Universitat de Girona

GIRONA UNDERWATER VISION AND ROBOTICS

Underwater 3D Laser Scanner with Ray-Tracing Based Multiple Refraction Distortion Minimization

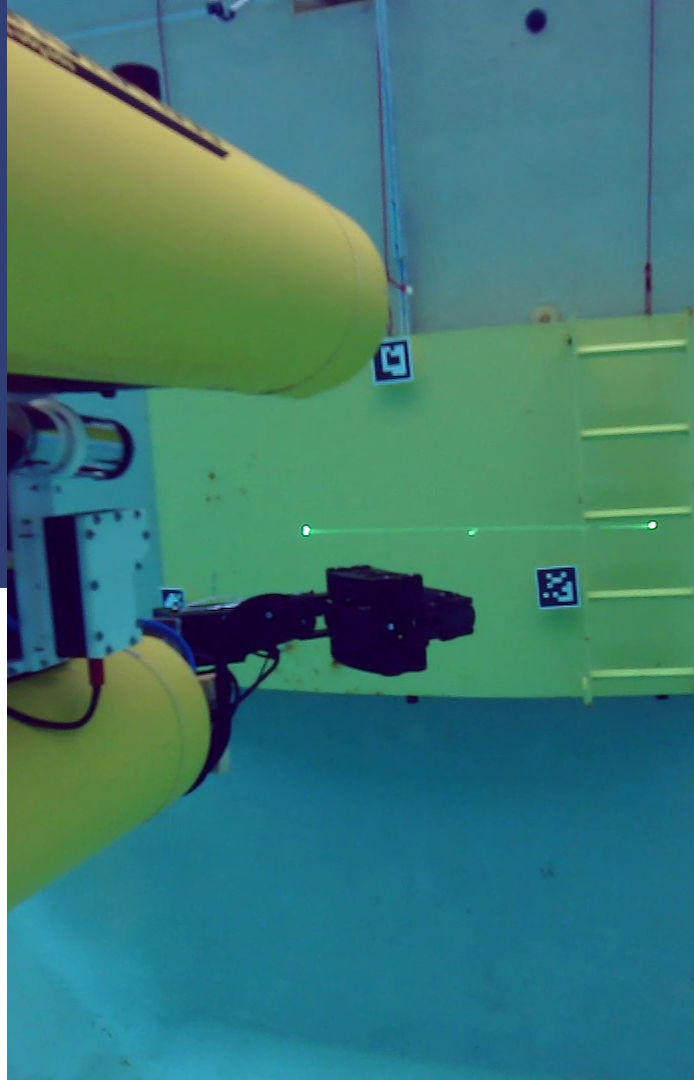
Josep Forest

As PhD supervisor of:

