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

## Max Schwarz and Sven Behnke

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



## **ANA Avatar XPRIZE Competition**



Requires mobility, manipulation, human-human interaction

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



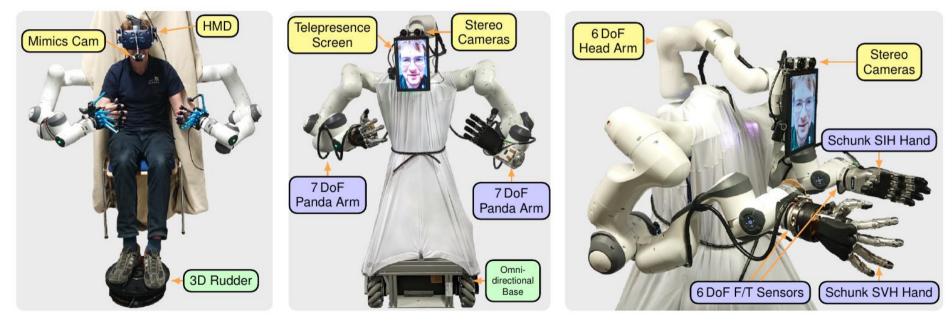


## NimbRo Avatar 2021



Two-armed avatar robot designed for teleoperation with immersive visualization & force feedback

Operator station with HMD, exoskeleton and locomotion interface



#### [Schwarz et al. IROS 2021]





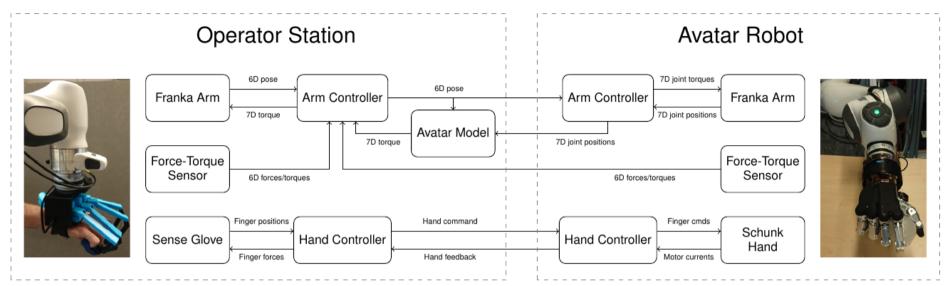
# Team NimbRo Semifinal Submission





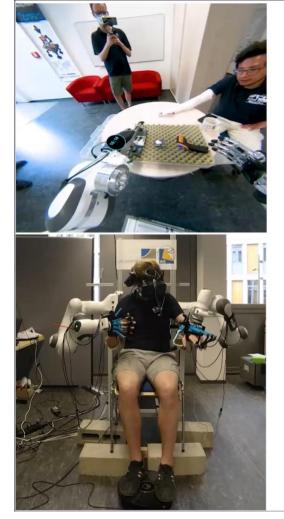
[Schwarz et al. IROS 2021]

