Marine Systems & Robotics
Unit 05
Towards diver-robot interaction

http://impact.uni-bremen.de/

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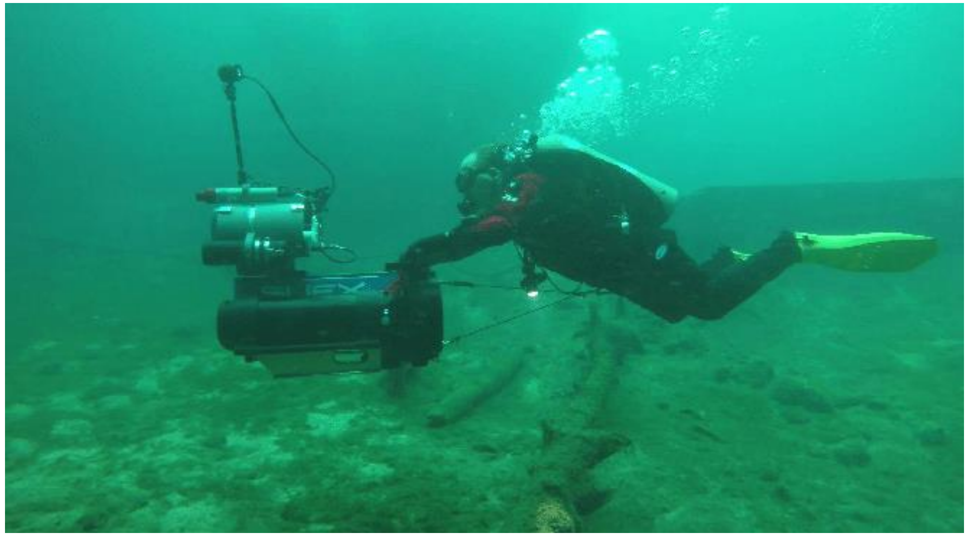
What is human-robot interaction (HRI)?

- robotics focuses on operation in the physical world
- HRI focuses on the social world
- HRI is even more multidisciplinary
  - human-computer interaction
  - robotics, AI
  - psychology, sociology
  - philosophy
- underwater HRI
  - somewhat limited social aspect
  - the focus is on the task rather than everyday interactions

Bartneck, C., Belpaeme, T., Eyssel, F., Kanda, T., Keijsers, M., & Sabanovic, S. (2020). **Human-Robot Interaction – An Introduction**. Cambridge: Cambridge University Press.

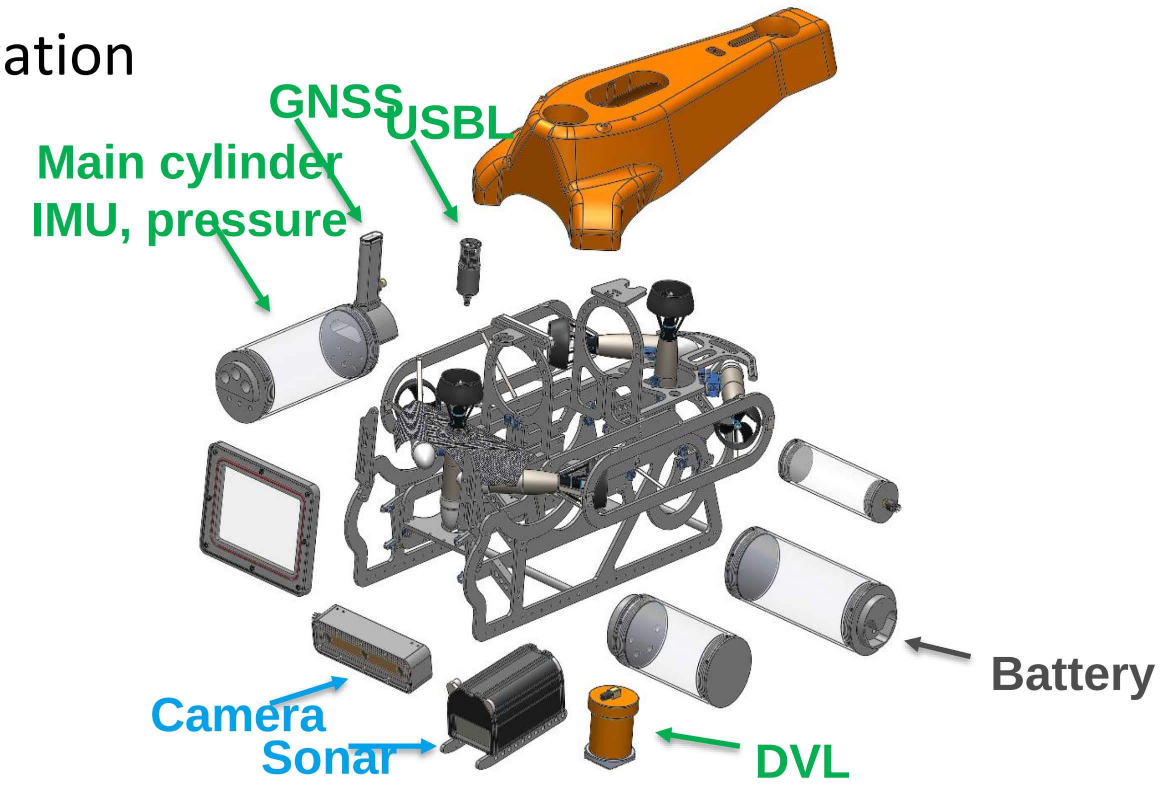
Diving challenges

- dependence on technical equipment
  - additional mission related sensors
  - strict rules about depth changes to avoid health issues
- impaired visibility
- constant external disturbances
  - additional problems when no visible reference
- basic navigation
  - compass/depth/time



Underwater vehicles

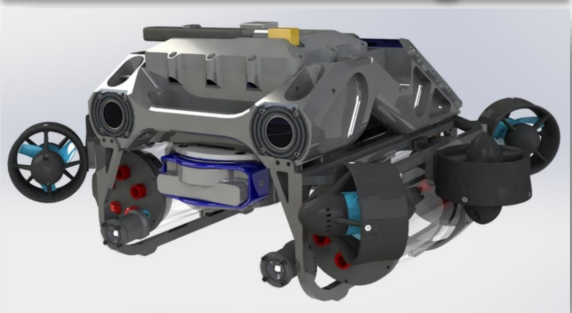
- can carry many sensors
  - stable by design – better sensor orientation
- decent navigation underwater
- easily surface on demand
- problems:
  - object manipulation
  - scene interpretation
  - decision making



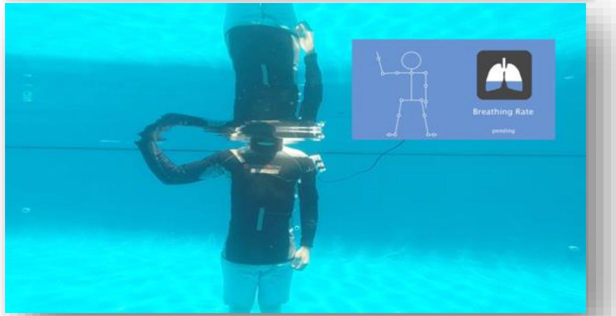
Synergy between diver and robot

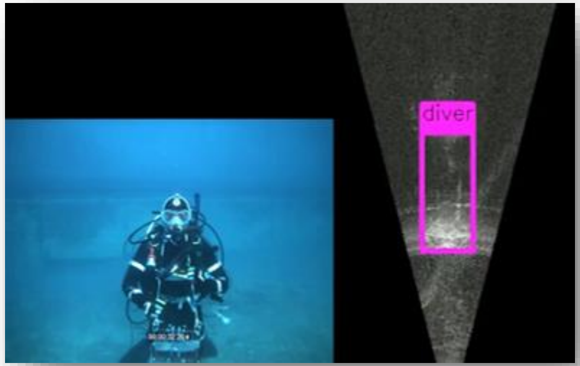
Building blocks (engineering only)

vehicle design

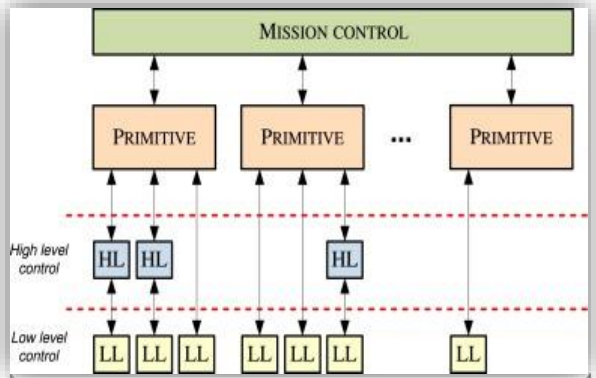


wearable sensors





perception



NGC

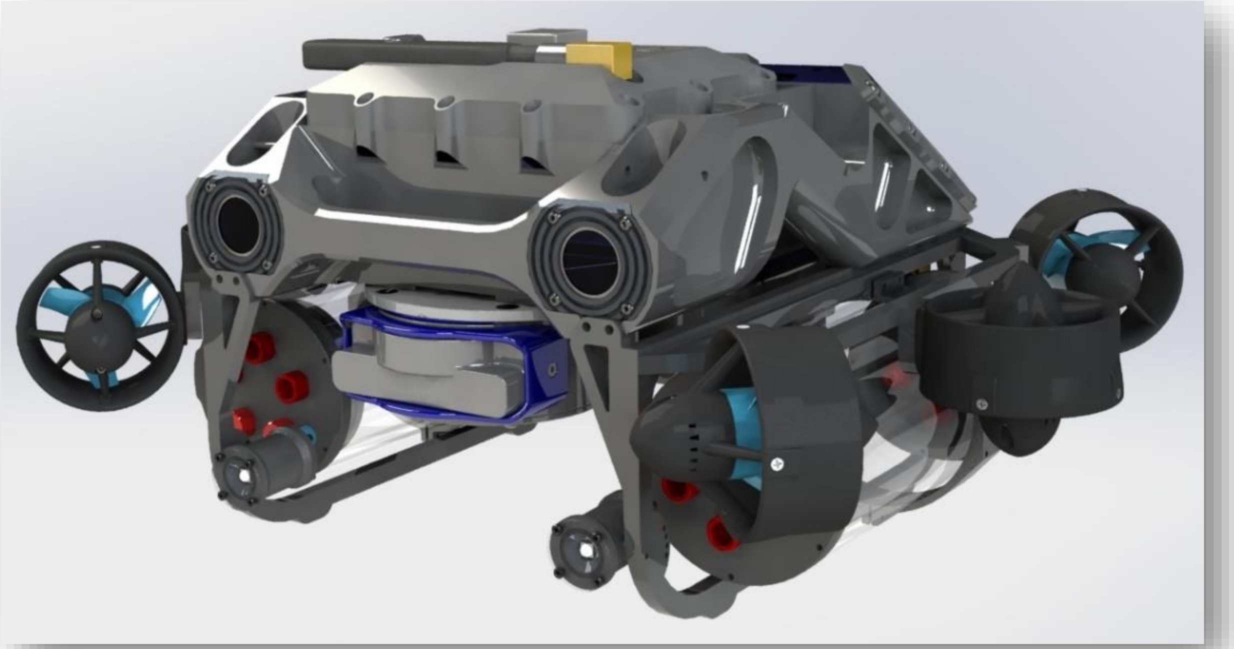
interaction

Expected outcomes

- review modalities applicable in diver-robot interaction
- learn how wearable sensors are used for physiological measurements
- introduce basic literature for further research in the field

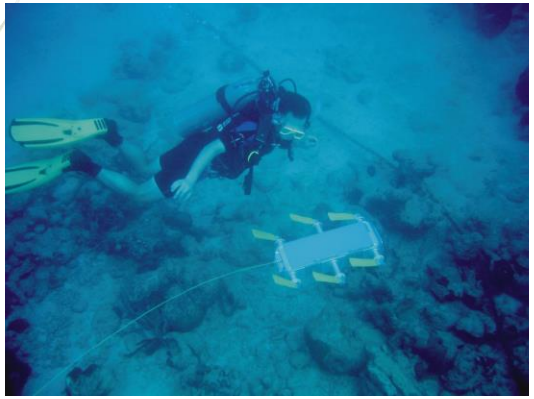
- learn how sensors are used for perception and localization of divers
- demonstrate a simple control algorithm for tracking and guidance

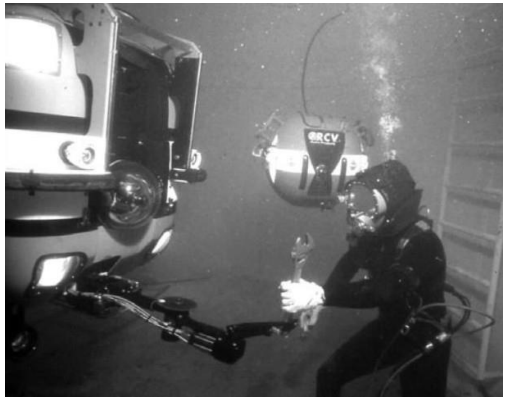
Vehicle design



Types of underwater vehicles

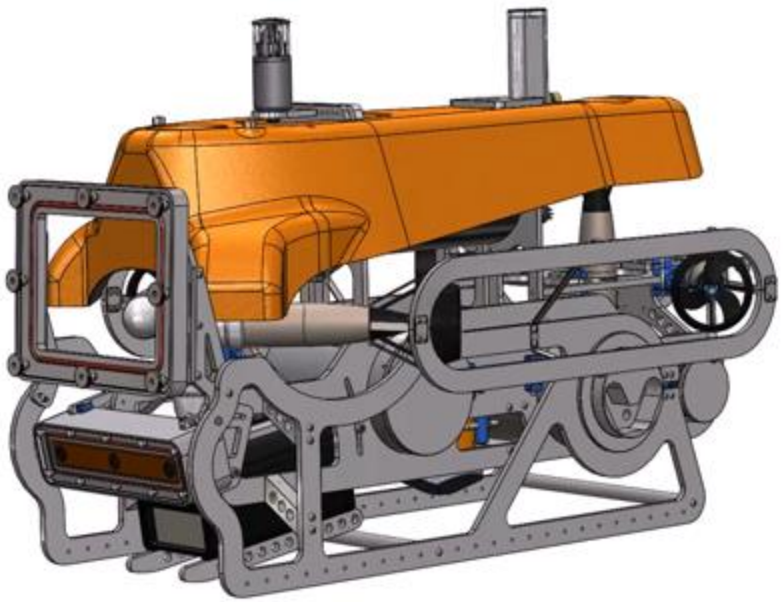
- ROV, HROV
  - good for Wizard of OZ studies
  - can be untethered for AUV operations
  - hover capabilities,
    easier sensor placement
  - nonhumanoid form
- humanoid ROV
  - maybe in the future





