

Robotized measurements for geometric and acoustic characterization of unknown structures

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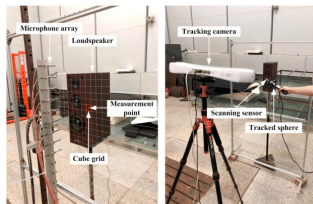
November 21, 2023



Introduction - Context



Geometric measurements [1]



Acoustic measurements [2][3]



⇒ Measurements and metrology operations are often tedious, time-consuming and unadaptable.

Introduction - Objectives

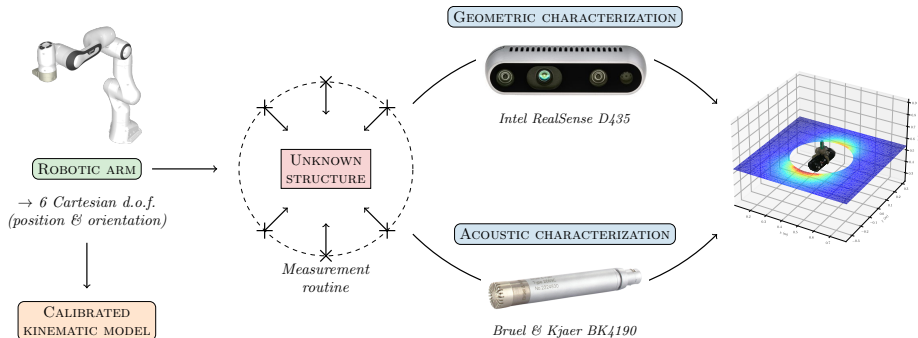


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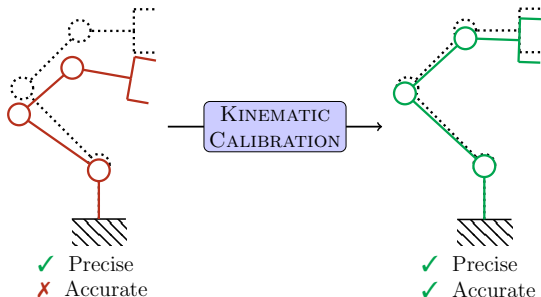
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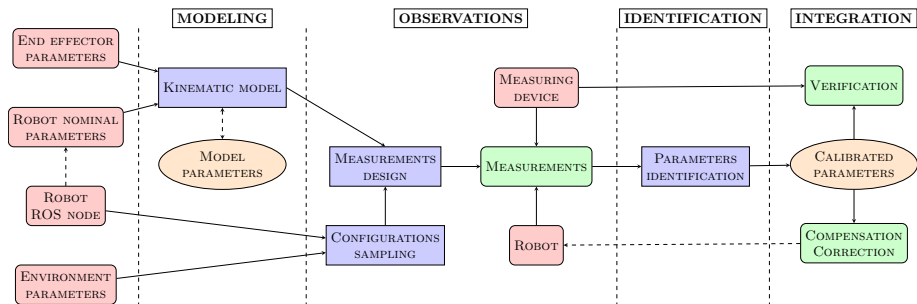
Robot arm kinematic calibration [4]

→ **Initial assessment** : Serial robots have a *high positioning repeatability* but a *poor absolute accuracy*.

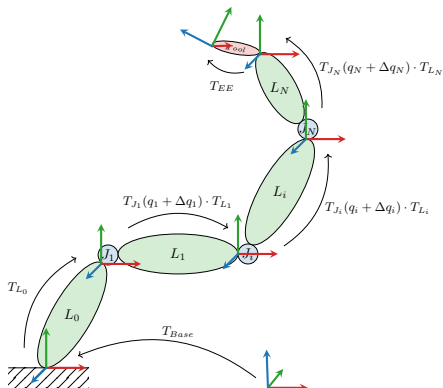


→ **Aftermath assessment** : There is no complete and off-the-shelf kinematic calibration tool !

