From Intuitive Immersive Telepresence Systems to Conscious Service Robots

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Telepresence Systems

- Enable a human operator to be present at a remote location
- Capture remote location with cameras, microphones, force & haptic sensors, etc.
- Display remote measurements to the operator
- Capture operator movements, speech, and expressions
- Transfer them to avatar robot





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]





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

- 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



[Schwarz et al. IROS 2021]





Team NimbRo Semifinal Submission







Manipulation with Force and Haptic Feedback



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





Team NimbRo Semifinal Team Video

Tasks

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

4. Measure blood pressure

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





NimbRo Avatar: Immersive Visualization



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





[Schwarz and Behnke Humanoids 2021]

NimbRo Avatar: Immersive Visualization

Avatar Robot



Wide-Angle Stereo



UNIVERSITÄT BO

HMD View









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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		
AVATAR	A P K I	ΖE

[XPRIZE]

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

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 MileDragonTree 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

10. Feel texture





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

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Face Animation @ Finals

Team UNIST





Northeastern [12]

Ours (NimbRo)





i-BOTICS

Team AVATRINA [13]





Pollen Robotics



Haptic Perception

Sensors in the finger tips



Actuators on the hand exoskeleton







[Pätzold et al. SMC 2023]

Roughness Perception



Dataset of Rough and Smooth Objects



[Pätzold et al. SMC 2023]