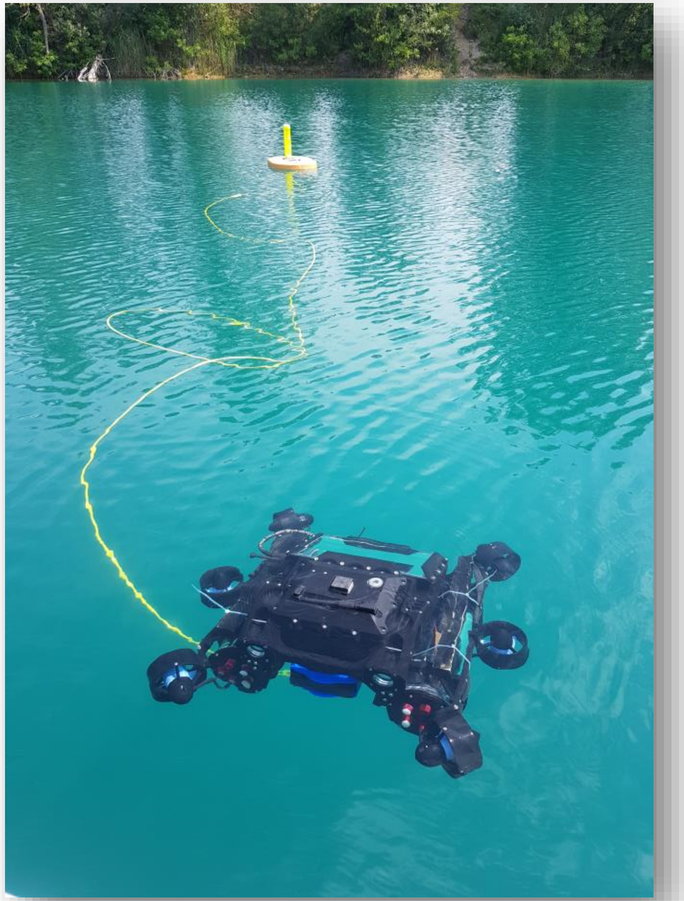
CADDY AUV - Buddy

- build from scratch
- sensors for perception and diver localization
  - Seatrac USBL
  - ARIS3000 multibeam sonar
  - XB3 stereo camera
- diver interaction
  - underwater tablet
- drawback
  - size and weight



Adriatic AUV - D2

- COTS hand-held diver navigator
  - added propulsion modules
  - Jetson Xavier for perception
- components
  - screen for direct interaction
  - 2 lights (1 diver aiding, 1 communication)
  - LED indicators



Interacting with the diver

Common HRI modalities

- spatial interaction
  - positioning to initiate HRI
- nonverbal
  - gaze, rhythm, timing, imitation
  - gesture, posture, movement, touch
- verbal

Modalities in diver-robot interaction

- focus on transmitting information rather than emotion
- spatial interaction
  - interesting for approach phase with more divers
  - detecting the diver desired to initiate communication
- nonverbal
  - gesture, movement, touch (haptic), light emblems
  - gaze can be used in sense of
    - eye tracking in the diving mask
    - head/mask orientation/direction
- verbal
  - only in special cases in diving
- other modalities (more human-computer interaction)
  - augmented and regular displays

Gesture based communication

Gesture based communication

- most common way of diver communication
  - commonly used when verbal communication is not possible on land
- types of gestures
  - dietic - pointing to specific things
  - iconic – nonverbal cues to support verbal interaction (e.g., mime a object)
  - symbolic (emblems) - convey specific meaning
  - beat – supporting rhythm in speech (e.g., moving arms)
- diving gestures are symbolic
- for nonhumanoid robots these are used for diver to robot communication

Gesture based communication

- common diving gestures
  - can be static and dynamic
- focus on basic information
- complex scenario issues
  - need a domain specific language

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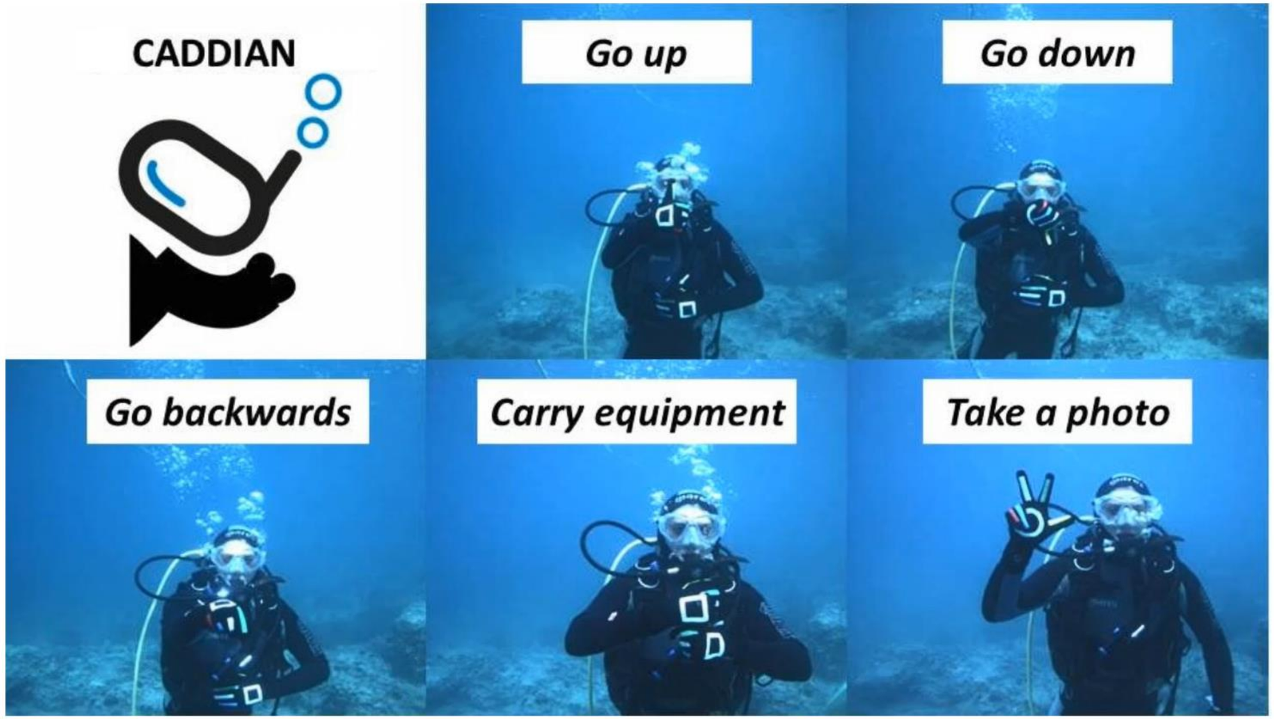
Caddian gesture language

- 40 gestures
  - extend the diver vocabulary with domain specific gesture

Group	Commands/Messages	
Problems	I have an ear problem I'm out of air [air almost over] I depleted air I'm cold I have vertigo	I'm out of breath Something is wrong [diver] Something is wrong [environment] I have a cramp
Movement	Take me to the boat Take me to the point of interest Go X Y $X \in Direction$ $Y \in \mathbb{N}$	You lead (I follow you) I lead (you follow me) Return to/come X $X \in Places$
Interrupt	Stop [interruption of action] Let's go [continue previous action]	Abort mission General evacuation
Setting Variables	Keep this level (actions are carried out at this level) Level Off (AUV cannot fall below this level) Set point of interest Give me light (switch on the on board lights) No more light (switch off the on board lights)	Free level ("Keep this level" command does not apply any more) Slow down/Accelerate Give me air (switch on the on board oxygen cylinder) No more air (switch off the on board oxygen cylinder)
Feedback	No (answer to repetition of the list of gestures) Ok (answer to repetition of the list of gestures)	I don't understand (repeat please)
Works	Wait n minutes $n \in \mathbb{N}$ Tell me what you're doing Carry a tool for me Do this task or list of task n times $n \in \mathbb{N}$ Tessellation of point of interest/boat/here	Tessellation X * Y area $X, Y \in \mathbb{N}$ Photograph of X * Y area $X, Y \in \mathbb{N}$ Stop carrying the tool for me [release] Photograph of point of interest/boat/here
$Direction = \{ahead, back, left, right, Up, Down\}$		
$Places = \{pointofinterest, boat, here\}$		



Chiarella, D.; Bibuli, M.; Bruzzone, G.; Caccia, M.; Ranieri, A.; Zereik, E.; Marconi, L.; Cutugno, P. **A Novel Gesture-Based Language for Underwater Human–Robot Interaction**. *J. Mar. Sci. Eng.* **2018**, *6*, 91.

Caddian gesture language

- robustness via clearly defined syntax
  - start/end communication
  - robot can detect error and request repeat of last gesture
  - robot can validate the complete gesture chain
- additional robustness through robot tablet
  - display recognized command and ask for confirmation

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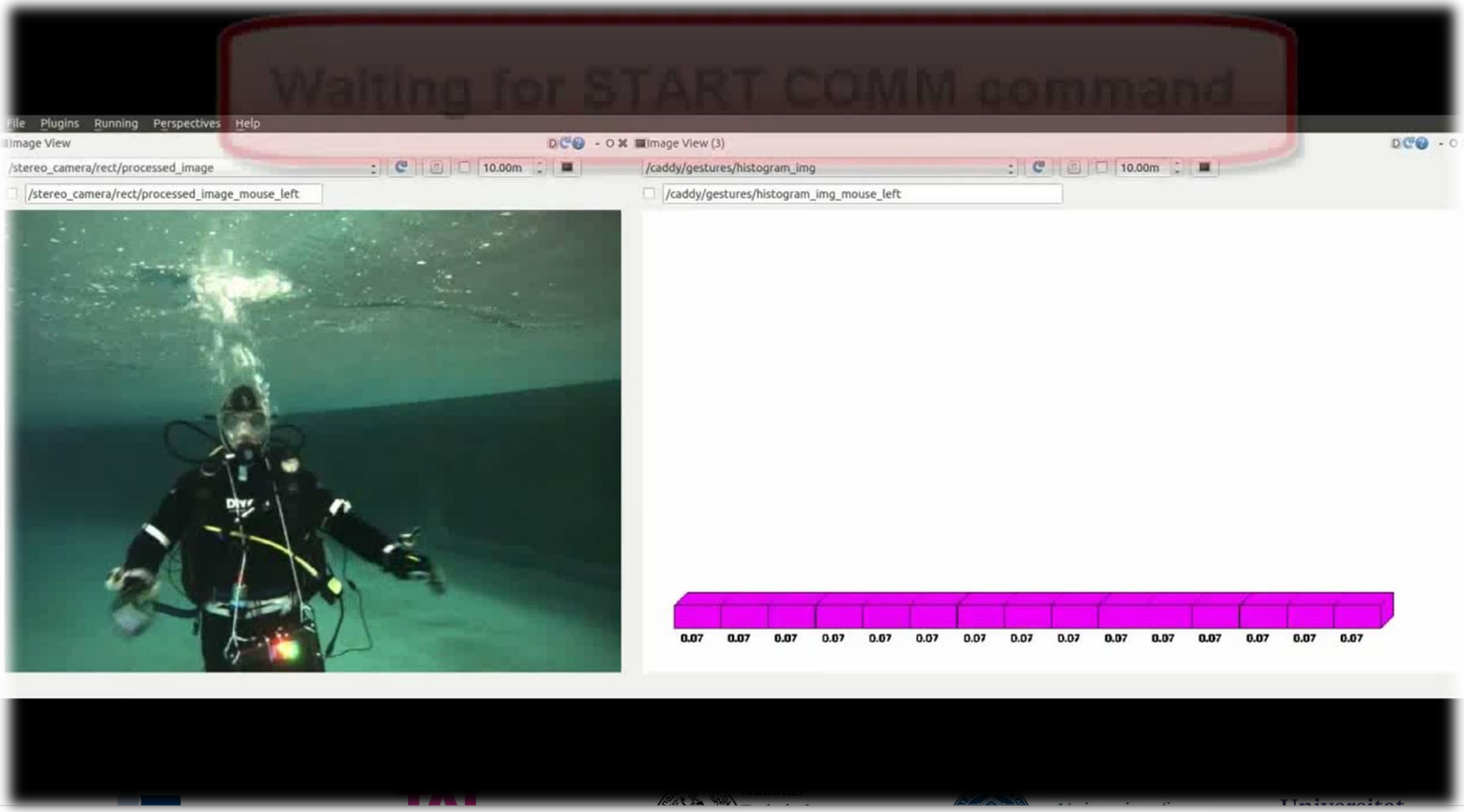
Gesture recognition



A. Gomez Chavez, A. Ranieri, D. Chiarella and A. Birk, "**Underwater Vision-Based Gesture Recognition: A Robustness Validation for Safe Human-Robot Interaction**," in *IEEE Robotics & Automation Magazine*, doi:

Gesture based communication

- learning curve
  - shown as small for Caddian but still exists
  - additional cognitive load for the diver
- requires robust and fast image processing
  - many gestures can take up a lot of diving time
  - recognizing glove, fingers is complex in underwater
- requires the diver to face the camera
  - the robot needs to understand the spatial hint that communication is desired

Marker based communication

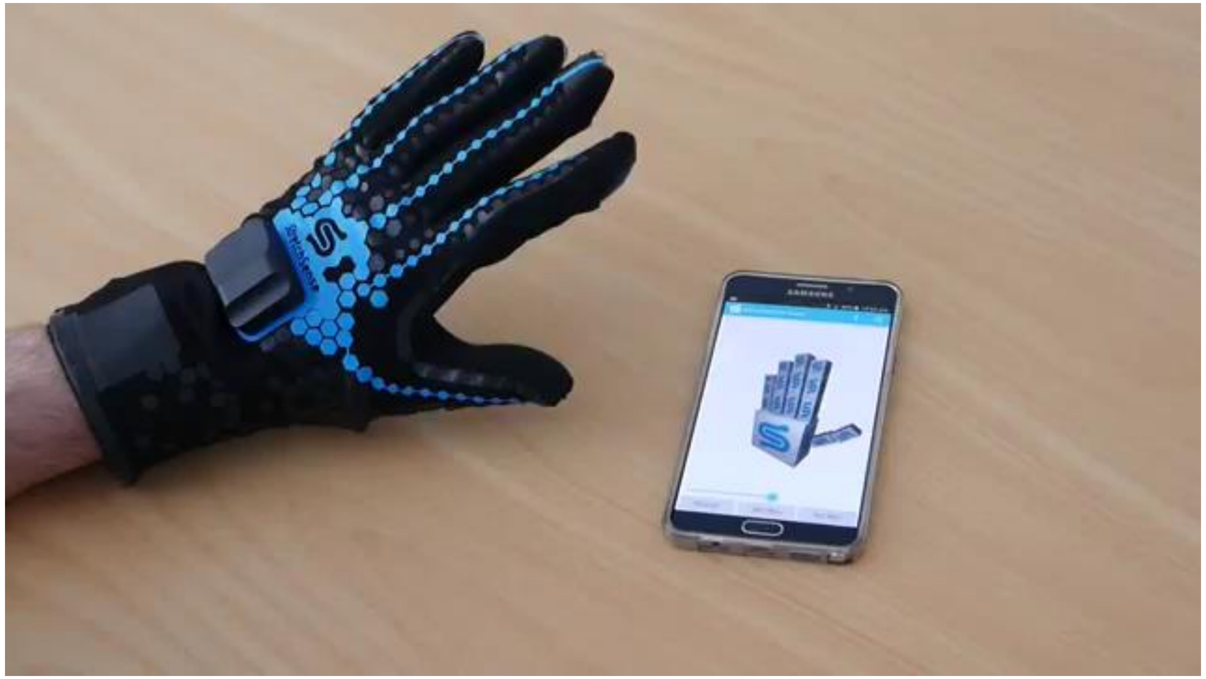
- alternatives to recognizing hand gestures
  - fiducial markers
- easier image processing
  - existing recognition software
- more complex for divers
  - carry all marker and assemble sentences

J. Sattar, E. Bourque, P. Giguere and G. Dudek, "**Fourier tags: Smoothly degradable fiducial markers for use in human-robot interaction**," Fourth Canadian Conference on Computer and Robot Vision (CRV '07), 2007, pp. 165-174, doi: 10.1109/CRV.2007.34.

