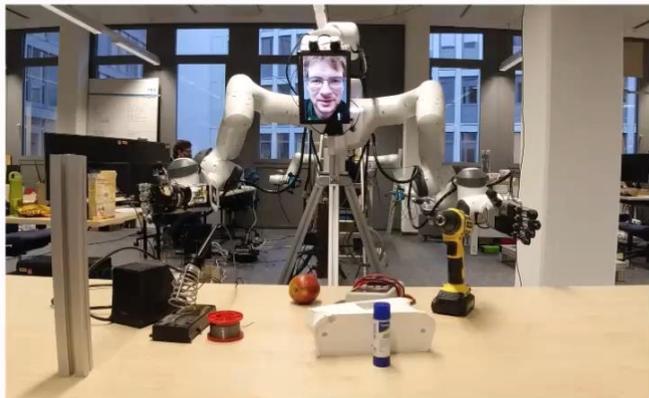


- 4K wide-angle stereo video stream
- 6D neck allows full head movement
 - Very immersive
- Spherical rendering technique hides movement latencies
 - Assumes constant depth

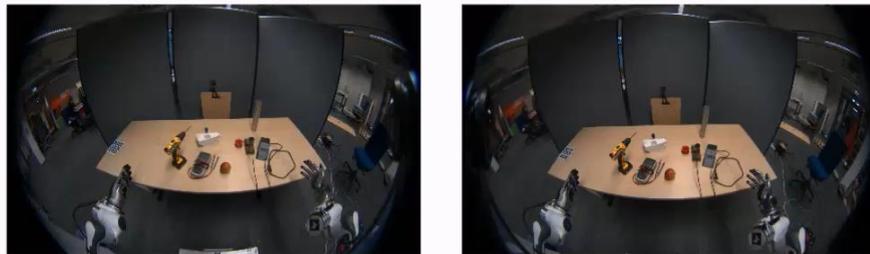


NimbRo Avatar: Immersive Visualization

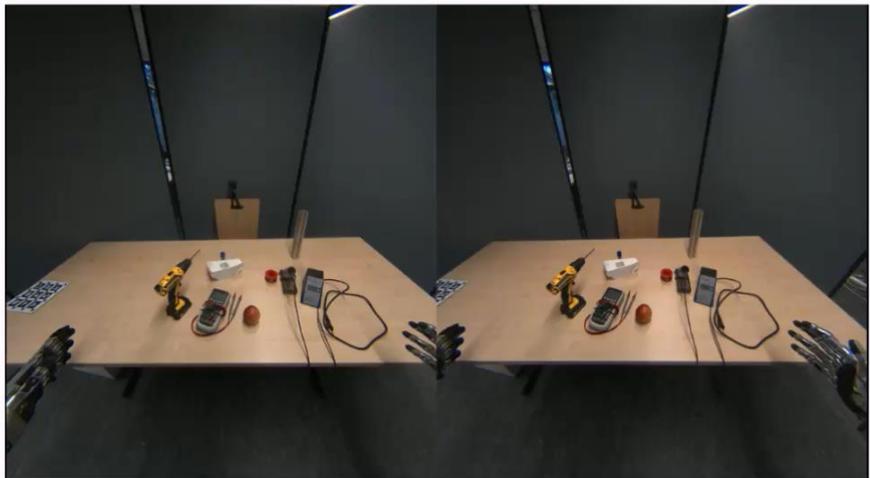
Avatar Robot



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



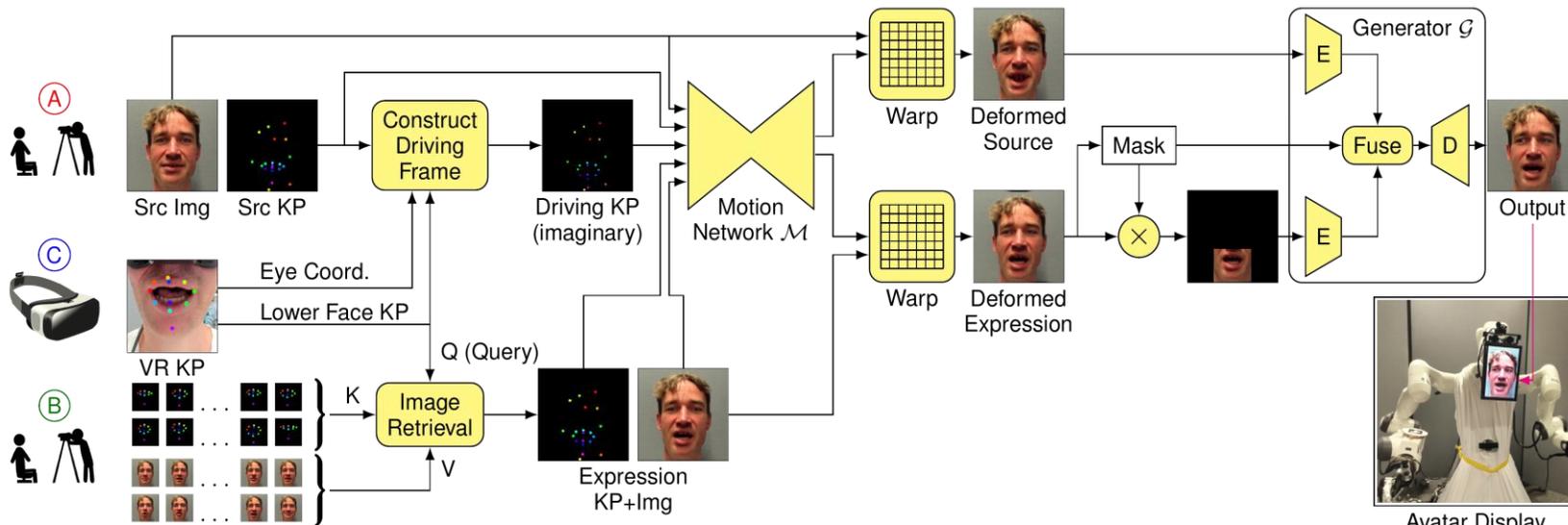
Left Eye



Mouth



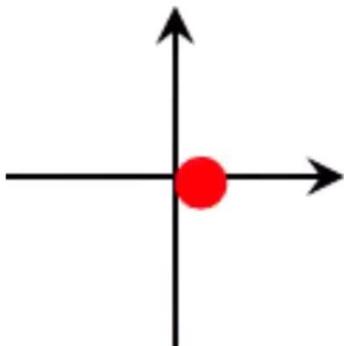
Right Eye



[Rochow et al. IROS 2022]