Finals Task 10: Retrieve a Rough Stone

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





Operator Training





Introduction

Locomotion Grasping



Monitoring crew

Free experiments

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

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

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



Operator Crew GUI

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Operator Crew GUI

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otto/sysmon/st	ate 🔽	/rosmon_otto_arms/state 💟	Aux Image 4.25 MBit/s	5GHz 0 p/s	2.4GHz 0 p/s	15:42.29 /otto/monitor R	ight tracking pose is not valid (tracker turned o	off?)	1 AN			
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HDD	Usage 55% (397G free)	/arduino0 0.05	System 0.00 MRit/s	5010 0-0	a true	15:43.07 /anna/right/driver 0	ong delay in decoder tto right arm command is too old (141.240874364s)		Votto/left/driver/wrench	Votto/right/driver/wrench		
Network	All 9 devices checked	/otto/left/driver 0.00	System 0.00 MDID'S	SGHZ 0 p/s	2.4GHZ 0 p/s	15:43.08 /anna/left/driver 0	tto left arm command is too old (141.256047258s)		Forest Contract of	Course -		
	52.0 Hz (delay 0.07s)	/otto/left/ft 0.04	Control 0.17 MBit/s	5GHz 0 p/s	2.4GHz 0 p/s	15:43.15 /avatar_vr /	anna/birds_eye/out/compressed: Dropping old frame	es	10 The conce	10 TOTCE		
Mouth cam	56.2 Hz (delay 0.09s)	/otto/right/driver 0.28	TF 1.35 MBit/s	5GHz 0 p/s	2.4GHz 0 p/s	15:43.19 /otto/left/driver E	-Stop released (mode 1), back to control			×		
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				-10 Z	-10 Z		
Difference Cam	28.7 Hz (delay 0.11s)	/otto/state_pub 0.05	Janna/left/commander/sta	atus 🔻 🚺 /anna/right/cor	mmander/status		ode! osmon: /otto/left/driver died from signal 6					
Arm Left TF	Delay: 19.86s		X lanna llaft learnin	anda (anna/rid	abt/commondor	15:43.51 /rosmon_otto_arms r	osmon: starting '/otto/left/driver'		Torque	Torque		
Arm Left Comm	No message	/rosmon otto network/state			gnocommander	15:43.23 /otto/left/driver R 15:43.49 /otto/left/commander S	obot is locked, I'm going to unlock it					
Arm Right TF	Delay: 0.00s	No message				15:43.60 /otto/left/commander G	ot error: 'eRessourcePending'		-4 Z	-4 Z		
Glove Left	96.4 Hz (delay 0.06s)		Status: EXEC Join	nts Status: EXEC	Joints	15:43.60 /otto/left/driver C			- Pourphoess			
Glove Right	96.4 Hz (delay 0.06s)		Reason: NOMINAL	Reason: NOMIN	NAL <u>J1 J2</u>	15:43.88 /otto/left/driver 0	perator is present, not disabling.		irouchpers detector client/com	fidanca		
	936.1 Hz (delay 0.05s)	sense_glove/GestureGUI sense_glove/GestureGUI	× Action: inactive	J4 Action: Inactive	5 4	15:43.26 /rosmon_otto_arms r	osmon: /otto/left/driver died from signal 6		1.2			
FT right	935.1 Hz (delay 0.06s)	0.08 rad Thumb	rot Dewet off	LO Dours	ick j5 j6	15:43.27 /rosmon_otto_arms r	osmon: starting '/otto/left/driver'		0.8			
kudder Pedal	47.7 Hz (delay 0.07s)	0.690 Max	Power on	Powe		15:43.69 /otto/monitor C	buld not get kinematic tracker pose: Lookup would	i require extrapolation 0.093787322s into the	0.4			
Eye Tracking	51.0 Hz (delay 0.11s)	-0.09 rad Thumb	fle /otto/left/commander/sta	tus 🔽 /otto/right/com	nmander/status 🛛 💟	p	ast. Requested time 1667688190.188990593 but the	e earliest data is at time 1667688190.282778025,				
R Calibration	Trackers/Arms not working	1.315 Min	/otto/left/comma	nder /otto/rig	ht/commander	15:43.24 /otto/left/driver W	aiting for EStop release	rt_tracker_ttnkj to frame [vr_ttnk]	/otto/haptics_sender/stats			
Audio	Running	0.10 rad Max oth	er			15:43.71 /avatar_vr /	anna/basler/right/image/h264: waiting for transfo	orm: Query anna_basler_right_optical_frame <-		Bardanata		
amulus Otto	Registered on server	0.280 Max	Status: SS2 loir	ats Status: 552	loints	15:43.24 /otto/left/driver W	<pre>ina_nominal_nead_link: Would require extrapolation aiting for E -Stop release</pre>		[£] 988	Packet rate		
Recording			Reason: NOMINAL	Reason: NOMIN	NAL	15:43.69 /otto/monitor C	ould not get kinematic tracker pose: Lookup would	i require extrapolation 9.993824820s into the	at 2010 and 2010	Time		
HDMI	58.2 Hz (delay 0.06s)	▼ VR × ▼ Glove	× Action: inactive	Action: inactive	13 14	P W	ast. Requested time 1667688190.188990593 but the nen looking up transform from frame <u>Fotto arm let</u>	e earliest data is at time 1667688200.182815552, /t tracker link] to frame [vr link]				
Bagfile	Paused	VR Calibration 🗸 Up Cali	b Lock 15	Lo	ick J5 16		anna/basler/left/image/h264: waiting for transfor	rm: Query anna_basler_left_optical_frame <-	· 문 왕	Closs concealment		
		🗸 90° Cal	b Downer off	Douve	ar off	a second se	nna_nominal_nead_link: would require extrapolation		<u>40</u>			

