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

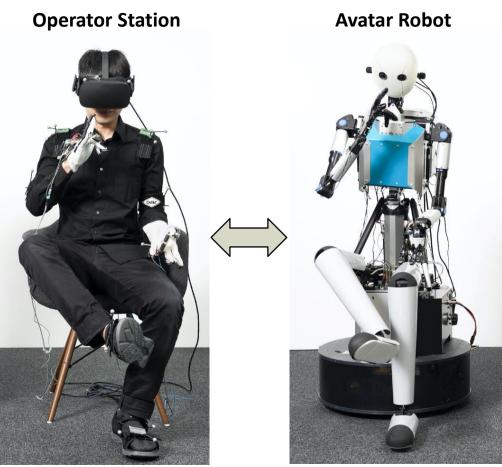
## Sven Behnke

University of Bonn Computer Science Institute VI – Intelligent Systems and Robotics Autonomous Intelligent Systems



#### **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





#### **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]



[Pollen Reachy]



[NASA Robonaut]



[Telexistence]

[Stanford OceanOneK]



[Intuitive Da Vinci]



[KAIST DRC Hubo]





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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



#### **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.



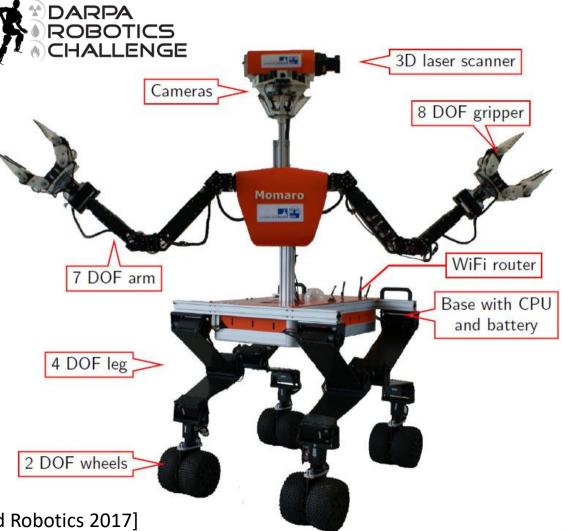


[Schwarz, Stückler, Behnke, HRI 2014]



### Mobile Manipulation Robot Momaro

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



7 [Schwarz et al. Journal of Field Robotics 2017]

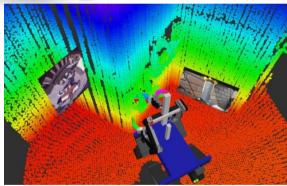
#### **Manipulation Operator Interface**

 3D headmounted display

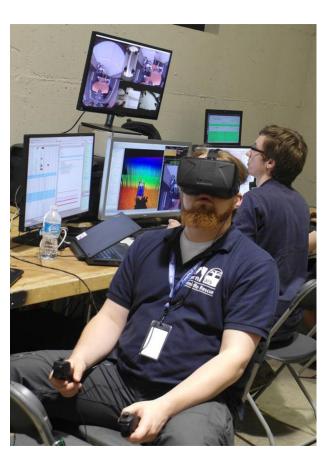


 3D environment model + images











[Rodehutskors et al., Humanoids 2015]

#### **DARPA Robotics Challenge**





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#### Team NimbRo Rescue

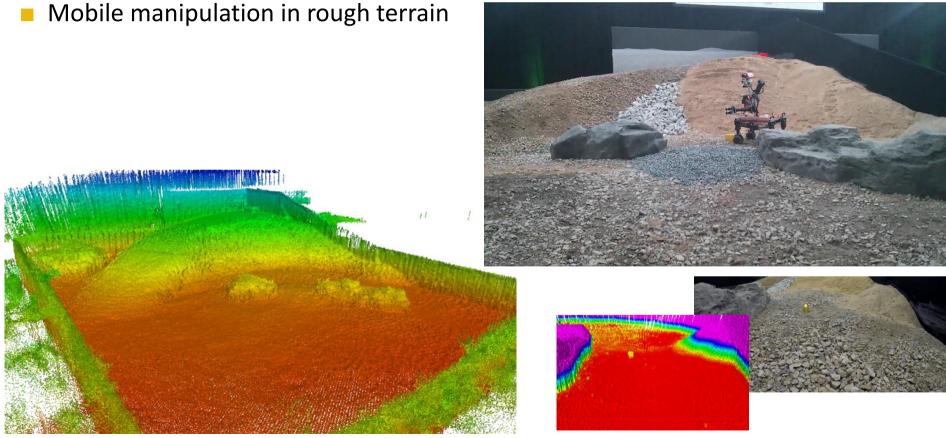
## Best European Team (4<sup>th</sup> place overall), solved seven of eight tasks in 34 minutes

KEEP OUT

<sup>10</sup> [Schwarz et al. Journal of Field Robotics 2017]



#### DLR SpaceBot Cup 2015



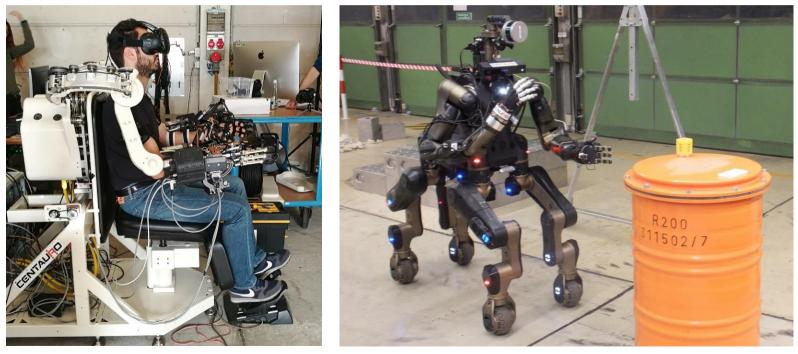
[Schwarz et al., Frontiers on Robotics and Al 2016]





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

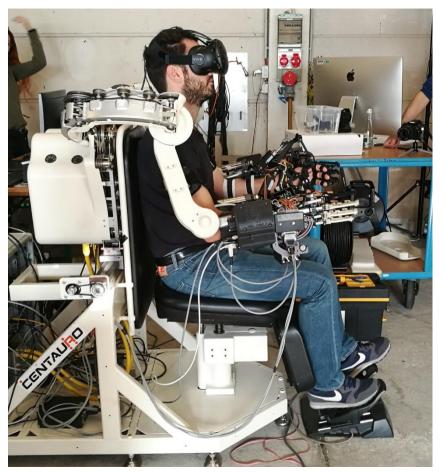
Four-legged robot with steerable wheels and anthropomorphic upper body
 Immersive teleoperation through exoskeleton with HMD







#### **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**

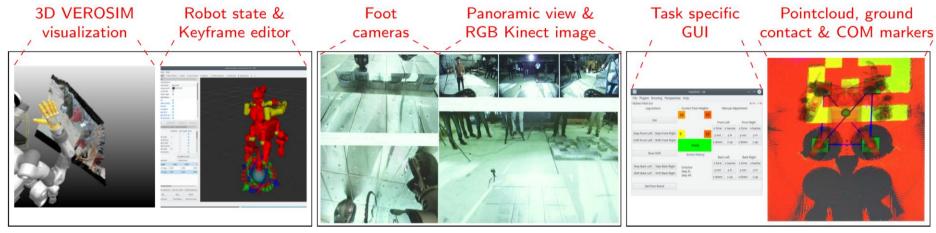
- Hand exoskeleton
- Independent Fingers
- Force feedback

#### Navigation3 DoFs Pedals



[Klamt et al., Journal of Field Robotics 2020]