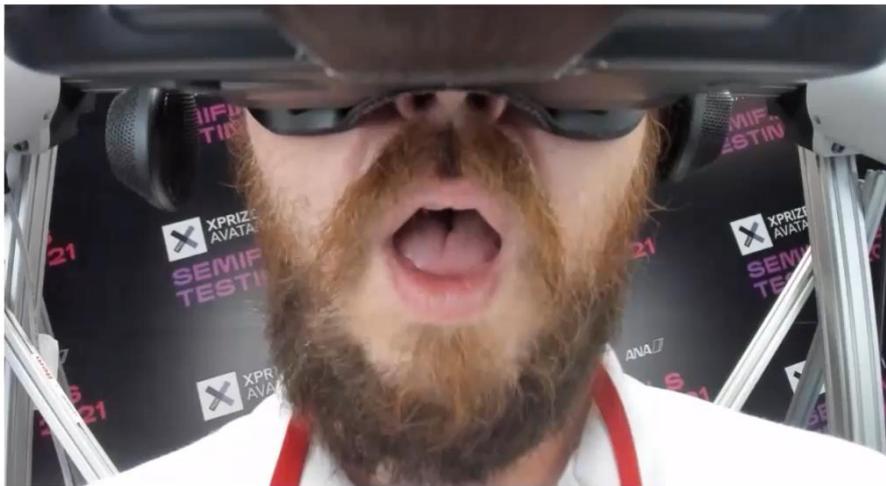
NimbRo Avatar: Operator Face Animation

Gaze
Direction

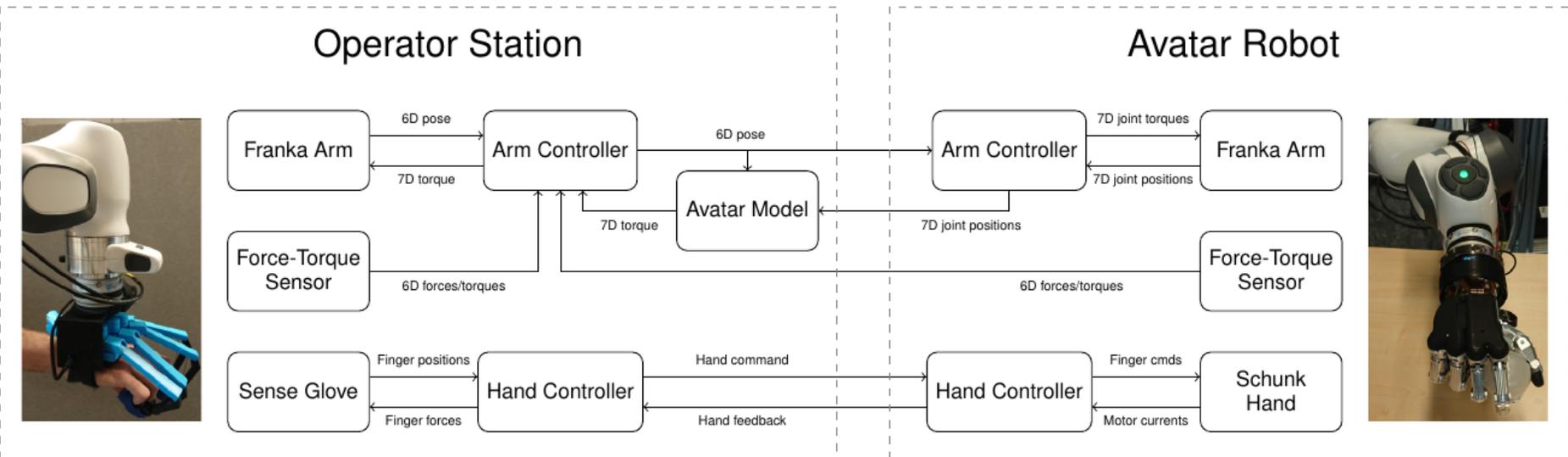


Output

Mouth Cam



NimbRo Avatar: Manipulation with Force and Haptic Feedback

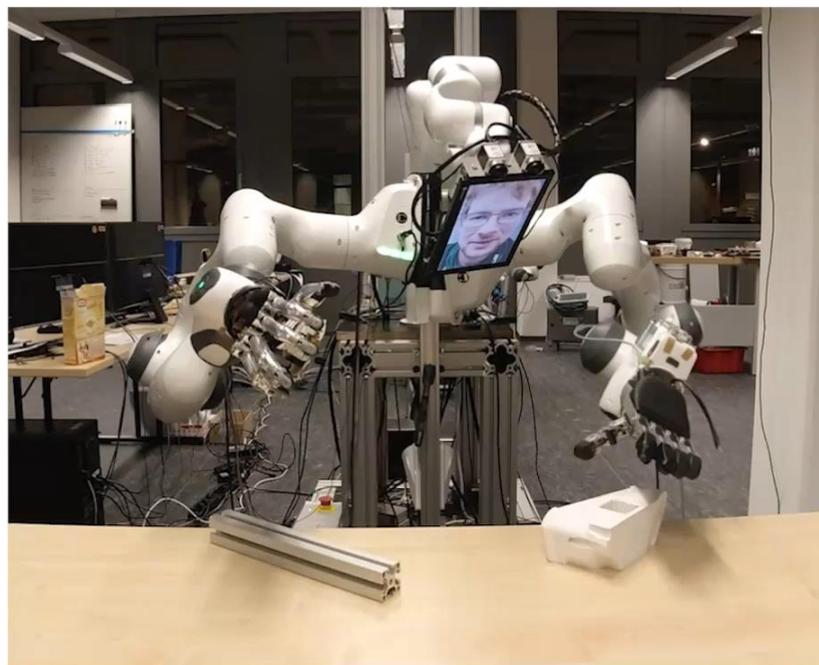


- Arm exoskeleton (Franka Emika Panda), F/T sensor (OnRobot HEX), hand exoskeleton (SenseGlove)
- Avatar side: Arm + F/T sensor + Schunk SVH / SIH hand
- Provides force feedback for wrist and haptic feedback for fingers
- Avatar limit avoidance using predictive model to reduce latencies

