

# MARIS

*Italian National Project on*

## ***Marine Autonomous Robotics for Interventions***

*2014-2015*



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# MARIS Consortium



GENOVA

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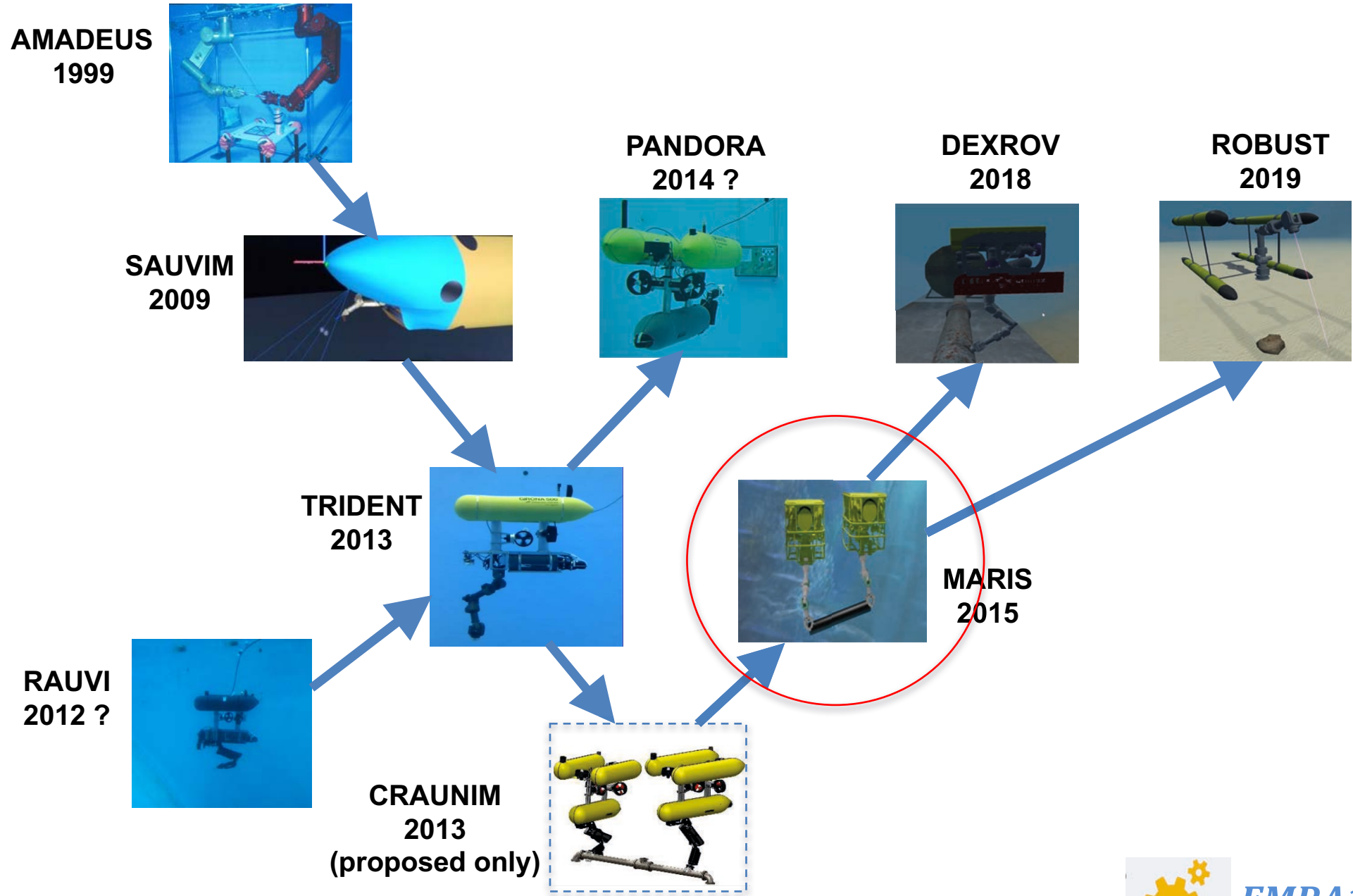
CASSINO

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# Underwater Intervention Robotics: a bit of history

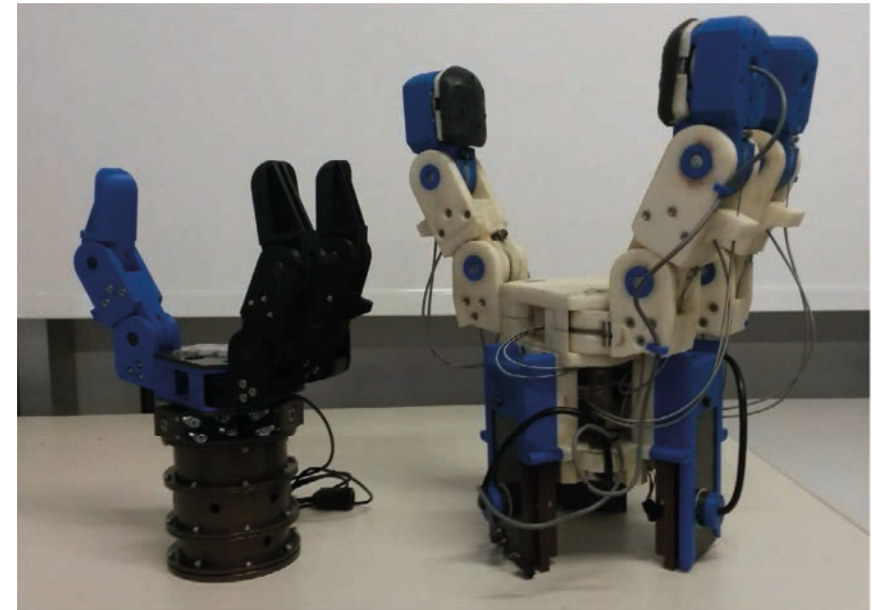
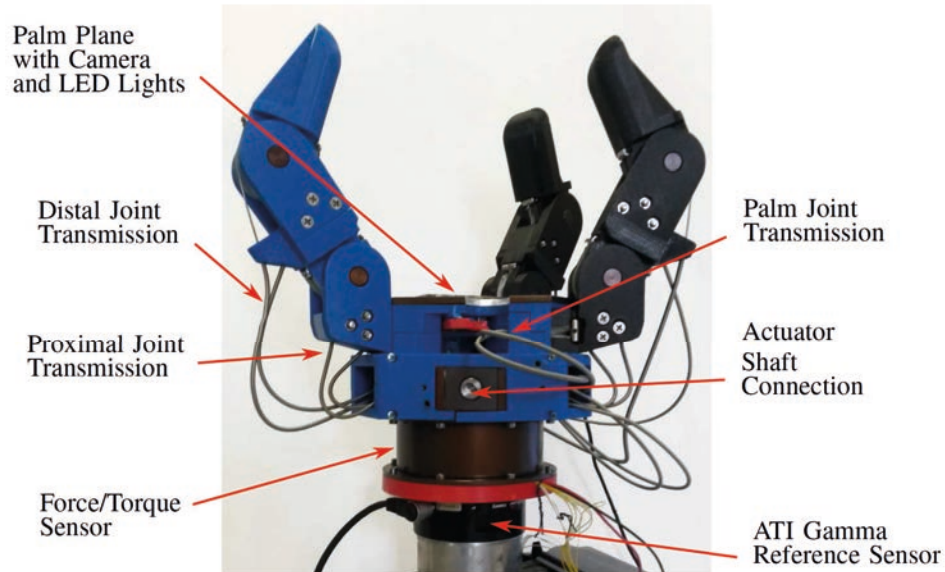


# MARIS Project Objectives

Accordingly with the idea of however continuing progressing along the lines foreseen from TRIDENT in the CRAUNIM proposal, at Italian national level the MARIS project could be therefore established, with the following general objectives

- ① Improving the technology on **underwater gripper** devices toward state of the art, by including both power and precision grasp/manipulation
- ② Establishing, and possibly improving, beyond the state of the art, the know-how on **underwater vision systems** and methods.
- ③
  - a) - Extending the applicability of **Task-Priority Control** approach toward an as much as possible wide generality of actions. to be performed by individual UVMS's .
  - b) - **Formalizing**/consolidating it within a **unified functional and algorithmic framework**
  - c) - Proposing it as a **best control practice for UVMS's**
- ④ Developing policies and algorithmic methods for the coordinate control of **cooperating UVMS's**
- ⑤ Integrating the above within two UVMS's (while improving their lower **level Dynamic Control Layers** beyond the state of the art) with proof-of-concept validating trials performed on both individual and cooperating agents

# Underwater Grippers - 1



4.5 kg in air, 1 kg in water

8 dofs coupled, cable-based transmission moved by 3 actuators

Integrated optoelectronic F/T sensor at the palm

Max fingertip force in worst conditions 150N

Object size: 10–220mm cylinder

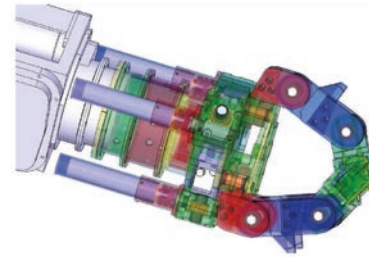
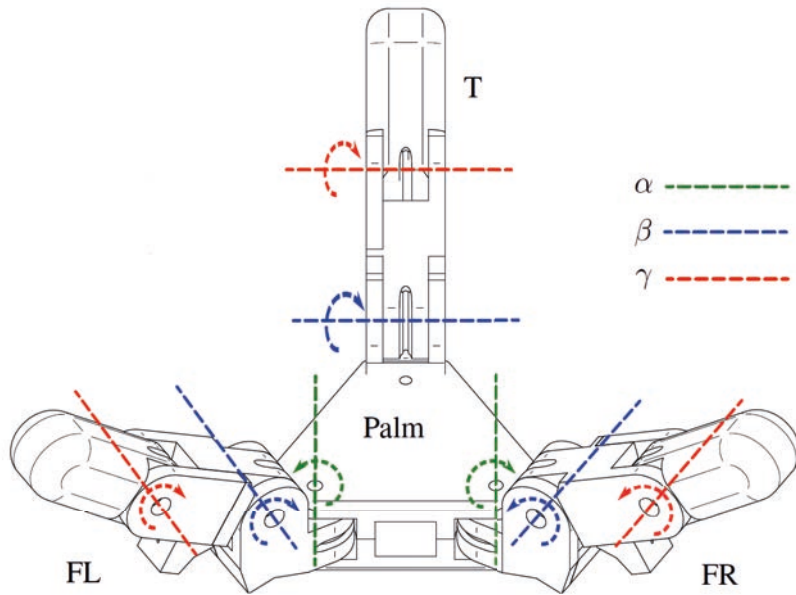
Max object weight: 20 kg with power grasp