### **Teleoperation with Joystick and Spacemouse**



Monitor 1



Monitor 3

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





#### **CENTAURO Evaluation @ KHG: Locomotion Tasks**





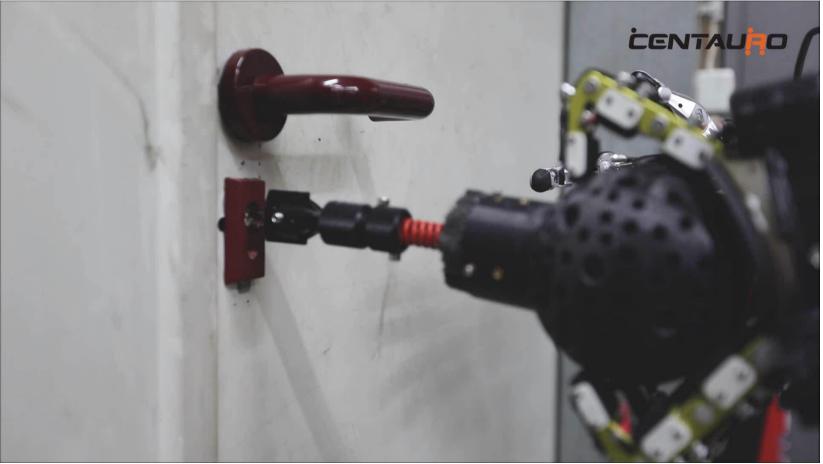
[Klamt et al. RAM 2019]

#### **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











#### **ANA Avatar XPRIZE Competition**



Required mobility, manipulation, human-human interaction

Focused on the
 immersion in
 the remote
 environment
 and the presence
 of the remote
 operator

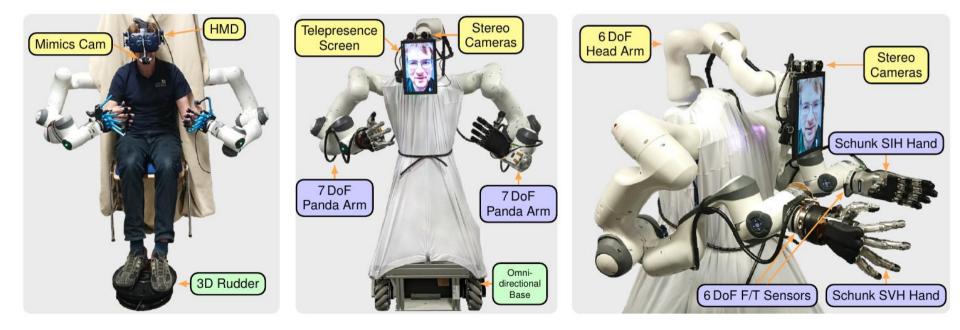


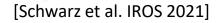


#### NimbRo Avatar 2021



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



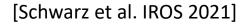






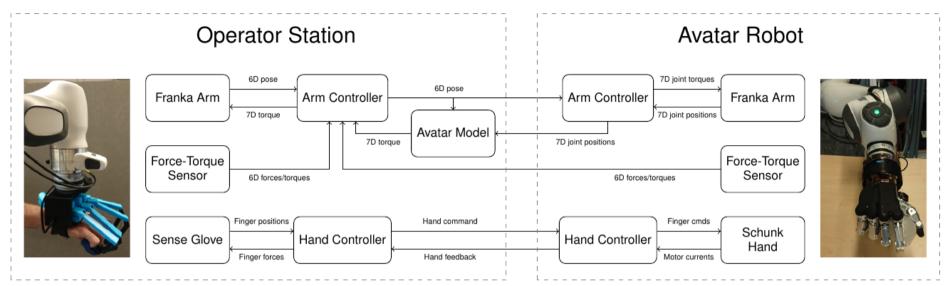
## Team NimbRo Semifinal Submission $ANA = X PRIZE^{*}$







### **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





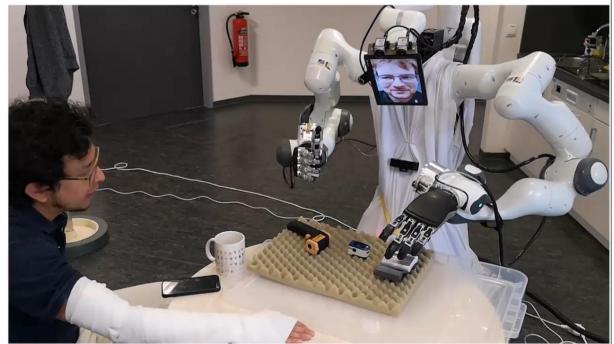
### Team NimbRo Semifinal Team Video

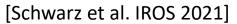
#### Tasks

- 1. Make a coffee
- 2. Greet the recipient
- 3. Measure temperature

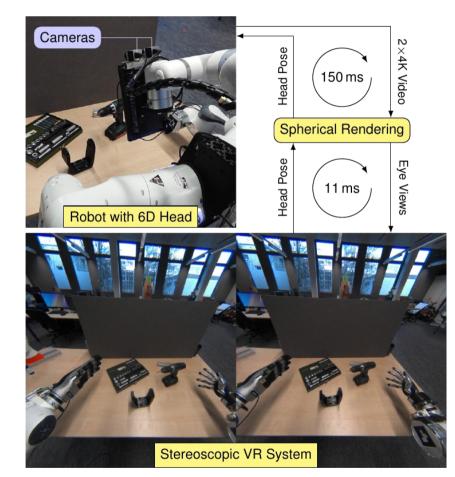
#### 4. Measure blood pressure

- 5. Measure oxygen saturation
- 6. Help recipient with jacket

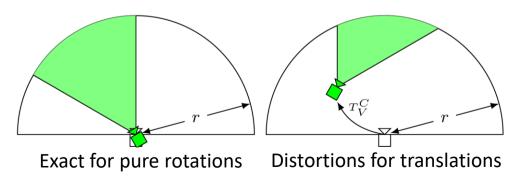




#### **NimbRo Avatar: Immersive Visualization**



- 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





[Schwarz and Behnke Humanoids 2021]

#### **NimbRo Avatar: Immersive Visualization**

#### Avatar Robot

#### Operator

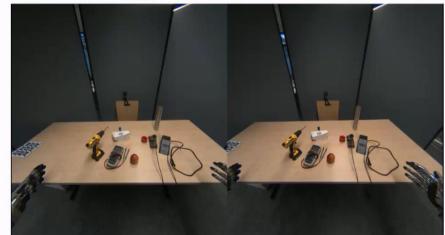


#### Wide-Angle Stereo





**HMD** View





#### **NimbRo Avatar: Operator Face Animation**

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

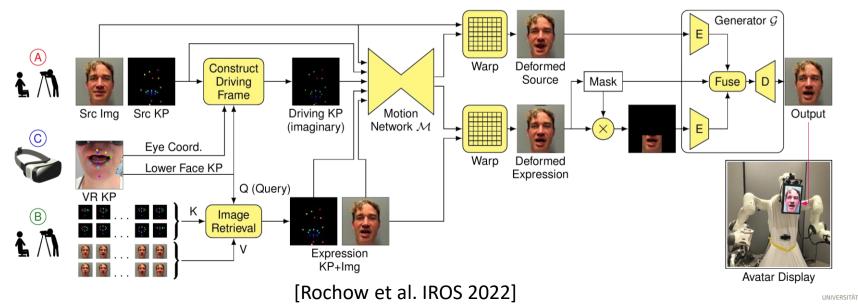




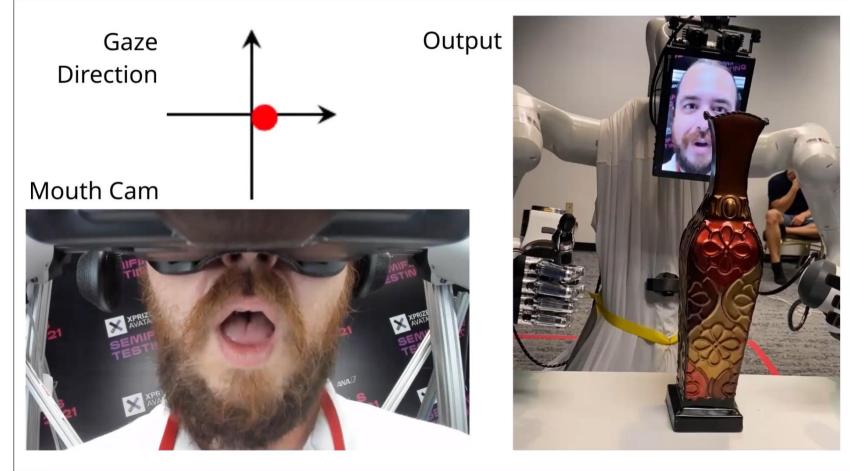


Right Eye

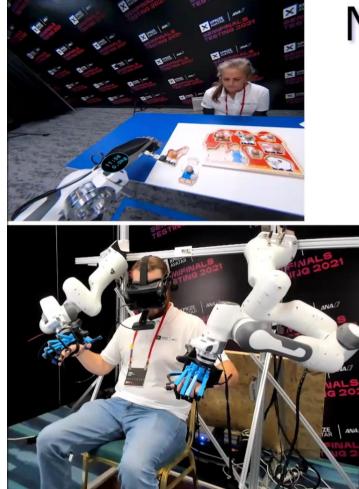
Generate animated operator face using a warping neural network