Dr. Miguel Castillón PhD Thesis

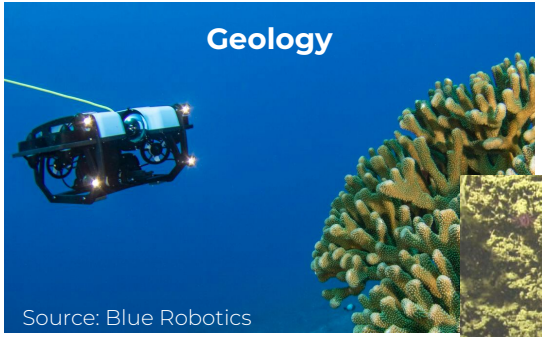
in coordination with Pere Ridao

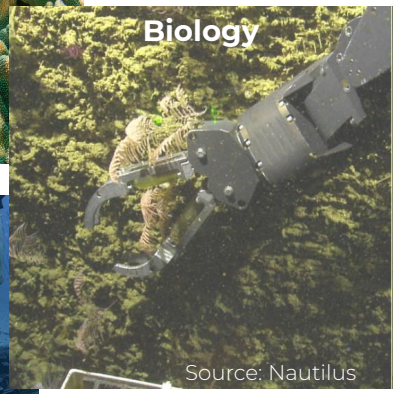
10 February 2023



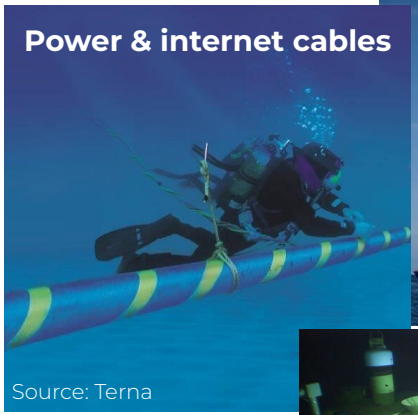
Motivation

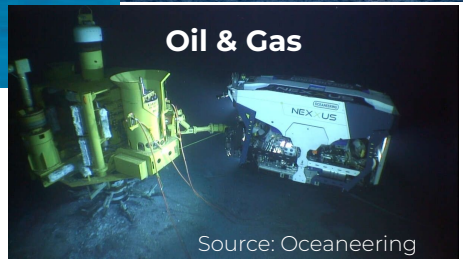
Science





Industry

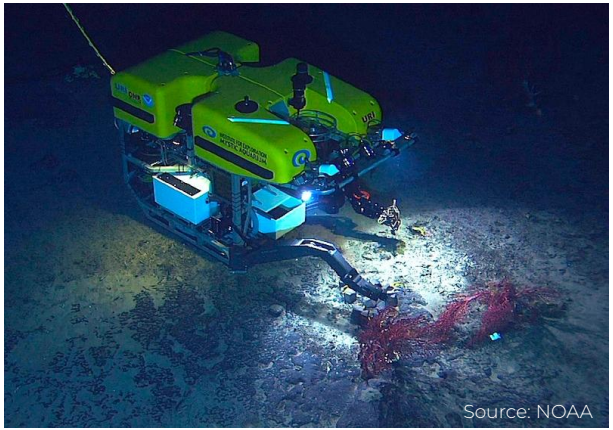




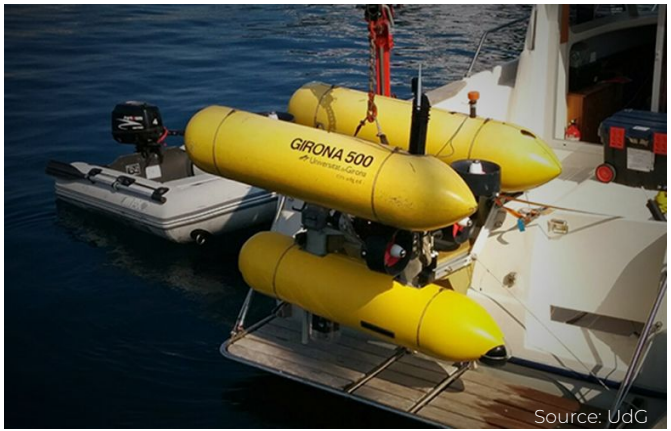
Underwater vehicles

Submarines

ROVs



AUVs



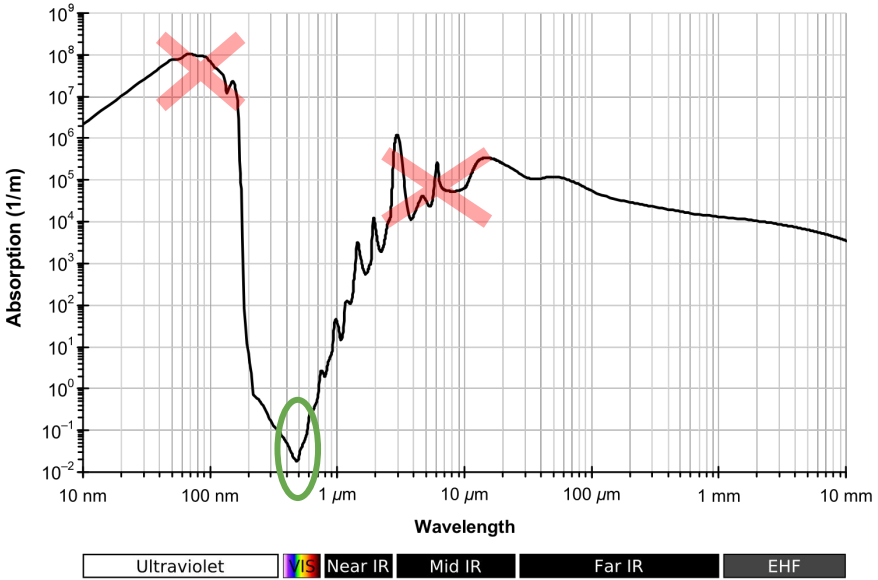
Less **Autonomy** More

Accurate underwater 3D perception

Source: UdG

Accurate underwater 3D perception

Light absorption

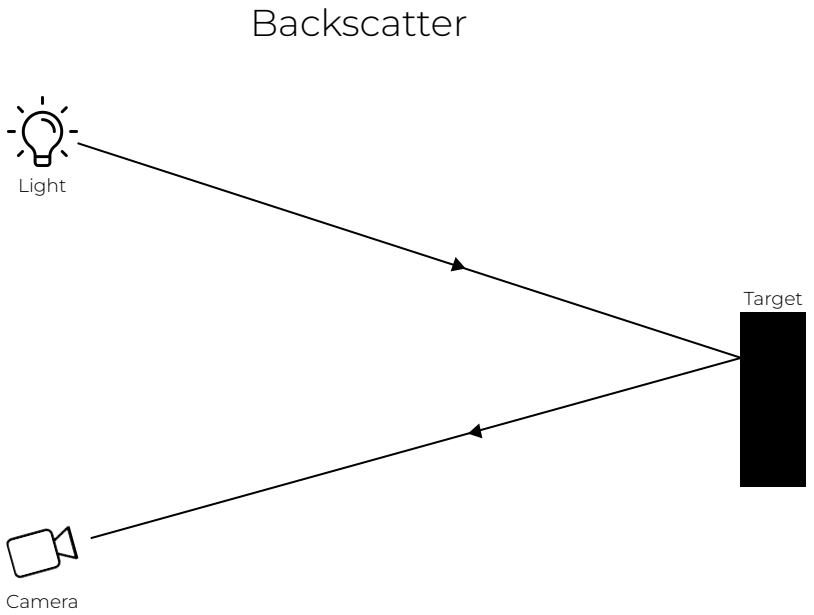


Accurate underwater 3D perception

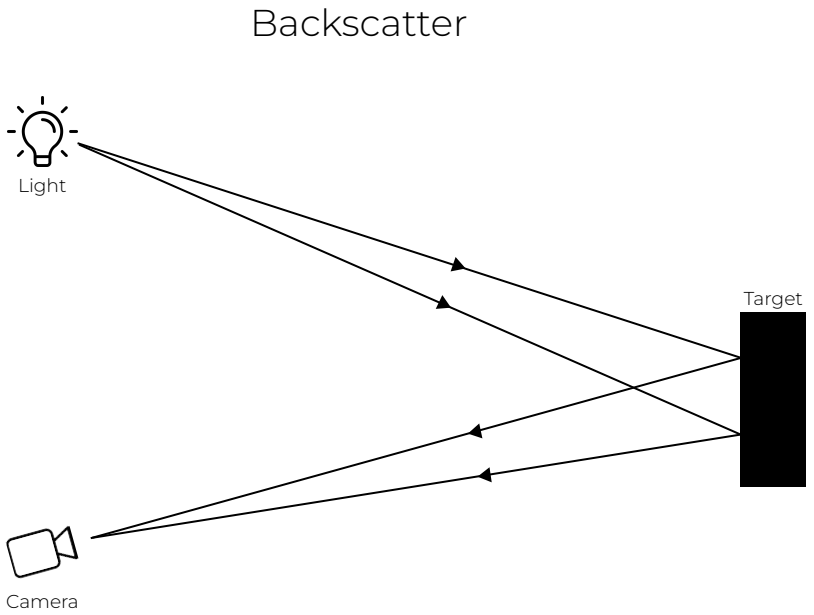
Backscatter