Operator Crew GUI

Anna	×	control_box/Clock	× Otto						network_dis	splay/network_di	splay		×	Section 3 Sectio	×Ŧ	Left Eye X	🛛 🔻 Right Eye 🛛 🕹 🗙
/anna/sysmon/s	tate 🔽	100.07	Movemer	nt			0	uff				Freq: 5.76 GHz					
Battery	Power supply 100%	400:37										Associated since:			· //	(and the second	Contraction of the
CPU	Usage 15.11%		Send Cm	ds		On	C	Off				RX: 390 MBit/s MCS 890MBt/s			1/10		
Temperature	CPU: 68° PCH: 67° SSD: 44°	Anna Core	× Otto									5 GHz					
HDD	Usage 32% (596G free)	/rosmon_anna_core/state	Head Con	ntrol		On	c	off									
USB		Node CF	U			12.00						TX- 390 MBit/s Mi	Robot				
Ping	All 6 connections checked	/anna/audio/carla 0.	IO Right Har	nd		On	C	out -	Operator	5.88 MBit/s	Router	ARRM 05 CC				100000260000000000	
Network	All 3 connections checked	/anna/audio/haptics 0.	3 Left Hand				C	off	Pipa	XPP17F	Ping	22.30 Mbi0s	PTT 1 28 0ms			Mouth	
Basler Left	46.3 Hz (delay 0.09s)	/anna/audio/interface 0.	5 Force / To	orque					RTT 0.0ms	AT NEL	RTT 0.1ms	Freq: 2.412 GHz	RTT 2 13.3ms			Mouul	Reconstruction
Basler Right	45.8 Hz (delay 0.07s)	/anna/audio/jack 0.	10									Associated since	NTP_synced			Mary 1	
Brio Front	19.7 Hz (delay 0.135)	/anna/audio/player 0.	1 Otto			Un	U.	лп —				Signal: -53 dBm				THE CAR	
Brio Rear	15.1 Hz (delay 0.155)	/anna/audio/thru_comm0.	Anna Fee	dback			C	off		28.22 MBit/s		RX: 58 MBit/s MCS 0 20MMBit/s		AT I WANTED		AVAL CON 1	TROTOPT
Hand Left	1.46° 2.48° 3.46° 4.44°	/anna/audio/thru_comm0.	Anna Lim	nits			c					2.4 GHz	-			ava/	
Hand Right	48.9 Hz (delay 0.04s)	/anna/audio/thru_naptic 0.				3703								1			
Magnet	3 sensors	/anna/audio/cirru_speak/0.	Atlas		-		_					TX: 26 MBit/s MC					
SVH Contact	193.2 Hz (delay 0.04s)	Anna Network	× Drive				C	Off				5.56 MBit/s		and all the second seco	a channaichte ann	100 100 59 1000000	1 10 10 10 10 10 10 10 10 10 10 10 10 10
Head	Delay: 0.02s	/anna/log_dansport 0.	11 Spine			On	C	off	Otto config	Anna Config	Otto conte	ct Log			× 🖘	Eye calibration	×
Arm Left	Delay: 0.02s	/anna/network_control_0	0					878) 	Tilter						Ban	Waiting	Start Stop
Arm Right	Delay: 0.02s	/anna/operator repub 0.	12 Recording	g	-				Time Nee		Ma					file:/home/avatar/eve_hags/ha	ig 2022.11.05.23.41.34 bag
FT left	480.2 Hz (delay 0.04s)	/anna/right/commander 0.	Record				C	off	15:41:34 /ot	tto/monitor	Ri	ssage ght tracking pose is not	valid (tracker turned)	off?)	Bag #In	ne. noneravatar/eye_bags/ba	g_2022-11-05-25-41-54.bag
FT right	479.9 Hz (delay 0.04s)	/anna/service_receiver 0.	0 Run						15:41.53 /av			nna/basler/right/image/h2	64: waiting for transf	orm: Query anna_basler_right_optical_frame -	-	Train 0%	
Wheels	Delay: 0.05s	/anna/syslog 0.	0 Voffeet			00						na_nominal_head_link: Wou	ld require extrapolation		Tra	in arrar 2 901907 dag	
Spine	0.90m (37%)	/anna/sysmon 0.	10			011		лц —	15:41.15 /av	atar_vr	/a	nna/basler/left/umage/h26 na nominal bead link: Wou	4: waiting for transfo ld require extrapolation	<pre>rm: Query anna_basler_left_optical_frame <- on</pre>		ni error. 5.691697 deg	