## **Manipulation with Force and Haptic Feedback**



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





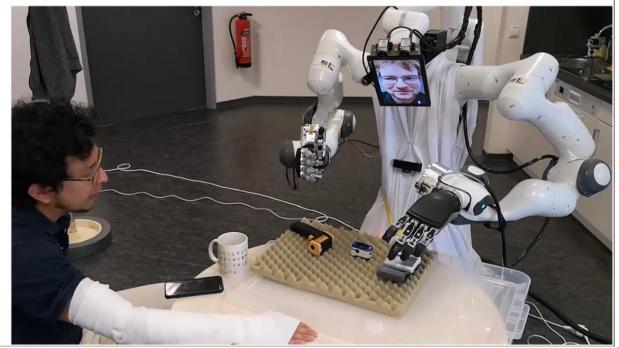
## Team NimbRo Semifinal Team Video

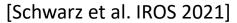
#### Tasks

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

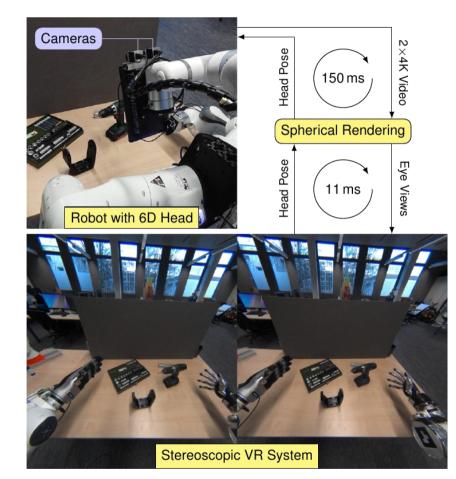
#### 4. Measure blood pressure

Measure oxygen saturation
 Help recipient with jacket

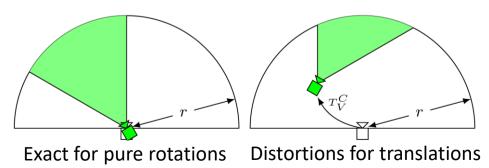




## **NimbRo Avatar: Immersive Visualization**



- 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

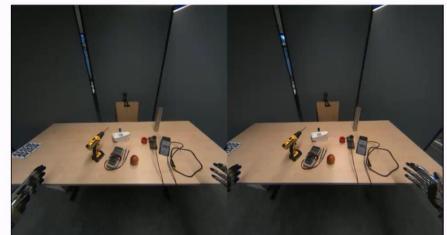


#### Wide-Angle Stereo

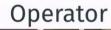


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HMD View









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

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

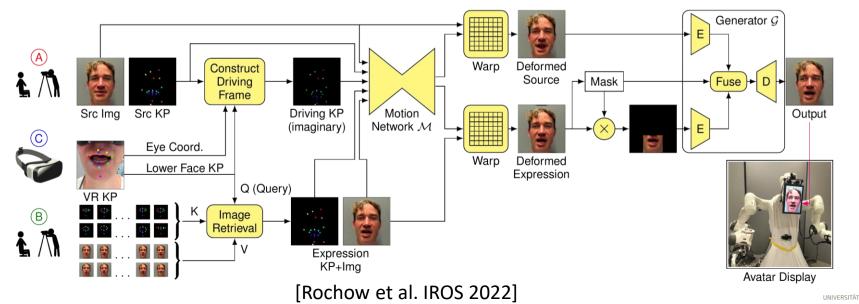




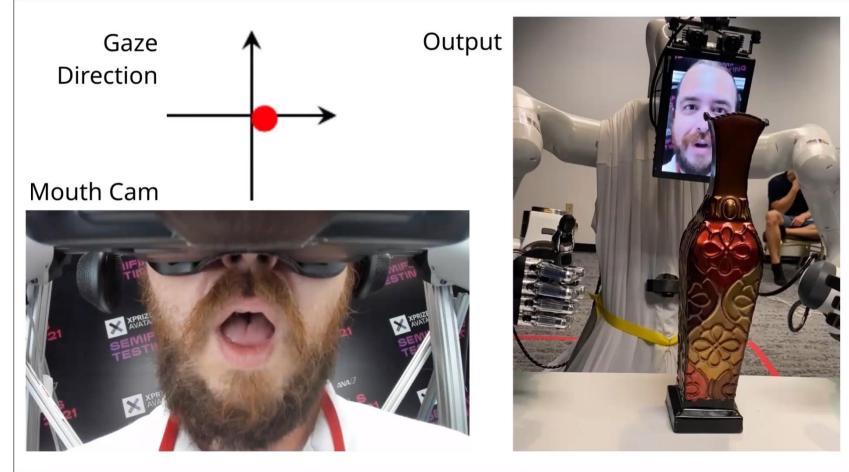


Right Eye

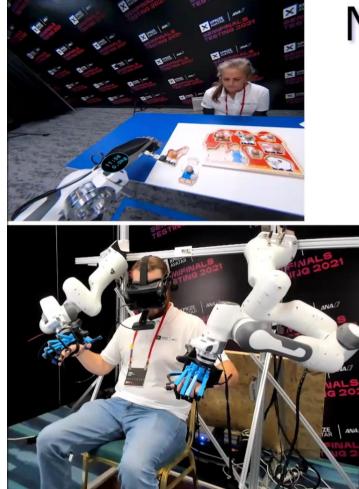
Generate animated operator face using a warping neural network