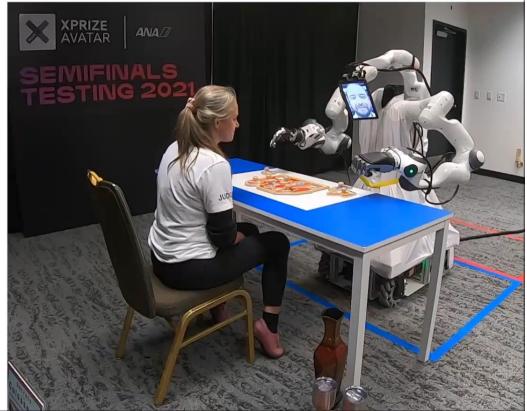
#### **NimbRo Avatar: Operator Face Animation**







### NimbRo Avatar Avatar XPRIZE Semifinals



[Schwarz et al. IROS 2021]



#### **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**

ANA			
ANA AVATAR	ΆΡ	KI	ΖE

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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



AvaDynamicsUNISTi-BoticsTangibleAVATRINAPollenJanusInbiodroidAvatar-HuboSNUAlterEgoiCubCyberselvesNimbRoNortheasternLast MileDragon Tree Labs



[Behnke et al. Robotics and Automation Magazine 2023]

#### **Finals Tasks**

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



Start



1. Move



2. Introduce

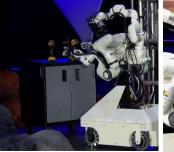


3. Confirm mission





4. Activate switch 5: Travel planet 6. Identify full canister 7: Place it



8. Narrow pathway

9: Use drill







#### **Finals Judged Scoring**

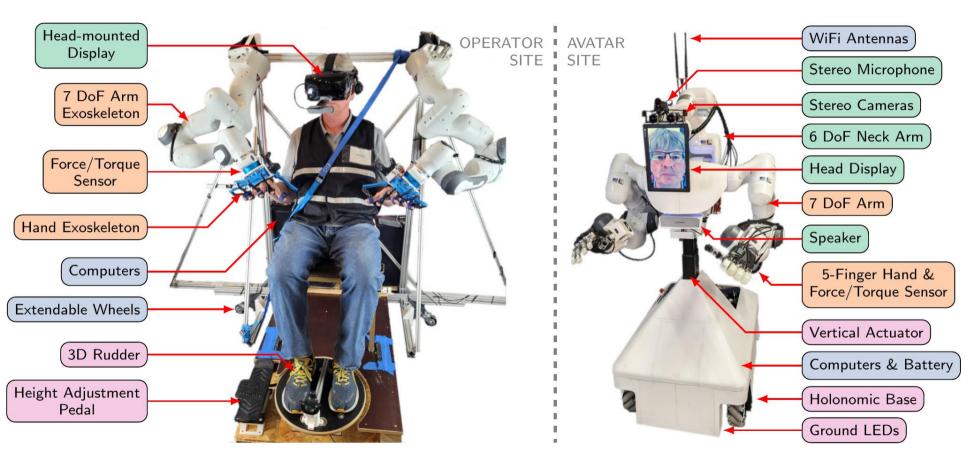
- **Operator Experience** (3 points)
  - The avatar system enabled the operator judge to feel present in the remote space and conveyed appropriate sensory information.
  - The avatar system enabled the operator judge to clearly understand (both see and hear) the recipient.
  - The avatar system was **easy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





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

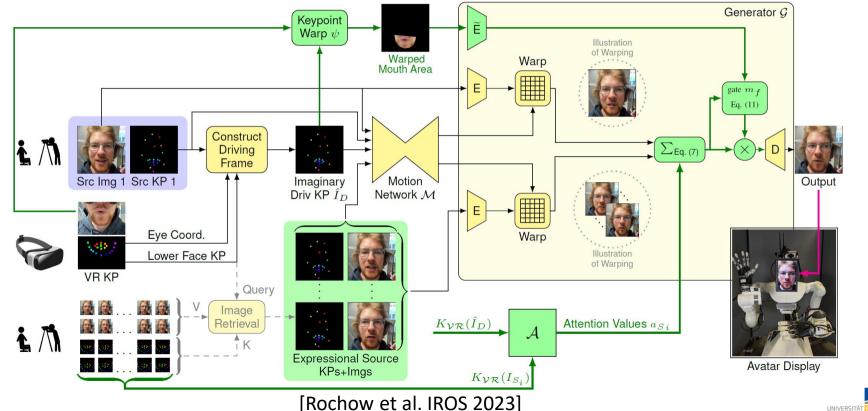
# Finals Test Run Day 1





# **Improved Operator Face Animation**

- Direct incorporation of mouth video
- Better temporal continuity



### **Face Animation @ Finals**

### Team UNIST





### Northeastern [12]

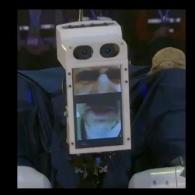
### Ours (NimbRo)





#### i-BOTICS

### Team AVATRINA [13]





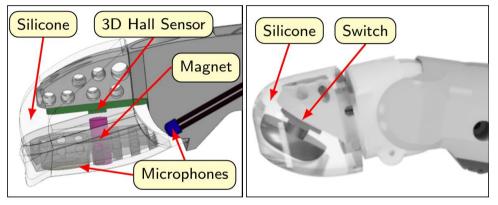
**Pollen Robotics** 



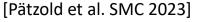
Source: Official XPRIZE Avatar live stream