G. Dudek, J. Sattar, and A. Xu, "**A visual language for robot control and programming: A human-interface study,**" in Proc. IEEE Int. Conf. Robot. Automat., Apr. 2007, pp. 2507–2513. doi: 10.1109/ROBOT.2007.363842.

Smart diving glove

- moving recognition on the diver
- benefits:
  - no need for image processing
  - independent of visibility condition
  - no line of sight
  - robust local processing
  - less recognition time
- drawback:
  - need to transmit data
  - transmission delay



Nađ, Đ., Walker, C.S., Kvasić, I., Antillon, D.O., Mišković, N., Anderson, I., & Lončar, I. (2019). **Towards Advancing Diver-Robot Interaction Capabilities**. IFAC-PapersOnLine, 52, 199-204.

Smart diving glove

Inertial Measurement Unit

Integrated compass, accelerometer
and gyroscope

Prototyping Circuitry

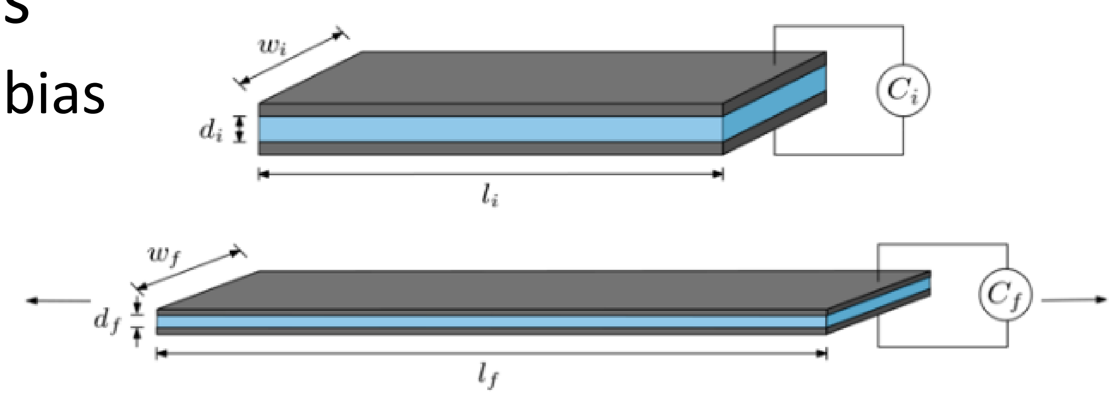
apacitance and Inertial measurements
translated into gestures

Strain sensor

Capacitance-based strain sensors
placed over each finger

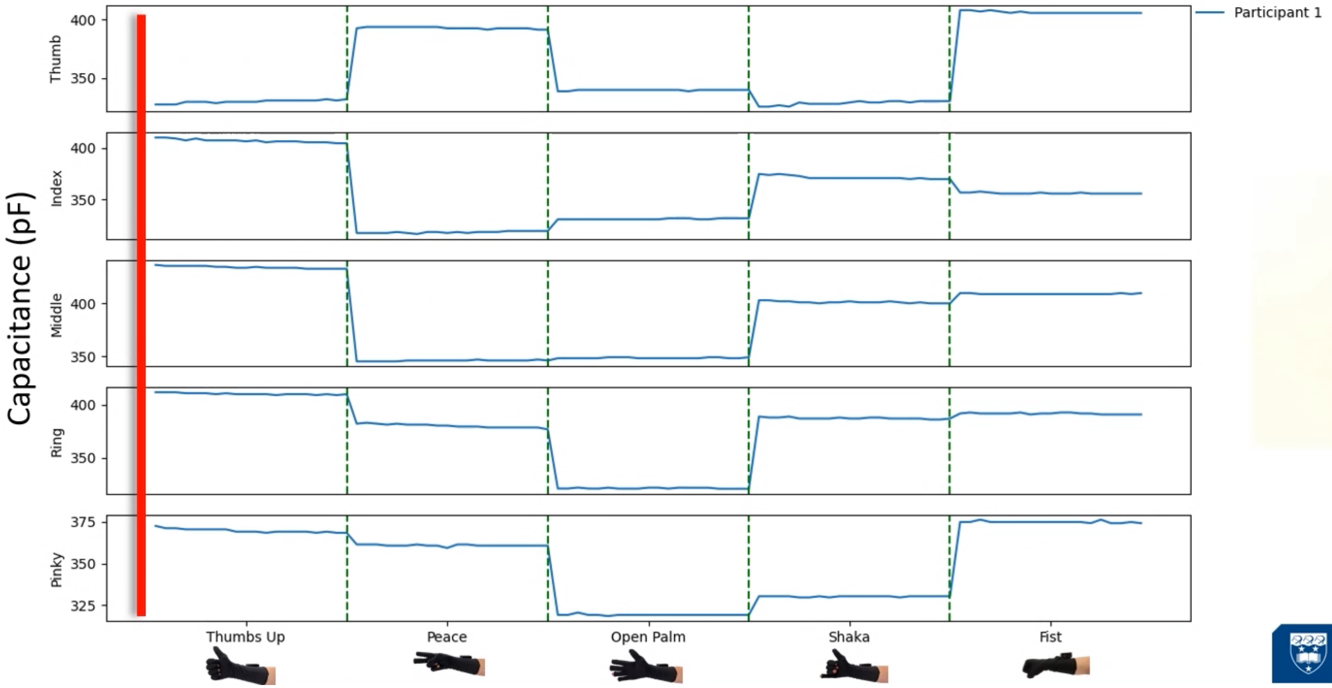
Smart diving glove

- smart materials (dielectric elastomers)
  - carbon-silicone electrodes + silicon dielectric
  - lightweight with high elasticity
- mechanical deformation -> change of capacitance
- low impact in underwater applications
  - compression effects can be removed as bias



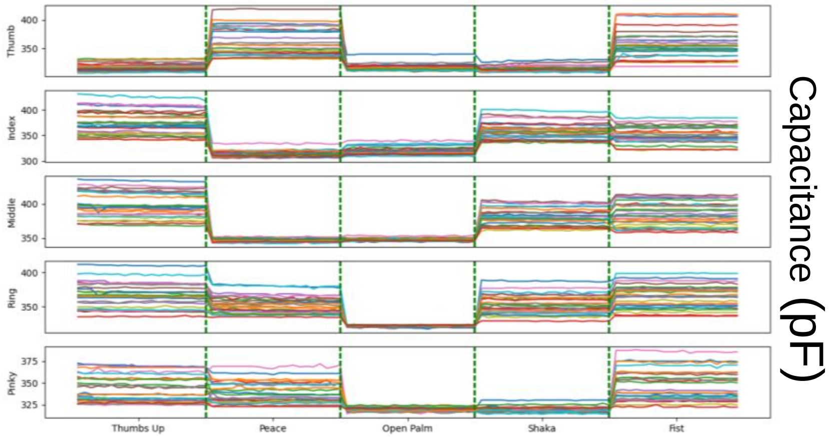
Smart diving glove

- stretch measurement of individual fingers
  - capacitance sensor

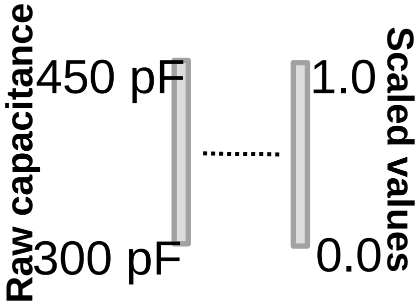


Smart diving glove

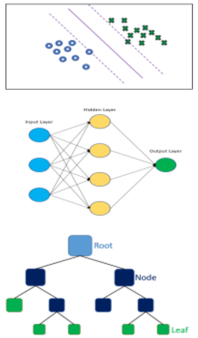
- measurement vary up to 40% across users
  - hand size, range of motion, glove positioning
- auto-calibration for adjusting to user
- arbitration for detected gesture



Raw capacitance values from sensors



Pre-process data



Trained machine learning classifier

Gesture recognition

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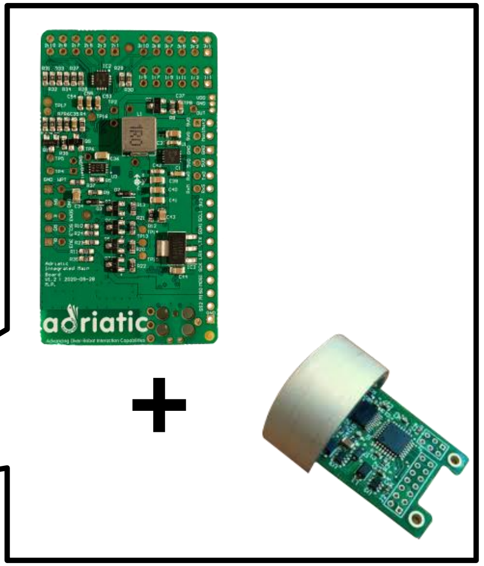
Smart diving glove

- putting it all together
  - visual and haptic feedback
  - bluetooth connection (debug/close range)
  - inertial and pressure measurement
  - OTA firmware updates
- acoustic communication backbone
  - diver<->diver/diver-master
  - diver<->robot



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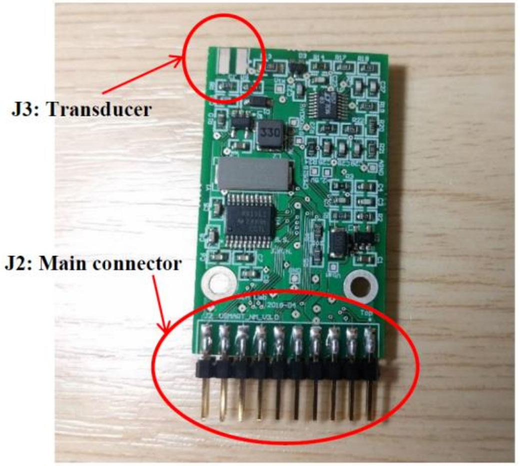
Smart diving glove

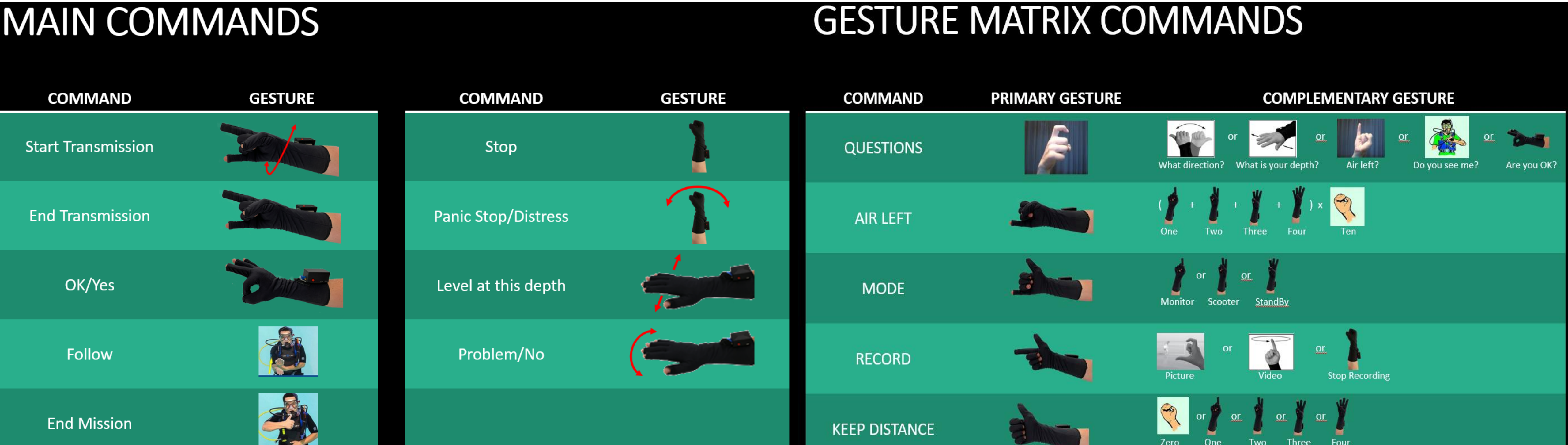
- miniature acoustic modems
  - ranging and communication
- bandwidth up to 460 bits/s
- data transmission delay >300ms
- easy integration on the glove



Potted modem (42mm diameter by 60mm long)

Smart diving glove

- main command set
  - start/end transmission guards + basic gestures
- variable command set
  - pick subset of available functions needed for mission
- CADDIAN need two gloves - requires synchronization



Smart diving glove

Movement based interaction

Movement based communication

- gesture focus on diver->robot communication
  - nonhumanoid robot need another modality
- whole vehicle movement leveraged to emulate gestures
  - no additional hardware
  - more robust to viewing angle
- design principle
  - reuse humanoid looking features in design (camera?)
  - exaggerated motions
  - imitate human gestures were possible

Fulton, M., Edge, C., & Sattar, J. (2019). **Robot communication via motion: Closing the underwater human-robot interaction loop**. In 2019 International Conference on Robotics and Automation, ICRA 2019 (pp. 4660-4666). [8793491] (Proceedings - IEEE International Conference on Robotics and Automation; Vol. 2019-May). Institute of Electrical and Electronics Engineers Inc.. https://doi.org/10.1109/ICRA.2019.8793491

Movement based communication

- kineme
  - group of movements with an associated meaning
  - human equivalents easy to understand, other need learning