Both power and precision grasps can be executed

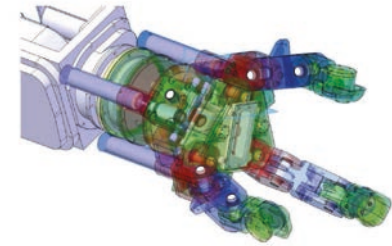


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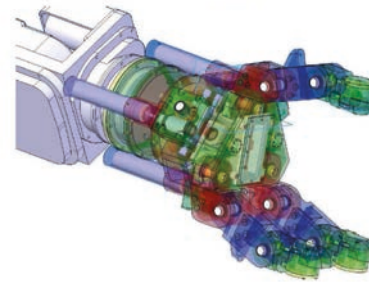
# Underwater Grippers - 2



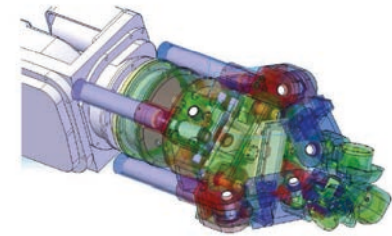
(a) Power grasp.



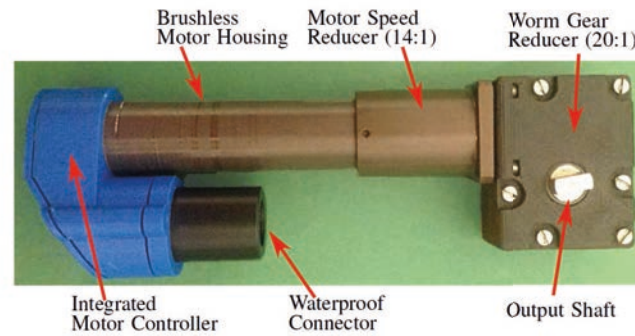
(b) Spherical grasp.



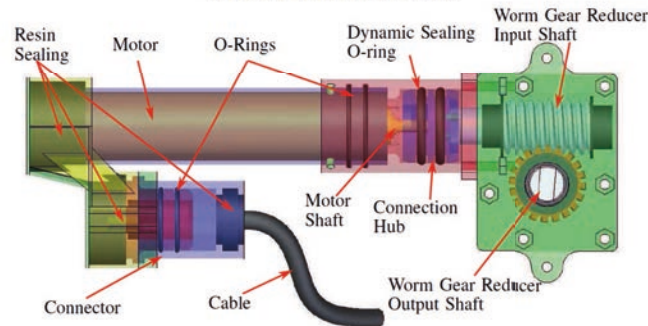
(c) Parallel grasp.



(d) Tripod precision grasp.



(a) Detail of the actuation module.



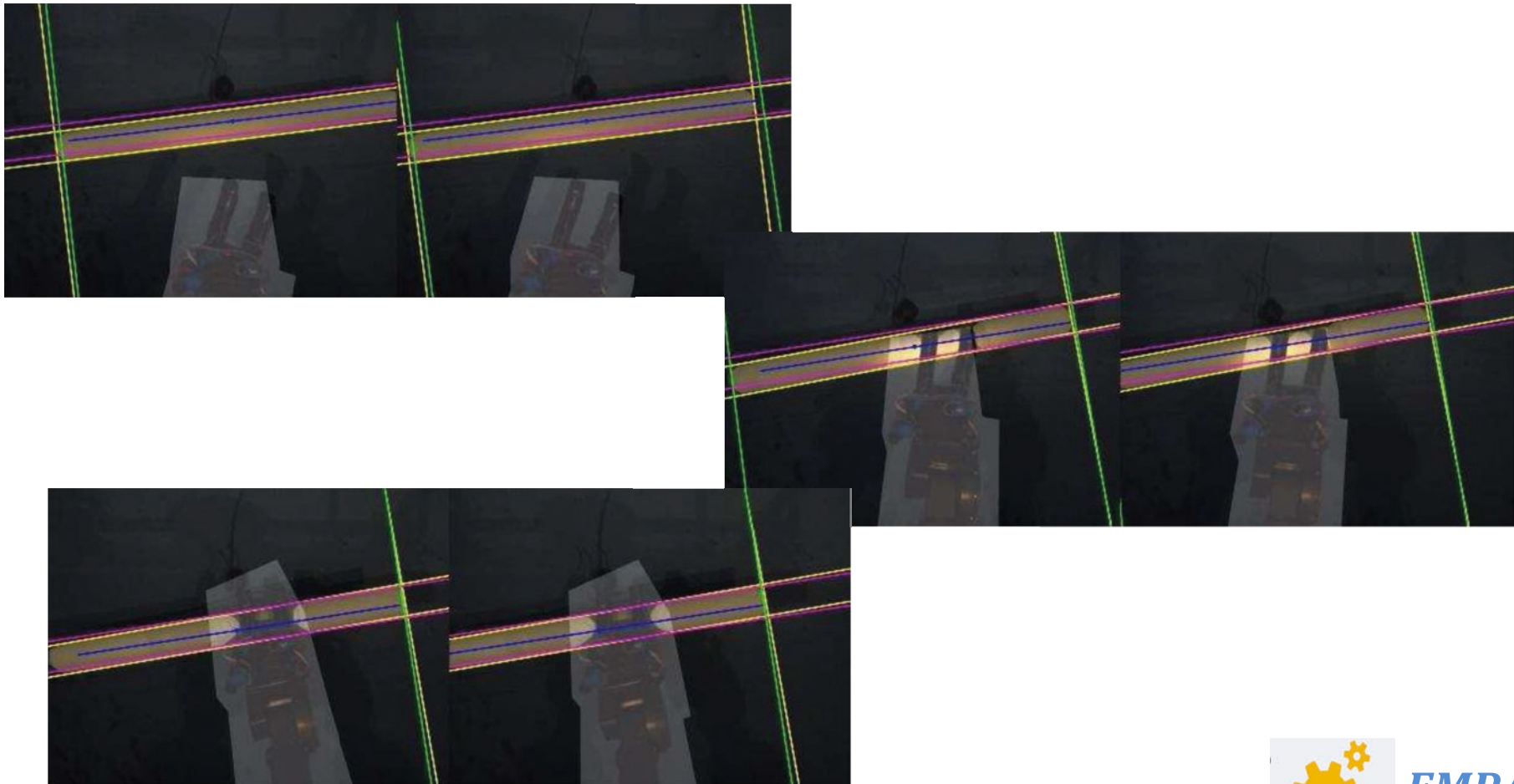
# Vision System - 1

Model-based stereo-vision algorithms

**Hand/arm occlusion avoidance via hand/arm re-projection on the image planes**

Capability of working within a wide range of lighting conditions

Customized hardware



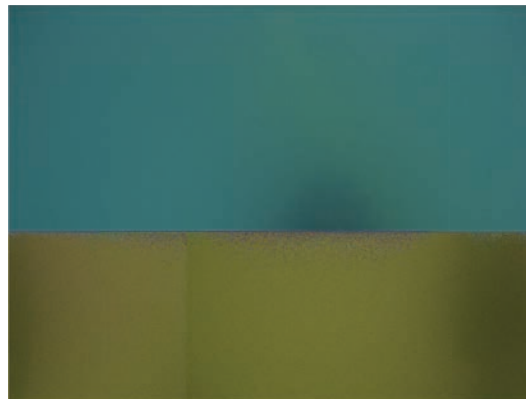
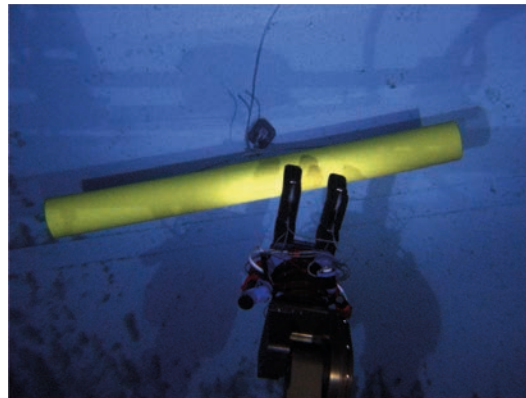
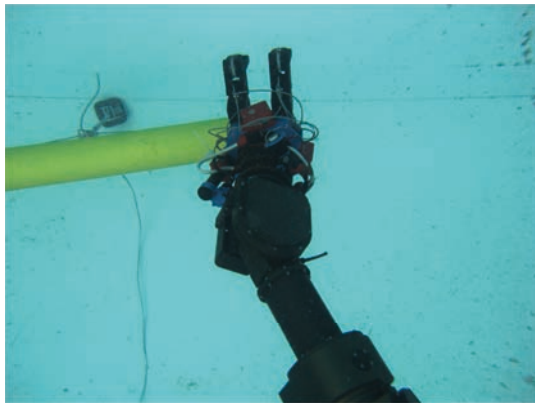
# Vision System - 2