NimbRo Avatar: Manipulation with Force and Haptic Feedback

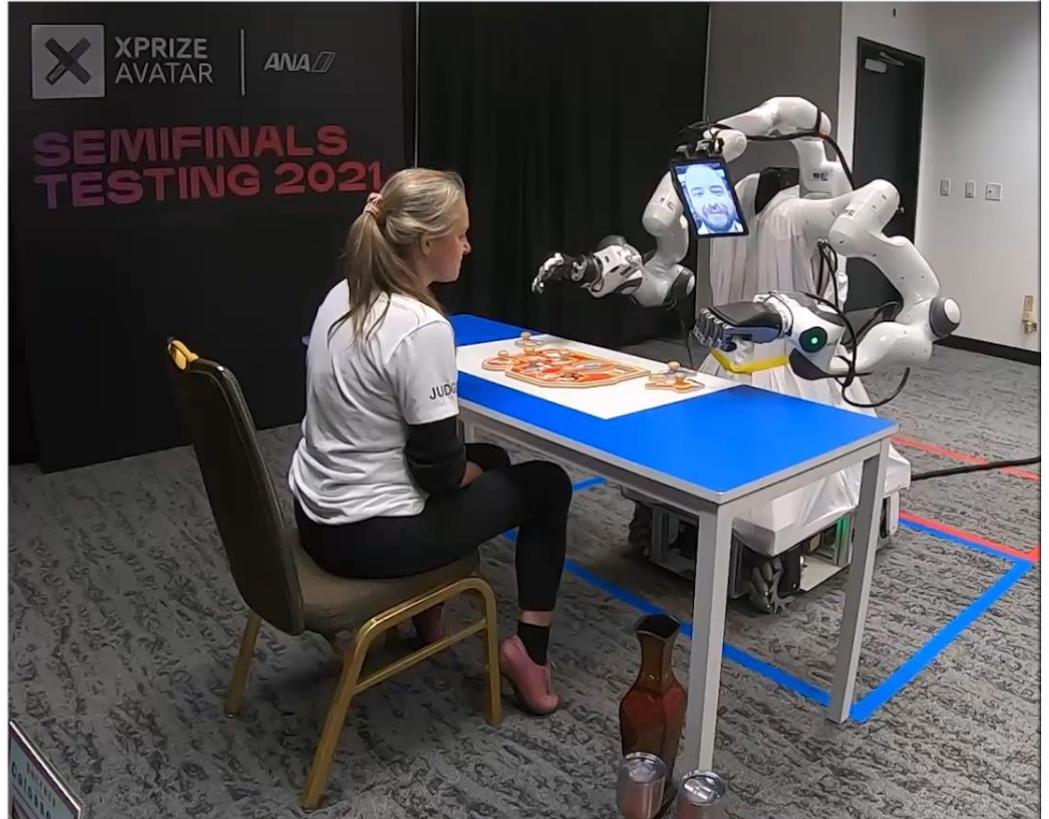
User Study Task

performed by a trained operator



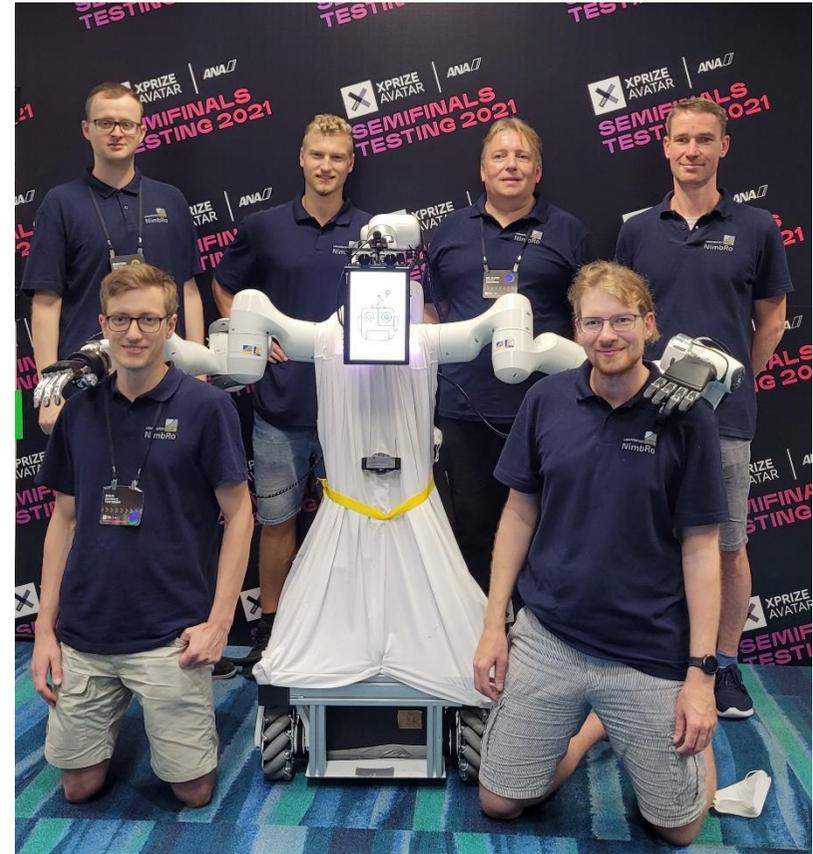
NimbRo Avatar

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



[Schwarz et al. IROS 2021]