Audio	Running	/anna/tf_static_agg 0.	0 /anna/ne	twork control					15:41.40 /se	ense alove	Co	uld not get Senseglove da	ta. Please check USB c	onnection.		Bird's Eye	Hand
Face display	Human	/anna/tf_transceiver 0.	18 Sustem	0.29 MBit/	a court	0.54	24645	0.010	15:41.59 /ot	to/eye_record	ler Op	ening bag file: /home/ava	tar/eye_bags/bag_2022-	11-05-23-41-34.bag			
E-Stop	OK Druged	/anna/transceiver 0.	14	0.35 110101	Junz	o µ/s	2.40HZ	0 p/s	15:41.63 /av			nna/basler/right/image/h2	64: waiting for transf	orm: Query anna_basler_right_optical_frame -		1000 Carlos Carlos	
вадніе	Paused	/atlas_receiver 0.	2 Feedback	s 5.32 MBit/s	5GHz	0 p/s	2.4GHz	0 p/s	15, 41 25 /ot	to louis record	an Ior Ro	na_nominal_nead_link: wou	to require extrapolation				
		/atlas_sender 0.	10 TF	4.16 MBit/s	5GHz	0 p/s	2.4GHz	0 p/s	15:42.07 /an	na/right/driv	er Ot	to right arm command is t	oo old (81,240440935s)				
		/config_server 0.	0 Cam Laft	7 16 MPit/		1000	2.450		15:42.08 /an	ina/left/drive		to left arm command is to	o old (81.255314612s)			1	
		/ping_node 0.	0 cam cert	7-10 MIDID	5GHZ	o p/s	2.4GHz	U p/s	15:42.46 /ot			ft tracking pose is not v					
🛡 Otto		🔻 rosmon arms	> Cam Righ	nt 7.39 MBit/s	SGHz	0 p/s	2.4GHz	0 p/s	15:42.22 /av		/a	nna/basler/left/image/h26	4: waiting for transfo	<pre>rm: Query anna_basler_left_optical_frame <-</pre>		and the second sec	
/otto/sysmon/sta	ate 🔽	/rosmon_otto_arms/state	🔨 🛛 Aux Imag	ge 4.25 MBit/s	5GHz	0 p/s	2.4GHz	0 p/s	15:42 29 /ot		an Ri	na_nominal_nead_tink: wou	valid (tracker turned)	off?)		201	
CPU	Usage 30.51%	Node CF	Ú			N1524020		CHARGO	15:42.87 /ot	to/monitor	Le	ft tracking pose is not v	alid (tracker turned o	ff?) (connected=true, valid=true, result=10:			
HDD	Usage 55% (397G free)	/arduino0 0.	5 /otto/net	twork_control/s	status				15:43.19 /av			ng delay in decoder				11111111916111151111	
USB	All 9 devices checked	/otto/faulhaber_comm 0.	2 System	0.00 MBit/s	s 5GHz	0 p/s	2.4GHz	0 p/s	15:43.07 /ar	nna/right/driv		to right arm command is t	oo old (141.240874364s		/ott	to/left/driver/wrench 🛛 🛛 🔽	/otto/right/driver/wrench
Network		/otto/left/driver 0.	0 Control	0.17 MBit/s	s sour	0.0/2	24642	0.0/6	15:43.08 /an	ina/left/drive		to left arm command is to	o old (141.256047258s)			Force	Force
Index cam	52.0 Hz (delay 0.07s)	/otto/left/ft 0.	4		JOHZ	0 p/s	2.40HZ	u p/s	15:43.15 / 4	atar_vr	/a	uld not get Sepreglove da	ta Ploaco chock USB o	es	10	أرهده والمرجع والمرجع	
Mouth cam	56.2 Hz (delay 0.09s)	/otto/right/driver 0.	18 TF	1.35 MBit/9	SGHz	0 p/s	2.4GHz	0 p/s	15:43.19 /ot	to/left/drive	er E-	Stop released (mode 1), b	ack to control			×	
Eye Left	25.1 Hz (delay 0.12s)	/otto/right/ft 0.	Aux Imag	je 2.92 MBit/s	5GHz	0 p/s	2.4GHz	0 p/s	15:43.19 /ot						ent -10		-10 Z
Eye Right	26.0 Hz (delay 0.11s)	/otto/rudder_3d 0.							45.43.50.4.5								