# **Haptic Perception**

### Sensors in the finger tips



 Actuators on the hand exoskeleton

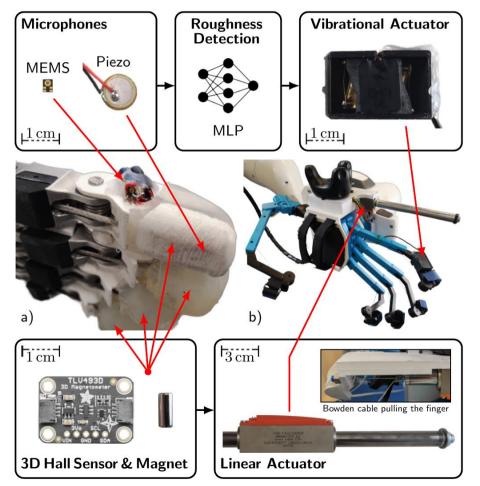








### **Roughness Perception**



#### **Dataset of Rough and Smooth Objects**



#### [Pätzold et al. SMC 2023]

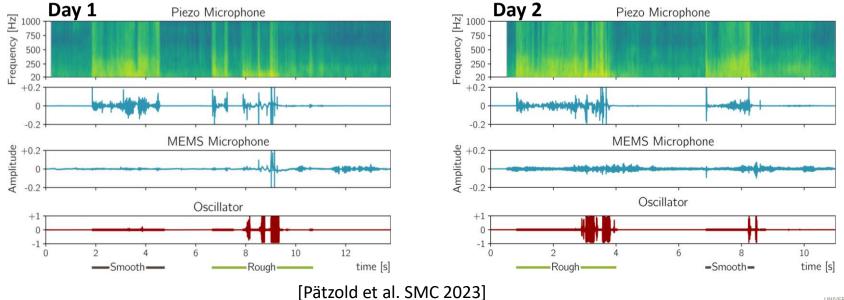


# **Finals Task 10: Retrieve a Rough Stone**

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



UNIVERSITÄT



### **Operator Training**





Introduction

Locomotion Grasping



Monitoring crew

Free experiments

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

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

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



# **Operator Crew GUI**

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Glove Right	96.4 Hz (delay 0.06s)			15:43.88 /otto/left/driver	Operator is present, not disabling.		/roughness_detector_client/confid-	ence 🔽
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VR Calibration	Trackers/Arms not working	1.315 Min	/otto/left/commander /otto/right/commander		Waiting for EStop release		/otto/haptics_sender/stats	
Audio Iamulus Otto	Running Registered on server	0.10 rad Max other	er		/anna/basler/right/image/h264: waiting for transfo anna_nominal_head_link: Would require extrapolatio	orm: Query anna_basler_right_optical_frame <-		Packet rate
Jamulus	Paused	0.280 Max	Status: SS2 Joints Status: SS2 Joints		Waiting for E -Stop release		Ĩ.	
Recording	1997/9000-9555 - 1997/958		Reason: NOMINAL TO Reason: NOMINAL TO D	15:43.69 /otto/monitor	Could not get kinematic tracker pose: Lookup would past. Requested time 1667688190.188990593 but the when looking up transform from frame [otto_arm_lef	d require extrapolation 9.993824820s into the	and the second s	Time
HDMI		<b>▼</b> VR × <b>▼</b> Glove ×	Action, mactive js ja Action, mactive js ja		when looking up transform from frame [otto_arm_lef	<pre>rtlest data is at time 100/088200.182815552, ft_tracker_link] to frame [vr_link]</pre>	Packet I	oss Concealment
bagnie	Paused	V Calibration 🗸 Up Calib	D Lock J5 J6 Lock J5 J6		/anna/basler/left/image/h264: waiting for transfor anna_nominal_head_link: Would require extrapolatio	rm: Query anna_basler_left_optical_frame <-	王 80	
		🗸 90° Calib	D Power off 17 Power off 17		anna_nomenae_nead_ttnk: would require extrapolatio		e 40	M h