Meaning	Kineme	Human Eqiv?	Meaning Type
Yes	Head nod (pitch)	Yes	Response
No	Head shake (yaw)	Yes	Response
Maybe	Head bobble (roll)	Yes	Response
Ascend	Ascend, look back, continue	No	Spatial
Descend	Descend, look back, continue	No	Spatial
Remain At Depth	Circle and barrel roll slowly	No	Spatial
Look At Me	Roll heavily and erratically	No	Situation
Danger Nearby	Look around" then quick head shake	No	Situation
Follow Me	Beckon with head, then swim away	Yes	Spatial
Malfunction	Slowly roll over and pulse legs intermittently	No	State
Repeat Previous	"Cock an ear" to the human	Yes	Response
Object of Interest	Orient toward object, look at human, proceed	Yes	Spatial
Battery Low	Small, slow loop-de-loop	No	State
Battery Full	Large, fast loop-de-loop	No	State
I'm Lost	Look from side to side slowly as if confused	No	State

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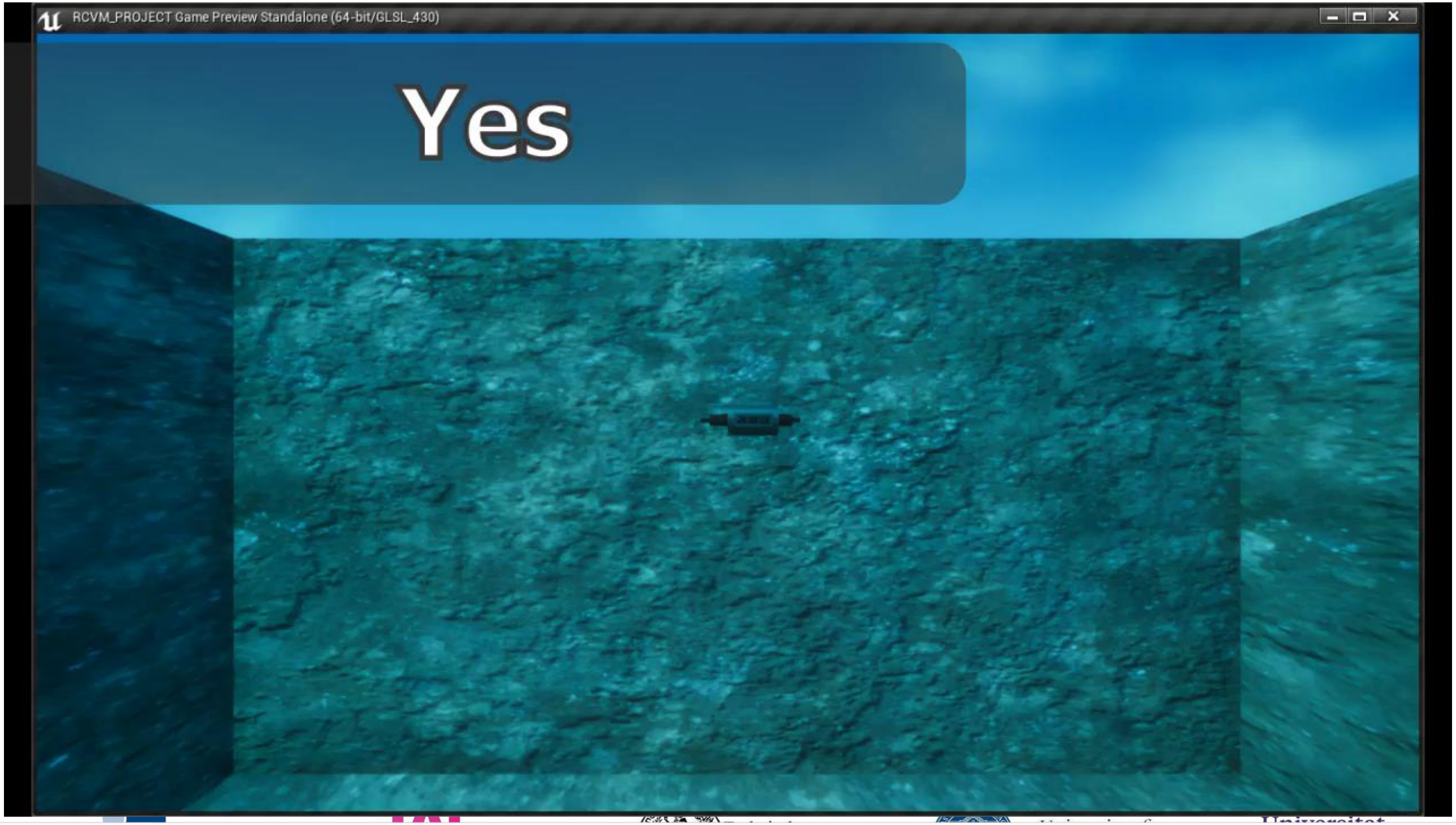
Movement based communication



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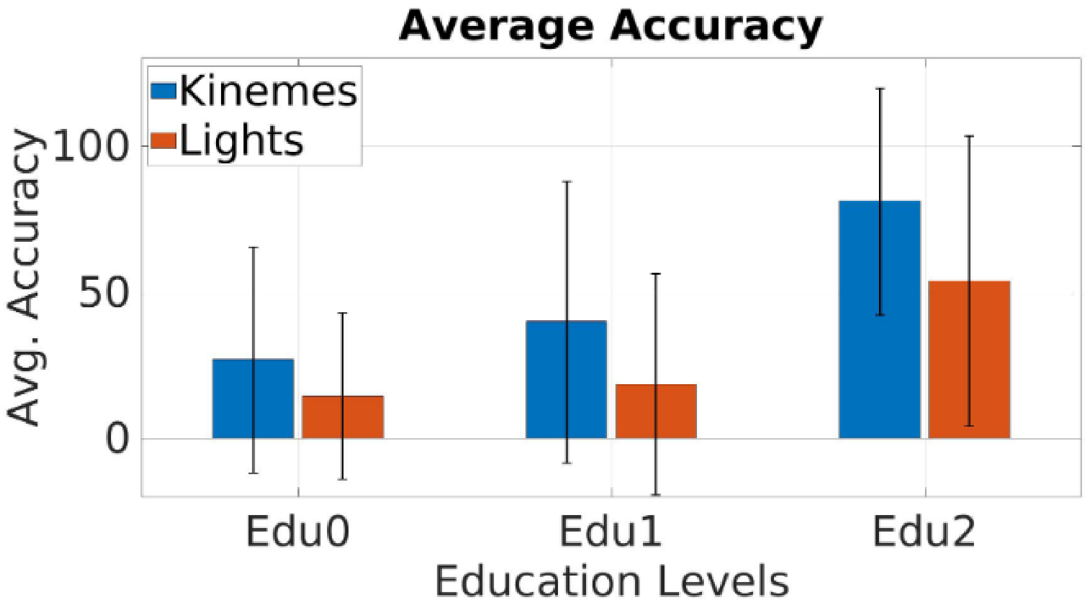
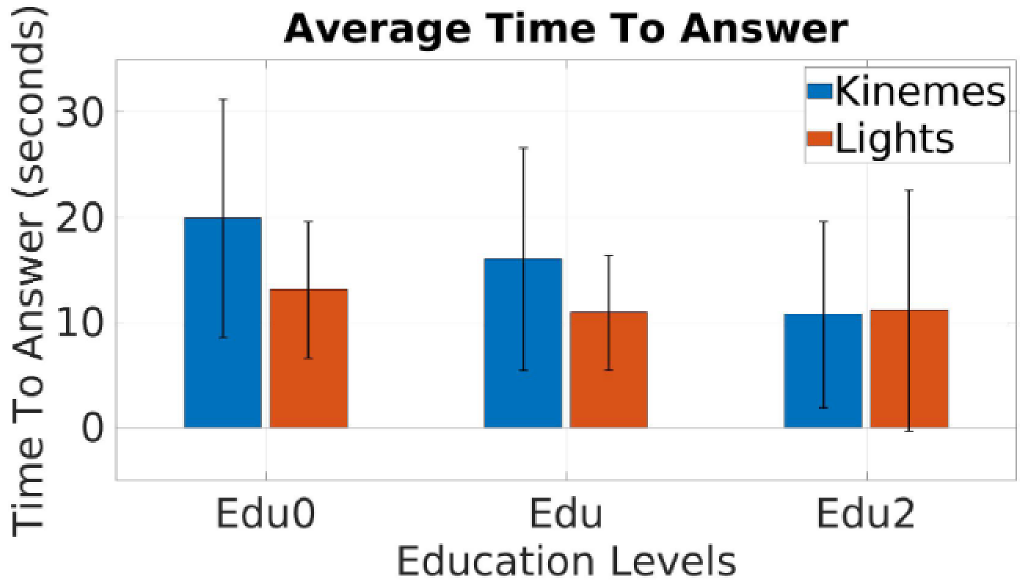
Movement based communication

- compared to light signals (N=24)
  - better accuracy of recognition





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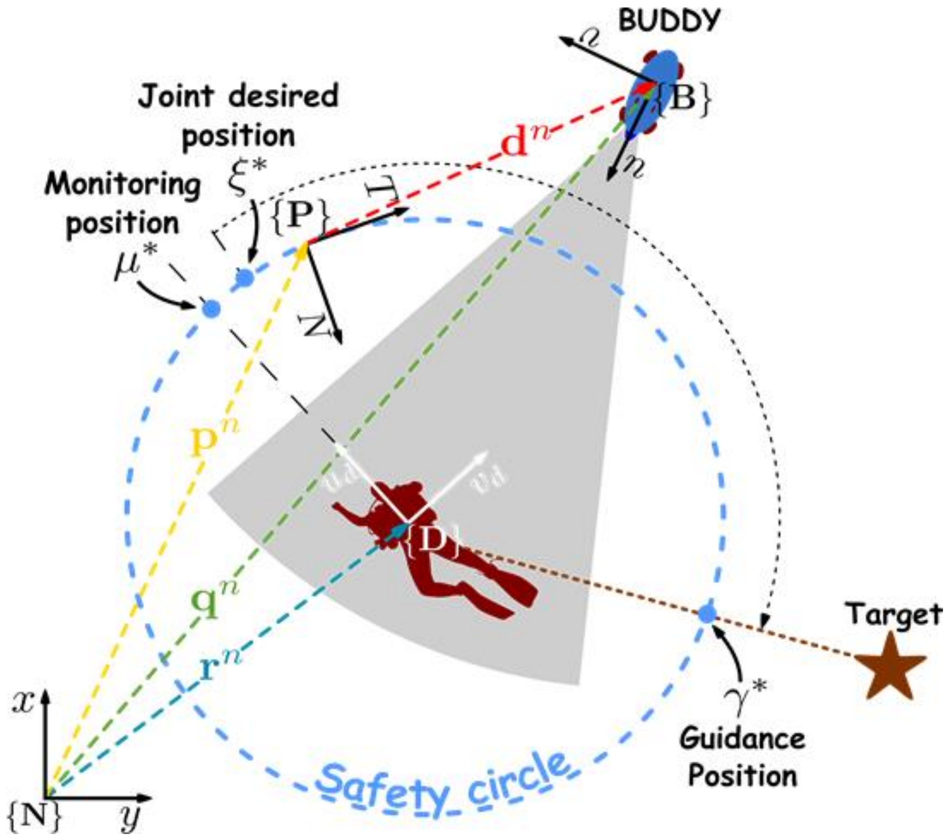
Movement based communication

- benefits
  - no additional hardware
  - surpass light coding
  - better visibility from distance than lights
- drawbacks
  - require control of all DoFs
  - can lose diver from sight
  - impact on navigation accuracy (e.g., DVL for high roll, pitch)
  - need line-of-sight

Spatial interaction

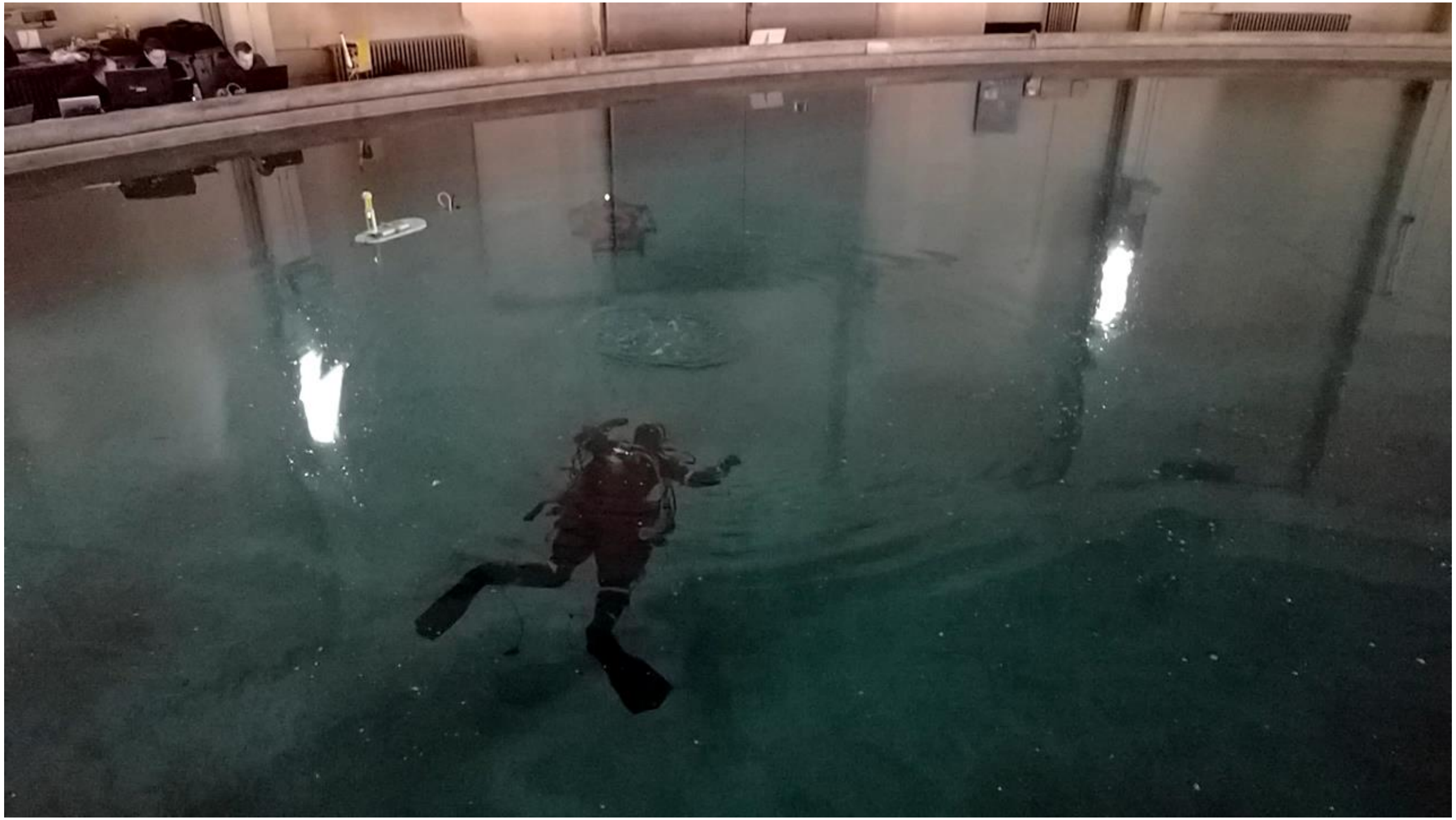
Spatial interaction

- maintaining diver's private space
  - circular or elliptic safety area
  - allow monitoring from any point
  - swimming left/right of diver
- position in front of the diver
  - initiate communication via tablet/gesture
- provide guidance
  - suggesting direction
  - point to target
- handling uncooperative behaviour