Target

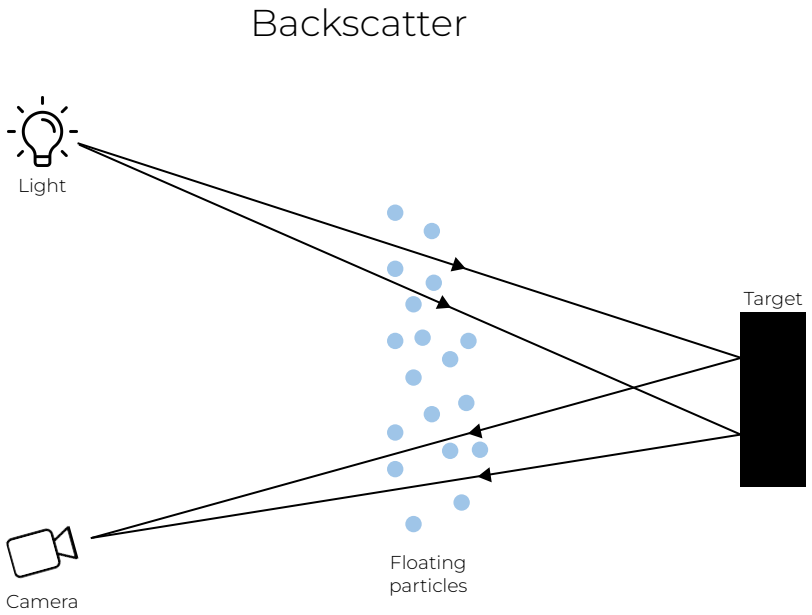
Accurate underwater 3D perception



Accurate underwater 3D perception



Accurate underwater 3D perception



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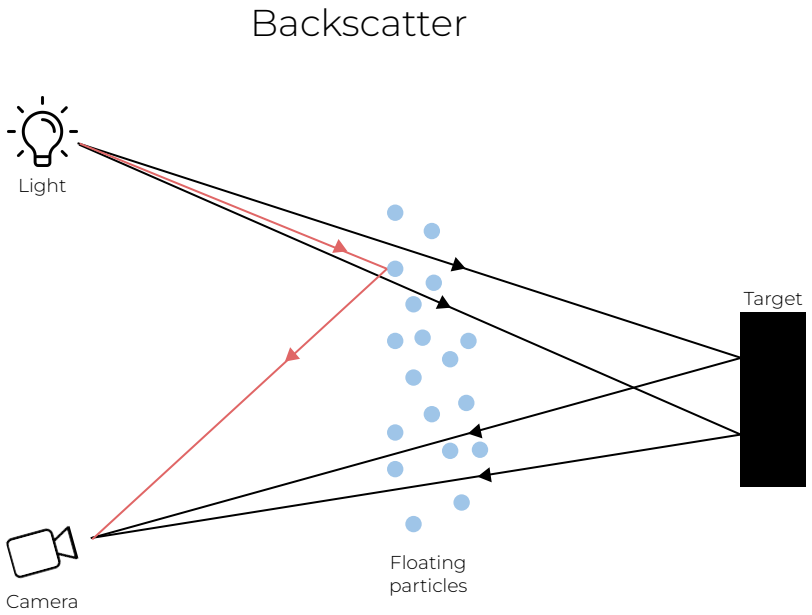
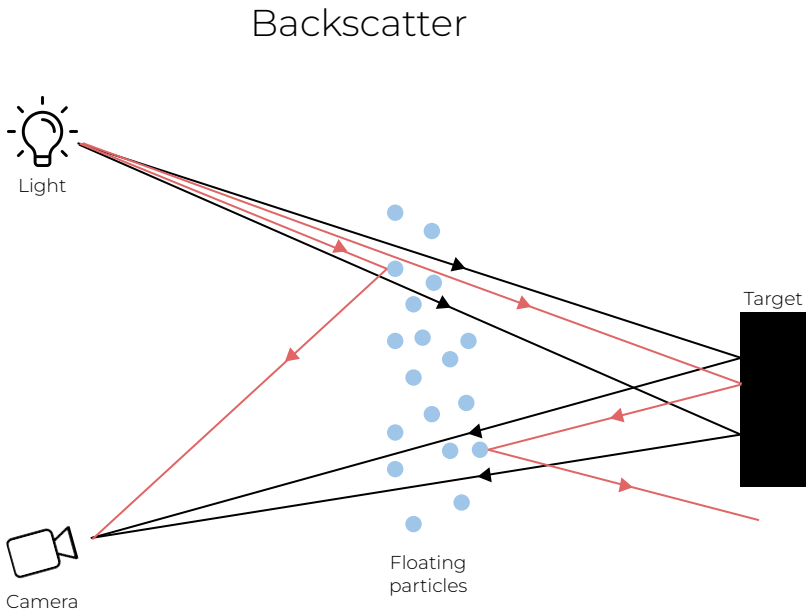
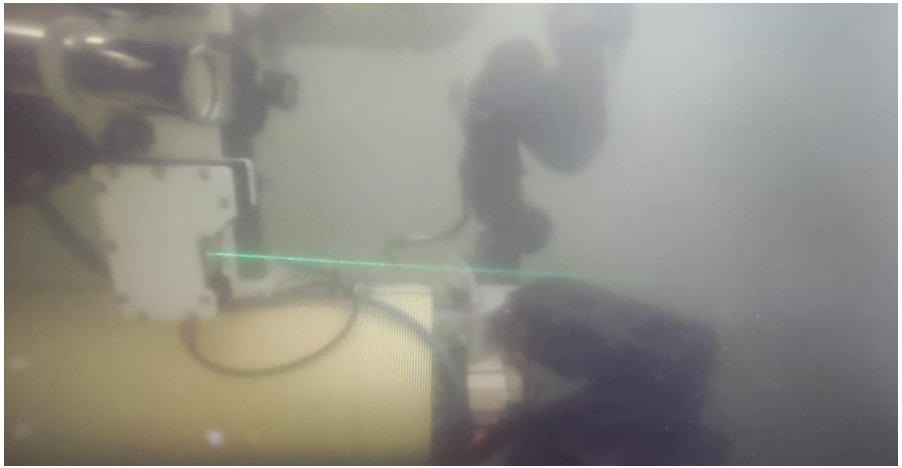


Accurate underwater 3D perception



Accurate underwater 3D perception

Backscatter



3D sensing technologies

Technology	Range	Resolution / Accuracy	Backscatter robustness	Affordability	Measurement density	Refresh rate

3D sensing technologies

Technology	Range	Resolution / Accuracy	Backscatter robustness	Affordability	Measurement density	Refresh rate
Sonar						