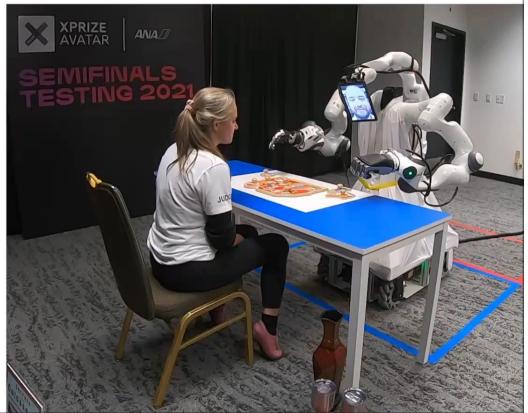
### **NimbRo Avatar: Operator Face Animation**







## NimbRo Avatar Avatar XPRIZE Semifinals

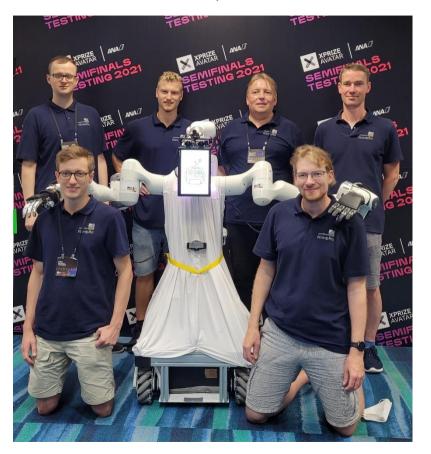


[Schwarz et al. IROS 2021]