Nađ Đ, Mandić F, Mišković N. **Using Autonomous Underwater Vehicles for Diver Tracking and Navigation Aiding**. *Journal of Marine Science and Engineering*. 2020; 8(6):413. https://doi.org/10.3390/jmse8060413

Spatial interaction – Maintain formation



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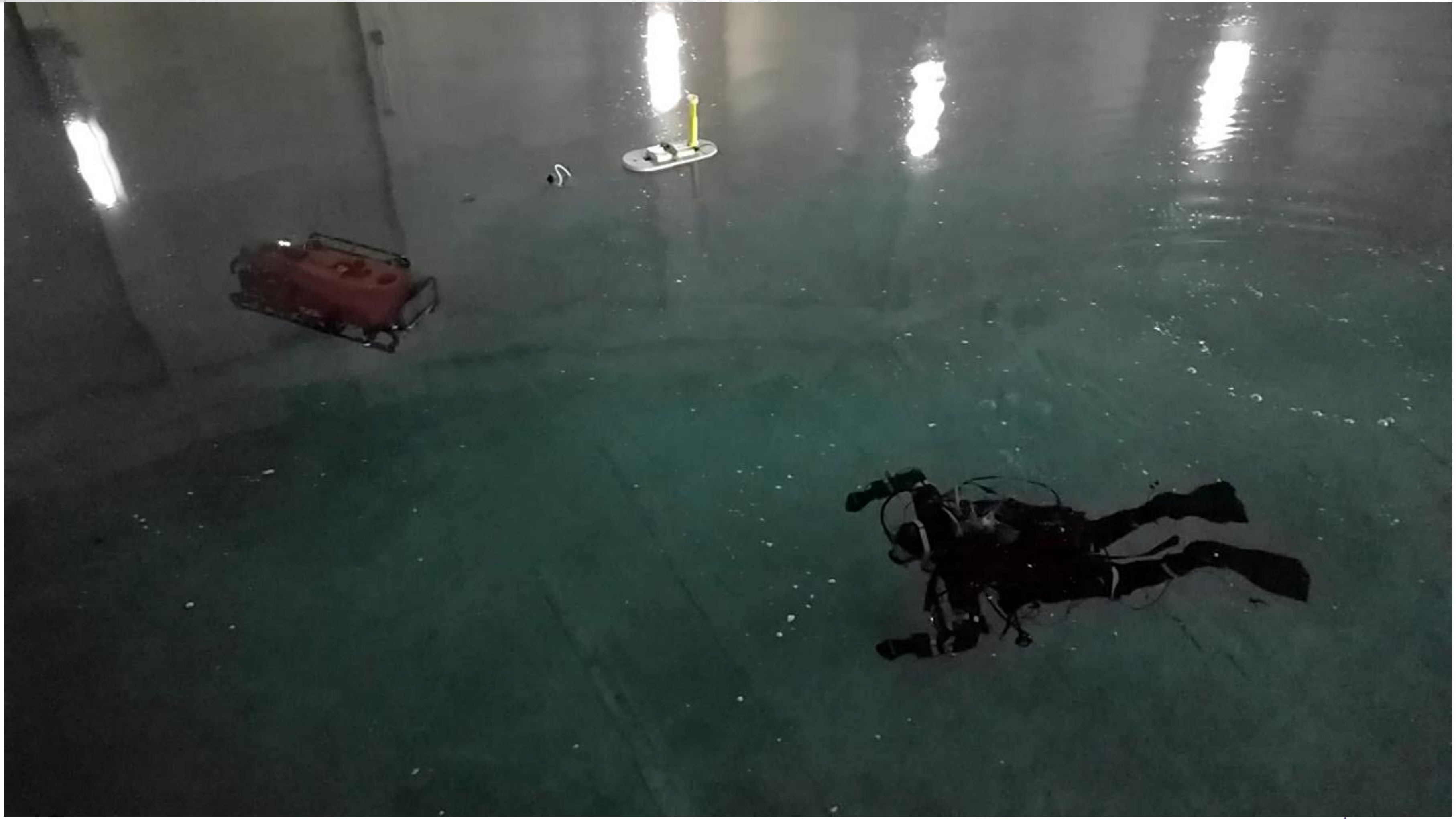
Spatial interaction – Pointing



Other forms of interaction

Light based communication

- single color lights (most vehicles)
  - flashing, brightness changes
- led array or strips
  - encoding based communication
  - learning curve
- general guidelines
  - use cultural mapping (red = bad)
  - limit blinking speed
  - share code parts for related information (e.g, first light indicates family of statuses)
  - use existing diver light signals

Light signal	Example	Comments
Green ON		Everything is OK.
Red ON		SYSTEM error.
Green blinking slow		OK/YES
Red blinking slow		NOT OK.
One flash		Are you OK?
Two flashes		Don't move.
Three flashes		Descend
Four flashes		Ascend
Five flashes		Emergency, surface immediately

Haptic based communication

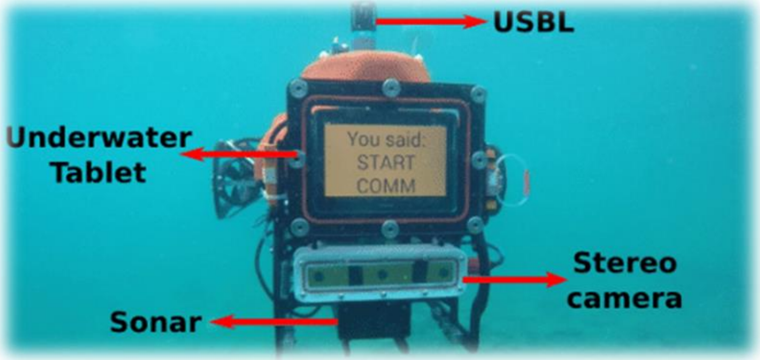
- applicable to smart diving glove
  - initiated by robot via acoustics
  - local glove information (e.g., recognized gesture)
  - wireless buddy-line

Vibration name		Comments
Attention grabbing vibration.		Grabs the diver's attention so he can focus on the following signal.
YES		Used a quick nonvisual answer to a question. Can be accompanied by light confirmation.
NO		Used a quick nonvisual answer to a question. Can be accompanied by light confirmation.
Acknowledge		Separate signal to indicate command reception or that the vehicle established comms.
One pull		Are you OK?
Two pulls		Don't move.
Three pulls		Descend
Four pulls		Ascend
Five pulls		Emergency, surface immediately.

- robot oriented haptics
  - compliant control (e.g., adjusting the robot position while in dynamic positioning manually for lighting)

Displays

- underwater displays
  - tablets for info and status display
- smart or diving watches
  - small displays but easy BLE connection
- augmented displays
  - from basic info to full details
  - sensitive to localization errors



Verbal communication

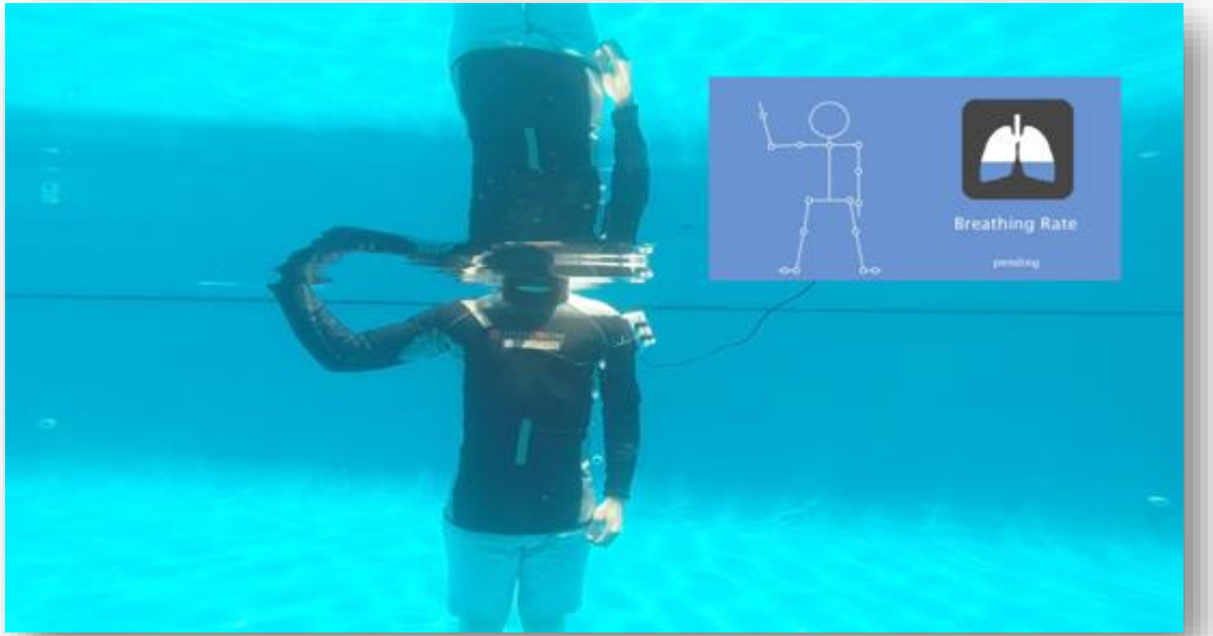
- full-face masks
  - incorporates microphone and speaker
- underwater speakers
  - robot to diver communication?
  - exist in pools
  - too bulky to install on small vehicle

OTS Guardian

Overview of interaction modalities

Modality	Direction	Benefits	Drawbacks
Gestures via camera	Diver -> Robot	- natural - no additional equipment	- line of sight - complex processing
Gestures via glove	Diver -> Robot Robot->Diver (haptics/light)	- easier/faster processing - no line of sight - offers haptic extension	- need acoustic and glove
Kinemes	Robot -> Diver	- no additional equipment - easier to interpret than lights	- better NGC algorithms - line-of-sight
Spatial interaction	Robot -> Diver	- navigation aiding - indicate interaction	- need diver attitude estimate
Lights	Robot -> Diver	- easy to implement	- learning curve
Haptics (vibration)	Robot -> Diver	- easy to implement	- limited vocabulary
Displays	Robot -> Diver	- transmit a lot of information	- cumbersome for vehicle - small screens
Verbal	Diver <-> Robot	- no line of sight - almost natural	- need speech processing/synth. - need extra equipment - slower talking than on land

Wearable sensors

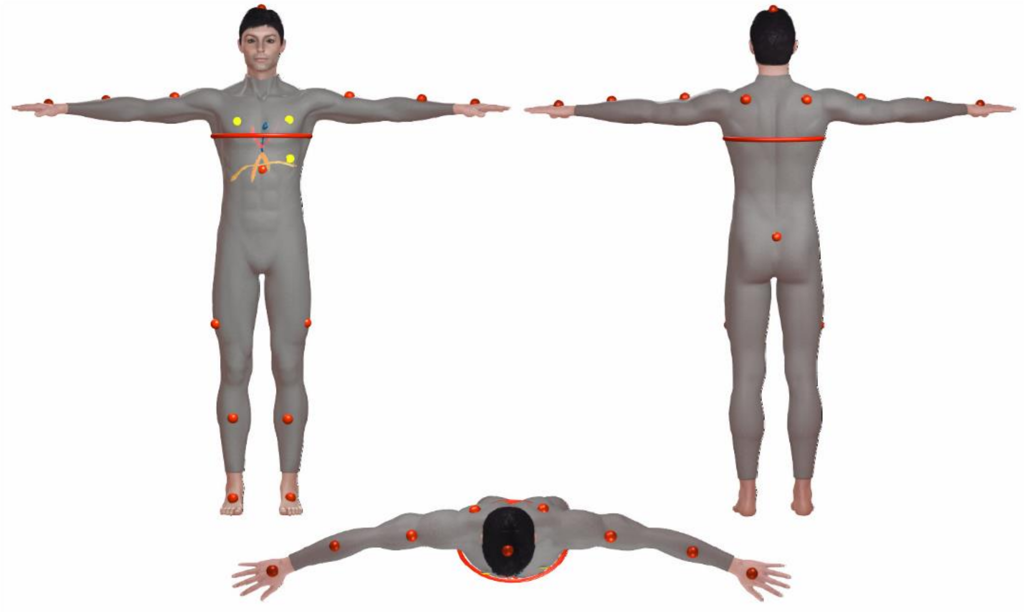


Why physiological measurements?