## **Operator Crew GUI**

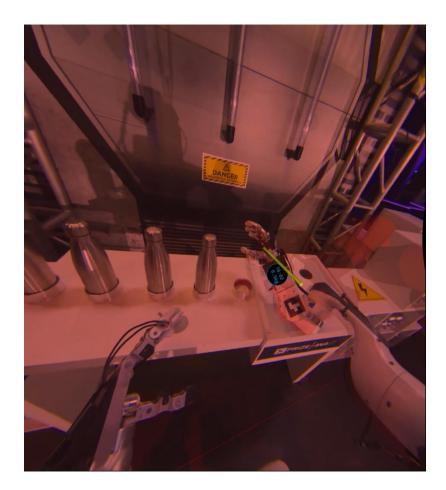
<b>T</b> Anna	X		Otto				network_display/network_display	>	× ▼ Basler	🗙 🔻 Left Eye 🛛 🛛 🗙	▼ Right Eye ×
/anna/sysmon/s	tate 🔽	400.27	Movement	On		Off		Freq: 5.76 GHz			
Battery	Power supply 100%	400:37	Send Cmds	On		off		Associated since: Signal: -64 dBm			10000
CPU	Usage 15.11% CPU: 68° PCH: 67° SSD: 44°		Otto	on		511		RX: 390 MBit/s MCS 8900MH8z/s			
Temperature HDD	Usage 32% (596G free)	/rosmon anna core/state 🔻	Head Control	On		off		5 GHz			
USB	All 11 devices checked	Node CPU		23274		2.8		TX: 390 MBit/s Mi Robot			
Ping	All 6 connections checked	/anna/audio/carla 0.00	Right Hand	On		off	Operator 5.88 MBit/s Router	22.30 MBit/s Ping		3 INTER 100 226(0 INTER 101	26.0
Network Basler Left	All 3 connections checked 46.3 Hz (delay 0.09s)	/anna/audio/haptics 0.03 /anna/audio/interface 0.05	Left Hand	On	(	Off	Ping XPRIZE Ping			▼ Mouth ×	
Basler Right	45.8 Hz (delay 0.07s)	/anna/audio/interface 0.05 /anna/audio/jack 0.00	Force / Torque				RTT 0.0ms RTT 0.1ms				and the second second
Brio Front	19.7 Hz (delay 0.13s)	/anna/audio/player 0.01	Otto	On	(	Off		Signal: -53 dBm		And the second second	
Brio Rear Hand Cam	15.1 Hz (delay 0.15s) 15.0 Hz (delay 0.11s)	/anna/audio/thru_comm0.26	Anna Feedback	On	(		28.22 MBit/s	RX: 58 MBit/s MCS 0 20MMBit/s	15 International States of the	AVAL CONTRACT	THE TO DET
Hand Left	1: 46°, 2: 48°, 3: 46°, 4: 44°	/anna/audio/thru_comm0.00 /anna/audio/thru_haptic 0.01	Anna Limits	On				2.4 GHz		4017	
Hand Right	48.9 Hz (delay 0.04s)	/anna/audio/thru_speak-0.01	Atlas					TX: 26 MBit/s MC			
Magnet	3 sensors	Zanna (audio, sandar 0.02 ▼ Anna Network	Drive	On	(	off		5.56 MBi//s			
SVH Contact Head	193.2 Hz (delay 0.04s) Delay: 0.02s	/anna/monitor 0.00	Spine	On		Off				X <b>v</b> Eye calibration	×
Arm Left	Delay: 0.02s	/anna/monitor 0.01 /anna/network_control 0.00	Recording				Filter		16	Bag: Waiting	Start Stop
Arm Right	Delay: 0.02s	/anna/operator_repub 0.02	Record	On		Off	and the second	lessage	and the second sec	Bag file: /home/avatar/eye_bags/bag	CARGE AND
FT left FT right	480.2 Hz (delay 0.04s) 479.9 Hz (delay 0.04s)	/anna/right/commander 0.00		on		511	15:41.34 /otto/monitor	light tracking pose is not valid (tracker turned	off?)	#Images: L:356, R:356, D:1639	
Wheels	Delay: 0.05s	/anna/service_receiver 0.00 /anna/syslog 0.00	Run		-	810.	15:41.55 /avatar_vt	anna/basler/right/image/h264: waiting for transf nna_nominal_head_link: Would require extrapolati	ion: Query anna_baster_right_opticat_frame <- ion	Train 0%	
Spine	0.90m (37%)	/anna/sysmon 0.10	Y Offset	On	(	Off	15:41.15 /avatar_vr	anna/basler/left/image/h264: waiting for transfo nna_nominal_head_link: Would require extrapolati	orm: Query anna_basler_left_optical_frame <-	Train error: 3.891897 deg	Hand     X
Audio Face display	Running Human	/anna/tf_static_agg 0.00	/anna/network_control/s	tatus			15:41.40 /sense_glove	ould not get Senseglove data. Please check USB c		■ Bird's Eye     ×	▼ Hand X
E-Stop	OK	/anna/tf_transceiver 0.08 /anna/transceiver 0.04	System 0.39 MBit/s	5GHz 0 p/s	2.4GHz	0 p/s	15:41.59 /otto/eye_recorder	pening bag file: /home/avatar/eye_bags/bag_2022-	-11-05-23-41-34.bag		
Bagfile	Paused	/atlas receiver 0.04	Feedback 5.32 MBit/s	5GHz 0 p/s	2.4GHz	0 p/s		anna/basler/right/image/h264: waiting for transf nna_nominal_head_link: Would require extrapolati	ion to the second start of the		
		/atlas_sender 0.00	TF 4.16 MBit/s	5GHz 0 p/s	2.4GHz	0 p/s	15:41.25 /otto/eye_recorder	Recording stopped. Htto right arm command is too old (81.240440935s)			
		/config_server 0.00	Cam Left 7.16 MBit/s		100000000		15:42.08 /anna/left/driver	tto left arm command is too old (81.255314612s)		2	
-		/ping_node 0.00			2.4GHz	0 p/s	15:42.46 /otto/monitor	eft tracking pose is not valid (tracker turned o	off?) (connected=true, valid=true, result=101)	7 14 2	
<b>₹</b> Otto			Cam Right 7.39 MBit/s	5GHz 0 p/s	2.4GHz	0 p/s		anna/basler/left/image/h264: waiting for transfo nna_nominal_head_link: Would require extrapolati	orm: Query anna_basler_left_optical_frame <- ion	TO STORE	
/otto/sysmon/st	Usage 30.51%	/rosmon_otto_arms/state V Node CPU	Aux Image 4.25 MBit/s	5GHz 0 p/s	2.4GHz	0 p/s		light tracking pose is not valid (tracker turned eft tracking pose is not valid (tracker turned o			
CPU HDD	Usage 55% (397G free)	/arduino0 0.05	/otto/network_control/st	atus						1111111111961171341171	
USB	All 9 devices checked	/otto/faulhaber_comm 0.02	System 0.00 MBit/s	5GHz 0 p/s	2.4GHz	0 p/s	15:43.07 /anna/right/driver 15:43.08 /anna/left/driver	ong delay in decoder itto right arm command is too old (141.240874364s itto left arm command is too old (141.256047258s) anna/birds_eye/out/compressed: Dropping old fram ould not get Senseglove data. Please check USB c		/otto/left/driver/wrench	/otto/right/driver/wrench
Network	All 4 connections checked	/otto/left/driver 0.00 /otto/left/ft 0.04	Control 0.17 MBit/s	5GHz 0 p/s	2.4GHz	0 p/s	15:43.08 /anna/tert/driver 15:43.15 /avatar_vr	anna/birds eve/out/compressed: Dropping old fram	) Nes	Force	Force
Index cam Mouth cam	52.0 Hz (delay 0.07s) 56.2 Hz (delay 0.09s)	/otto/left/ft 0.04 /otto/right/driver 0.28	TF 1.35 MBit/s	5GHz 0 p/s	2.4GHz	0 p/s	15:43.98 /sense_glove	ould not get Senseglove data. Please check USB c		10 X	10 X
Eye Left	25.1 Hz (delay 0.12s)	/otto/right/ft 0.07	Aux Image 2.92 MBit/s	5GHz 0 p/s	2.4GHz	0 p/s	15:43.19 /otto/left/driver 15:43.19 /otto/left/driver	-Stop released (mode 1), back to control ranka::ControlException: libfranka: Move command		0 Y	0 Y -10 Z
Eye Right	26.0 Hz (delay 0.11s)	/otto/rudder_3d 0.01								-10 Z	
Operator Cam Arm Left TF	28.7 Hz (delay 0.11s) Delay: 19.86s	/otto/state_pub 0.05	/anna/left/commander/s				15:43.50 /rosmon_otto_arms 15:43.51 /rosmon_otto_arms	osmon: /otto/left/driver died from signal 6 osmon: starting '/otto/left/driver'		Torque	Torque
Arm Left Comm	No message	rosmon network ×	/anna/left/comm	nande /anna	right/com	mander	15:43.23 /otto/left/driver	obot is locked, I'm going to unlock it		4 0 Y	4 <b>X</b>
Arm Right TF	Delay: 0.00s	/rosmon_otto_network/state No message					15:43.49 /otto/left/commander	etting brakes to 0 of error: 'eRessourcePending'		-4 Z	0 Y 4 Z
Arm Right Comr Glove Left	n 0% 96.4 Hz (delay 0.06s)		-	nts Status: EXE		Joints	15:43.60 /otto/left/driver				
Glove Right	96.4 Hz (delay 0.06s)		Reason: NOMINAL	1 j2 Reason: NC		J1 J2		hecking if operator is present perator is present, not disabling.		Roughness	
FT left	936.1 Hz (delay 0.05s)	₹ sense_glove/GestureGUI 🗙	Action: inactive	3 J4 Action: inac		J3 J4				/roughness_detector_client/confide 1.2	nce
FT right Rudder	935.1 Hz (delay 0.06s) Ready	0.08 rad Thumb ro	Lock Power off	7	Lock ower off	15 16	15:43.27 /rosmon_otto_arms	osmon: starting '/otto/left/driver'		0.8	
Pedal	47.7 Hz (delay 0.07s)	0.690 Max	roweron		ower on		15:43.24 /otto/left/driver 15:43.69 /otto/monitor	laiting for EStop release ould not get kinematic tracker pose: Lookup woul ast. Requested time 1667688190.188990593 but th	ld require extrapolation 0.093787322s into the		
Eye Tracking	51.0 Hz (delay 0.11s)		/otto/left/commander/st	atus 🔽 /otto/right	commander/stat	tus 🔽		ast. Requested time 1667688190.188990593 but th then looking up transform from frame [otto_arm_le	ne earliest data is at time 1667688190.282778025,	0	
VR Calibration	Trackers/Arms not working	1.315 Min	/otto/left/comm	ander /otto/	right/comn	nander		aiting for E -Stop release		/otto/haptics_sender/stats	<b>X</b>
Audio Jamulus Otto	Running Registered on server	0.10 rad Max other						anna/basler/right/image/h264: waiting for transf nna_nominal_head_link: Would require extrapolati	form: Query anna_basler_right_optical_frame <- ion	N P	acket rate
Jamulus	Paused	0.280 Max	Status: SS2 Jo	nts Status: SS2		Joints	15:43 24 /otto/left/driver	laiting for E Ston release		ېرونې کې	m. Amminian from the late
Recording			Reason: NOMINAL	Reason: NC	MINAL	J1 J2	15:43.69 /otto/monitor	ould not get kinematic tracker pose: Lookup woul	ld require extrapolation 9.993824820s into the	E - 0	Time
HDMI Bagfile	58.2 Hz (delay 0.06s) Paused	<b>▼</b> VR × <b>▼</b> Glove ×	Action: inactive	3 J4 Action: inac	tive	J3 J4		ould not get kinematic tracker pose: Lookup woul ast. Requested the 1667680190.188998593 but th hen lookung up transform from frame [otto_arm_le anna/boaster/left/lmage/h264. waiting for transfo nma_nominal.head_link: Would require extrapolati	eft_tracker_link] to frame [vr_link]	Packet Lo	ss Concealment
a digrade		VR Calibration VD Calib	Lock	5 ]6	Lock	J5 J6		anna/basler/left/image/h264: waiting for transfo nna nominal head link: Would require extranolati	orm: Query anna_basler_left_optical_frame <- ion	Fi 88	
		🗹 90° Calib	Power off	72	ower off	177				<u>e 40</u>	M A