3D sensing technologies

Technology	Range	Resolution / Accuracy	Backscatter robustness	Affordability	Measurement density	Refresh rate
Sonar	++		++			

3D sensing technologies

Technology	Range	Resolution / Accuracy	Backscatter robustness	Affordability	Measurement density	Refresh rate
Sonar	++	--	++			--

3D sensing technologies

Technology	Range	Resolution / Accuracy	Backscatter robustness	Affordability	Measurement density	Refresh rate
Sonar	++	--	++	+	-	--

3D sensing technologies

Technology	Range	Resolution / Accuracy	Backscatter robustness	Affordability	Measurement density	Refresh rate
Sonar	++	--	++	+	-	--
Cameras						

3D sensing technologies

Technology	Range	Resolution / Accuracy	Backscatter robustness	Affordability	Measurement density	Refresh rate
Sonar	++	--	++	+	-	--
Cameras				++		++

3D sensing technologies

Technology	Range	Resolution / Accuracy	Backscatter robustness	Affordability	Measurement density	Refresh rate
Sonar	++	--	++	+	-	--
Cameras		+	--	++		++

3D sensing technologies

Technology	Range	Resolution / Accuracy	Backscatter robustness	Affordability	Measurement density	Refresh rate
Sonar	++	--	++	+	-	--
Cameras	-	+	--	++	-	++

3D sensing technologies

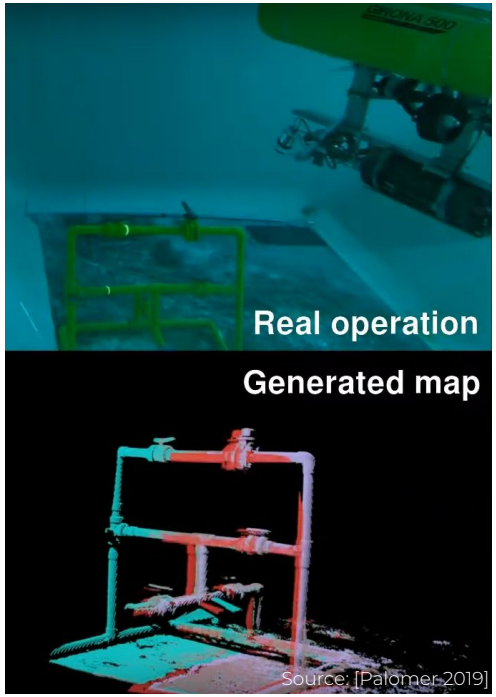
Technology	Range	Resolution / Accuracy	Backscatter robustness	Affordability	Measurement density	Refresh rate
Sonar	++	--	++	+	-	--
Cameras	-	+	--	++	-	++
Laser	-	++	-	-	++	++

Why a laser scanner?

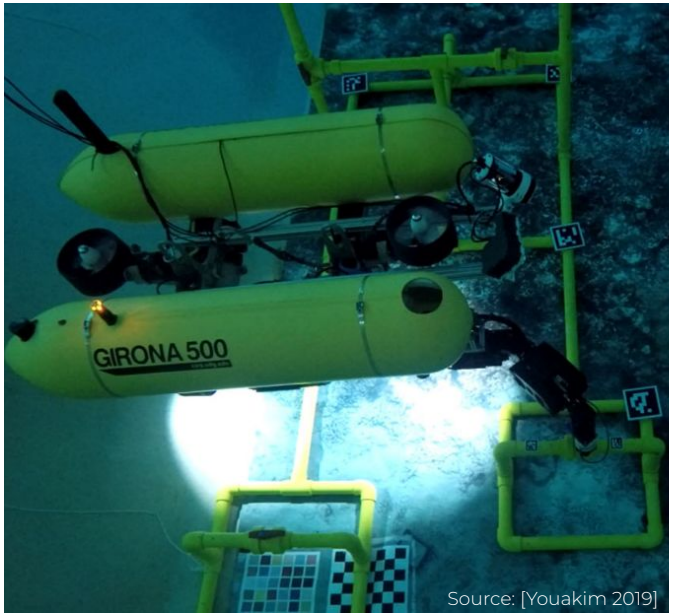
- longer range bc light highly collimated
- high resolution and density → ideal for manipulation and close-range accurate inspection

Underwater laser scanning

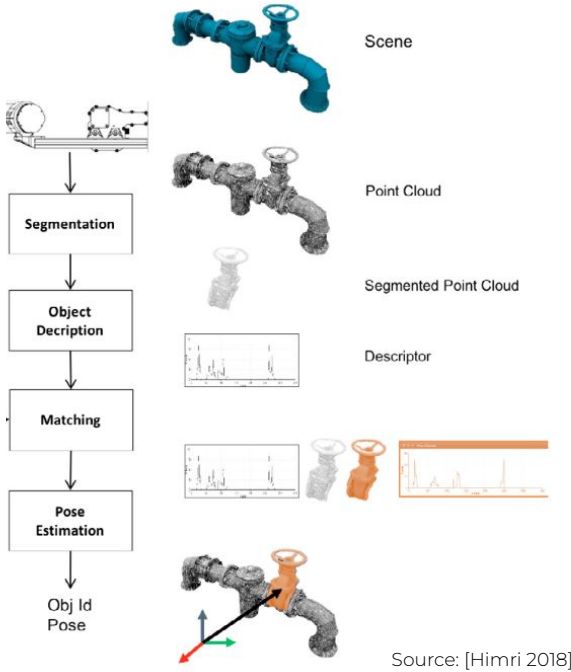
Mapping



Motion planning



Object recognition



Goal of the work

To enhance the 3D sensing capabilities of underwater vehicles by enabling the dynamic acquisition of high-accuracy, distortion-free 3D point clouds.