Model-based stereo-vision algorithms

Hand/arm occlusion avoidance via hand/arm re-projection on the image planes

**Capability of working within a wide range of lighting conditions**

Customized hardware



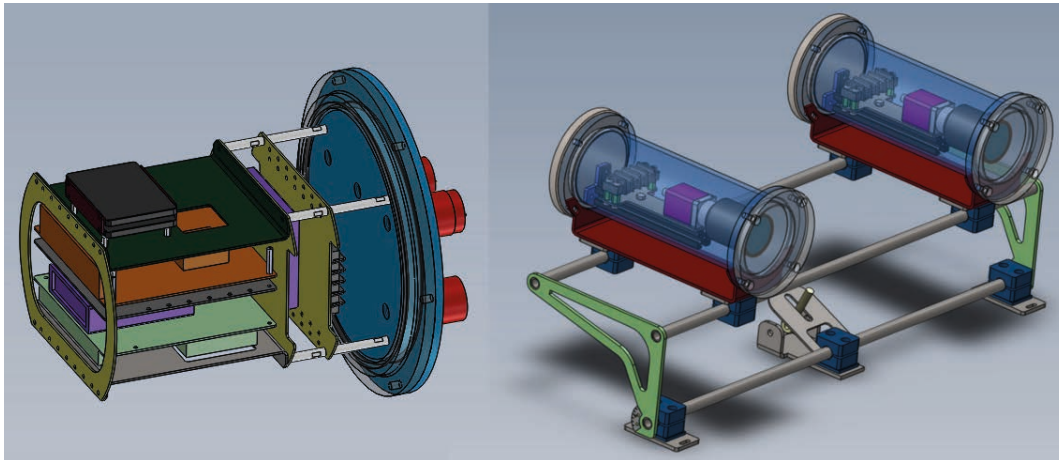
# Vision System - 3

Model-based stereo-vision algorithms

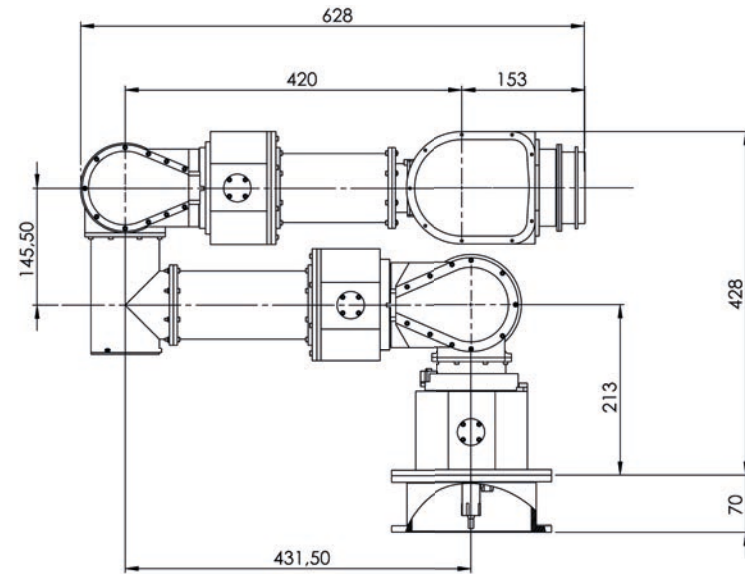
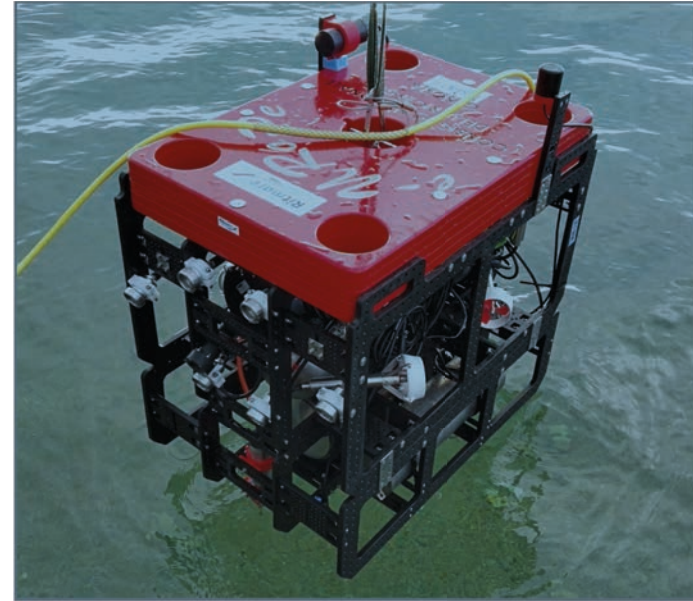
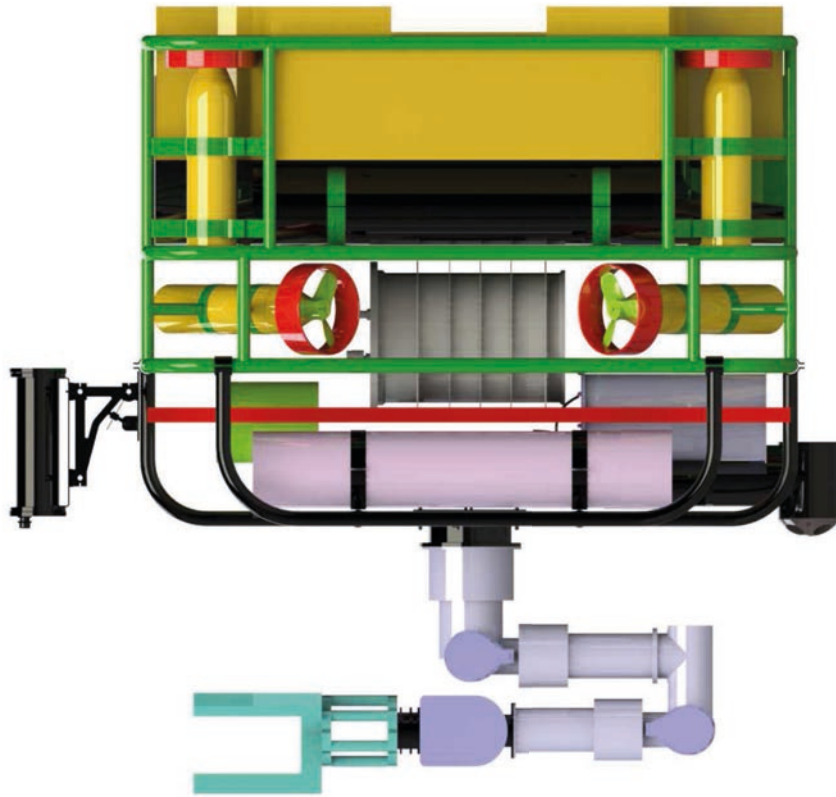
Hand/arm occlusion avoidance via hand/arm re-projection on the image planes