New Finals Requirements

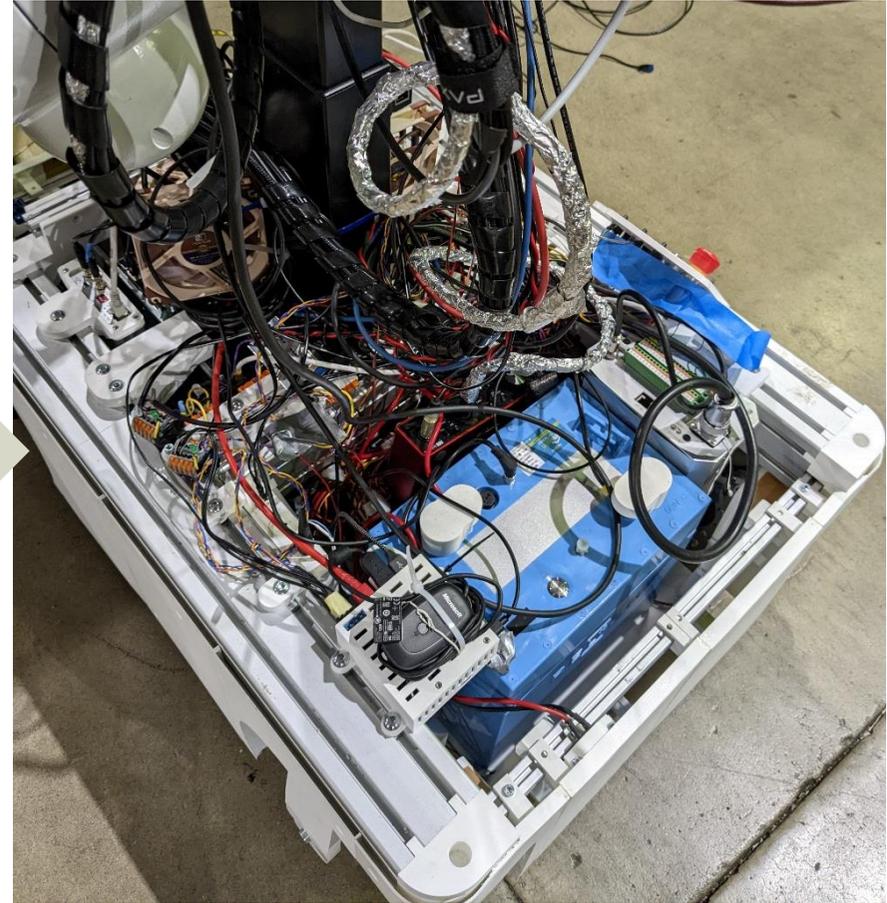
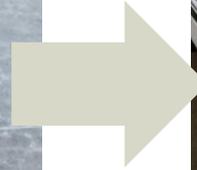
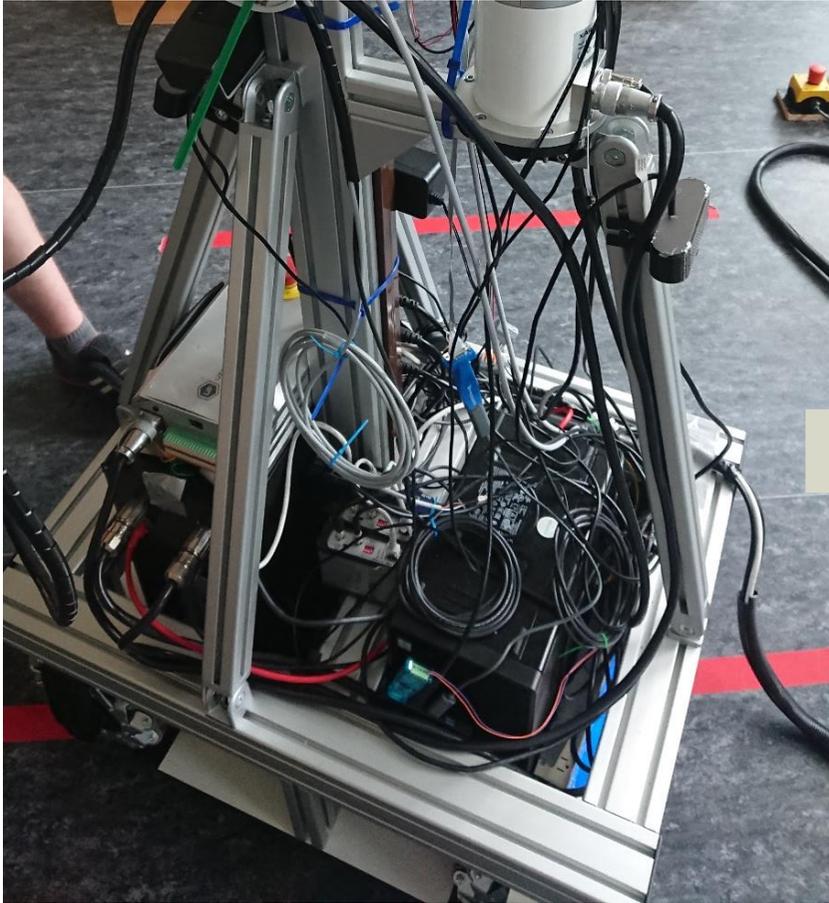
- Untethered avatar robot, more mobility
- Movable operator station
- 10 tasks in a sequence, including haptics
- System reliability extremely important
- Tasks fulfillment has highest importance in scoring
- Subjective criteria also important
- Trial time to break ties