Outline

- Underwater laser scanner
  - State of the art
  - Refraction: laser plane deformation
  - Ray-tracing model to counteract refraction
  - Intrinsic and extrinsic calibration
  - Sea trials
- Non-rigid point cloud registration
  - State of the art
  - Coherent Point Drift (CPD)
  - Linewise non-rigid registration
- Conclusions
  - Contributions
  - Future work

Underwater
3D laser scanner

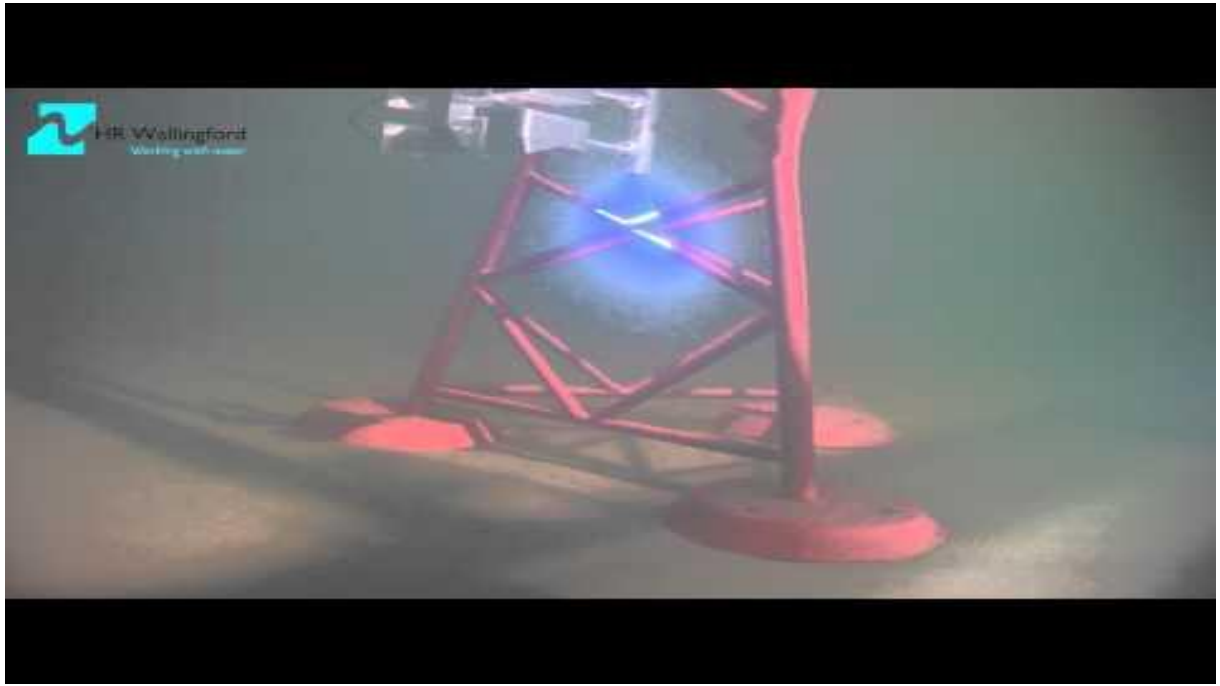
State of the art: underwater 3D scanners

Light projection

State of the art: underwater 3D scanners

Light projection

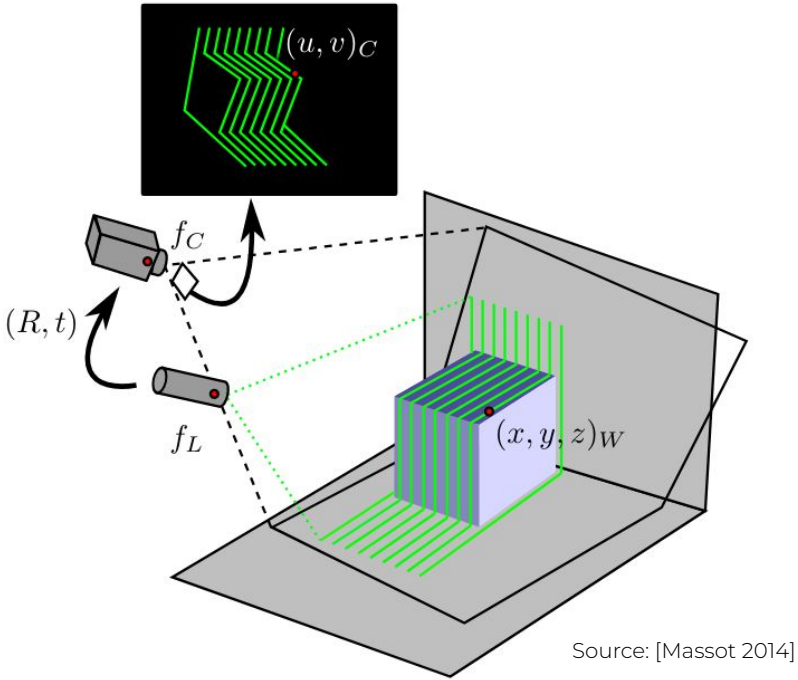
- Profilers



State of the art: underwater 3D scanners

Light projection

- Profilers
- One-shot

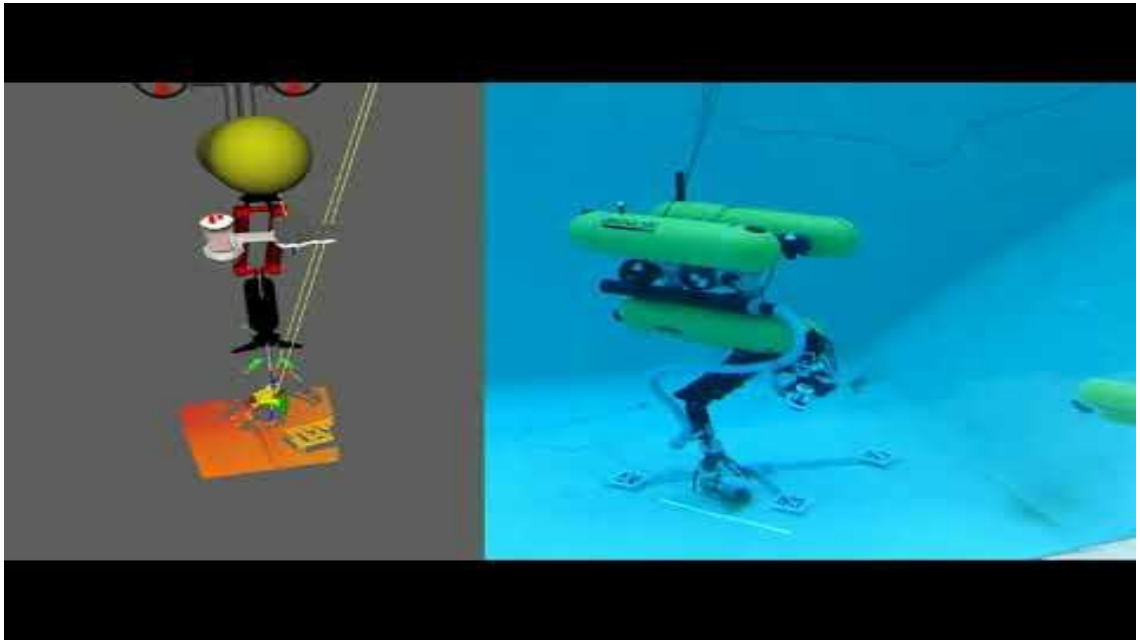


Source: [Massot 2014]