Capability of working within a wide range of lighting conditions

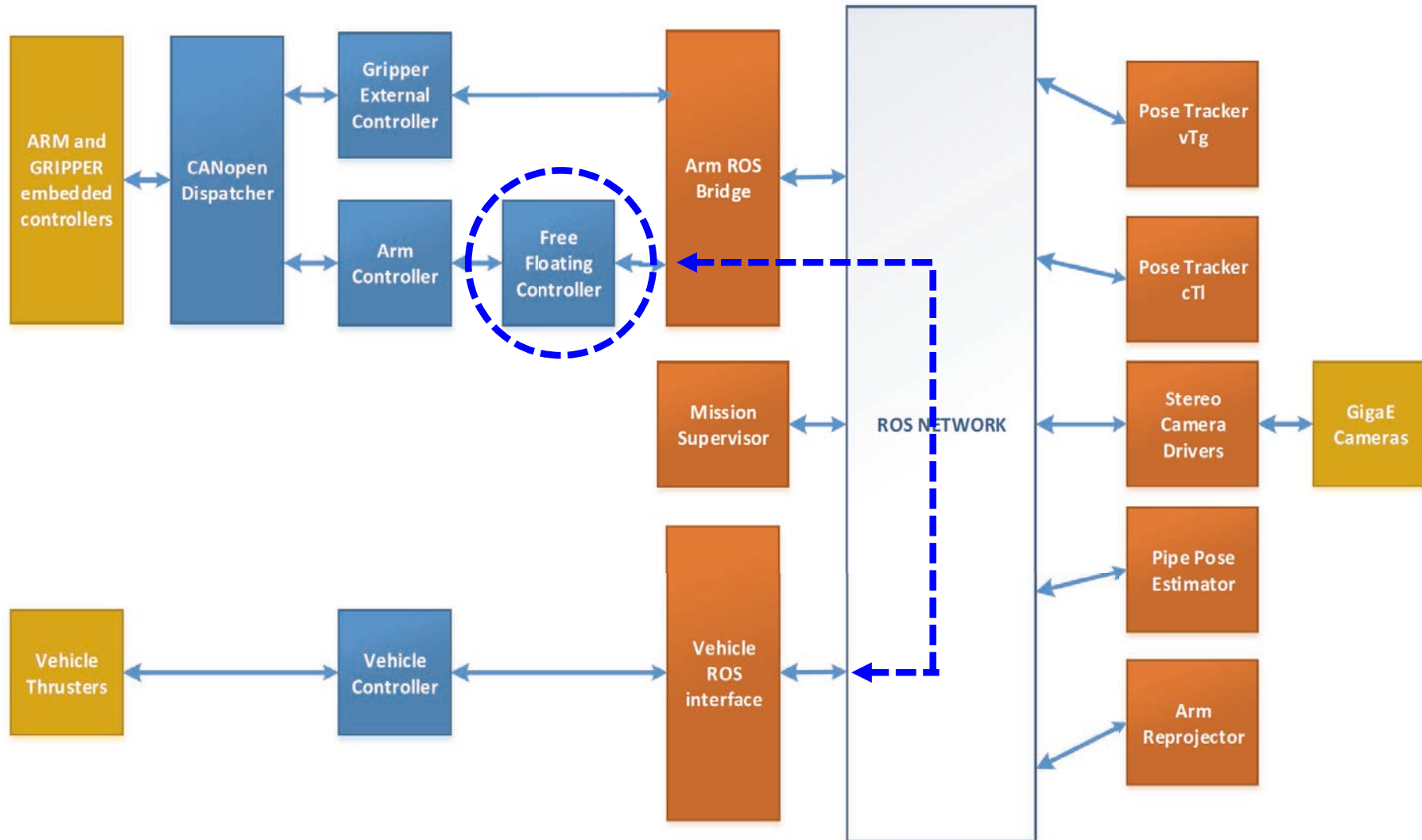
**Customized hardware**



# Integrated System



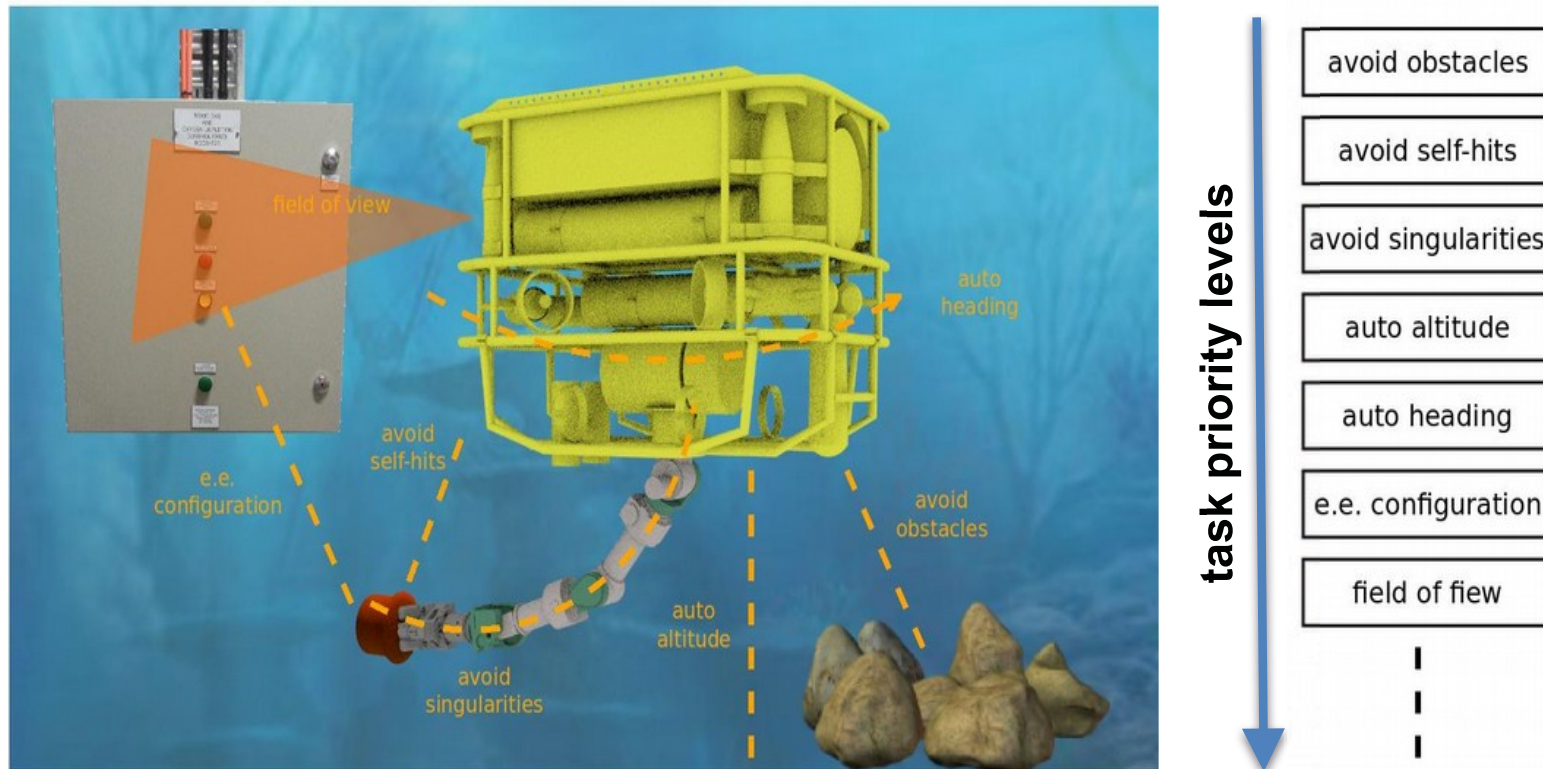
# Software Architecture



# Control of Individual UVMS - 1

(Free Floating Controller)

- Objectives:** Extending the applicability of **Task-Priority Control** approach
- Formalizing-consolidating it within a **Unified Framework**
- Proposing it as a **Best control practice** for UVMS



The task-priority control approach in one image

# Control of Individual UVMS - 3

## Tsk Priority Control: a complete formalization

### Control Objectives and Priorities

#### **Inequality** control objectives

Typically represent **safety and/or operational-enabling conditions**; to be **preliminary achieved**, and then maintained, for assuring safe and reliable execution of the ultimate action goal (e.g. object grasping)

Consequently they generally have **higher priorities**

#### **Equality** control objectives

Typically represent the **ultimate action goal** (e.g. object grasping), to be executed under safe and reliable conditions. Consequently they generally have **lower priorities**

# Control of Individual UVMS - 3

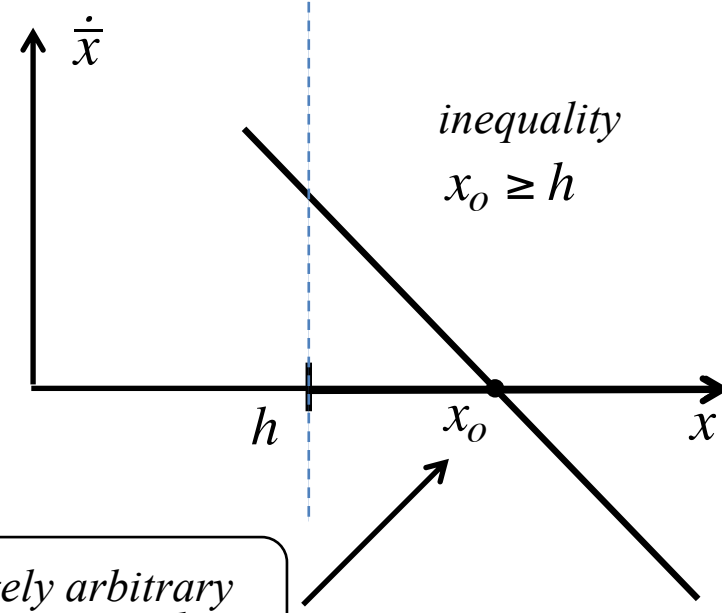
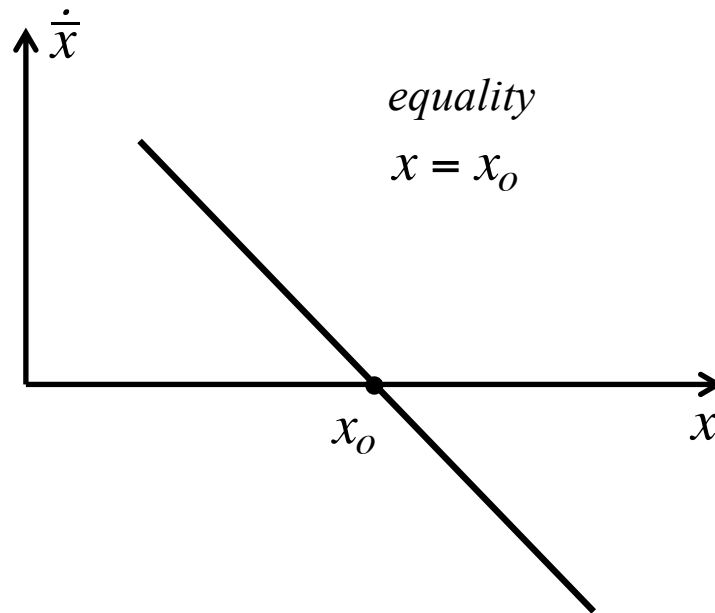
## Reactive reference rates

With  $\mathcal{X}$  the generic scalar variable involved in a control objective, let  $\dot{\hat{x}}$  be any reactive (or feedback) rate that, in case it could be directly applied, it would drive  $\mathcal{X}$  toward a value  $x_0$  located inside the validity interval of the corresponding control objective

$$\dot{\hat{x}} = \dot{\hat{x}}(x)$$

*For instance*

$$\dot{\hat{x}} = -\gamma(x - x_0) \quad ; \quad \gamma > 0$$



*Largely arbitrary within  $x_0 > h$*

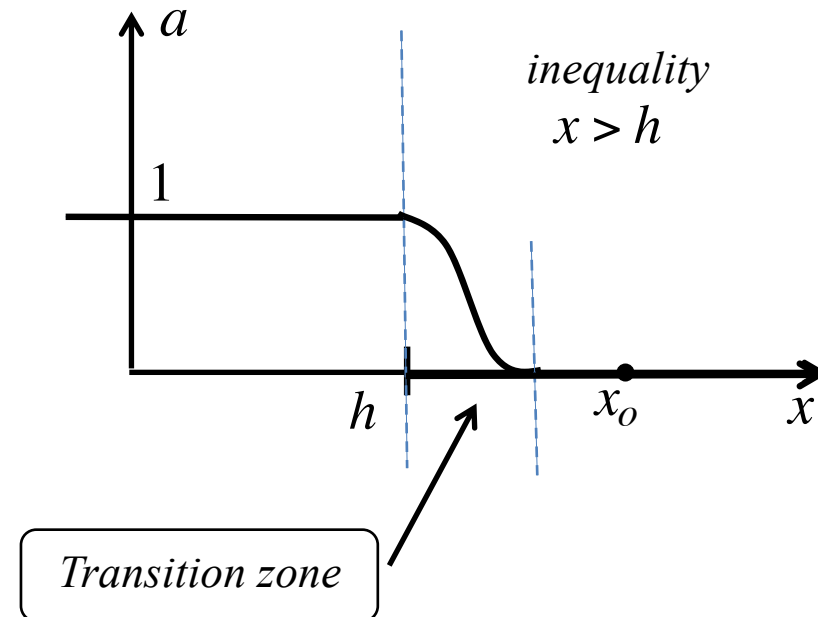
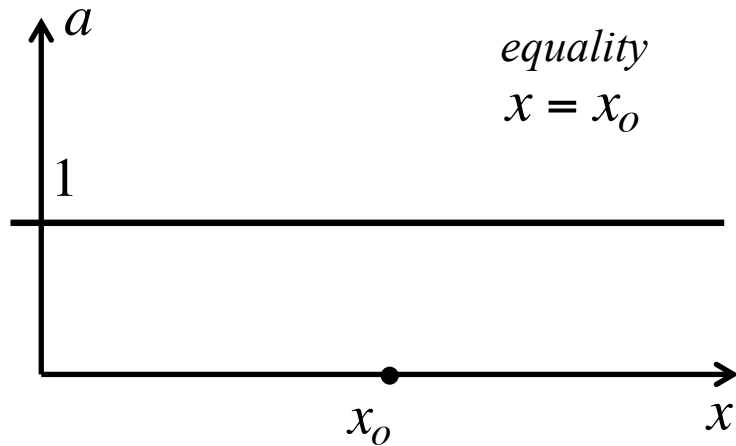