Finals Test Run Day 1

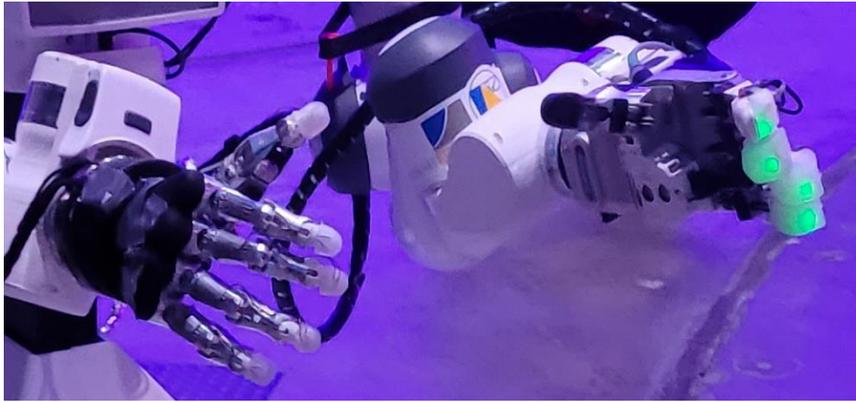


System Changes for Tetherless Operation

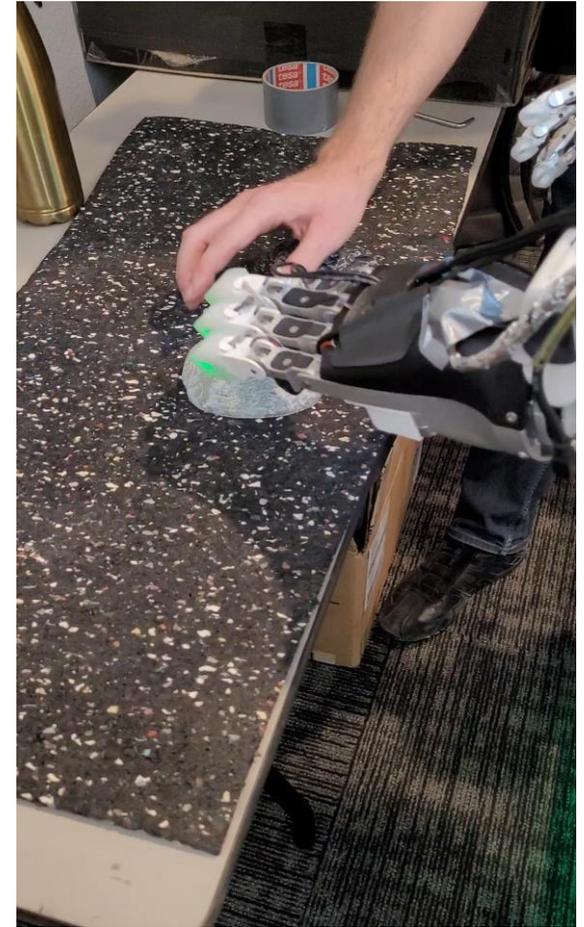


Haptic Perception

- Sensors in the finger tips



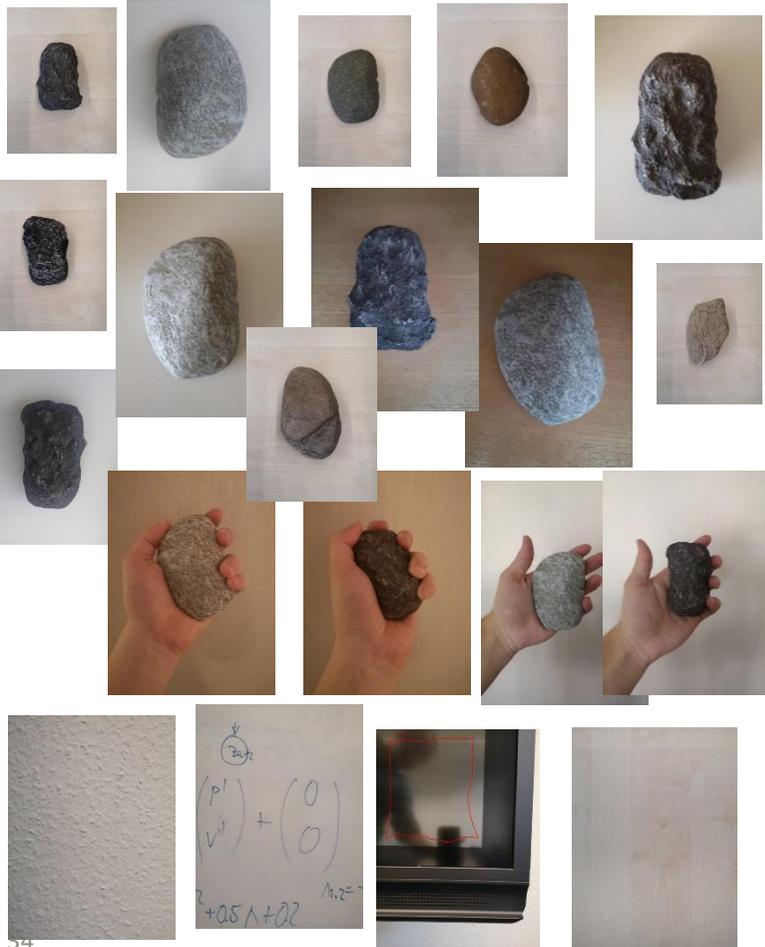
- Actuators on the hand exoskeleton



Haptics Perception



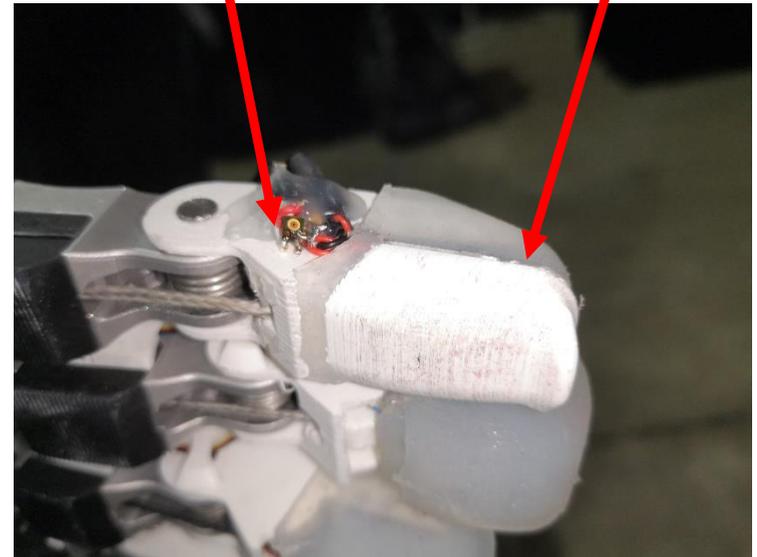
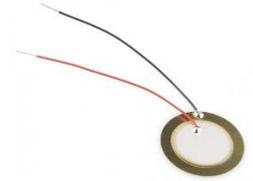
Roughness Sensing



Mems
Microphone



Contact
Microphone



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

▼ Anna Core

▼ /rosmon_anna_core/state

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_comm05	0.00
/anna/audio/thru_haptic01	0.01
/anna/audio/thru_speak01	0.00
/anna/audio/thru_speak02	0.00
/anna/audio/thru_speak03	0.00
/anna/audio/thru_speak04	0.00
/anna/monitor	0.01
/anna/network_control	0.00
/anna/operator_repub	0.02
/anna/service_receiver	0.00
/anna/sylog	0.00
/anna/symon	0.10
/anna_tf_static_agg	0.00
/anna_tf_transceiver	0.08
/atlas/transceiver	0.04
/atlas_receiver	0.02
/atlas_sender	0.02
/i.config_server	0.00
/ping_node	0.00

▼ Otto

rosmon arms

rosmon_otto_arms/state

Node	CPU:
/arduno	0.00
/otto/raulhaver_comm	0.02
/otto/left/driver	0.00
/otto/left	0.02
/otto/right/driver	0.04
/otto/right	0.28
/otto/rudder_3d	0.07
/otto/state_pub	0.05

▼ /rosmon_network

rosmon_otto_network/state

No message

▼ sense_glove/GestureGUI

Rudder	0.08 rad	Thumb rot
Pedal	0.690	Max
Eye Tracking	-0.09 rad	Thumb flt
VR Calibration	1.315	Min
Audio	0.10 rad	Max other
Jamulus Otto	0.280	Max

▼ VR

VR Calibration

VR Calibration	Up	Calib
	90°	Calib
	Calib	

▼ Otto

otto/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/commander

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

▼ /anna/right/commander

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

▼ /otto/left/commander

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

▼ /otto/right/commander

Status: SS2	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

5.88 MB/s

XPRIZE

Router

22.30 MB/s

Ping RTT 0.0ms

28.22 MB/s

Robot

2.4 GHz

TX: 26 MB/s MCS 8 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 error:	0%		
Train error:	3.891891 deg		