## **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





## **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

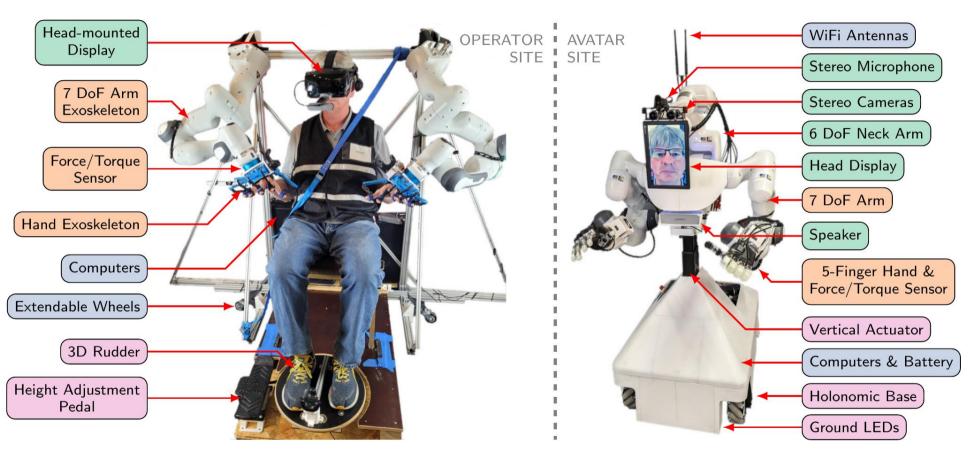








## NimbRo Avatar Finals System





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

## Finals Test Run Day 1



## **Face Animation @ Finals**

#### Team UNIST





#### Northeastern [12]

#### Ours (NimbRo)





#### i-BOTICS

#### Team AVATRINA [13]



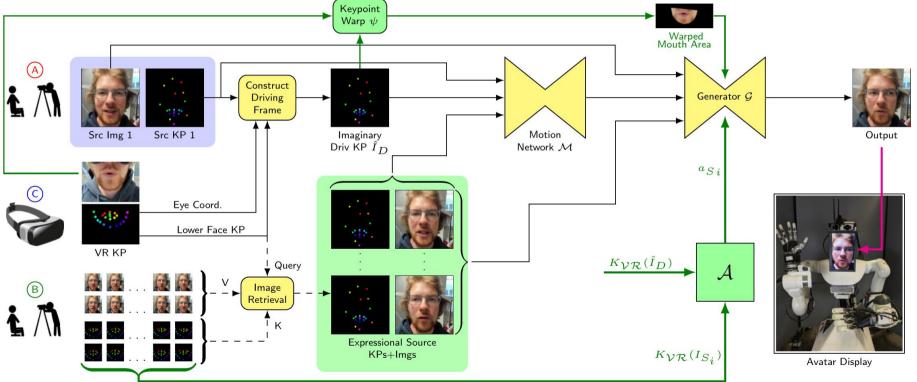


**Pollen Robotics** 



## **Improved Operator Face Animation**

- Better temporal continuity
- Direct incorporation of mouth video

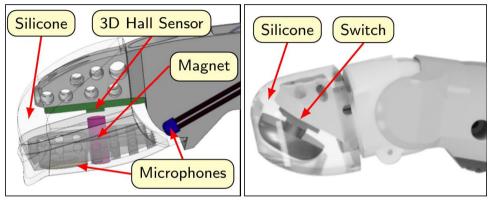


[Rochow et al. 2023, submitted to IROS]

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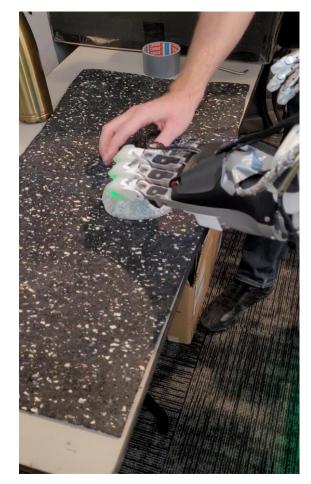
## **Haptic Perception**

## Sensors in the finger tips



## Actuators on the hand exoskeleton

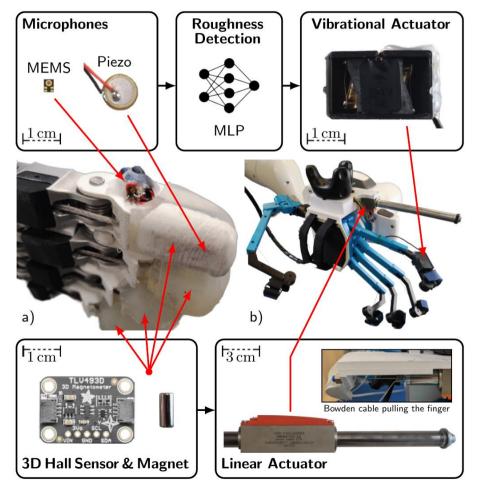






[Pätzold et al. SMC 2023]

## **Roughness Perception**



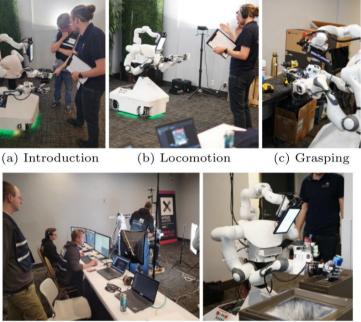
## Dataset of rough and smooth objects



[Pätzold et al. SMC 2023]

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

## **Operator Training**



(d) Monitoring crew

(e) Free experiments

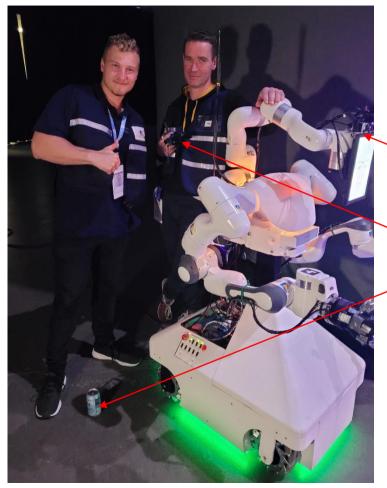
Training	Time [min]
System overview	3
Face animation video w/o HMD	2
Put on HMD	1
Face animation video with HMD	2
Strap in hands	4
Enable arm and hand control	3
Locomotion training $(T1, T5, T8)$	4
Training switch and canister (T4, T6, T7)	5
Training power drill (T9)	5
Training stones $(T10)$	10
Enjoy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