- diving safety
  - hearth, respiration rate, movement
  - real-time insight into diver state
  - detection of anomalous conditions
- diver training
  - motion and pose analysis

DiverNet

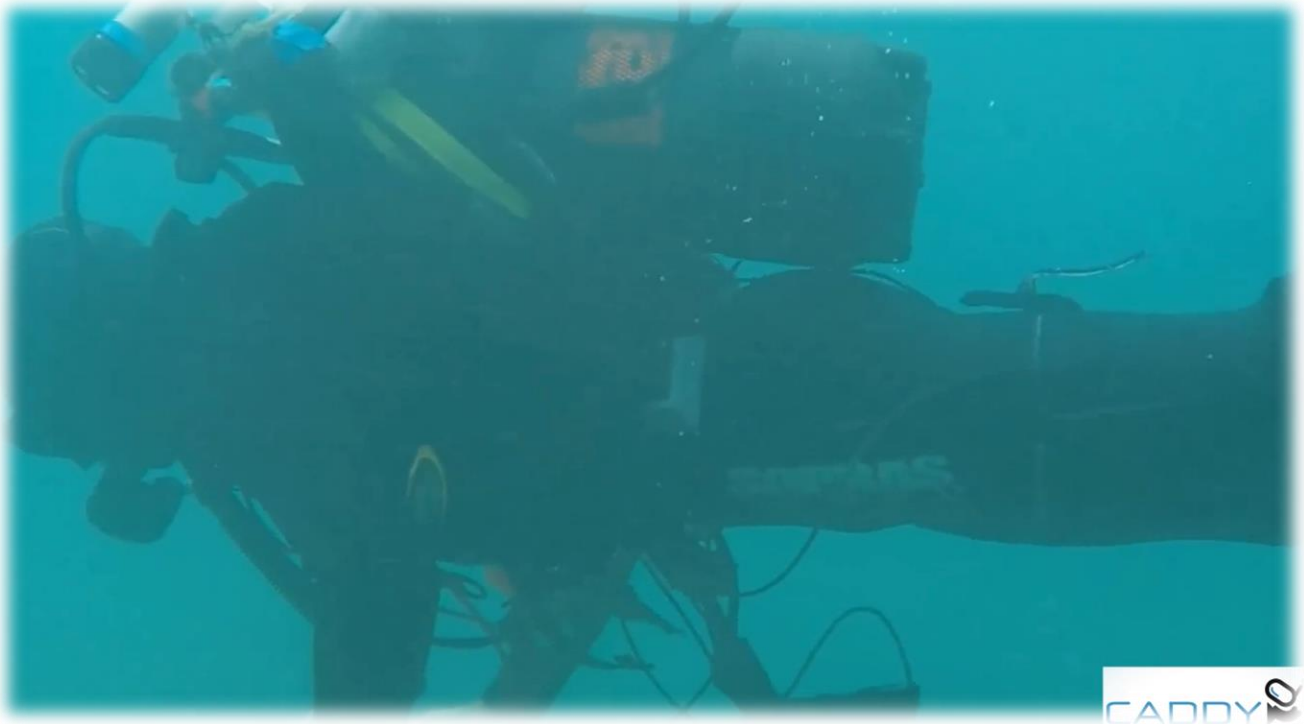
- inertial diving suit
- 17 9-axis IMU
  - 2 shoulders
  - 3 for each extremity
  - 2 torso
  - 1 head
- full pose reconstruction
- general diver attitude (heading)
- head orientation
  - useful for gaze direction



G. M. Goodfellow, J. A. Neasham, I. Rendulić, Đ. Nađ and N. Mišković, "**DiverNet — A network of inertial sensors for real time diver visualization**," 2015 IEEE Sensors Applications Symposium (SAS), 2015, pp. 1-6

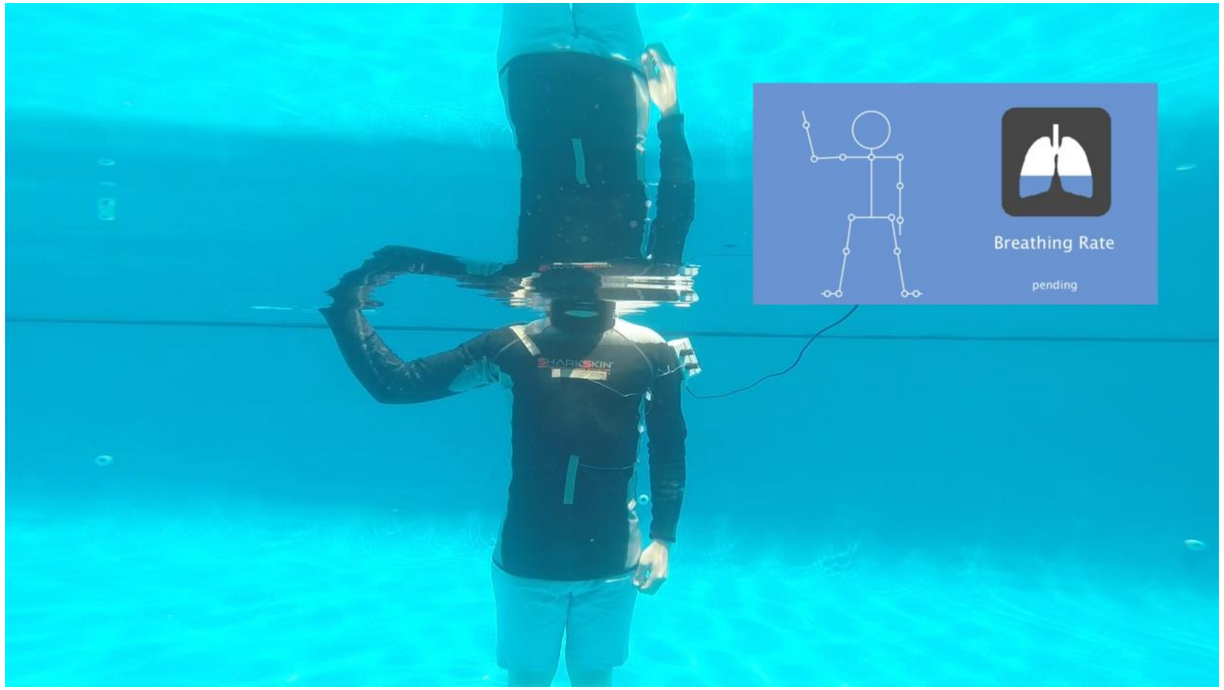
DiverNet

- benefits
  - direct joint measurement with single sensor
- drawbacks
  - calibration and magnetic interference
  - cumbersome embedding into suit



Smart wetsuit

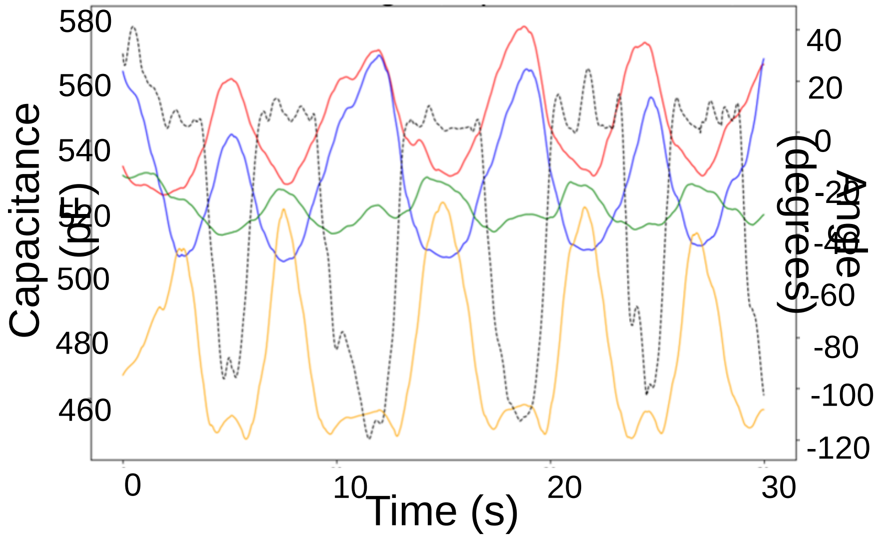
- dielectric elastomers
- advantage over IMUs
  - no magnetic interference
  - easy calibration
  - embeddable into suit
- more sensors per joint
  - 5 sensors for shoulder and elbow



Derek Orbaugh, Christopher Walker, Samuel Rosset, and Iain Anderson "**Jumping into virtual reality with dielectric elastomer sensors**", Proc. SPIE 11587, Electroactive Polymer Actuators and Devices (EAPAD) XXIII, 22 March 2021

Smart wetsuit

- shoulder and elbow the most complex
  - mapping more sensor to actual movement angle
  - automatic calibration for different divers



Elbow flexion/extension

Shoulder flexion/extension

Shoulder horizontal adduction/abduction

Shoulder rotation

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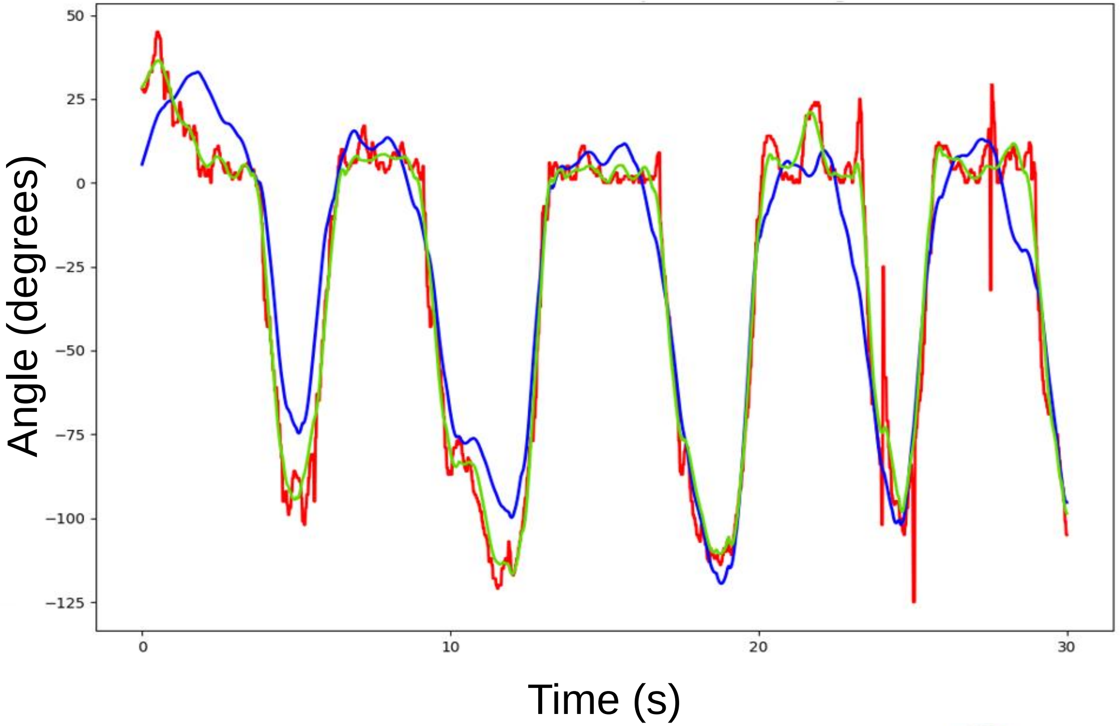
Smart wetsuit

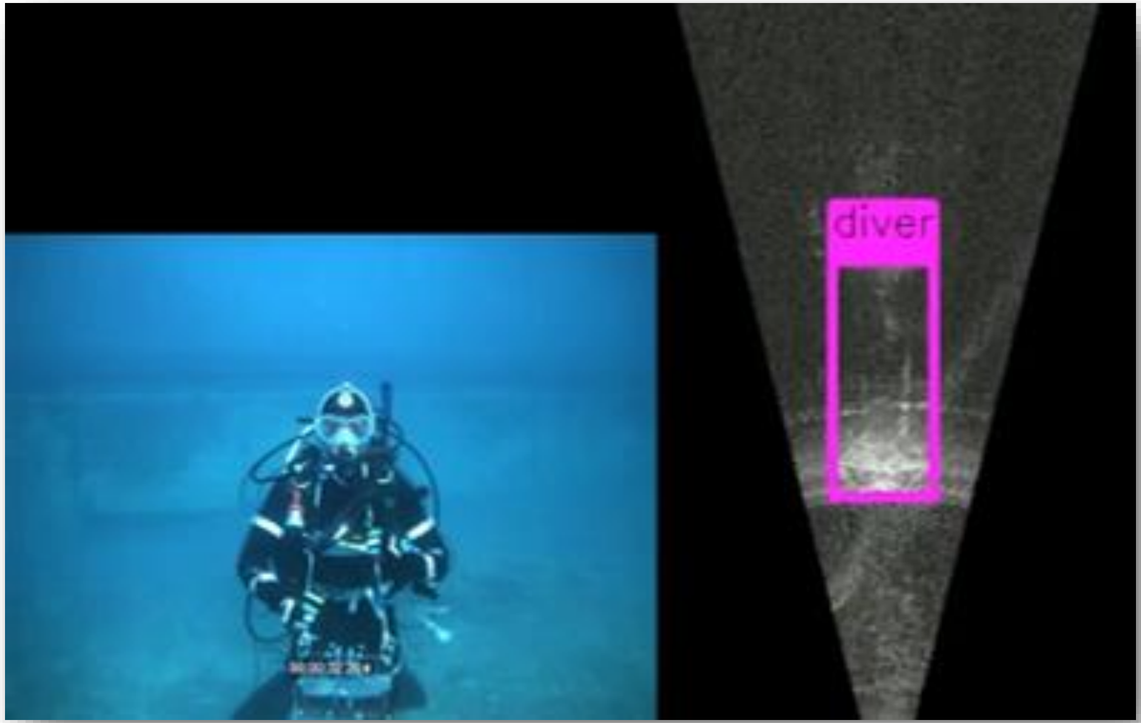
- comparison with optical measurement (monocular camera)
  - two regressors
  - RMSE of 5-10 degrees between joint angles