Operator Cam	28.7 Hz (delay 0.11s)	/otto/state_pub 0.	/anna/lef	ft/commander/	/status 🗸 🕯	/anna/right/co	ommander/sta	tus 💟	15:43.50 /ro	smon_otto_arr		smon: /otto/lert/driver d	ted from signal b			Torque	Torque
Arm Left TF	Delay: 19.86s	rosmon network	💛 /anna	/left/com	mande	/anna/ri	ight/comr	nander	15:43.23 /ot	to/left/drive	r Ro	hot is locked. I'm going	to unlock it				4 X
Arm Dight TE	Delays 0.00c	/rosmon_otto_network/sta	e 🔻 👘						15:43.49 /ot	to/left/comma	nder Se	tting brakes to 0				Y	0- Y
Arm Right Com	n 0%	No message	Charterine EX	<i>VEC</i> 1	ninta C	hat in EVEC		Infato								Z	-4 Z
Glove Left	96.4 Hz (delay 0.06s)		Status: EX	VEC]	oints a	status: EXEC		joints	15:43.60 /ot	tto/left/drive						Poursboars	
Glove Right	96.4 Hz (delay 0.06s)		Reason: N	NOMINAL	J1 J2	Reason: NOMI	INAL	J1 J2	15:43.71 /ot	to/left/drive	er Ch	ecking if operator is pre	sent			Rouginess	
FT left	936.1 Hz (delay 0.05s)		Action: in	active	J3 J4	Action: inactive	e	J 3 J4	15:43.26 /rr			smon: /otto/left/driver/d	ied from signal 6		/rou	ughness_detector_client/confide -	ince 🔛 🔛
FT right	935.1 Hz (delay 0.06s)	0.08 rad Thur	ub rot	Lock	J5 J6	Lo	ock	J5 J6	15:43.27 /rd	smon_otto_arm	is ro	smon: starting '/otto/lef	t/driver'		1-	2	
Rudder	Ready	0.00100	Pov	wer off	17	Pow	er off	17		to/left/drive		iting for EStop release			0.	8	
Pedal	47.7 Hz (delay 0.07s)	0.690 Max							15:43.69 /ot			uld not get kinematic tra	cker pose: Lookup woul	d require extrapolation 0.093787322s into th	ie 0.4	4	
Eye Tracking	51.0 Hz (delay 0.11s)	-0.09 rad Thur	b fle /otto/left	t/commander/s	status 🔻 🛛	/otto/right/cor	mmander/stat	us 🔽			pa	st. Requested time 16676	con frame Lotto arm le	e earliest data is at time 1667688190.282770	1023,	0	
VR Calibration	Trackers/Arms not working	1.315 Min	/otto/	left/comm	nander	/otto/rig	aht/comm	hander	15:43.24 /ot	to/left/drive	wa Wa	iting for E -Stop release	Fom Frame [occo_arm_cc		Int	to/bantics_sender/stats	
Audio	Running	0.10 rad Max	other				<u>, , , , , , , , , , , , , , , , , , , </u>		15:43.71 /av		/a	nna/basler/right/image/h2	64: waiting for transf	orm: Query anna_basler_right_optical_frame -	<-		
Jamulus Otto	Registered on server	0.280 Max	Lange of the land								an	na_nominal_head_link: Wou	ld require extrapolation		ZH.	P	acket rate
Jamulus	Paused		Status: SS	52 J	oints S	status: SS2		Joints	15:43.24 /ot	to/monitor	Wa Co	uld not get kinematic tra	cker pose: Lookup would	d require extrapolation 9 993824920e into th	ate and a	208	
HDMI	58 2 Hz (delay 0.06s)	Arrowskield Die d															
Bagfile	Paused	Giove	Action: in	active	J3 J4 4	Action: inactive	e	J3 J4				en looking up transform f	rom frame [otto_arm_le	ft_tracker_link] to frame [vr_link]		Packet Lo	oss Concealment
gine		VR Calibration 🗸 Up	Calib L	Lock	J5 J6	Lo	ock	J5 J6	15:43.72 /av		/a	nna/basler/left/image/h26	4: waiting for transfo ld require extranalation	rm: Query anna_basler_left_optical_frame <- on	2H	80	
		🗸 90°	Calib Roy	weroff	1277		or off	177			an	ha_nom that_nead_ttik: Wou	ta require extrapolatio			40	