State of the art: underwater 3D scanners

Light projection

- Profilers
- One-shot
- Mechanical beam steering



State of the art: underwater 3D scanners

Light projection

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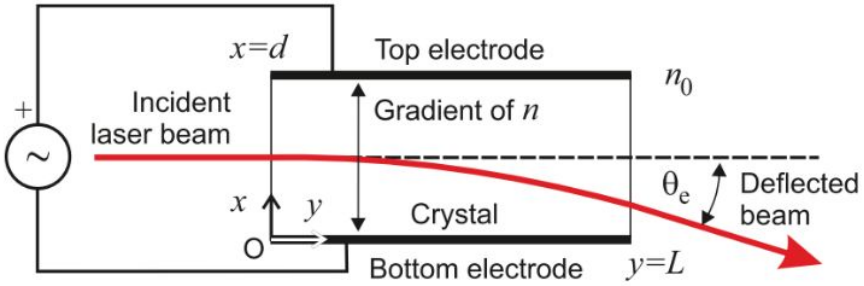
- Non-mechanical beam steering



Source: [Römer 2014]

State of the art: underwater 3D scanners

Light projection

- Profilers
- One-shot
- Mechanical beam steering
- Non-mechanical beam steering

Light sensing

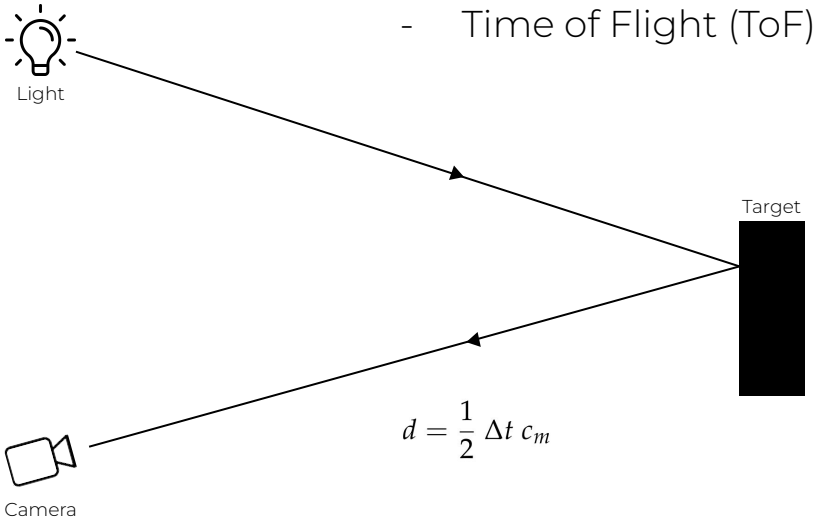
State of the art: underwater 3D scanners

Light projection

- Profilers
- One-shot
- Mechanical beam steering
- Non-mechanical beam steering

Light sensing

- Time of Flight (ToF)



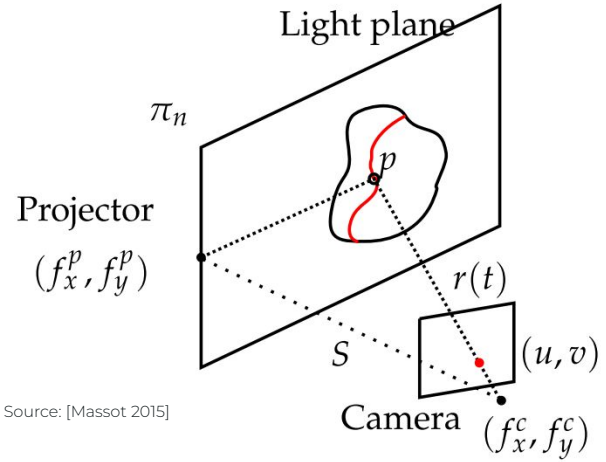
State of the art: underwater 3D scanners

Light projection

- Profilers
- One-shot
- Mechanical beam steering
- Non-mechanical beam steering

Light sensing

- Time of Flight (ToF)
- Triangulation



Source: [Massot 2015]

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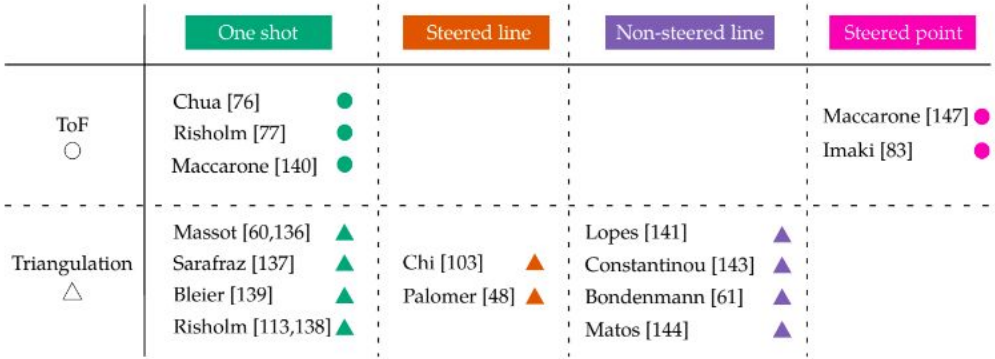
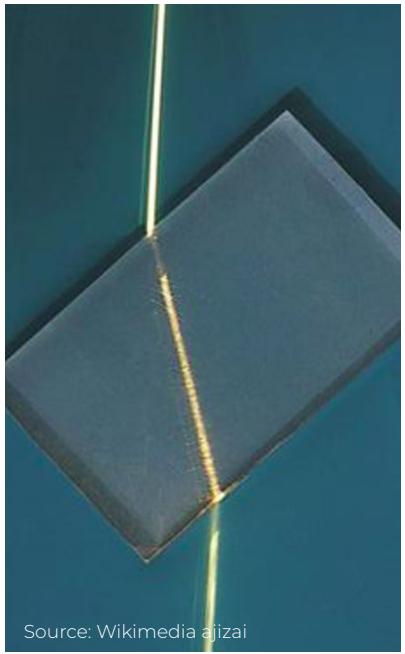