Step 1 : Define a kinematic calibration procedure



Description of the overall kinematic calibration procedure



Seeked model properties

- **Faithfulness** : Compliance with the robot true behaviour;
- **Completeness**, but without any **redundancy** : Model defined by a determined set of parameters;
- **Continuity** : Continuous function of the parameters;

Modeling (2)

Full-pose geometric modeling

$$\begin{aligned} T(\mathbf{q}, \boldsymbol{\pi}) = & T_{Base}(\boldsymbol{\pi}_{Base}) \cdot T_{Link_0}(\boldsymbol{\pi}_{L_0}) \\ & \cdot [T_{Joint_1}(\mathbf{q}_1 + \Delta\mathbf{q}_1, \boldsymbol{\pi}_{J_1}) \cdot T_{Link_1}(\boldsymbol{\pi}_{L_1})] \dots \\ & \cdot [T_{Joint_N}(\mathbf{q}_N + \Delta\mathbf{q}_N, \boldsymbol{\pi}_{q_N}) \cdot T_{Link_N}(\boldsymbol{\pi}_{L_N})] \cdot T_{EE}(\boldsymbol{\pi}_{EE}) \end{aligned}$$

Where $\boldsymbol{\pi} = (\boldsymbol{\pi}_{Base}, \boldsymbol{\pi}_{J_i}, \boldsymbol{\pi}_{L_i}, \boldsymbol{\pi}_{EE})$ are the *kinematic model parameters*

Partial-pose geometric modeling [5][6]

$$\begin{aligned} (P^i(\mathbf{q}, \boldsymbol{\pi}))_{i=1\dots M} = & T_{Base}(\boldsymbol{\pi}_{Base}) \cdot T_{Link_0}(\boldsymbol{\pi}_{L_0}) \\ & \cdot [T_{Joint_1}(\mathbf{q}_1 + \Delta\mathbf{q}_1, \boldsymbol{\pi}_{J_1}) \cdot T_{Link_1}(\boldsymbol{\pi}_{L_1})] \dots \\ & \cdot [T_{Joint_N}(\mathbf{q}_N + \Delta\mathbf{q}_N, \boldsymbol{\pi}_{q_N}) \cdot T_{Link_N}(\boldsymbol{\pi}_{L_N})] \cdot T_{EE_i}(\boldsymbol{\pi}_{EE_i}) \Big|_P \end{aligned}$$

Where EE_i refers to the end effector point $i \in \{1\dots M\}$

Redundancy elimination for revolute joints [7]

→ If the current and previous joints are **colinear**

⇒ Remove the closest translation orthogonal to the common rotation axis among the previous links transformations.

→ If the current and previous joints are **orthogonal**

⇒ Remove the rotation in the previous link transformation corresponding to the current joint rotation axis.

+ **Base** and **Tool** transformations simplification.

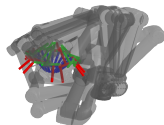
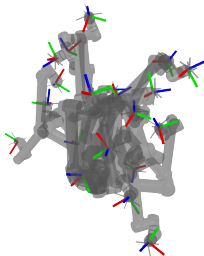
Observations

→ **Open-loop observations**, using internal monitoring (joints encoders) and external measurements (end effector points positions).

↪ *How to pick the measured robot configurations ?*

- 1 Perform a **reachable** and **task-oriented** sampling of the robot workspace [8];

Random sampling



3D scan inspired sampling

- 2 Choose the configurations maximizing **parameters O_1 identifiability** using combinatorial optimization [9].

Positioning accuracy optimization

$$\pi^* = \arg \min_{\pi} \sum_{i=1}^{N_{\text{meas.}}} \sum_{j=1}^{N_{EE}} \underbrace{\left\| P^j(q_i, \pi) - P_{\text{measured}}^j(q_i) \right\|^2}_{\epsilon_i^j}$$

Where ϵ_i^j defines the *positioning error* of the end effector point j for the i -th measurement.

→ The sum of **positioning errors** over all end effector points and measurement configurations defines the **robot accuracy**.