# Control of Individual UVMS - 4

## Activation function

Associated with each reactive reference rate a corresponding activation function  $a = a(x)$  of continuous sigmoidal type is always associated as in figure

$$a = a(x) \in [0,1]$$



# Control of Individual UVMS - 5

## Clusters of Prioritized Control Objectives

### **k-th priority-level Reactive Reference Rate Vector**

In correspondence of all scalar variables related with control objective at the same level  $k$  of priority, define the associated reference-rate vector

$$\dot{\bar{x}}_k \doteq \text{col} [\dot{\bar{x}}_{1k}, \dot{\bar{x}}_{2k}, \dots, \dot{\bar{x}}_{n_k k}]$$

### **k-th priority-level Activation Matrix**

Also associate to the  $k$ -th feedback reference vector the corresponding activation matrix

$$A_k \doteq \text{diag} [a_{1k}, a_{2k}, \dots, a_{n_k k}]$$

# Control of Individual UVMS - 6

## Task-priority inverse-kinematic problem

At each sampling time, perform the following sequence of **nested quadratic minimizations** (listed in a descending order of priority for increasing index)

- For  $k = 1, 2, \dots, N$  do: ( $N$ : number of assigned priority levels;  $S_0 \doteq R^n$ )

$$S_k \doteq \left\{ \underset{\dot{y} \in S_{k-1}}{\text{arg R-min}} \left\| A_k (\dot{x}_k - J_k \dot{y}) \right\|^2 \right\}$$

∴

where

$$\dot{y} \doteq \begin{bmatrix} \dot{q} \\ v_1 \\ v_2 \end{bmatrix} = \left. \begin{array}{l} \text{Arm joint velocity vector} \\ \text{Vehicle linear velocity vector on its body frame} \\ \text{Vehicle angular velocity vector on in its body frame} \end{array} \right\} \text{system velocity vector}$$

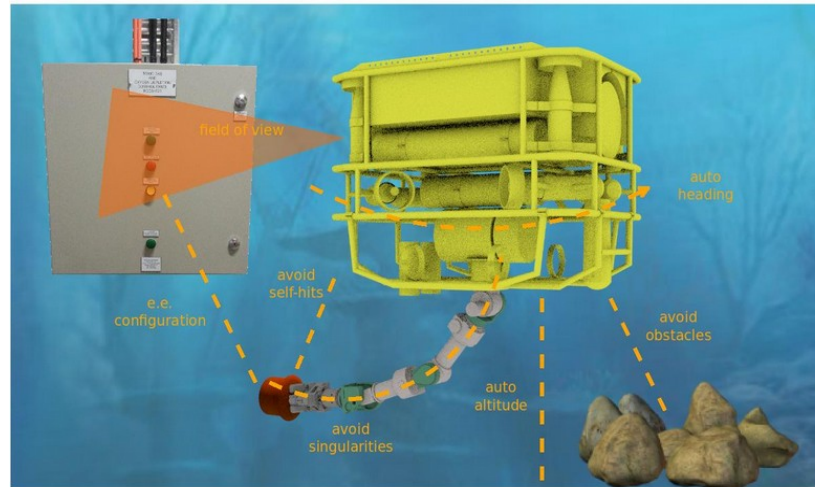
$$\dot{x}_k = J_k \dot{y} \quad \text{Jacobian relationship of the actual rates of the involved control objective vector } x_k$$

**R-min** Standing for “regularized minimization”: strictly necessary for managing with continuity the algorithmic singularities (or quasi-singularity) arising whenever at least a task (i.e, a row in the argument of the above quadratic form) is in the transition zone)



# Control of Individual UVMS - 7

## Example



- 1 Joint limits  
Camera Centering
- 2 Manipulability  
Camera Distance  
Camera Height
- 3 Horizontal attitude
- 4 End Eff. Approach
- 5 **Vehicle motion  
minimality**

$$S_1 = \left\{ \underset{\dot{y}}{\operatorname{argmin}} \left( \sum_{i=1}^7 \left\| \alpha_{q_i} (\dot{\bar{q}}_i - \dot{q}_i) \right\|^2 + \left\| \alpha_{\xi} (\dot{\bar{\sigma}}_{\xi} - J_{\xi} \mathbf{v}) \right\|^2 \right) \right\}$$

$$S_2 = \left\{ \underset{\dot{y} \in S_1}{\operatorname{argmin}} \left( \left\| \alpha_{\mu} (\dot{\bar{\mu}} - J_{\mu} \dot{q}) \right\|^2 + \left\| \alpha_d (\dot{\bar{d}} - J_d \mathbf{v}) \right\|^2 + \left\| \alpha_h (\dot{\bar{h}} - J_h \mathbf{v}) \right\|^2 \right) \right\}$$

$$S_3 = \left\{ \underset{\dot{y} \in S_2}{\operatorname{argmin}} \left( \left\| \alpha_{\phi} (\dot{\bar{\phi}} - J_{\phi} \mathbf{v}_2) \right\|^2 \right) \right\}$$

$$S_4 = \left\{ \underset{\dot{y} \in S_3}{\operatorname{argmin}} \left\| \dot{\bar{x}}_e - J_e \dot{y} \right\|^2 \right\} \quad \dot{\bar{x}}_e = \begin{bmatrix} \dot{\bar{r}} \\ \dot{\bar{\theta}} \end{bmatrix}$$

$$S_5 = \underset{\dot{y} \in S_4}{\operatorname{argmin}} \left\| \mathbf{v} \right\|^2$$



# Control of Individual UVMS - 8

## Algorithmic translation

The sequence of nested quadratic minimizations directly translate into the following **unified**, simple, **structurally invariant**, algorithmic framework

$$\rho_0 \doteq 0 \quad \bar{G}_0 \doteq 0 \quad Q_0 \doteq I$$


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$$\text{for } k = 1, 2, \dots, N \quad G_k \doteq A_k J_k \quad \dot{\bar{\sigma}}_k \doteq A_k \dot{\bar{x}}_k$$

$$\bar{G}_k \doteq G_k Q_{k-1}$$

$$\dot{\bar{\rho}}_k = (I - Q_{k-1} \bar{G}_k^\# G_k) \dot{\bar{\rho}}_{k-1} + Q_{k-1} \bar{G}_k^\# \dot{\bar{\sigma}}_k$$

$$Q_k = Q_{k-1} (I - \bar{G}_k^\# \bar{G}_k) \quad \longrightarrow \quad S_k = \left\{ \dot{y} = \dot{\bar{\rho}}_k + Q_k \dot{z}_k \ ; \ \forall \dot{z}_k \right\}$$

---


$$S_N = \left\{ \dot{y} = \dot{\bar{\rho}}_N + Q_N \dot{z}_N \ ; \ \forall \dot{z}_N \right\}$$

*In case some arbitrariness still exists (i.e.  $Q_N \neq 0$ ) then it can be used for the additional task motion minimality (for instance the vehicle motion)*