Bird's Eye

Hand

Force

Force	10
X	0
Y	0
Z	-10

Torque

Torque	10
X	0
Y	0
Z	-10

Roughness

roughness_detector_client/confidence

Confidence	1.2
0.8	
0.4	
0.0	

Packet rate

Packet Loss Concealment

Filter

Time Node Message

```
15:41:34 /otto/monitor Left 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
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=10)
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
Left tracking pose is not valid (tracker turned off?) (connected=true, valid=true, result=10)
15:43:19 /avатар_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 /avатар_vr /anna/birds_eye/out/compressed: Dropping old frames
15:43:98 /sense_glove Could not get Senseglove data. Please check US connection.
E-Stop released (mode 1), back to control
franka:ControlException: L2ofranka: Move command rejected: command not possible in the current
mode
rosmon: /otto/left/driver died from signal 6
rosmon: starting '/otto/left/driver'
Robot is locked, I'm going to unlock it...
Setting brakes to 0
Getting if '@ResourcePending'
Could not lock/unlock brakes: state ABORTED/got error from Franka: eResourcePending
Checking if present...
Operator is present, not disabling.
rosmon: /otto/left/driver died from signal 6
rosmon: starting '/otto/left/driver'
Waiting for E-Stop release...
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]
Waiting for E-Stop release...
/anna/basler/right/lnage/h264: waiting for transform: Query anna_basler_right_optical_frame <-
anna_nominal_head_link: Would require extrapolation
Waiting for E-Stop release...
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]
/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