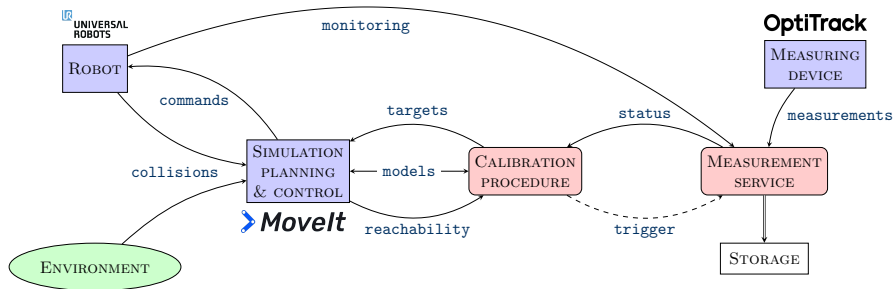
Verification

→ Validate the calibrated parameters with the accuracy obtained on a new set of randomly picked measurements.

Integration

- **Compensation**: Integrate the calibrated parameters directly in the robot controller.
- **Correction** : Build a new robot description with the calibrated parameters.

Step 2 : Handle the hardware-software interfaces



Description of the hardware-software interfaces

→ *Movel*t motion planning framework API
+ custom overlay : `robot_arm_tools`

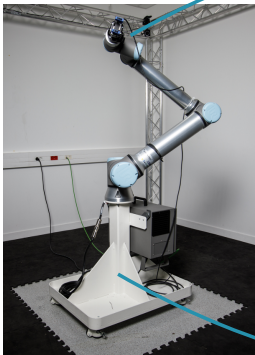
Simulation

- *Collision* and *singularity* aware motion planning tool, providing *reachability* insights;
- *Modular* yet *generic* planning and kinematic pipelines, with *custom constraints*;
- A simplified definition and integration of common use-cases;

Real robot

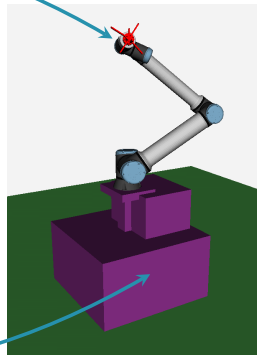
- *User-friendly* and *high-level* integration of real robots ROS controllers;
- *Dynamic interruption* and *low-level recovery* of motion execution;
- A logging solution to monitor and recover multiple waypoint trajectory execution.

External environment integration



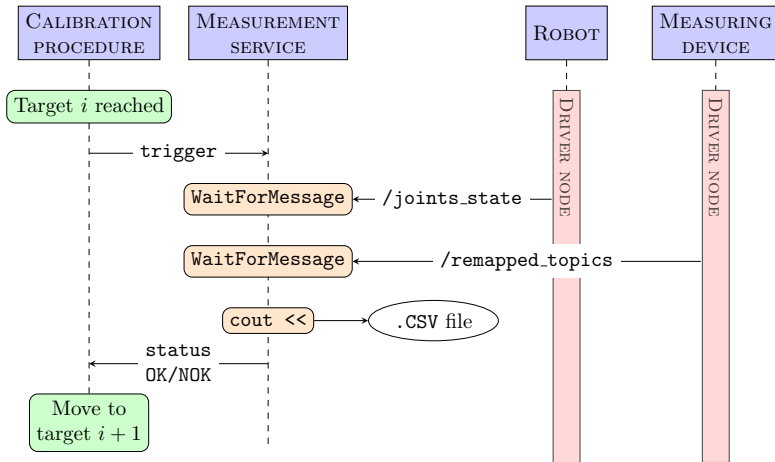
Automated URDF/XACRO
generation from
STL mesh file
↔ `/robot_description`
tweakage

User defined YAML file
with basic
geometric primitives
↔ `moveit_visual_tools`
overlay



Measuring devices integration

→ Creation of a *generic ROS service `MeasurementService`* for motion and measurements synchronization.



Experimental validation setup - Robots



Universal Robots - UR10e

- 6 axis
- 18 geometric parameters



Franka Emika - Panda

- 7 axis
- 22 geometric parameters

+ 6 Base and $3 \times M$ Tool parameters

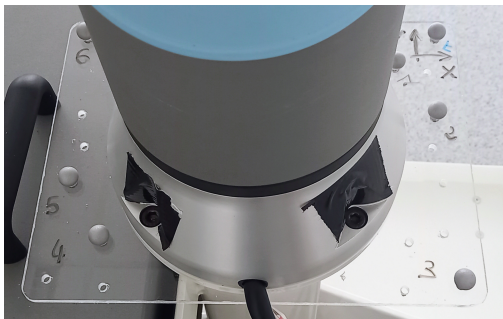
Experimental validation setup - External measuring device

→ **Optitrack** position tracking tool.