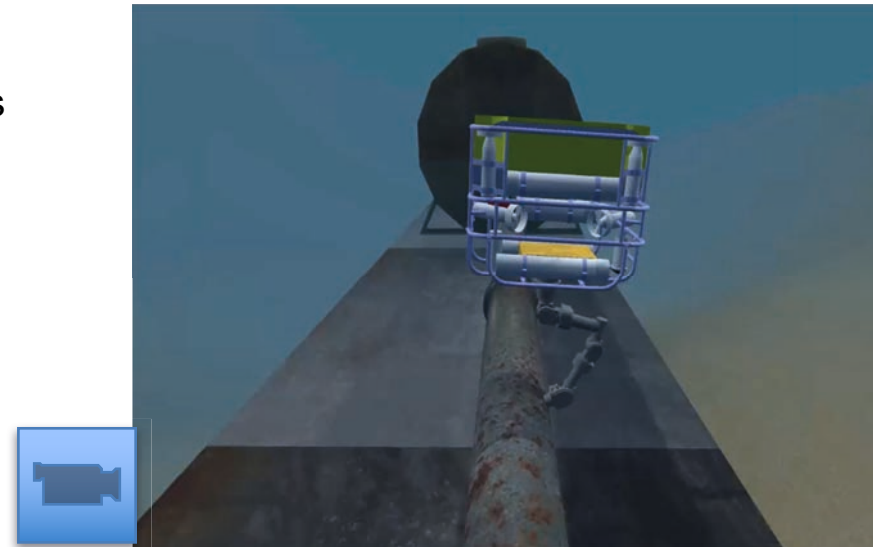
# Control of Individual UVMS - 9

## Extentions: Constrained motions & Interaction control

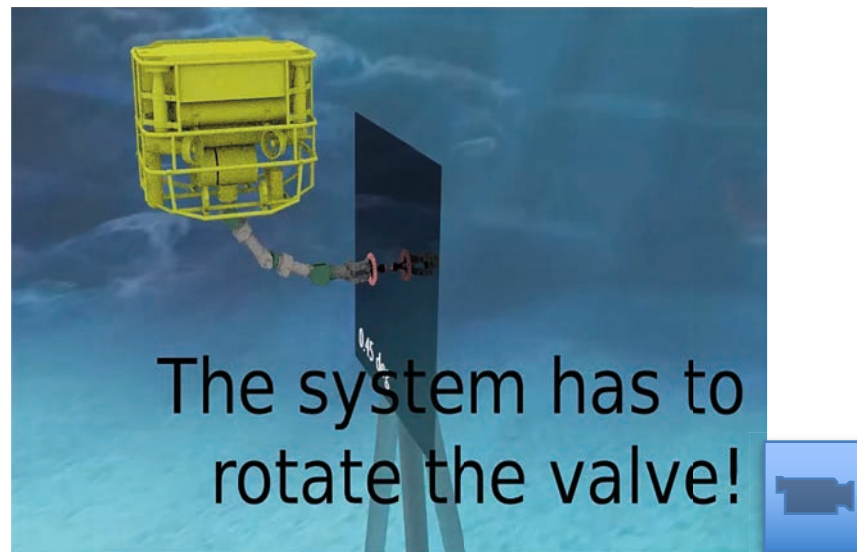
Constrained and interaction control tasks always to be located at the **highest priority level**

Both **Impedance** and/or **hybrid motion/force** control are allowed

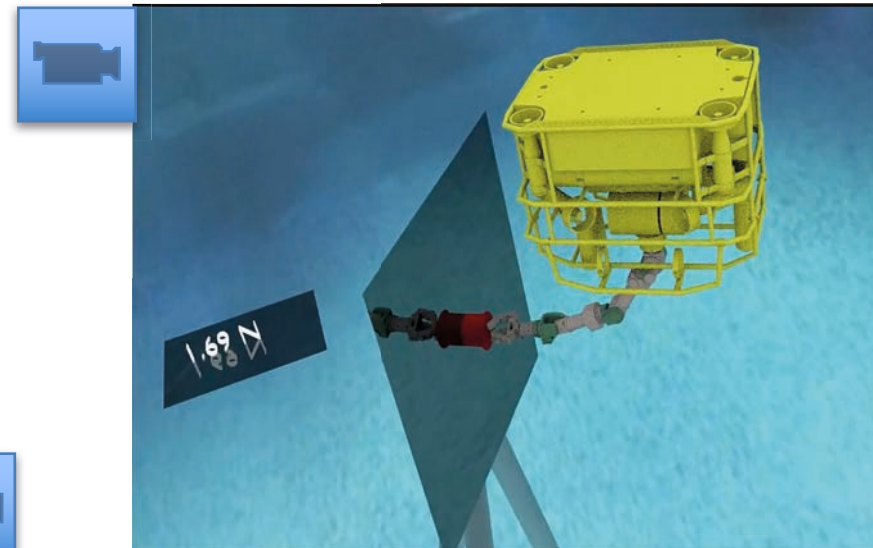
*Pipe inspection*



*Turn valve*

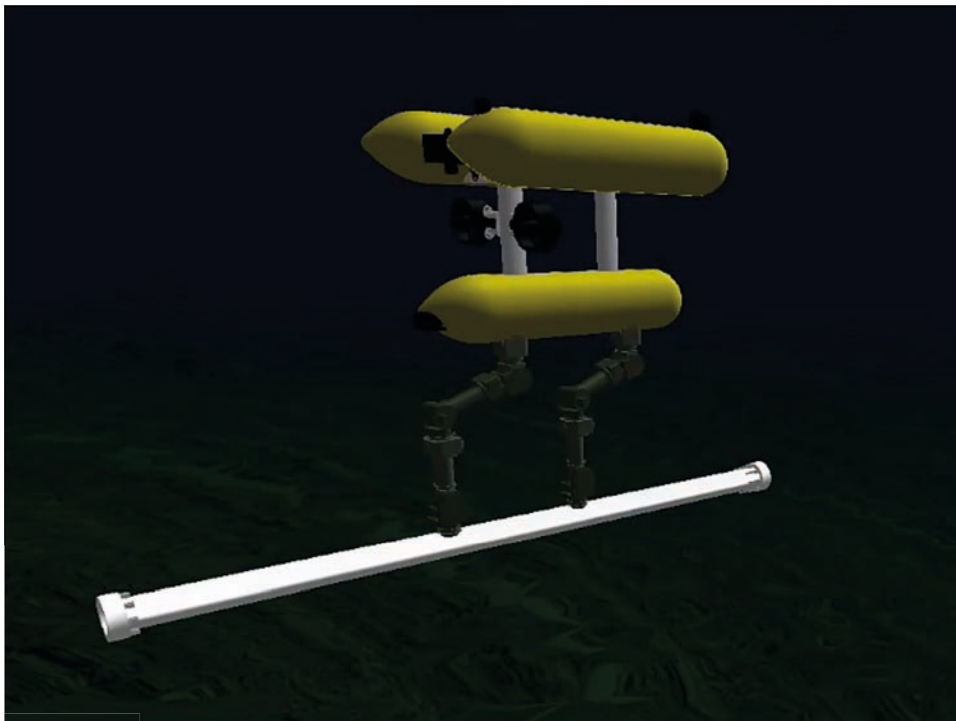


*Push button*

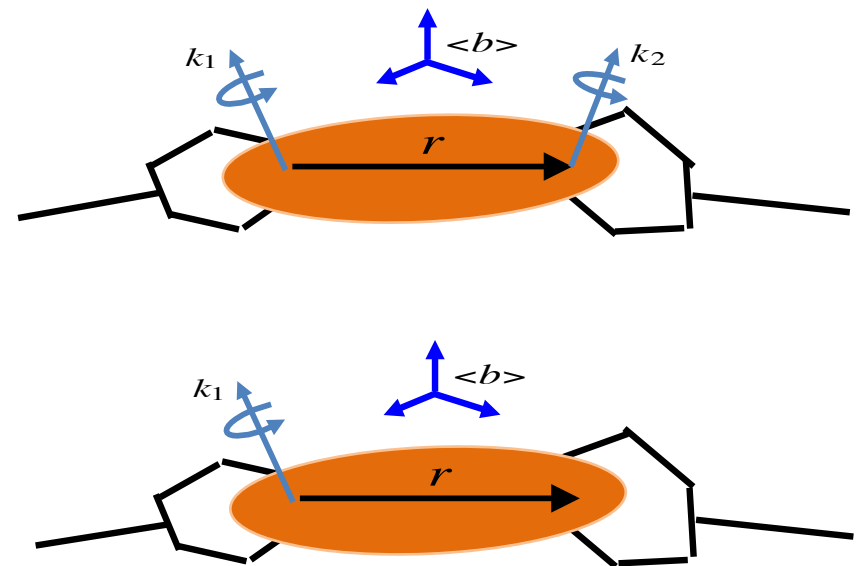


# Control of Individual UVMS - 10

- Extensions:**
- **Dual-arm UVMS** → Multi-arm UVMS
  - **Constrained motions & interaction control** within dual-arm manipulation & transportation
  - **Non-firm-grasp object manipulation**
  - **Explicit compensation** (other than implicitly via visual feedback) of the **vehicle-motion inaccuracies** (provided measurable)



Dual arm



Non-firm-grasp manipulation



# Control of Individual UVMS - 11

## Preliminary Conclusions

Task priority control procedure currently seems qualifying as the **best-practice** for managing a wide variety of possible underwater intervention actions , while always remaining within a **unified invariant control framework**.

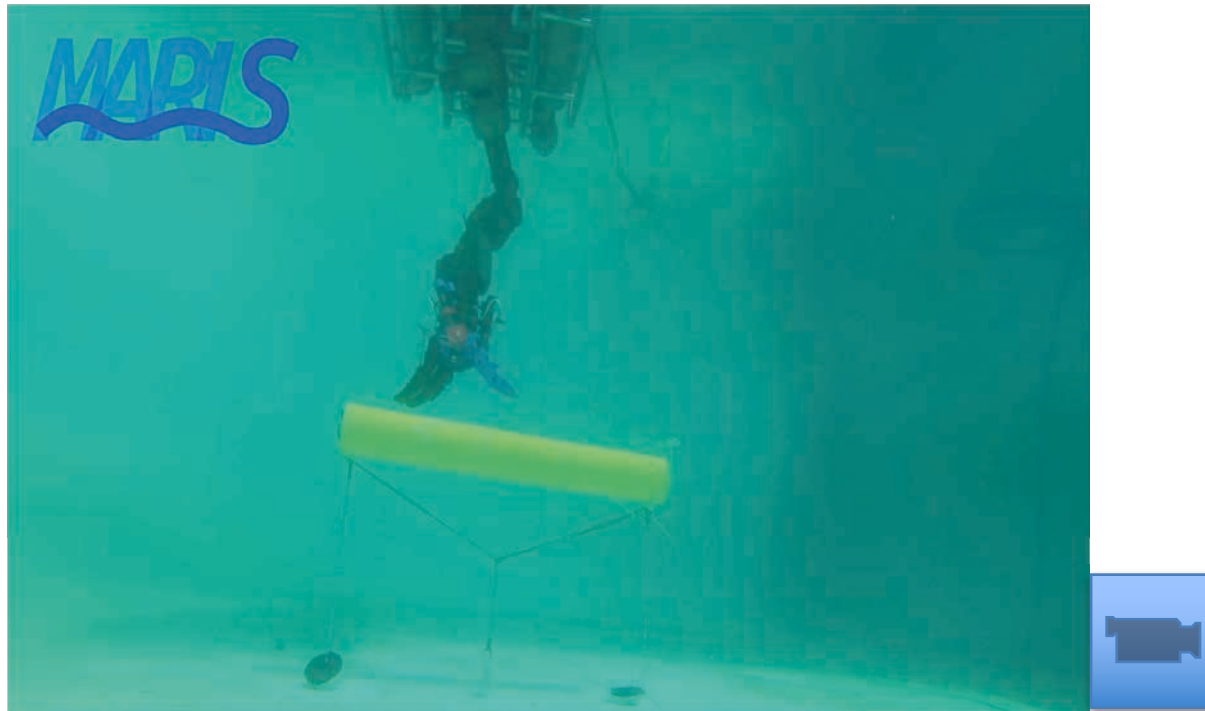
## Open problems and current research

- Task priority control actually only constitutes the so called **Kinematic Control Layer (KCL)** which is in charge of real time outputting reference velocity signals (for the arms and the vehicle); to be concurrently tracked by the **Dynamic Control Layer (DCL)**.
- The KCL should therefore output its reference signal within the “**DCL bandwidth**” (i.e. “**KCL slower**” than DCL).
- KCL gains and parameters must be therefore tuned to the DCL performances
- Such tuning process (mostly due to the generally high number of the KCL parameters) is generally **long and tedious** (different simulation sessions; then followed by experimental trials to the scope).
- **Best practices** for KCL parameter tuning **do not exist yet**. Assessing them is currently under investigation; together with the possibility of also devising auto-tuning procedures