anna/system/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
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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

control_box/Clock

400:37 Anna Core | | | | |------------------------|----|-----| | rosmon_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 Network Control | | | | | | | |-----------|-----------|------|-------|--------|-------| | 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: 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 | | HDMI | 58.2 Hz (delay 0.06s) | | Bagfile | Paused |

network_display/network_display

Freq: 5.76 GHz
Associated since: Signal: -64 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
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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	Y	Z
0	X	Y	Z
-10	X	Y	Z

Torque

4	X	Y	Z
0	X	Y	Z
-4	X	Y	Z

Roughness

roughness_detector_client/confidence

Packet rate

Packet Loss Concealment

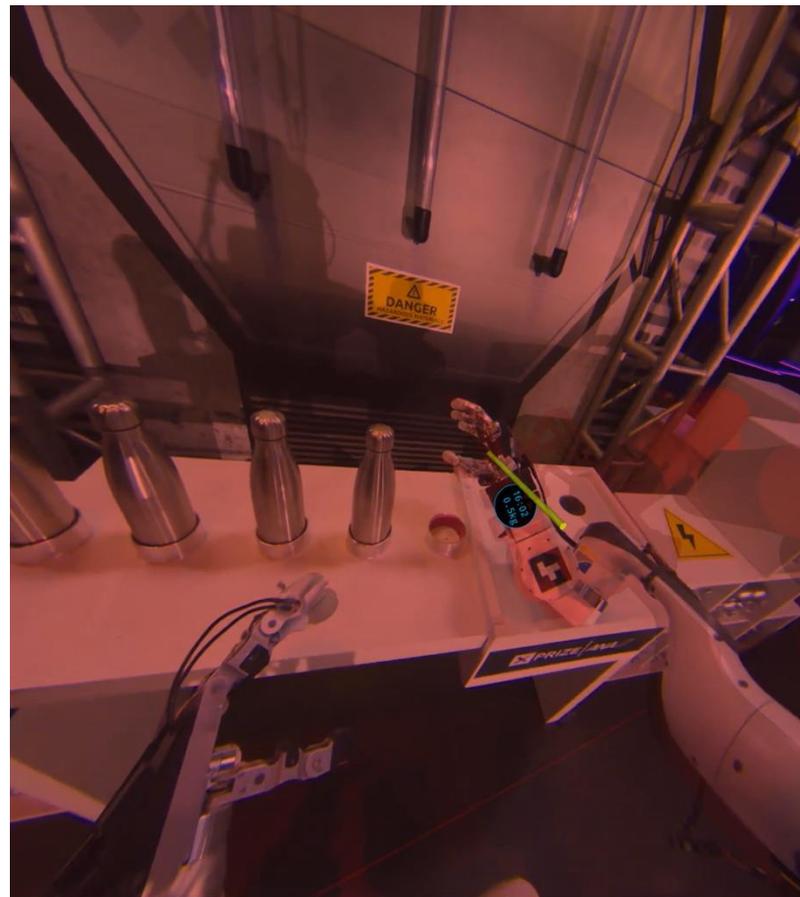
Otto config

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 USB 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	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 USB 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	Checking if 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 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

Reliability Features

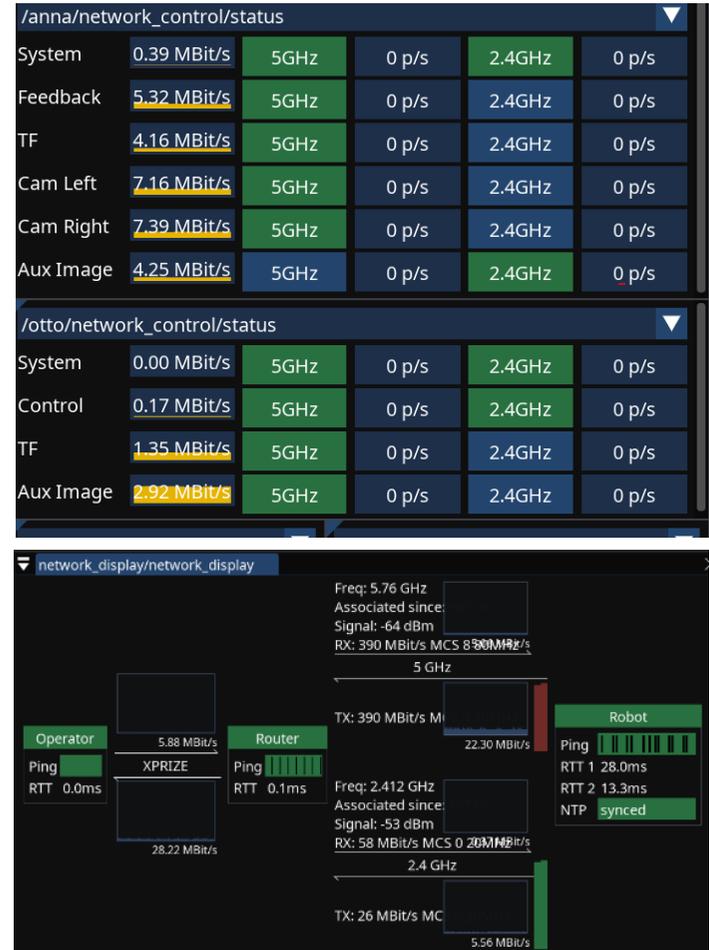
1. Operator crew awareness
2. Automatic arm resets
3. ROS node respawn
4. State- and connectionless network system (pure UDP)
5. Redundant WiFi connections
6. PC Watchdog



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



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



Team NimbRo



Questions?