# **Operator Crew GUI**

<b>₹</b> Anna	×	▼ control_box/Clock ×	Otto			network_display/network_display	>	<ul> <li>✓ ■ Basier</li> </ul>	🗙 🔻 Left Eye	X 🔻 Right Eye X
/anna/sysmon/st	ate 🔽	400.27	Movement	On	Off		Freq: 5.76 GHz			
Battery	Power supply 100%	400:37	Send Cmds	On	Off		Associated since Signal: -64 dBm			
	Usage 15.11%		Otto	UII	- On		RX: 390 MBit/s MCS 890MH8z/5			
Temperature	CPU: 68° PCH: 67° SSD: 44° Usage 32% (596G free)	/rosmon anna core/state					5 GHz			Con the second
	All 11 devices checked	Node CPU	Head Control	On	Off					
		/anna/audio/carla 0.00	Right Hand		Off	Operator 5.88 MBit/s Router	TX: 390 MBit/s Mi Robot			
a construction of the second	All 3 connections checked	/anna/audio/haptics 0.03	Left Hand		Off	Ping XPRIZE Ping	22.30 MBit/s Ping RTT 1 28.0ms			X ₹ Reconstruction X
	46.3 Hz (delay 0.09s) 45.8 Hz (delay 0.07s)	/anna/audio/interface 0.05	Force / Torque			RTT 0.0ms RTT 0.1ms			Modul	× • Reconstruction
Brio Front	45.8 Hz (delay 0.075) 19.7 Hz (delay 0.135)	/anna/audio/jack 0.00 /anna/audio/player 0.01	Otto	On	Off		Associated since: NTP synced		C-6 1.	
Brio Rear	15.1 Hz (delay 0.15s)	/anna/audio/thru_comm 0.26	Anna Feedback	On	Off	28.22 MBit/s	Signal: -53 dBm RX: 58 MBit/s MCS 0 2010/IMBit/s		TXHR	MALL AREA
Hand Cam	15.0 Hz (delay 0.11s)	/anna/audio/thru_comm0.00				28.22 MBID/5	2.4 GHz	100	AVAL CON ALL	The street
	1: 46°, 2: 48°, 3: 46°, 4: 44° 48,9 Hz (delay 0.04s)	/anna/audio/thru_haptic 0.01	Anna Limits	On	Off					and the second
	48.9 Hz (delay 0.04s) 3 sensors	/anna/audio/thru_speak-0.01	Atlas				TX: 26 MBit/s MC			
	193.2 Hz (delay 0.04s)	▼ Anna Network ×	Drive		Off		5.56 MBit/s		in. 591	( IN 181 180.72   11 19 191
Head	Delay: 0.02s	/anna/monitor 0.01	Spine		Off	Otto config Anna Config Otto cor	ntext Log		🗙 🔻 Eye calibration	×
	Delay: 0.02s	/anna/network_control 0.00	Recording			T Filter		<u> </u>	Bag: Waiting	Start Stop
Arm Right FT left	Delay: 0.02s 480.2 Hz (delay 0.04s)	/anna/operator_repub 0.02	Record	On	Off	Time Node	Message		Bag file: /home/avatar/eye_bags/	bag_2022-11-05-23-41-34.bag
	479.9 Hz (delay 0.04s)	/anna/right/commander 0.00 /anna/service_receiver 0.00	Run			15:41.34 /otto/monitor 15:41.53 /avatar_vr	Right tracking pose is not valid (tracker turned /anna/basler/right/image/h264: waiting for transf	orrr:) orm: Ouery anna basler right optical frame <-	#Images: L:356, R:356, D:1639	
	Delay: 0.05s	/anna/syslog 0.00	Y Offset	07	Off		/anna/basler/right/image/h264: waiting for transf anna_nominal_head_link: Would require extrapolati		Train 0%	
	0.90m (37%)	/anna/sysmon 0.10	- Honset	Un.	UI	15:41.15 /avatar_vr	/anna/basler/left/image/h264: waiting for transfo anna_nominal_head_link: Would require extrapolati	rm: Query anna_basler_left_optical_frame <- .on	Train error: 3.891897 deg Bird's Eye	X <b>▼</b> Hand X
	Running Human	/anna/tf_static_agg 0.00	/anna/network_control/s	status		15:41.40 /sense_glove	Could not get Senseglove data. Please check USB c		onu sieve	
	ок	/anna/tf_transceiver 0.08 /anna/transceiver 0.04	System 0.39 MBit/s	5GHz 0 p/s	2.4GHz 0 p/s	15:41.59 /otto/eye_recorder 15:41.63 /avatar_vr	Opening bag file: /home/avatar/eye_bags/bag_2022-	11-05-23-41-34.bag		
Bagfile	Paused	/atlas_receiver 0.04	Feedback 5.32 MBit/s	5GHz 0 p/s	2.4GHz 0 p/s	10141.00 / dvatar_vi	/anna/basler/right/image/h264: waiting for transf anna_nominal_head_link: Would require extrapolati	on		8
		/atlas_sender 0.00	TF 4.16 MBit/s	5GHz 0 p/s	2.4GHz 0 p/s	15:41.25 /otto/eye_recorder	Recording stopped.			
		/config_server 0.00	Cam Left 7.16 MBit/s			15:42.07 /anna/right/driver 15:42.08 /anna/left/driver	Otto right arm command is too old (81.240440935s) Otto left arm command is too old (81.255314612s)		9	
		/ping_node 0.00		5GHz 0 p/s	2.4GHz 0 p/s	15:42.46 /otto/monitor	Left tracking pose is not valid (tracker turned o			
<b>₹</b> Otto		➡ rosmon arms	Cam Right 7.39 MBit/s	5GHz 0 p/s	2.4GHz 0 p/s	15:42.22 /avatar_vr	/anna/basler/left/image/h264: waiting for transfo anna_nominal_head_link: Would require extrapolati	<pre>rm: Query anna_basler_left_optical_frame &lt;- on</pre>	Total In	
/otto/sysmon/sta		/rosmon_otto_arms/state 🔽	Aux Image 4.25 MBit/s	5GHz 0 p/s	2.4GHz 0 p/s	15:42.29 /otto/monitor	Right tracking pose is not valid (tracker turned		1 A STA	
CPU	Usage 30.51%	Node CPU /arduino0 0.05	/otto/network_control/si	atus			Left tracking pose is not valid (tracker turned o long delav in decoder	off?) (connected=true, valid=true, result=101)		ÎRI
HDD USB	Usage 55% (397G free) All 9 devices checked	/otto/faulhaber_comm 0.02	System 0.00 MBit/s		2.4GHz 0 p/s	15:43.07 /anna/right/driver	Otto right arm command is too old (141.240874364s		/otto/left/driver/wrench	Votto/right/driver/wrench
Network	All 4 connections checked	/otto/left/driver 0.00	Control 0.17 MBit/s	5GHz 0 p/s	2.4GHz 0 p/s	15:43.08 /anna/left/driver 15:43.15 /avatar_vr	Otto left arm command is too old (141.256047258s)		Force	Force
Index cam	52.0 Hz (delay 0.07s)	/otto/left/ft 0.04				15:43.15 /avatar_vr 15:43.98 /sense glove	/anna/birds_eye/out/compressed: Dropping old fram Could not get Senseglove data. Please check USB c	onnection.	10 <b>x</b>	
Mouth cam	56.2 Hz (delay 0.09s) 25.1 Hz (delay 0.12s)	/otto/right/driver 0.28 /otto/right/ft 0.07		5GHz 0 p/s	2.4GHz 0 p/s	15:43.19 /otto/left/driver	E-Stop released (mode 1), back to control		0 Y	0 Y
Eye Left Eye Right	25.1 HZ (delay 0.125) 26.0 Hz (delay 0.115)	/otto/rudder_3d 0.01	Aux Image 2.92 MBit/s	5GHz 0 p/s	2.4GHz 0 p/s	15:43.19 /otto/left/driver	<pre>franka::ControlException: libfranka: Move command mode!</pre>		-10 Z	-10 Z
Operator Cam	28.7 Hz (delay 0.11s)	/otto/state_pub 0.05	/anna/left/commander/s	tatus 🔽 🚺 /anna/right/co	mmander/status 🛛 🔽	15:43.50 /rosmon_otto_arms			Torque	Torque
Arm Left TF	Delay: 19.86s		/anna/left/comr	nande /anna/ri	aht/commander		rosmon: starting '/otto/left/driver' Robot is locked, I'm going to unlock it		4 x	4 x
Arm Left Comm Arm Right TF	No message Delay: 0.00s	/rosmon_otto_network/state 🔻	anna/lete com	anac vannavni	gnatominander		Setting brakes to 0		0 Y	0 Y
Arm Right Comn		No message	Status: EXEC [c	ints Status: EXEC	loints		Got error: 'eRessourcePending'		-4 Z	-4 Z
Glove Left	96.4 Hz (delay 0.06s)		Reason: NOMINAL	Reason: NOMI		15:43.60 /otto/left/driver 15:43.71 /otto/left/driver	Could not lock/unlock brakes: state ABORTED/Got e Checking if operator is present		<b>Roughness</b>	×
Glove Right	96.4 Hz (delay 0.06s)	-	Action: inactive	Action: inactive			Operator is present, not disabling.		/roughness_detector_client/confi	idence 🛛 🔽
FT left FT right	936.1 Hz (delay 0.05s) 935.1 Hz (delay 0.06s)	sense_glove/GestureGUI ×	Lock	15 16 Lo		15:43.26 /rosmon_otto_arms	rosmon: /otto/left/driver died from signal 6		1.2	
Rudder	Ready	0.08 rad Thumb ro	Power off	7 Powe	er off	15:43.27 /rosmon_otto_arms 15:43.24 /otto/left/driver	rosmon: starting '/otto/left/driver' Waiting for EStop release			
Pedal	47.7 Hz (delay 0.07s)	0.690 Max	z			15:43.69 /otto/monitor	Walting for EStop release Could not get kinematic tracker pose: Lookup woul past. Requested time 1667680190.188990593 but th When looking up transform from frame [otto_arm_le	d require extrapolation 0.093787322s into the		
Eye Tracking	51.0 Hz (delay 0.11s)		/otto/left/commander/st	atus 🔽 /otto/right/cor	nmander/status 🛛 🔽		past. Requested time 1667688190.188990593 but th when looking up transform from frame <u>Fotto arm le</u>	e earliest data is at time 1007088190.282778025, ft_tracker_link] to frame [vr_link]	0	
VR Calibration Audio	Trackers/Arms not working	1.315 Min	/otto/left/comm	ander /otto/rig	ht/commander	15:43.24 /otto/left/driver	Waiting for E -Stop release		/otto/haptics_sender/stats	<b>X</b>
Audio Iamulus Otto	Running Registered on server	0.10 rad Max other				15:43.71 /avatar_vr	/anna/basler/right/image/h264: waiting for transf anna_nominal_head_link: Would require extrapolati	orm: Query anna_basler_right_optical_frame <- .on	Z	Packet rate
Jamulus	Paused	0.280 Max	Status: SS2 Jo	ints Status: SS2	Joints	15:43.24 /otto/left/driver	Waiting for E -Stop release			yn hannen fan de la
Recording			Reason: NOMINAL	1 12 Reason: NOMI	NAL J1 J2	15:43.69 /otto/monitor	Could not get kinematic tracker pose: Lookup woul past. Requested time 1667688190.188990593 but th when looking up transform from frame [otto_arm_le	d require extrapolation 9.993824820s into the	Rat Rat	Time
HDMI Bacfile	58.2 Hz (delay 0.06s) Paused	▼ VR X ▼ Glove X	Action: inactive	Action: inactive	J3 J4		when looking up transform from frame [otto_arm_le	<pre>ift_tracker_link] to frame [vr_link]</pre>	Packet	Loss Concealment
Daynic	rauseu	VR Calibration 🗸 Up Calib	Lock	15 j6 Lo	ckj5j6		/anna/basler/left/image/h264: waiting for transfo anna_nominal_head_link: Would require extrapolati	<pre>rm: Query anna_basler_left_optical_frame &lt;- on</pre>	王 88 	
		V 90° Calib	Power off	POW/	pr off		united in the product of the second of the s		e 40 . I t ta	Al Alian a