# Individual UVMS – Integrated Pool Trials

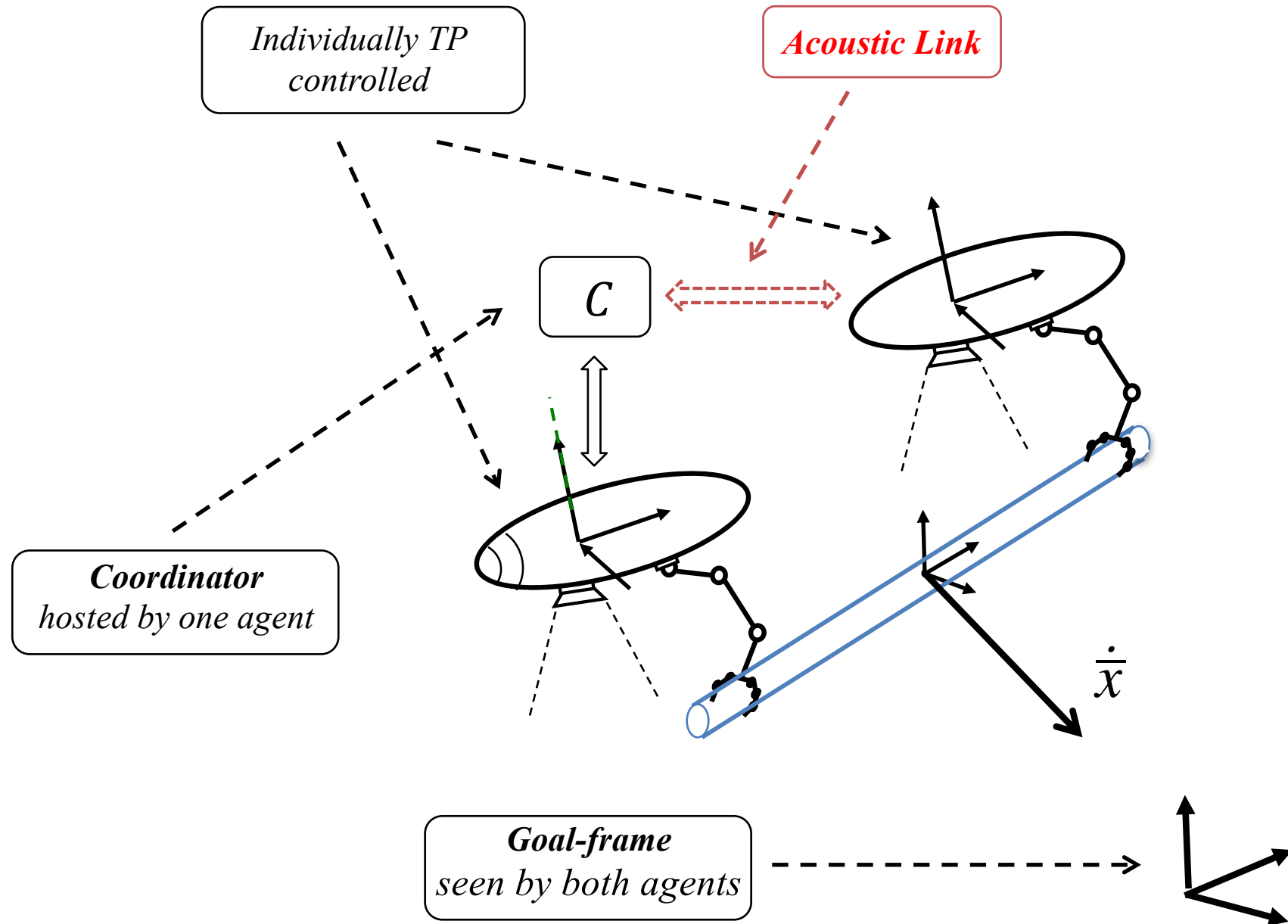
## Benchmarking evaluation

- With 20 repeated grasping trials, 14 where successful ones(70%)
- Encouraging, to the aim of a near-future transfer to real applications



*MARIS Integrated pool trials*

# Control of Cooperative UVMS - 1



# Control of Cooperative UVMS - 2

## Why a Coordinator?

### *Fundamental considerations*

- Theoretically a Coordinator could be designed in such a way to override the individual TP controllers, in case it could acquire **all the individual information**; thus implementing a **centralized TP controller** for the overall resulting system → An **unthinkable solution!!**
- I should therefore work only on the basis of a **reduced set** of exchanged information, possibly only **regarding the ultimate action goal** (i.e. the capability or not of tracking the required object velocity  $\dot{\bar{x}}$  by part of each agent)
- The possibility of not succeeding in tracking  $\dot{\bar{x}}$  by part of one or both agents is due to the fact that both agents are assumed having such tracking task at the **lowest priority level** (for primarily caring about their individual safety & operational requirements)
- In this case, if the resulting **different** object reference velocities are applied, the object might move with an **uncontrolled** resulting velocity and subjected to **uncontrolled** stresses
- Locating the task tracking of  $\dot{\bar{x}}$  at the highest priority level, inside each agent, **could be** a solution; but at the cost of **risking to violate** at least some of the individual **safety and/or operational requirements** of the agents
- In this case, however, the **high-redundancy** of each agent may obviously greatly **helps in mitigating such risks**; that however **cannot ever be zeroed**

# Control of Cooperative UVMS - 3

## Coordination policy

- ① At each sampling time the agents formerly compute their respective object velocities  $\hat{\dot{x}}_1, \hat{\dot{x}}_2$  which result as if each one of them were the sole handling the object; with the object velocity task  $\bar{\dot{x}}$  located at the **lowest priority**
- ② The coordinator **acoustically receives**  $\hat{\dot{x}}_2$  from Agent 2, while locally also acquire  $\hat{\dot{x}}_1$  from Agent 1 and evaluate the following convex (barycentric) combination

$$\hat{\dot{x}} = \frac{1}{\mu} (\mu_1 \hat{\dot{x}}_1 + \mu_2 \hat{\dot{x}}_2) \quad ; \quad \mu = \mu_1 + \mu_2 \quad ; \quad \mu_1, \mu_2 > 0$$

with

$$\mu_1 = \mu_0 + \left| \bar{\dot{x}} - \hat{\dot{x}}_1 \right| \quad ; \quad \mu_2 = \mu_0 + \left| \bar{\dot{x}} - \hat{\dot{x}}_2 \right| \quad ; \quad \mu_0 > 0$$

- ③ The coordinator **acoustically transfer**  $\hat{\dot{x}}$  to Agent 2 and locally to Agent 1
- ④ The agents locate the (now common)  $\hat{\dot{x}}$  at the **highest priority**, as the **new object reference velocity** to be tracked; and consequently individually evaluate their respective system velocity vectors  $\hat{y}_1, \hat{y}_2$  to be then applied (now with guaranteed tracking of  $\hat{\dot{x}}$ )

The coordination policy always act in favor of the Agent currently exhibiting a greater difficulty in tracking the object reference velocity  $\bar{\dot{x}}$ .

It provides the **best-compromise** between the needs of the Agents of primarily caring for their individual safety and operational requirements; and the need of however moving the object, while avoiding unc

Only require a **full-duplex acoustic transmission of six numbers**

The same typical frequency of **10-20 Hz** for vision cameras should also be assured by **current acoustic modem technologies**. If not (e.g. **1Hz**) the entire TPC process should **be proportionally slowed down**.

# Control of Cooperative UVMS - 4

## Current research activities

In order to further reducing the acoustic communication effort, the Agents should be put in the condition of communicating **only when necessary**; which means when both the object velocity errors are above a pre-defined threshold.