Smart wetsuit

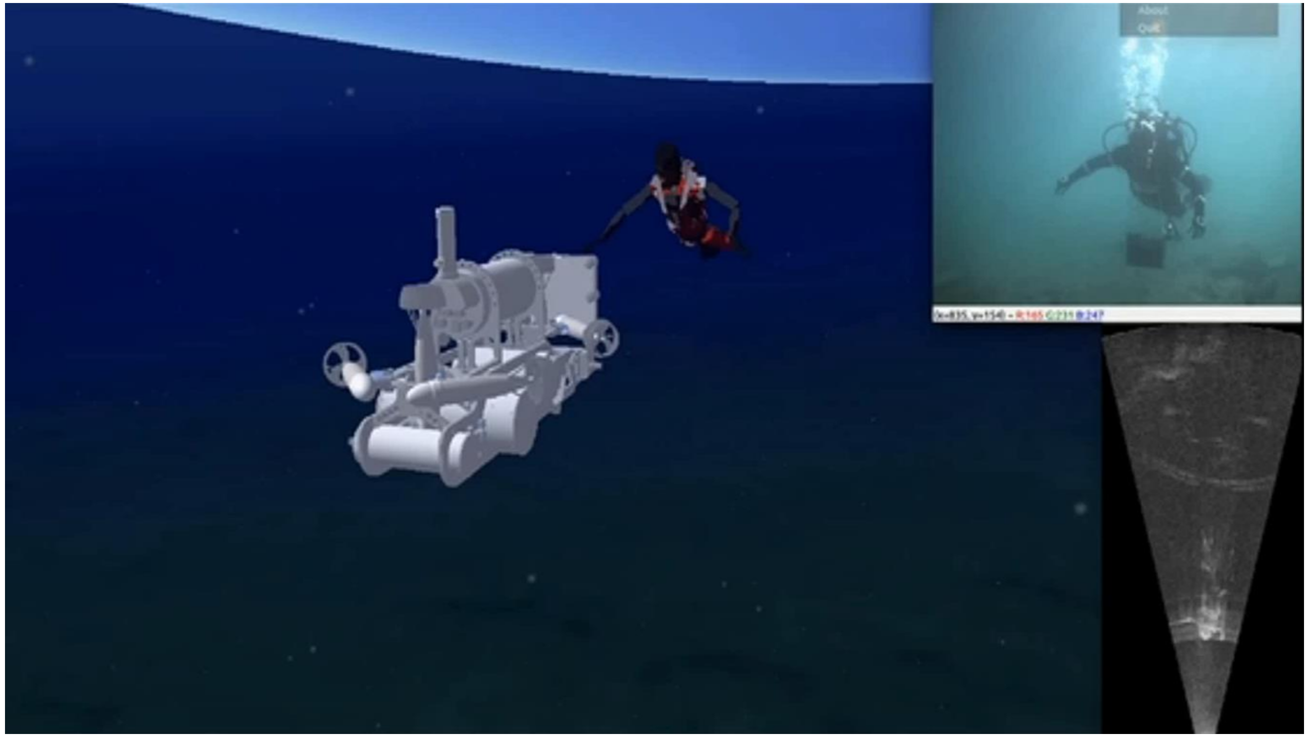
Shoulder + elbow movement example

Perception



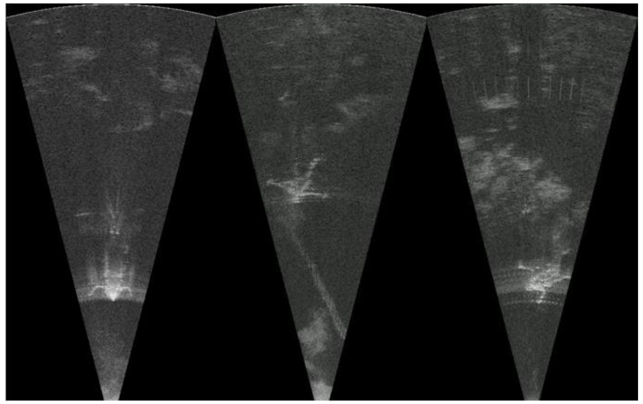
Perception

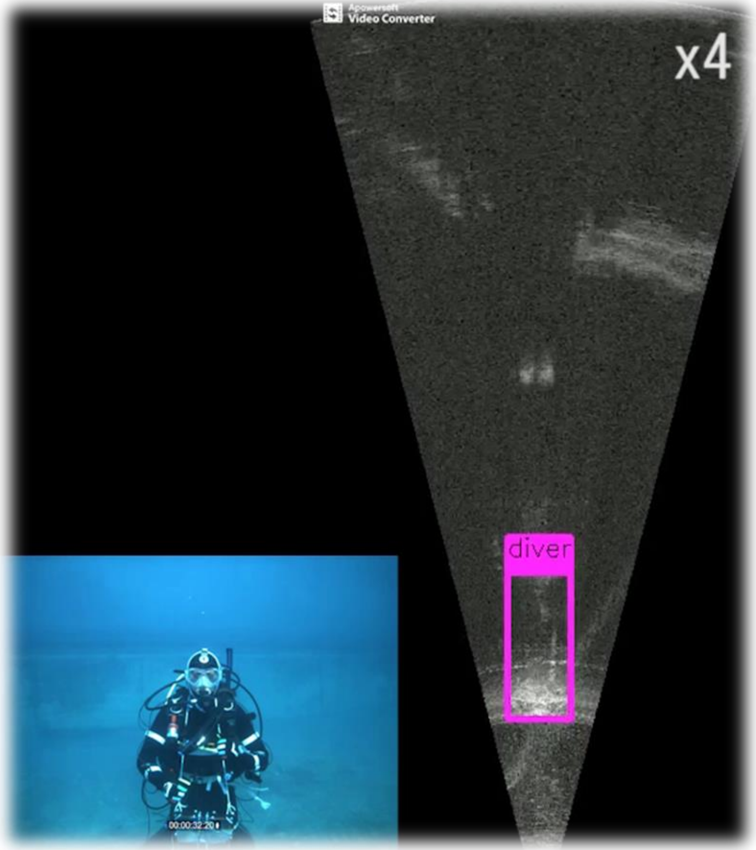
- camera and sonar
- camera
  - dependent on visibility
  - limited range
  - cost effective
  - stereo for 3D
- sonar
  - independent on visibility
  - medium to high range
  - range and bearing
  - expensive



Sonar as main vision sensor

- deep learning
  - common approach in video
  - limited datasets with divers
- virtually no diver sonar datasets
  - 2000 images training set (Aris Explorer 3000)
  - 200 images validation set

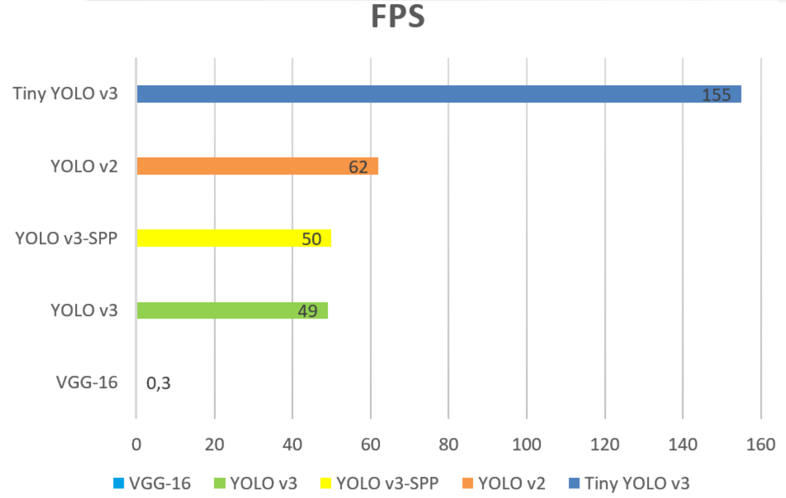


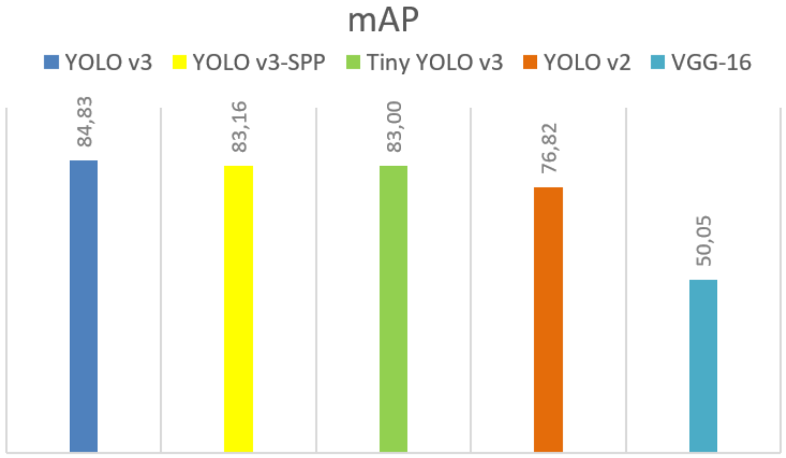


Sonar as main vision sensor

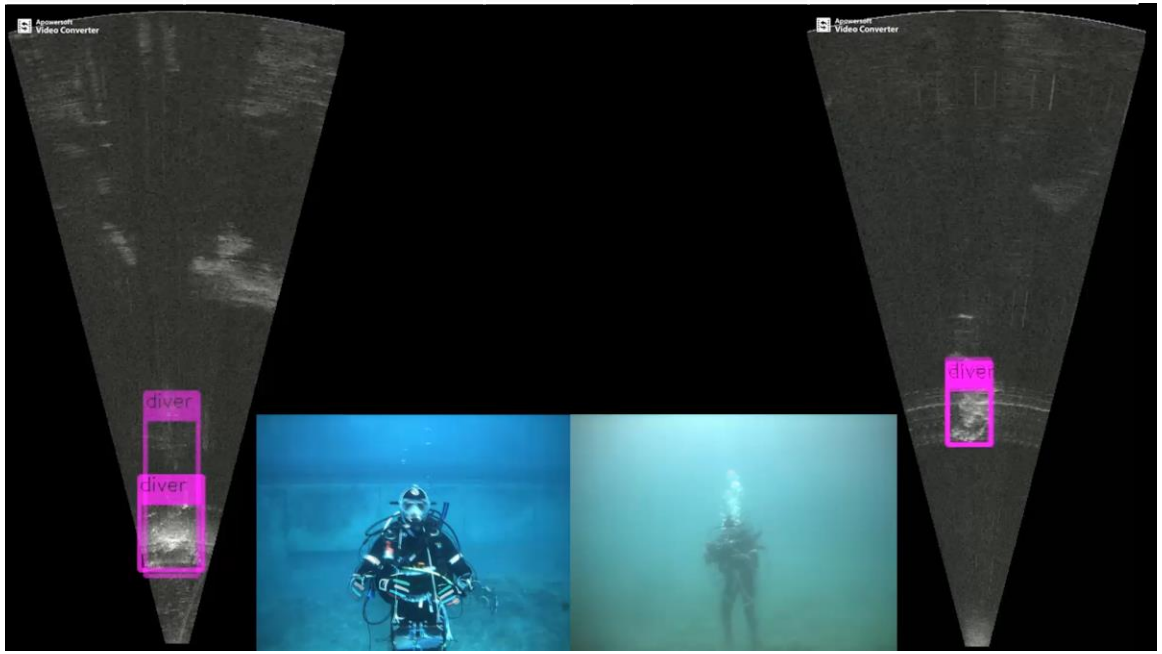
- 5 networks, same training data
  - VGG16
  - YOLOv2
  - YOLOv3
  - YOLO SPP
  - Tiny YOLO
- pretrained networks
  - extended with diver classes
- hardware
  - 2 x Nvidia GTX 1080 Ti
  - Intel Core i9 9900k @ up to 5GHz
- target
  - minimizing avg. loss
  - maximizing mAP

Results





Model	Layers	mAP	FPS	BFLOPS	Precision	Recall
VGG-16	16	50.05%	0.2-0.3	30.699	0.47	0.55
YOLOv2	26	76.82%	56-68	34.720	0.81	0.84
Tiny YOLOv3	21	83.00%	120-190	5.571	0.89	0.85
YOLOv3	53	84.83%	46-52	65.864	0.92	0.92
YOLOv3-SPP	53	83.16%	47-53	29.371	0.88	0.89



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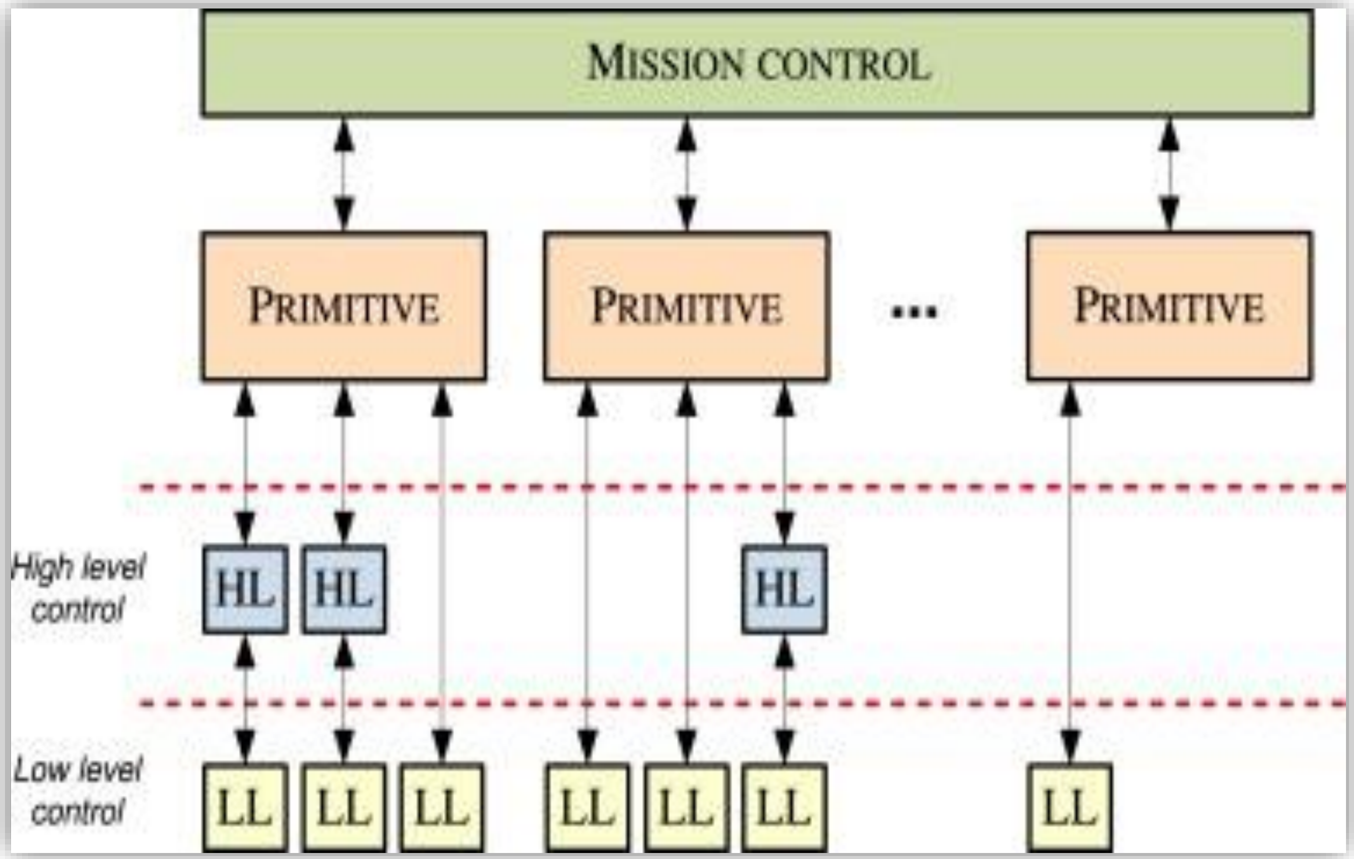
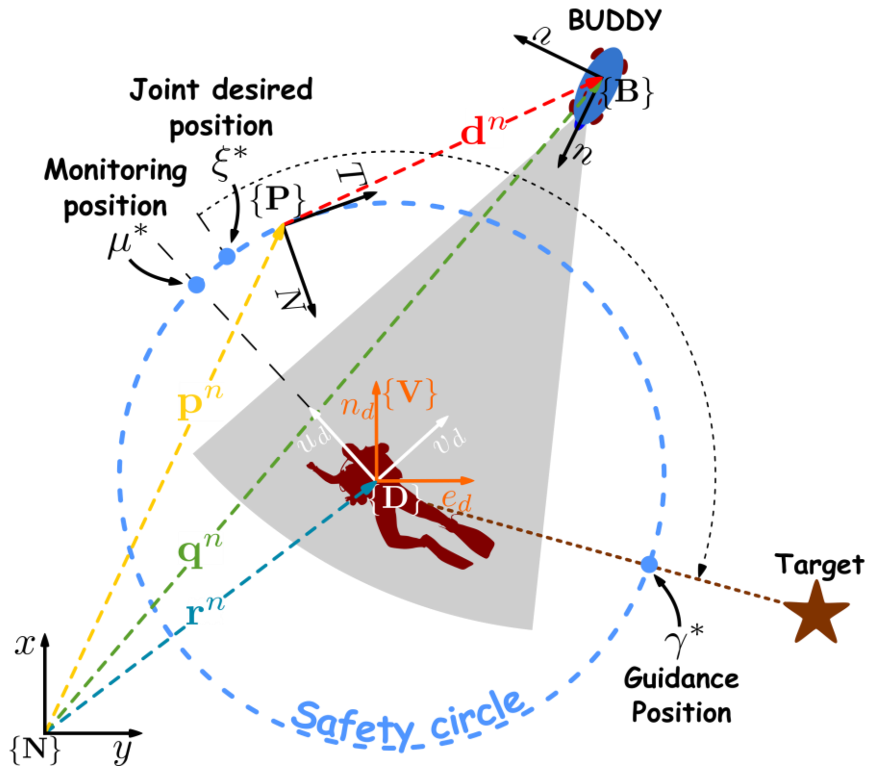
Control algorithms