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

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



## 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**

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## **Operator Crew GUI**

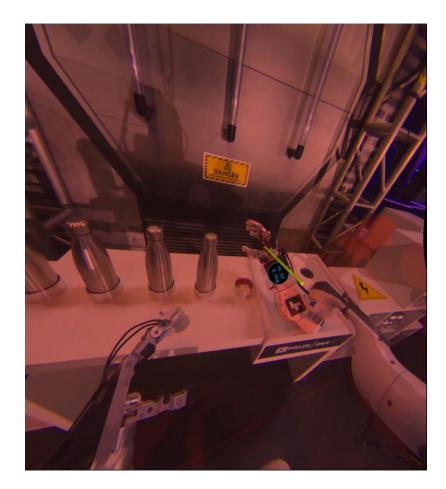
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/otto/sysmon/st	Usage 30.51%	/rosmon_otto_arms/state V Node CPU	Aux Image 4.25 MBit/s	5GHz 0 p/s	2.4GHz	0 p/s		light tracking pose is not valid (tracker turned eft tracking pose is not valid (tracker turned o			
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USB	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	ies	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
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)	ite in stringe	-	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	e 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					15:43.71 /avatar_vr	anna/basler/right/image/h264: waiting for transf nna_nominal_head_link: Would require extrapolati	form: Query anna_basler_right_optical_frame <-	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	d require extrapolation 9.993824820s into the	Terror and the second s	Time
HDMI Bagfile	58.2 Hz (delay 0.06s) Paused	<b>▼</b> VR × <b>▼</b> Glove ×	Action: inactive	3 J4 Action: inad	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 <- lon	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	×	🗧 🔻 Basier	🗙 🔻 Left Eye	🗙 🔻 Right Eye 🛛 🗙
/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			1000
	Usage 15.11%		Otto	UII	- On		RX: 390 MBit/s MCS 8500MH8z/5			
Temperature	CPU: 68° PCH: 67° SSD: 44° Usage 32% (596G free)	/rosmon anna core/state					5 GHz		A A A A A A A A A A A A A A A A A A A	Con la
	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		11111 111260 11111	
a construction of the second	All 3 connections checked	/anna/audio/haptics 0.03	Left Hand		Off	Ping XPRIZE Ping	22.30 MBR/s Ping RTT 1 28.0ms			× ₹ Reconstruction ×
	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	A V Reconstruction
Brio Front	43.8 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 20MMB#/s	has been a second and the second seco	I TXHR	
Hand Cam	15.0 Hz (delay 0.11s)	/anna/audio/thru_comm0.00				28.22 MBI05	2.4 GHz	100	AVA ~~ //	The stand of the
	1: 46°, 2: 48°, 3: 46°, 4: 44° 48.9 Hz (delay 0.04s)	/anna/audio/thru_haptic 0.01	Anna Limits	On	Off		·	A CONTRACTOR		a search and
	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	an all and a second	in. 59.1	(EIN 100 130.71 1 10 10
Head	Delay: 0.02s	/anna/monitor 0.01	Spine		Off	Otto config Anna Config Otto con	text Log		🗙 🔻 Eye calibration	×
	Delay: 0.02s	/anna/network_control 0.00	Recording			<b>V</b> 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	orr;) orm: Ouery anna basler right optical frame <-	#Images: L:356, R:356, D:1639	
	Delay: 0.05s	/anna/syslog 0.00	Y Offset	05	Off		/anna/basler/right/image/h264: waiting for transf anna_nominal_head_link: Would require extrapolati	on	Train 0% Train error: 3.891897 deg	
	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 extrapolatio	rm: Query anna_basler_left_optical_frame <- on		X ▼ 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		bitus eye	
	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	Opening bag file: /home/avatar/eye_bags/bag_2022-	11-05-23-41-34.bag	10000	
Bagfile	Paused	/atlas_receiver 0.04	Feedback 5.32 MBit/s	5GHz 0 p/s	2.4GHz 0 p/s	10.42.00 / avacar_vi	/anna/basler/right/image/h264: waiting for transfo anna_nominal_head_link: Would require extrapolatio	on on		6
		/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 extrapolatio	rm: Query anna_basler_left_optical_frame <- on	The second second	
/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 )		19 V.	
CPU	Usage 30.51%	Node CPU /arduino0 0.05	/otto/network_control/si	atus			Left tracking pose is not valid (tracker turned o long delay in decoder	ff?) (connected=true, valid=true, result=101)		ITH
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	es 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	franka::ControlException: libfranka: Move command mode!		-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	ht/commander		rosmon: starting '/otto/left/driver'		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		Robot is locked, I'm going to unlock it Setting brakes to 0		U 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		➡ Roughness	×
Glove Right	96.4 Hz (delay 0.06s)		Action: inactive	Action: inactive			Operator is present, not disabling.		/roughness_detector_client/confi	dence
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	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	Waiting for EStop release 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 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 the when looking up transform from frame <u>Fotto arm le</u>	e eartlest data is at time 100/088190.282778025, ft_tracker_link] to frame [vr_link]	0	
VR Calibration	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	
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 extrapolation	orm: Query anna_basler_right_optical_frame <- on	3	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.			man Aman management
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 the when looking up transform from frame [otto_arm_le	d require extrapolation 9.993824820s into the	transfer to the second se	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>ft_tracker_link] to frame [vr_link]</pre>	Packet	Loss Concealment
Daynic	rauscu	VR Calibration 🗸 Up Calib	Lock	15 j6 Lo	ck		/anna/basler/left/image/h264: waiting for transfo anna_nominal_head_link: Would require extrapolatio	<pre>rm: Query anna_basler_left_optical_frame &lt;- on</pre>	Files	
		V 90° Calib	Power off	POW/	pr off		analitation and prededictions induced require excitabolar		e 40	Market and