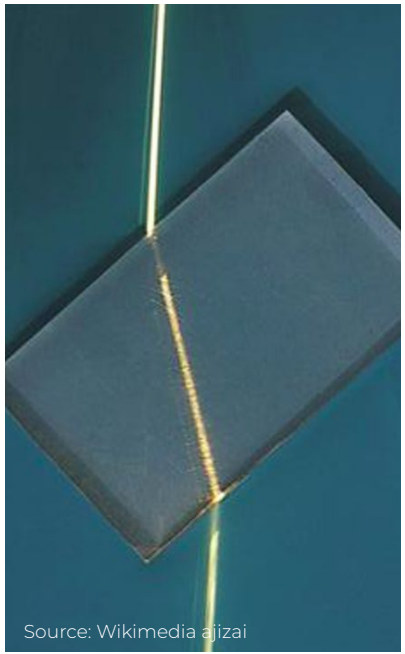
SoA performance: mm accuracy at a few meters

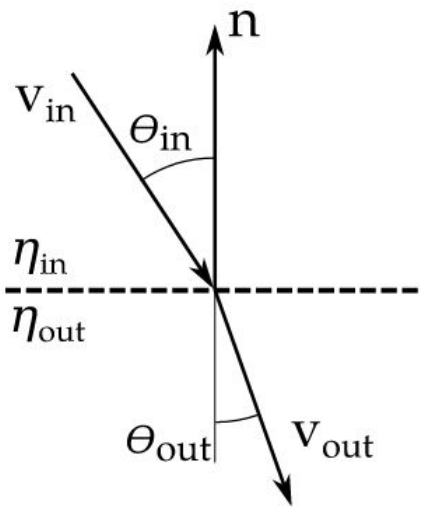
Refraction in 3D: plane deformation



Source: Wikimedia ajizai

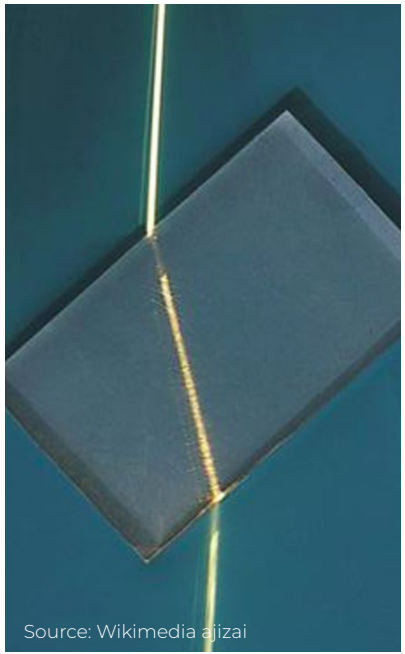
Refraction in 3D: plane deformation

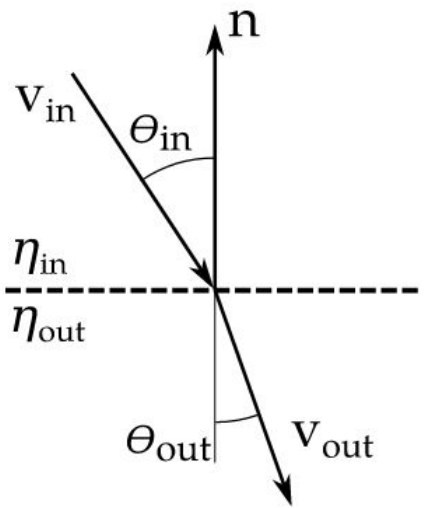




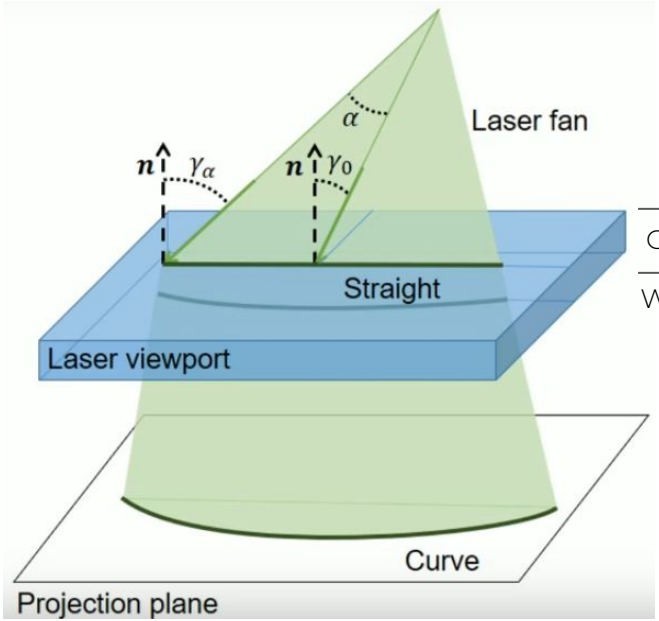
$$\boldsymbol{v}_{out} = \frac{\eta_{in}}{\eta_{out}} (\boldsymbol{n} \times (-\boldsymbol{n} \times \boldsymbol{v}_{in})) - \boldsymbol{n}\sqrt{1 - \left(\frac{\eta_{in}}{\eta_{out}}\right)^2 (\boldsymbol{n} \times \boldsymbol{v}_{in}) \cdot (\boldsymbol{n} \times \boldsymbol{v}_{in})}$$