# **Reliability Features**

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



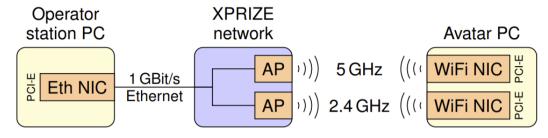


## **Network Details**

- Separate ROS cores for operator station and avatar
- Pure UDP, no re-connect / initialization
- Main camera stream (stereo 2472×2178 @46 fps) is HEVCencoded & decoded on GPU (NVENC).

Total bandwidth: ~14 MBit/s

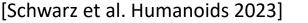
- Control data is sent redundantly
- Monitoring packet loss



#### WiFi Bandwidth Requirements

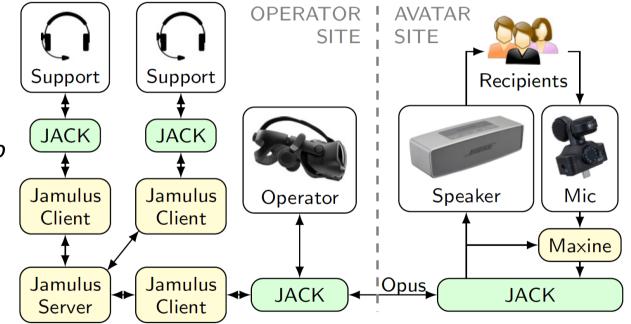
Down	nlink fror	n avatar		Uplink to avatar					
Channel	annel MBit/s		2.4 GHz	Channel	MBit/s	5 GHz 2.4 GH			
Arm feedback	8.5	$\checkmark$	×	Arm control	4.9	$\checkmark$	$\checkmark$		
Transformation	s 4.1	$\checkmark$	×	Transformations	s 1.4	$\checkmark$	×		
Main cameras	14.7	$\checkmark$	×	Operator face	5.7	$\times$	$\checkmark$		
Hand camera	5.5	×	$\checkmark$	Audio	0.4	$\checkmark$	$\checkmark$		
Diagnostics	0.4	$\checkmark$	$\checkmark$						
Audio	0.4	$\checkmark$	$\checkmark$						
Total [MBit/s]		28.1	6.3	Total [MBit/s]		6.7	11.0		

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

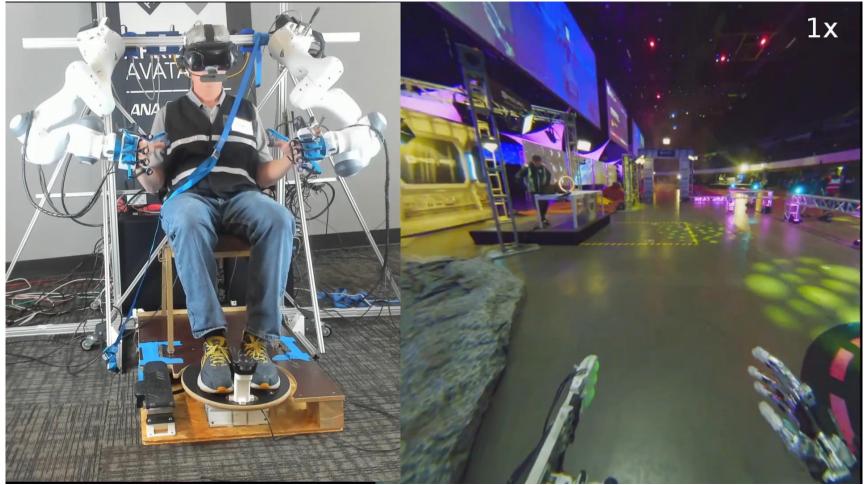


# **Audio Details**

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



## **Finals Day 2 Testing**





### **Finals Results**

ANA	RIZE
AVATAR	<b>KIZE</b>

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
		[XPR	IZE]		