↔ 6 *Prime 13* cameras
⇒ ± 0.2 mm accuracy.

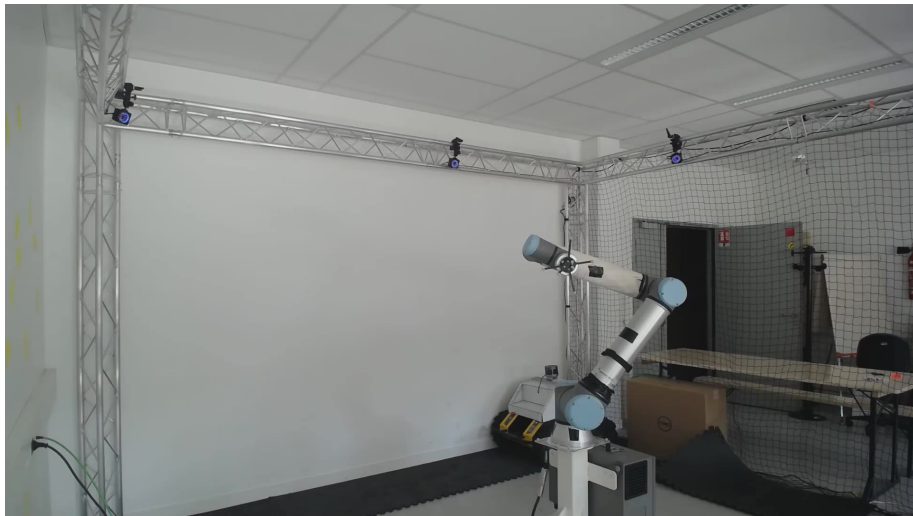
Experimental validation setup - Measurements bodies



→ Robot base and end effector points
measurements bodies.

$M = 7$ reflective spheres in a precise 3D
layout.

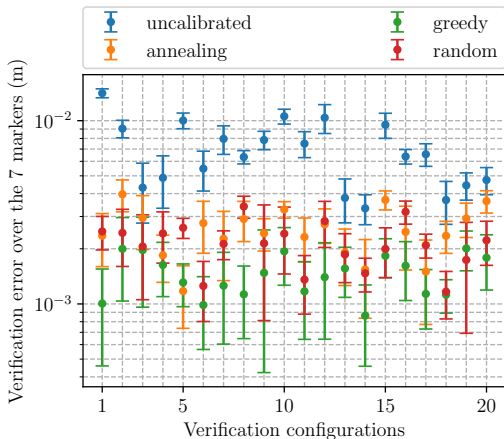
Example of calibration measurements



Calibration measurements of an UR10e (speed $\times 2$)

Experimental validation - Results (Panda)

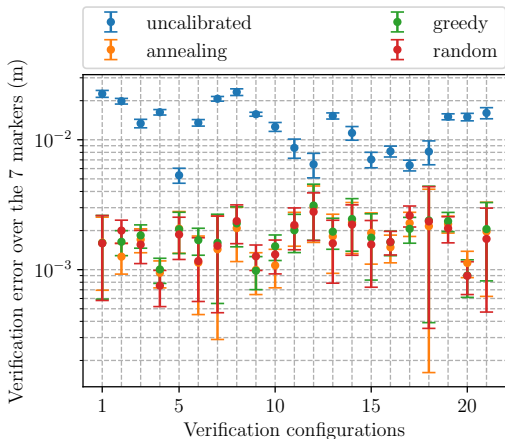
	F.E. Panda
Total parameters	49
Measurements configurations	98
Overall duration (h)	4.38
Modeling (min)	55
Measurements (h)	3.1
Identification (min)	22
Initial accuracy (mm)	7.66
Best final accuracy (mm)	1.63
Improvement rate	78.7%



Average positioning errors over the 7 markers with and without calibration

Experimental validation - Results (UR10e)

	UR10e
Total parameters	45
Measurements configurations	90
Overall duration (h)	7.03
Modeling (min)	45
Measurements (h)	6.0
Identification (min)	17
Initial accuracy (mm)	14.4
Best final accuracy (mm)	2.03
Improvement rate	85.9%



Average positioning errors over the 7 markers with and without calibration

- **Allow full-pose and indirect measurements**

↔ In particular, investigate the combined camera-robot calibration opportunity.