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	link fror	n avatar		Uplink to avatar								
Channel	MBit/s	5 GHz	2.4 GHz	Channel	MBit/s	5 GHz	2.4 GHz					
Arm feedback	8.5	\checkmark	×	Arm control	4.9	\checkmark	\checkmark					
Transformations	4.1	\checkmark	×	Transformations	1.4	\checkmark	×					
Main cameras	14.7	\checkmark	×	Operator face	5.7	×	\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	
AVATAR	KIZE

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	<mark>=</mark> T1	— T2	— T3	T 4	T 5	T 6	T 7	T 8	T 9	T 10	Total
NimbRo	$\begin{array}{c}1\\2\\1 ightarrow2\end{array}$	00:00 00:00 0:00	00:18 00:08 -0:10	00:10 00:09 -0:01	01:35 01:31 -0:04	00:52 00:23 -0:29	01:00 00:32 -0:28	00:22 00:26 +0:04	00:06 00:09 +0:03	00:50 00:26 -0:24	01:56 01:04 -0:52	01:06 01:02 -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	$\begin{array}{c} 01:39 \\ 01:43 \end{array}$	$00:40 \\ 00:49$	$\begin{array}{c} 01:15 \\ 02:02 \end{array}$	$\begin{array}{c} 00:53 \\ 01:15 \end{array}$	$\begin{array}{c} 00{:}14\\ 00{:}18 \end{array}$	$\begin{array}{c} 00:50 \\ 00:51 \end{array}$	$\begin{array}{c} 05:06\\ 01:28 \end{array}$	$\begin{array}{c} 02:24 \\ 01:59 \end{array}$	$13:20 \\ 10:50$
Team Northeastern [25]	1	$00:00 \\ 00:00$	$\begin{array}{c} 00:33 \\ 00:16 \end{array}$	$\begin{array}{c} 00:24 \\ 00:19 \end{array}$	$\begin{array}{c} 02:\!08 \\ 01:\!47 \end{array}$	$\begin{array}{c} 01:43 \\ 00:52 \end{array}$	$\begin{array}{c} 04{:}03\\01{:}14\end{array}$	$01:27 \\ 01:05$	$\begin{array}{c} 00:36 \\ 00:15 \end{array}$	$\begin{array}{c} 01:56 \\ 01:00 \end{array}$	04:54	09:27	$12:50 \\ 21:09$
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]	$\frac{1}{2}$	$00:00 \\ 00:00$	$\begin{array}{c} 00:13\\ 00:19 \end{array}$	$\begin{array}{c} 00:26\\ 00:12 \end{array}$	01:23 01:36	$01:53 \\ 03:25$	01:57	01:52	02:07	02:57	09:47		$22:35 \\ 05:32$
NimbRo Day	1				8:3	15		 Own improvement 					nainly in
NimbRo Day	2		5:50							locomotion time			
Pollen Robotics Day	1							13:20	-	T9 (drill) & T10 (stone) signific			
Pollen Robotics Day	2						10:50			laster	than t		1115
Team Northeastern Day	2										21	1:09	
AVATRINA Day	1												24:47
	0:00	1 1	5:00)	1	0:00	15:00			20:0	20:00 25:00		
							Time [m	nin:sec]					

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³⁹ [Lenz et al. International Journal of Social Robotics 2023]

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



Human Cognitive System

Cognitive architecture of the human mind has evolved to continuously interact with changing environments and self-monitor



Cognitive functions according to Kahneman (2011) and Dehaene (2017)

My Objective

Develop methods for learning perception and planning for service robots, which go beyond unconscious routine tasks by incorporating conscious processing to cope with novel situations and self-monitor





Overall Approach

Equip service robots with key elements of human cognitive architecture
 Bottom-up approach ensures grounding of conscious processing



Cognitive functions according to Kahneman (2011) and Dehaene (2017)



Unconscious Perception & Tracking

- 1. Learning hierarchical representations
- 2. Learning 3D multimodal scene models
- 3. Learning object models & relations
- 4. Learning prediction and tracking

Scene compositionality

- Objects and scenes described by their constituent parts and their relations
- Infinite variants from a finite set of building blocks
- Exploit inductive biases like canonical frames, 3D projective geometry, camera motion, object relations, compositional structure, hierarchical categorization, ...