## **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, more to come: https://github.com/AIS-Bonn/nimbro\_network

/anna/netw	ork_control/s	tatus									
System	0.39 MBit/s	5GHz	0 p/s	2.4GHz	0 p/s						
Feedback	5.32 MBit/s	5GHz	0 p/s	2.4GHz	0 p/s						
TF	4.16 MBit/s	5GHz	0 p/s	2.4GHz	0 p/s						
Cam Left	7.16 MBit/s	5GHz	0 p/s	2.4GHz	0 p/s						
Cam Right	7.39 MBit/s	5GHz	0 p/s	2.4GHz	0 p/s						
Aux Image	4.25 MBit/s	5GHz	0 p/s	2.4GHz	0 p/s						
/otto/network_control/status											
System	– 0.00 MBit/s	5GHz	0 p/s	2.4GHz	0 p/s						
Control	0.17 MBit/s	5GHz	0 p/s	2.4GHz	0 p/s						
TF	1.35 MBit/s	5GHz	0 p/s	2.4GHz	0 p/s						
Aux Image	2.92 MBit/s	5GHz	0 p/s	2.4GHz	0 p/s						
Preq: 5.76 GHz Associated since Signal: -64 dBm RX: 390 MBit/s M 22.30 MBit/s Ping RTT 0.0ms     RTT 0.1ms     Freq: 2.412 GHz Associated since Signal: -64 dBm RX: 390 MBit/s M 22.30 MBit/s RTT 1 28.0ms RTT 1 28.0ms     RTT 1 28.0ms     RTT 2 13.3ms     NTP synced     State     State											
	28.22 MBit/s		Signal: -53 dBm RX: 58 MBit/s MCS 0 2.4 GHz TX: 26 MBit/s MC		Since						



## **Audio Details**

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





[Schwarz et al. 2023, arXiv:2303.03297, submitted to IROS]