- **Increase measurements robustness**

↔ Avoid robot induced obstructions while selecting measurements configurations, strengthen measurement redundancies.

- **Introduce actuator flexibilities and backlash in the kinematic model**

↔ Take the effects of gravity on the robot actuators into account [10], especially for heavy tools and sensors.

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Geometric characterization: context and motivation

→ An already tackled issue...



Example of robotized 3D scan setup :
RoboScan [11]

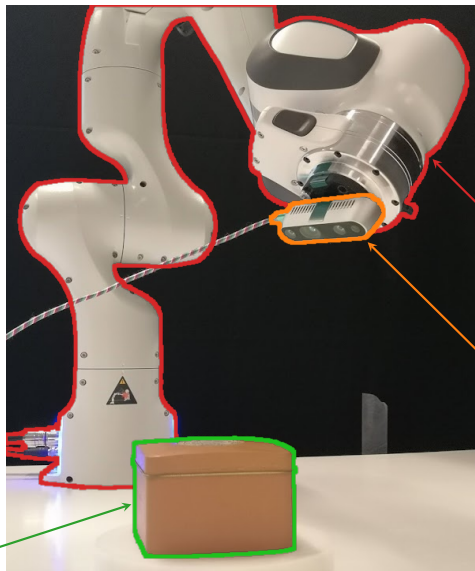
→ ...In various robotics fields.



Example of an outdoor RTABMAP 3D
cartography [12]

⇒ **Objective** : Retrieve the studied object *3D part* and *relative position* to the robot.

Robotized geometric measurements setup



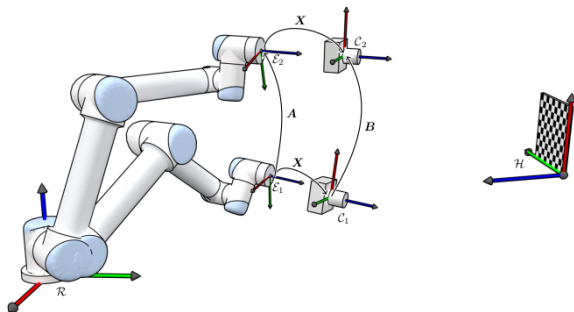
7 d.o.f. robot
Franka Emika
Panda

Intel Realsense
depth camera

Illustrative
object

Preliminary work : hand-eye calibration

⇒ **Goal** : Find the transformation between the robot flange and the camera optical center.



Credits : Torstein A. Myhre

→ Problem solved using the *MovelT* implementation of the quaternion approach proposed by [13].

Hand-eye calibration results

Hand-eye calibration reprojection error

	<i>Nominal model</i>	<i>Calibrated model</i>
24 half-spheric poses $8 \times \frac{\pi}{3}, 8 \times \frac{\pi}{4}, 8 \times \frac{\pi}{6}$	2.0 mm - 0.0045 rad	1.9 mm - 0.0045 rad
48 half-spheric poses $16 \times \frac{\pi}{3}, 16 \times \frac{\pi}{4}, 16 \times \frac{\pi}{6}$	2.3 mm - 0.0055 rad	2.3 mm - 0.0056 rad
<i>Estimation "error"</i>	1.0 mm - 0.015 rad	1.2 mm - 0.013 rad

Results hard to compare...

- High sensitivity to external parameters:
- Model and inverse kinematics impact;
- No ground truth data about the hand-eye transformation.