# Team NimbRo





# **Finals Timings**

							Time	1  [mm:ss]	]					
Team	Day	$Start^2$	<b>—</b> T1	<b>T</b> 2	<b>—</b> T3	<b>•</b> T4	<b>T</b> 5	<b>T</b> 6	<b>T</b> 7	<b>T</b> 8	<b>T</b> 9	<b>T</b> 10	Total	
NimbRo	$\begin{array}{c}1\\2\\1{ ightarrow}2\end{array}$	00:00 00:00 0:00	00:18 <b>00:08</b> -0:10	00:10 <b>00:09</b> -0:01	01:35 01:31 -0:04	00:52 <b>00:23</b> -0:29	01:00 <b>00:32</b> -0:28	<b>00:22</b> 00:26 <b>+0:04</b>	<b>00:06</b> 00:09 +0:03	00:50 <b>00:26</b> -0:24	01:56 <b>01:04</b> -0:52	01:06 <b>01:02</b> -0:04	08:15 05:50 -2:25	
Pollen Robotics	$\frac{1}{2}$	$00:00 \\ 00:00$	$\begin{array}{c} 00{:}10\\ 00{:}15 \end{array}$	00:09 00:09	$\begin{array}{c} 01:39 \\ 01:43 \end{array}$	$\begin{array}{c} 00:40 \\ 00:49 \end{array}$	$\begin{array}{c} 01:15 \\ 02:02 \end{array}$	$\begin{array}{c} 00:53 \\ 01:15 \end{array}$	$\begin{array}{c} 00:14 \\ 00:18 \end{array}$	$\begin{array}{c} 00:50 \\ 00:51 \end{array}$	$\begin{array}{c} 05:06 \\ 01:28 \end{array}$	$02:24 \\ 01:59$	$13:20 \\ 10:50$	
Team Northeastern [25]	1	$00:00 \\ 00:00$	$\begin{array}{c} 00:33 \\ 00:16 \end{array}$	$\begin{array}{c} 00:24 \\ 00:19 \end{array}$	$\begin{array}{c} 02:08 \\ 01:47 \end{array}$	$\begin{array}{c} 01:43 \\ 00:52 \end{array}$	$\begin{array}{c} 04{:}03\\01{:}14 \end{array}$	$\begin{array}{c} 01:27 \\ 01:05 \end{array}$	$\begin{array}{c} 00:36 \\ 00:15 \end{array}$	$\begin{array}{c} 01:56 \\ 01:00 \end{array}$	04:54	09:27	$12:50 \\ 21:09$	
AVATRINA [26]	$\frac{1}{2}$	$00:00 \\ 00:00$	$\begin{array}{c} 00:28\\ 00:24 \end{array}$	$\begin{array}{c} 00:23 \\ 00:12 \end{array}$	$\begin{array}{c} 02:03 \\ 01:39 \end{array}$	$\begin{array}{c} 01:45 \\ 01:05 \end{array}$	$\begin{array}{c} 03:10 \\ 02:50 \end{array}$	$\begin{array}{c} 06:17 \\ 00:48 \end{array}$	$\begin{array}{c} 00:19 \\ 00:11 \end{array}$	$\begin{array}{c} 02:24 \\ 01:30 \end{array}$	$\begin{array}{c} 03:10 \\ 02:43 \end{array}$	04:48	$24:47 \\ 11:22$	
i-Botics [51]	$\frac{1}{2}$	$00:00 \\ 00:00$	$\begin{array}{c} 00:13 \\ 00:19 \end{array}$	$\begin{array}{c} 00:26 \\ 00:12 \end{array}$	<b>01:23</b> 01:36	$\begin{array}{c} 01:53 \\ 03:25 \end{array}$	01:57	01:52	02:07	02:57	09:47		$22:35 \\ 05:32$	
NimbRo Day	1				8:3	15			-				nainly in	
NimbRo Day	2	5:50 locomotio												
Pollen Robotics Day	1							13:20	-	•		•	e) signifi	
Pollen Robotics Day	2						10:50			raster	faster than other teams			
Team Northeastern Day	2										21	:09		
AVATRINA Day	1			_									24:47	
	0:00	1 1	5:00	)	1	0:00	1 1	15:00		20:0	00	25	5:00	
							Time [m	in:sec]						

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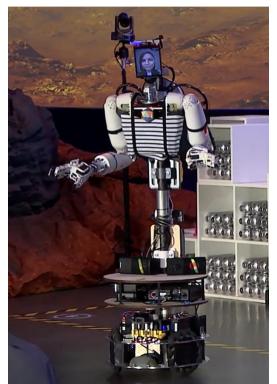
<sup>53</sup> [Lenz et al. International Journal of Social Robotics 2023]

### **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



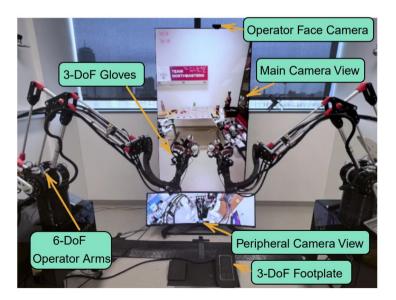


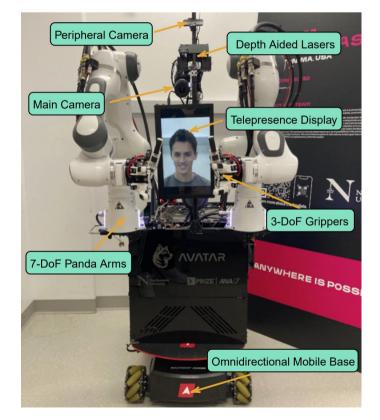
[Pollen Robotics]



## **3rd Place: Team Northeastern**

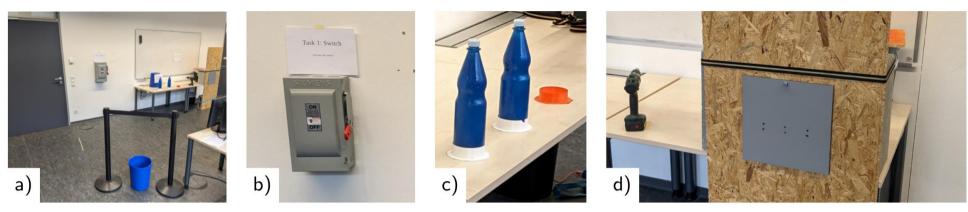
- Hydraulically actuated glove-gripper pair for haptic force feedback
- Non-immersive visualization with two monitors
- Projected laser lines aid 3D perception







## After the Competition: User Study in our Lab



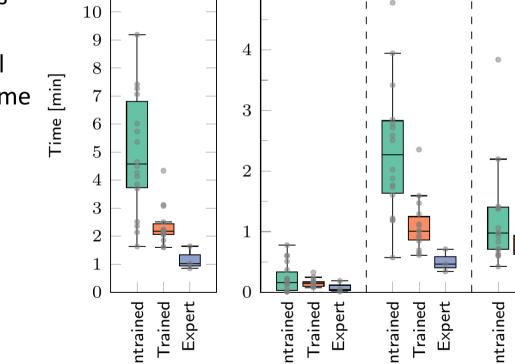
- Three tasks, similar to finals: a), b) Locomotion+Switch, c) Bottles, d) Drill
- 35 participants, 32 with no prior experience of the system
- All participants: 2 min intro video explaining the system (task agnostic)
- Three groups:
  - No training
  - 10 min task training, similar to Finals
  - Expert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

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



# 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.



5

Switch

Total Time

12

11

Time Per Task

**Bottles** 

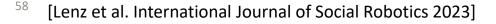
•

Drill

-rained Expert

### **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





<sup>[</sup>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?

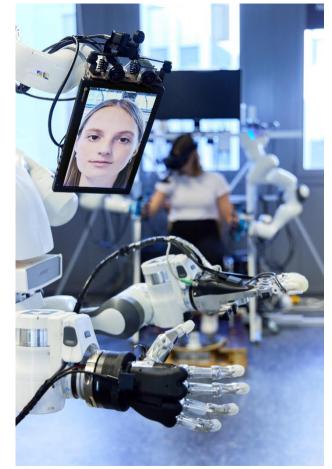


[Photographer: Volker Lannert]



# **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 highlevel 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]



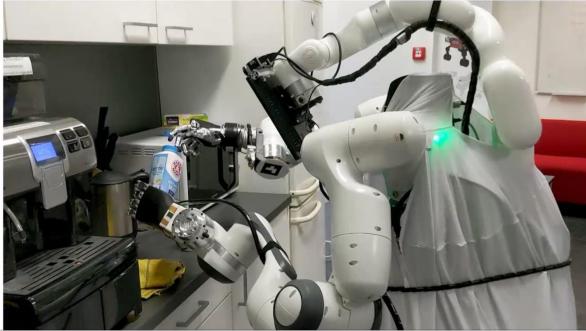
### **Unmatched Human Operators**





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

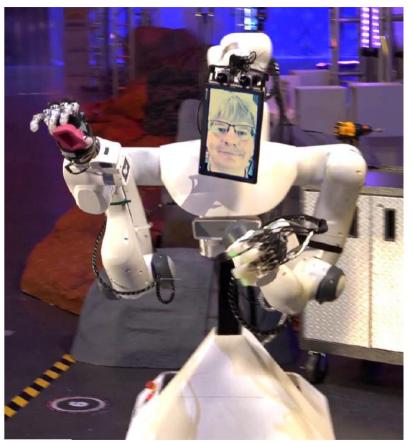






# Conclusions

- 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?**