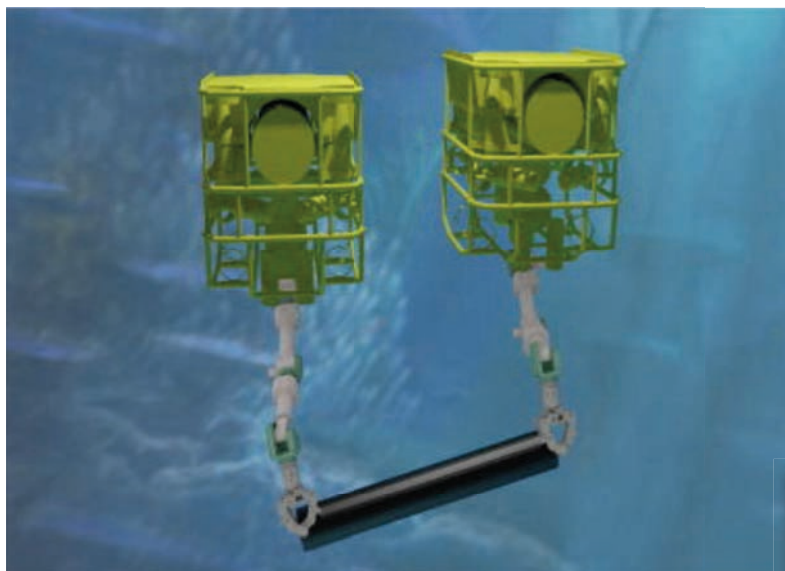
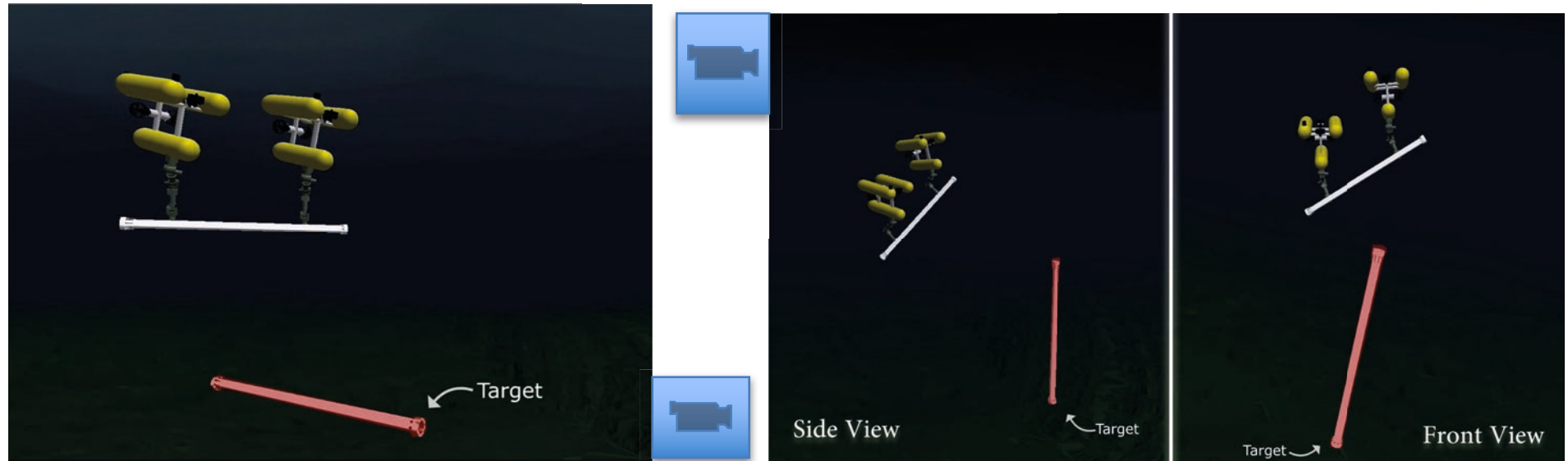
And this could therefore lead to the following **modified coordination policy**

- ① The Agents have synchronized clocks
- ② Logic signals (one bit of information; i.e. a pulse with no communication effort!) are full-duplex acoustically exchanged for making both agents aware if **both** the tracking errors are within a given threshold; or if **at least one** of them is outside it (or near to be outside).  
A simplifying alternative would be that the agent with the error within the threshold just does not transmit anything (no-reception at due time will be acknowledged )
- ③ If a received bit is logically 1, both agents slow-down, while starting exchanging their computed object velocity data. This is repeated until both bits return to the logic zero.

An alternative (or a synergic possibility) would be that of **discriminating the induced object stresses** (obviously they are the same for both agents) that could be used as **a measure of the difference between the commanded object tracking velocities**. Then acting as above whenever the stresses are above (or near to be above) a given threshold.

# Control of Cooperative UVMS - 5

## Simulation results



### *Velocity control based*

- *Object velocity tracking at the highest priority*
- *Explicit coordination*

### *Impedance control based*

- *Force reported to velocity*
- *Object velocity tracking at the highest priority*
- *No explicit coordination*
- *Trusting on redundancy*

# Control of Cooperative UVMS - 6

## Simulation results



A complete mission

***ACTION*** is a list of ***prioritized control objectives***  
To be ***concurrently*** achieved (via TPC)

Actions generally ***differ for their ultimate goal only***  
(safety and operational requirements are generally invariant).

Thus can be ***classified by their ultimate goal only***  
(e.g. object grasp, turn valve, push button, inspect pipe, plug, unplug, etc.)

***MISSION*** is an ***action sequence in a decision graph***

- ***actions are the nodes***
- ***arcs the decision alternatives***

***PLANNING*** is the process of ***organizing the action decision graph*** (possibly even in real time) and its ***management***

***Planning*** should be ***facilitated*** by the ***simplified actions classification*** induced by the TPC use

Decisions between action alternatives should be taken on the basis of the range value eventually attained by a suitable ***“action state vector”*** classifying the achievement (or not) of the action goal

***Action transitions*** can be made ***smooth*** via the use of additional activation functions overall modulating (in opposite sense) both the current and incoming new action

# Control of Cooperative UVMS - 7

## Integrated pool trials

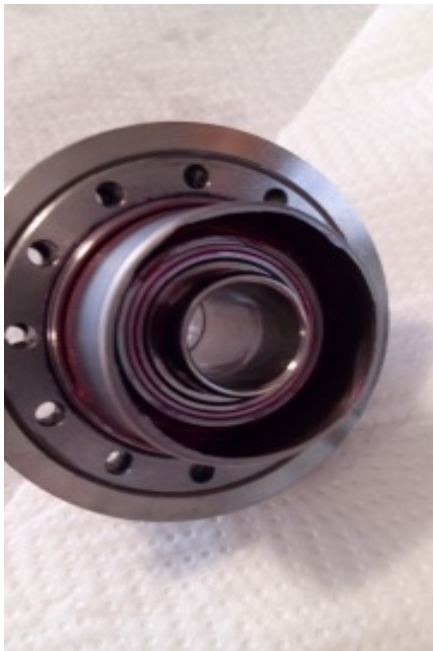
***Unfortunately ..... not a nice story .....***

*A serious accident occurred during the preliminary manual maneuvering of the systems toward the middle of the pool*

*An erroneous command made one of the systems crashing down to the pool bottom; seriously breaking two joints of one arm and partially one gripper*

*Repairs required more than 8 months: Harmonic Drive components from Japan, accurate machining of some parts and building new ones*

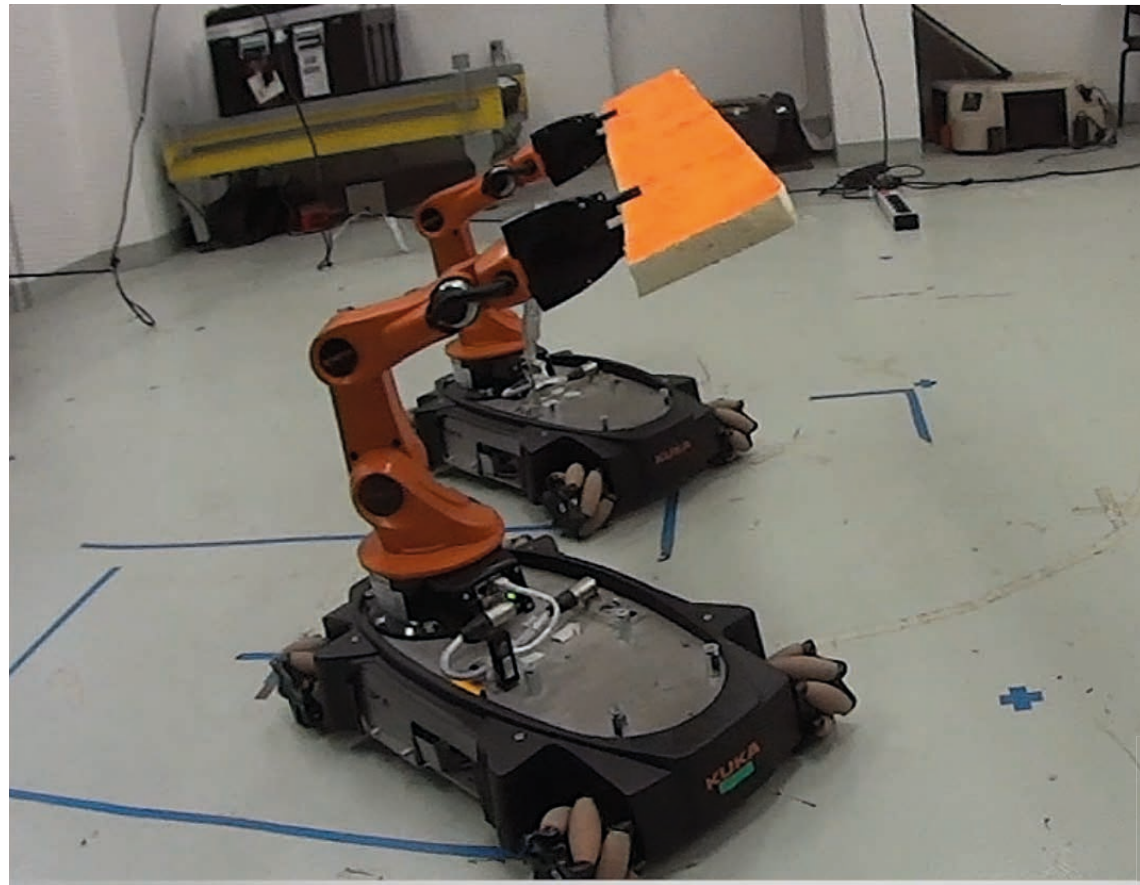
***The project was consequently Terminated .....***



# Control of Cooperative ~~UVMS~~ - 8

~~Integrated pool~~ trials .....

*..... and we had to be content with some ground trials only....*



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