Example of a robotized 3D scan

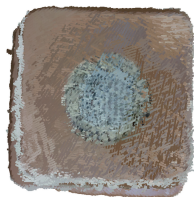


3D scan using an Intel Realsense D435 and an UR10e (speed $\times 3$)

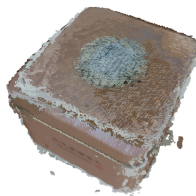
First 3D scan results



ICP



RTABMAP (GraphSLAM)



First results obtained after the geometric characterization
10 point clouds, circular trajectory of latitude $\frac{\pi}{4}$ rad and radius 20 cm

Projected work and perspectives

- **Assess the actual *impact of kinematic calibration* on hand-eye calibration**
- **Define a reference and a metric to *quantitatively evaluate the reconstruction quality***
 - ↔ Investigate reconstructions metrics depending on the nature of the generated data, and the relevant geometric objects [11][14].
- **Implement a more *accurate and robust registration algorithm***
 - ↔ Use a more adequate sensor, such as the close-range *D405 Intel Realsense*.
 - ↔ Investigate mobile robotics and SLAM solutions;
- **Integrate *real-time depth data* to improve of the robot motion [15].**

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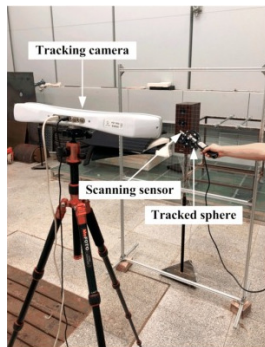
Acoustic characterization : context and motivation

→ **A shy use of robots in acoustics.**



Example of planar robotized acoustic measurements [16]

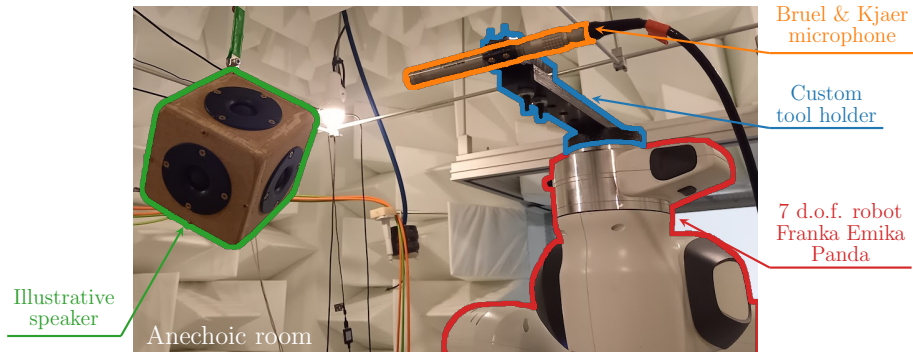
→ **An increasing need of high numbered 3D measurements.**



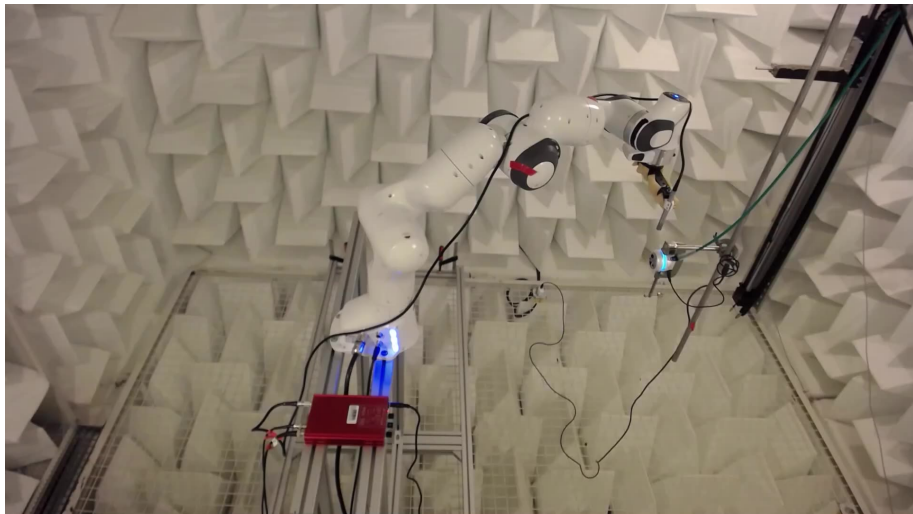
Example of 3D tracked acoustic measurements [2]

⇒ **Objective** : Reconstruct the acoustic field radiated by an unknown acoustic source.