Object-centric Video Prediction Decoupling Dynamics and Interaction



[Villar-Corrales et al. ICIP 2023]

- Scene parsing into object slots
- Video synthesis from objects and masks
- Predictor decouples temporal and relational attention



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Object-centric Video Prediction Data Sets

Obj3D

- Synthetic 3D objects
- Ball colliding with static objects
- Given 5 frames, predict next 5

MOVi-A

- Synthetic 3D objects
- Complex dynamics and occlusions
- Given 6 frames, predict next 8







Object-centric Video Prediction: Obj3D



[Villar-Corrales et al. ICIP 2023]



Object-centric Video Prediction: MOVi-A







Object-centric Video Prediction: Object Predictions





[Villar-Corrales et al. ICIP 2023]

Object-centric Video Prediction: Model Interpretability







Pred





[Villar-Corrales et al. ICIP 2023]

YOLOPose: Multi-Object 6D Pose Estimation using Keypoint Regression





[Amini et al. IAS 2022, Best Paper Award]



YOLOPose: Multi-Object 6D Pose Estimation using Keypoint Regression

Encoder self-attention



Object detections and decoder cross-attention



[Amini et al. IAS 2022, Best Paper Award]



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MOTPose: Attention-based Temporal Fusion for Multi-object 6D Pose Estimation

Propagating object embeddings, object descriptors, and poses



[Periyasamy, ICRA 2024]

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Unconscious Prediction and Control

- 1. Learning action-conditioned prediction
- 2. Learning to control in the now
- 3. Learning reusable skills
- 4. Learning from imitation and real-robot experience

Action compositionality

- Activities consists of sequence of actions, which can be decomposed into movement primitives
- Exploiting inductive biases like hierarchical structure, object binding, planning in the now, ...





Learning Interactive Functional Grasping



[Mosbach and Behnke CASE 2023, Best Paper Award]

Learning Pre-grasp Manipulation for Human-like Functional Grasping



 Dense multi-component reward function encodes desired functional grasp



Learns to reposition and reorient objects to achieve functional grasps







Grasp Anything: Augmenting Reinforcement Learning with Instance Segmentation to Grasp Arbitrary Objects

Teacher training



Teacher-guided sensorimotor learning



 Real-world deployment of promptable grasping policy



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Grasp Anything: Augmenting Reinforcement Learning with Instance Segmentation to Grasp Arbitrary Objects

Learned policy with improved object visibility is real-world deployable





Conscious Prediction and Planning

- 1. Learning a working memory
- 2. Learning working memory predictions
- 3. Learning conscious planning
- 4. Learning new conscious concepts

Systematic generalization



- Reuse task knowledge in infinitely many novel situations in which irrelevant items change
- Working memory as communication bottleneck
 - Focus on few items, ignore all others which are irrelevant for the task
 - Must combine multiple lower-level items to larger, composite items



Conscious Self-monitoring

- 1. Representing uncertainty
- 2. Predicting multiple plausible futures
- 3. Error detection and mitigation
- 4. Interactive learning

Self-aware

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- Being aware of own capabilities and limitations, dangers, etc.
- Systematically model and use uncertainty
 - Collect more information when needed
 - Avoid dangerous situations
 - Detect System 1 errors and mitigate them





Potential Impact

Consciousness is not a bug, but a feature!

- Will bring service robots to the next level
 - Systematically generalize skills and cope with novel situations



- Self-monitor perceptions and actions: obtain more information when needed, avoid risks, detect errors, and mitigate them
- Consciousness-inspired robots will have a high impact on economy and society since they will be **applicable to a large variety of open-ended domains**
- Will enable the creation of personal service robots which have the potential to change our society to the same degree personal and mobile computers changed it in the last decades



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
- Demonstrations can guide RL
- Consciousness needed for systematic
- generalization and self-monitoring



[XPRIZE]



Questions?