## **Finals Day 2 Testing**



## **Finals Timings**

30

							Time	[mm:ss	]				
Team	Day	Start	<b>—</b> T1	<b>•</b> T2	<b>T</b> 3	<b>•</b> T4	<b>T</b> 5	<b>—</b> T6	<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>	00:06 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	$01:39 \\ 01:43$	$\begin{array}{c} 00:40 \\ 00:49 \end{array}$	$\begin{array}{c} 01:15 \\ 02:02 \end{array}$	$00:53 \\ 01:15$	$\begin{array}{c} 00{:}14\\ 00{:}18 \end{array}$	$\begin{array}{c} 00:50 \\ 00:51 \end{array}$	$\begin{array}{c} 05:06 \\ 01:28 \end{array}$	$02:24 \\ 01:59$	13:20 10:50
Team Northeastern	$\frac{1}{2}$	$00:00 \\ 00:00$	$\begin{array}{c} 00:33\\ 00:16 \end{array}$	$\begin{array}{c} 00:24 \\ 00:19 \end{array}$	$\begin{array}{c} 02:\!08 \\ 01:\!47 \end{array}$	$\begin{array}{c} 01:43 \\ 00:52 \end{array}$	$\begin{array}{c} 04{:}03\\01{:}14\end{array}$	$01:27 \\ 01:05$	$\begin{array}{c} 00:36 \\ 00:15 \end{array}$	$\begin{array}{c} 01:56 \\ 01:00 \end{array}$	04:54	09:27	$12:5 \\ 21:0$
AVATRINA	$\frac{1}{2}$	$00:00 \\ 00:00$	$\begin{array}{c} 00:28 \\ 00:24 \end{array}$	$\begin{array}{c} 00:23 \\ 00:12 \end{array}$	$\begin{array}{c} 02:03 \\ 01:39 \end{array}$	$\begin{array}{c} 01:45 \\ 01:05 \end{array}$	$\begin{array}{c} 03:10 \\ 02:50 \end{array}$	$\begin{array}{c} 06:17 \\ 00:48 \end{array}$	$\begin{array}{c} 00:19 \\ 00:11 \end{array}$	$\begin{array}{c} 02:24 \\ 01:30 \end{array}$	$\begin{array}{c} 03:10 \\ 02:43 \end{array}$	04:48	$24:4 \\ 11:2$
i-Botics	$\frac{1}{2}$	$00:00 \\ 00:00$	$00:13 \\ 00:19$	$\begin{array}{c} 00:26 \\ 00:12 \end{array}$	<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		$22:3 \\ 05:3$
NimbRo Day	y 1	8:15 – Own improv locomotion										nainly	
NimbRo Day Pollen Robotics Day				5:50	)			13:20		•		0 (ston aster th	
Pollen Robotics Day	y 2					1	10:50			other t			
Team Northeastern Day	y 2										21	L:09	
AVATRINA Day	y 1												24:4
	0:00	1	5:00		1	0:00		15:00		20:0	00	25	5:00
et al. 2023, submitte	ed to In	ternati	onal Jo	ournal	of Soc		Time [m ootics]						UN

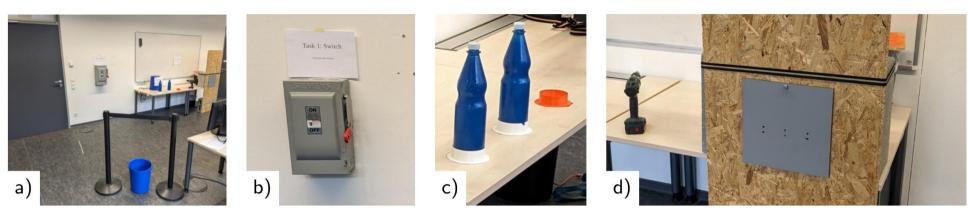


## Team NimbRo





## **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, <u>10 min task training</u>, expert team members similar to Finals



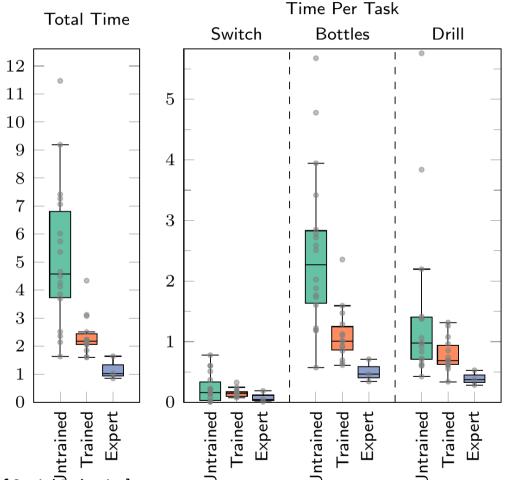
[Lenz et al. 2023, submitted to International Journal of Social Robotics]

## **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 <sup>1</sup>/<u>E</u>
- All participants were able to solve the tasks
- => System is very intuitive, but short instruction on tasks improves completion time.



**Fime** 



### **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



<sup>34</sup> [Lenz et al. 2023, submitted to International Journal of Social Robotics]

## **Questions?**

Join the Winning Team!

We are hiring.