Robotized acoustic measurements setup



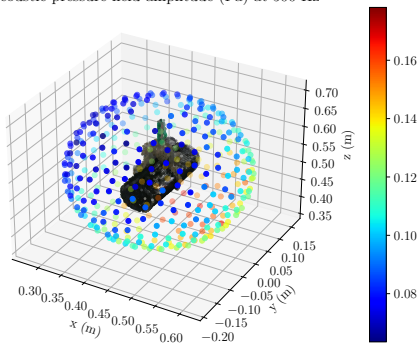
Example of robotized acoustic measurements



Acoustic directivity measurements using a Microflown PU probe and a Franka Panda in an Anechoic chamber (speed $\times 2$)

First reconstruction results - Measurements

Acoustic pressure field amplitude (Pa) at 500 Hz



Acoustic pressure field phase (rad) at 500 Hz

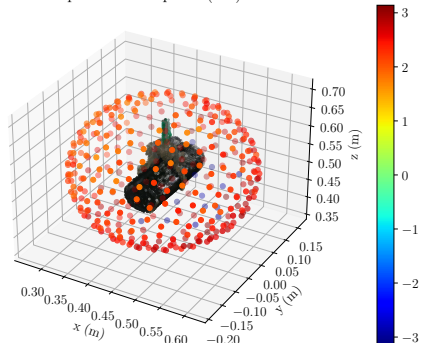


Figure 1: Sound pressure levels and phase measured at 500 Hz for each measured position

372 measurements, spherical mesh of radius 35 cm and resolution 5 cm

First reconstruction results - Boundary Elements Method

Acoustic pressure field amplitude (dB)

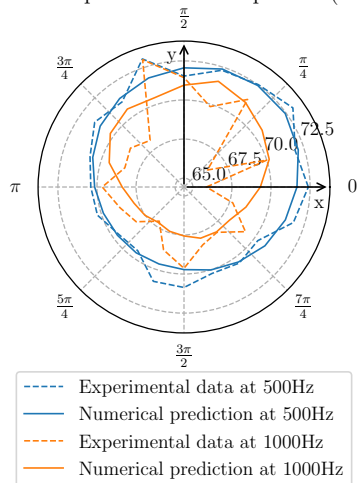


Figure 2: Predicted and measured sound pressure levels at 500 Hz and 1000 Hz
20 measurements, circular trajectory of latitude 0 rad and diameter 50 cm

First reconstruction results - Boundary Elements Method

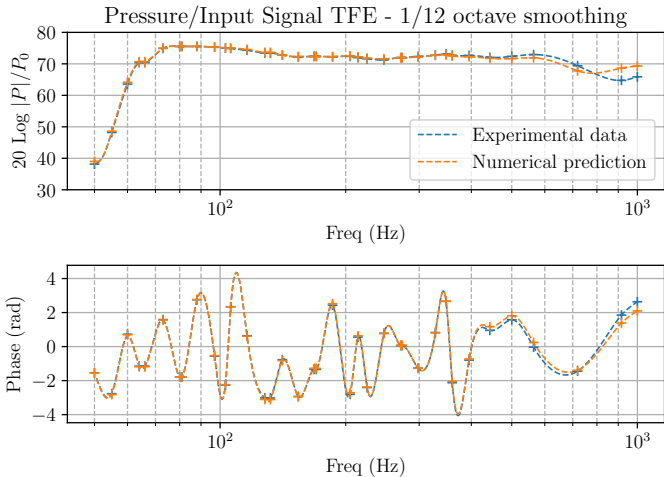


Figure 3: Predicted and measured data over the measurements frequential validity range

Measurement at a 0 rad longitude

- **Assess measurements and positioning uncertainties**
- **Reduce prediction errors at high frequencies**
 - ↔ Reduce the robot acoustic footprint using physical protections and smarter motion planning;
 - ↔ Perform close-range conformal measurements, and use high-order bended elements.
- **Investigate near-field acoustic holography opportunities**
 - ↔ Implement the dual near-field acoustic holography problem resolution;
 - ↔ Validate reconstructions using (robotized) displacement measurements !

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Thank you for your time and attention !


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