Guidance controller

- moving path
  - defined in {V}
- path following
  - collision free maneuvering
- path stabilization
  - monitor from specific point
  - inherent tracking
  - passive guidance
- virtual target PF
  - Frenet-Serret frame {P}



Guidance controller

- kinematics in {P}

$$\dot{\mathbf{d}}^p = -\mathbf{S}_p^n \mathbf{d} + \mathbf{R}_b^p \boldsymbol{\nu}_1 - \mathbf{R}_n^p \dot{\mathbf{r}}^{\mathbf{n}} - \dot{\tilde{\varpi}} \vec{\mathbf{t}} - \dot{\mu}^* \vec{\mathbf{t}}$$

- vehicle location in {P}

$$\mathbf{d}^p = \mathbf{d} = [s\, e\, h]^T$$

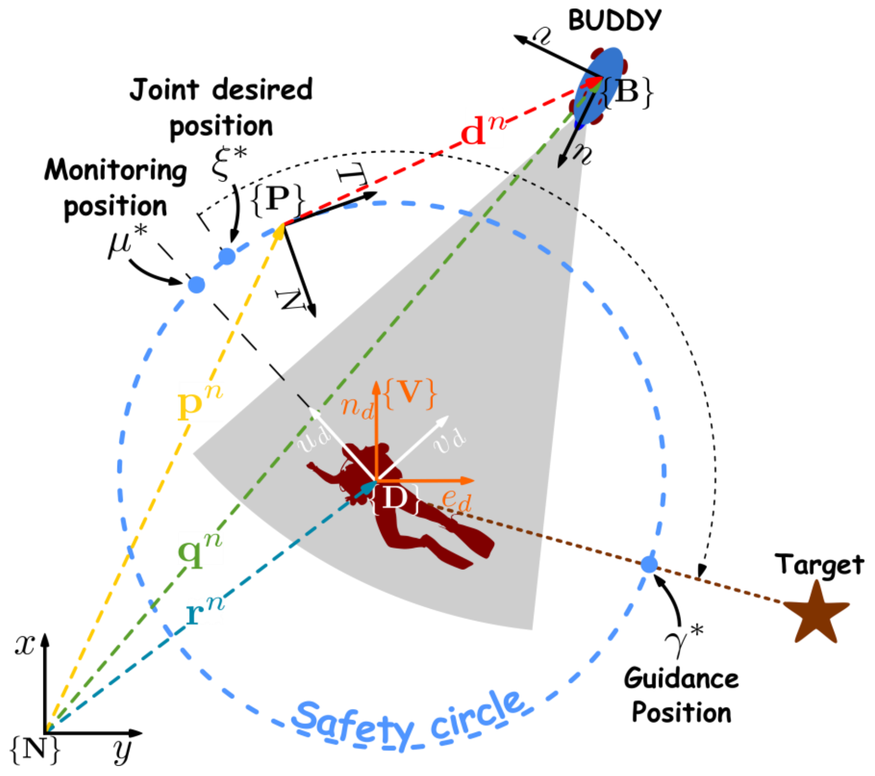
$$\mathbf{R}_p^n \mathbf{d}^p = \mathbf{q}^n - \mathbf{p}^n$$

- speed of frame {P}

$$\dot{\mathbf{p}}^p = \mathbf{R}_n^p \dot{\mathbf{r}}^n + \dot{\varpi} \vec{\mathbf{t}}$$

- path error

$$\tilde{\varpi} = \varpi - \mu^*$$



Guidance controller

- Lyapunov function

$$V = \frac{1}{2}\mathbf{d}^\intercal \mathbf{d} + \frac{\sigma_{\tilde{\varpi}}}{k_{\tilde{\varpi}}} \ln\cosh k_{\tilde{\varpi}} \tilde{\varpi}, \quad k_{\tilde{\varpi}}, \sigma_{\tilde{\varpi}} \in \Re_+^*$$

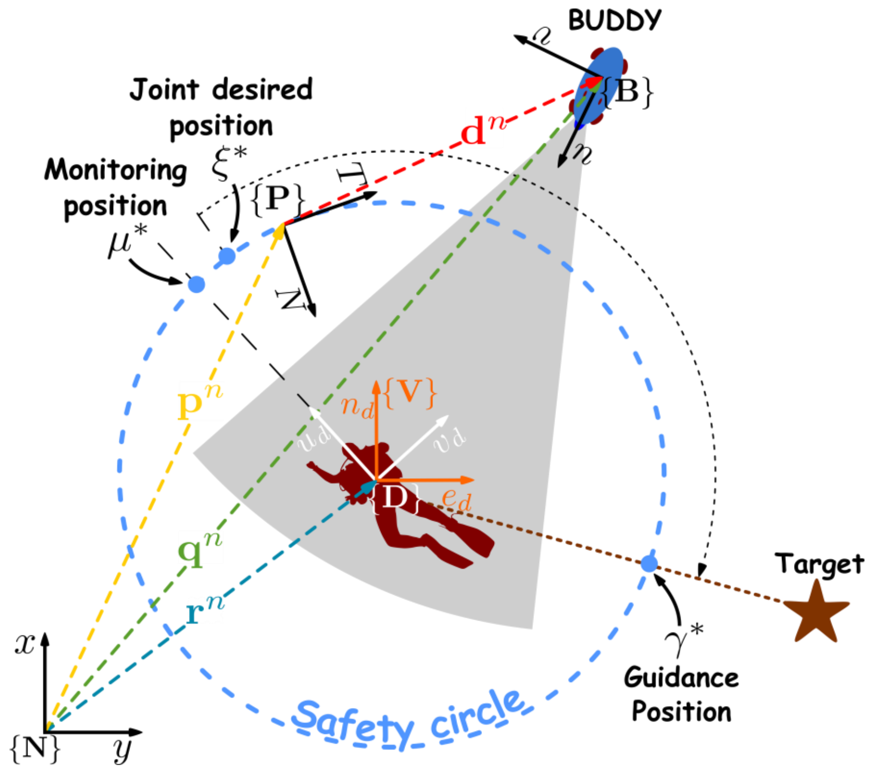
- {P} velocity set-point

$$\dot{\varpi}^* = k_{\varpi}\left(s - \sigma_{\tilde{\varpi}} \tanh k_{\tilde{\varpi}} \tilde{\varpi}\right) + \dot{\mu}^*, \;\; k_{\varpi} \in \Re_+^*$$

- velocity set-point

$$\boldsymbol{\nu}_1^* = \mathbf{R}_p^b \left(-\mathbf{K}_{p_d}\mathbf{d} + \mathbf{R}_n^p \dot{\mathbf{r}}^{\mathbf{n}} + \dot{\mu}^* \vec{\mathbf{t}}\right)$$

- low-level control
  - PIFF velocity control
  - backstepping design



Guidance controller

- heading control

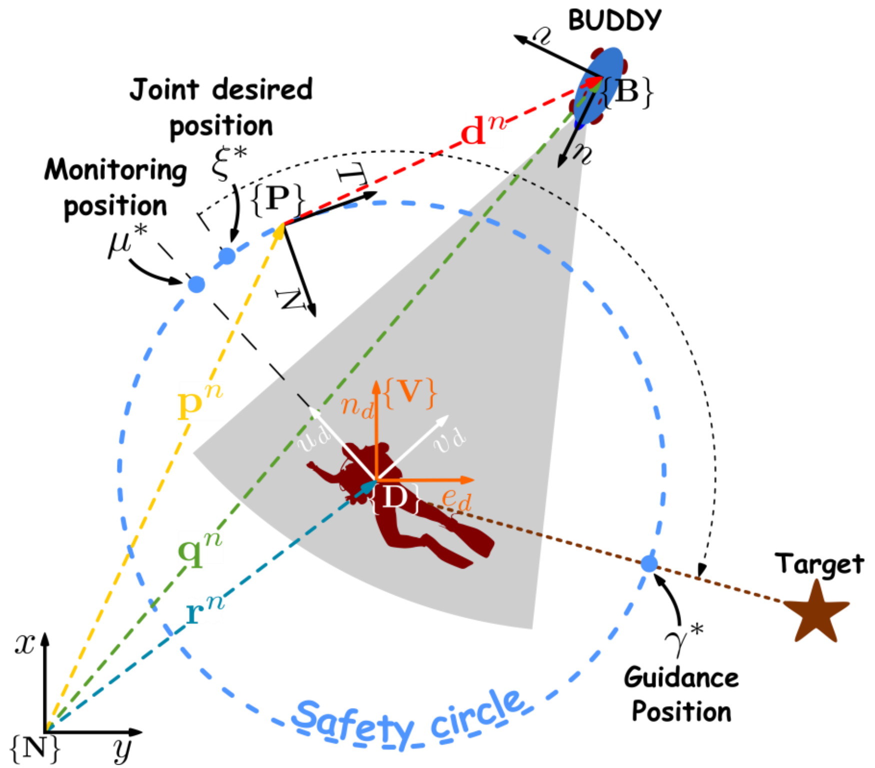
$$\Delta^* = \arctan \frac{y_d - y}{x_d - x}$$

- suggestive guidance
  - maintaining FOV

$$\xi^* = \mu^* + \frac{\sigma_{FOV}}{2} \tanh \frac{\gamma^* - \mu^*}{\kappa_\xi}$$

- pointer guidance
  - robust approach

$$\xi^* = \gamma^*$$



Final remarks

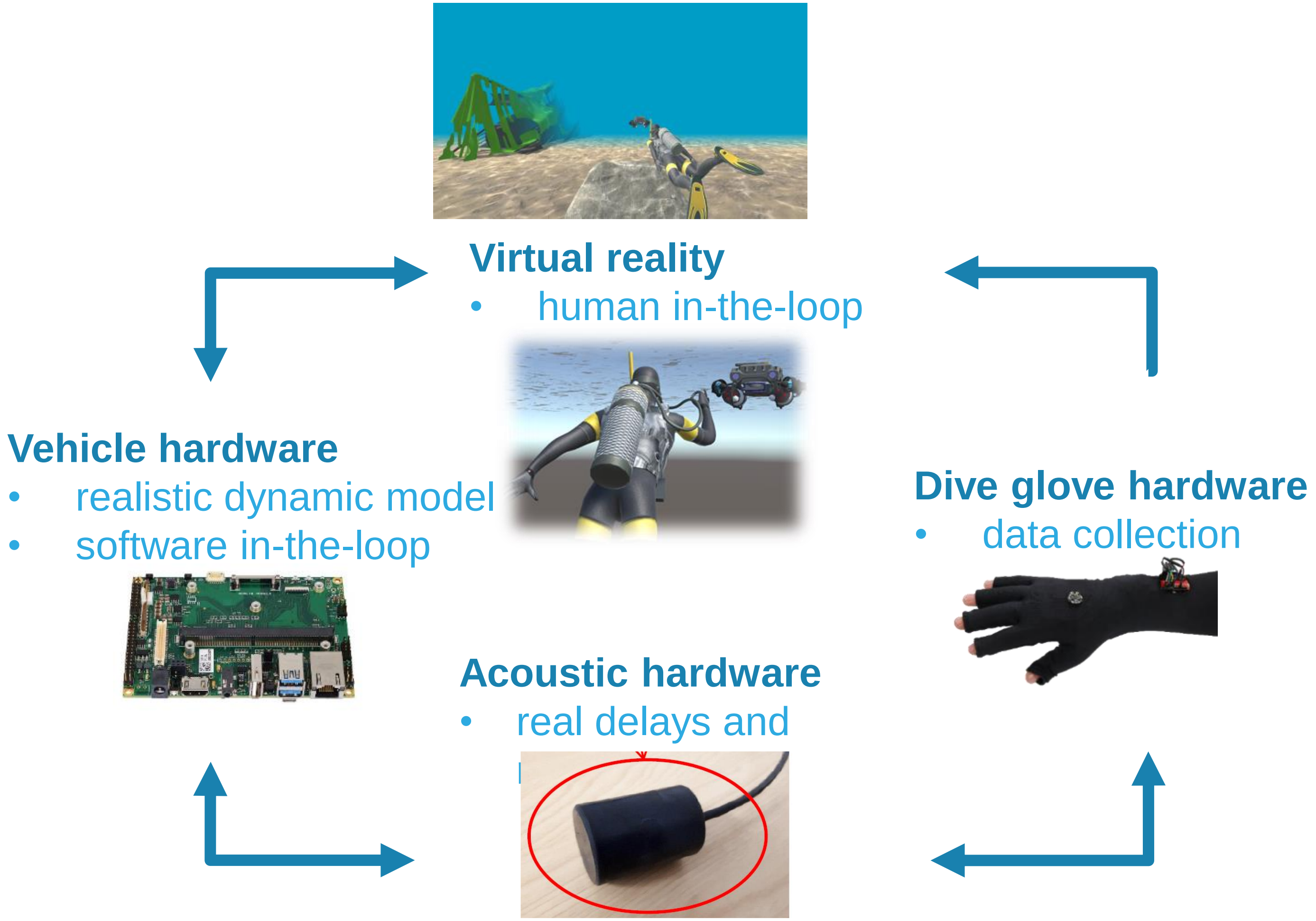
Final remarks

- user centric design
  - involve end users to compare features and modalities
- participatory design
  - involve users in initial vehicle design
- field experiments with divers
  - expensive, limited diving time
- first steps
  - HIL simulation
  - ROV operated by diver

Human and hardware in the loop simulation

Advantages

- cheaper training
- synthetic collection
- continuous testing
- diver involved in system design



Human and hardware in the loop simulation

Data collection

- very little existing dataset
- aim at sharing the dataset
  - good for publication and the community
  - helps with reproducibility of results
- investigate synthetic generation

Sung, M., Kim, J., Lee, M. et al. **Realistic Sonar Image Simulation Using Deep Learning for Underwater Object Detection.** Int. J. Control Autom. Syst. 18, 523–534 (2020). https://doi.org/10.1007/s12555-019-0691-3

Gomez Chavez A, Ranieri A, Chiarella D, Zereik E, Babić A, Birk A. **CADDY Underwater Stereo-Vision Dataset for Human–Robot Interaction (HRI) in the Context of Diver Activities**. *Journal of Marine Science and Engineering*. 2019; 7(1):16. https://doi.org/10.3390/jmse7010016

Questions ?