Refraction in 3D: plane deformation



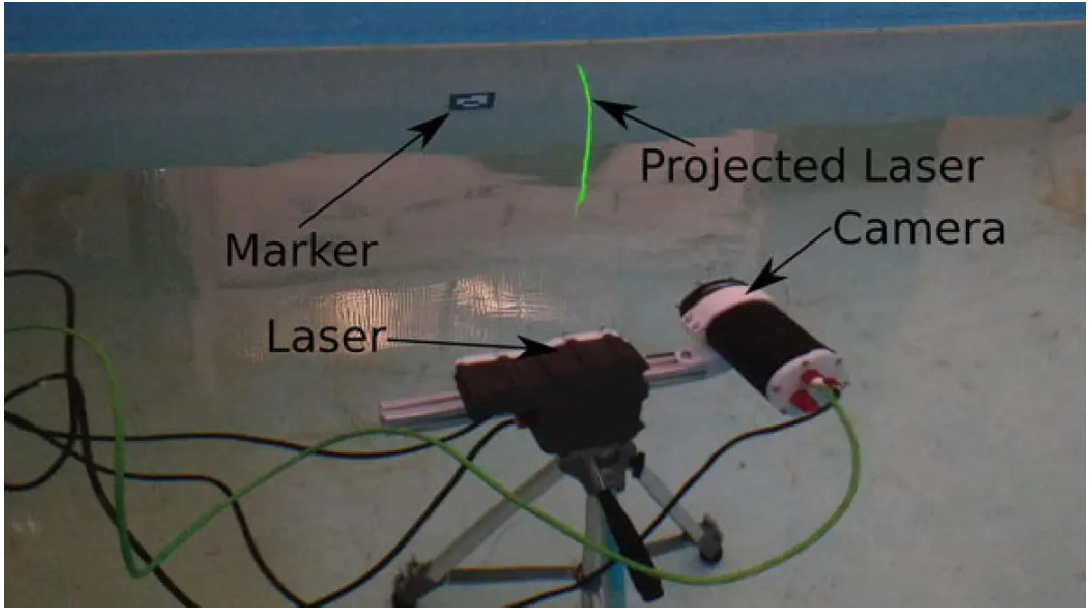


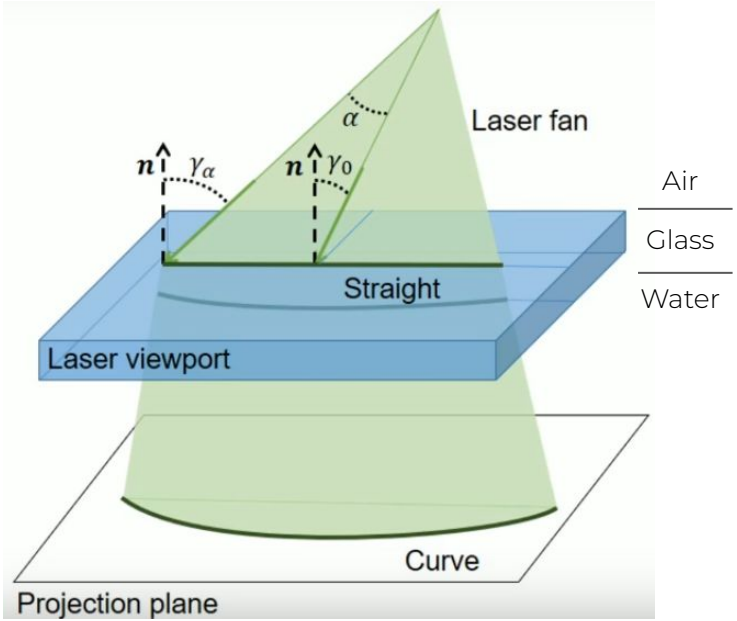
$$v_{out} = \frac{\eta_{in}}{\eta_{out}} (n \times (-n \times v_{in})) - n\sqrt{1 - \left(\frac{\eta_{in}}{\eta_{out}}\right)^2 (n \times v_{in}) \cdot (n \times v_{in})}$$



Source: [Palomer 2017]

Refraction in 3D: plane deformation





Source: [Palomer 2017]

Counteracting refraction

Motivation: triangulating using planes instead of cones is 8x faster

Counteracting refraction

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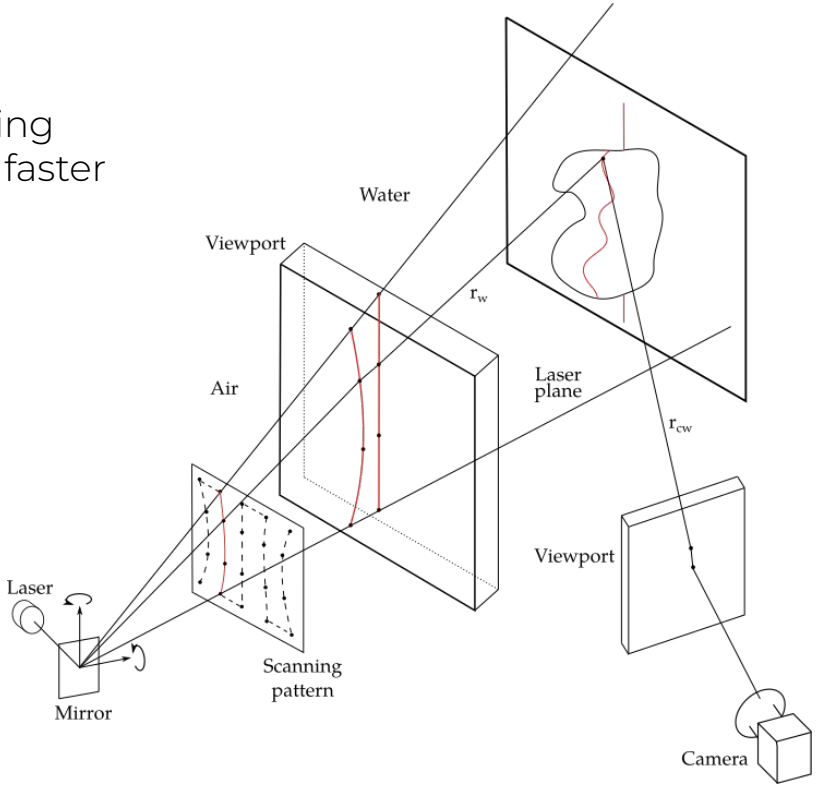
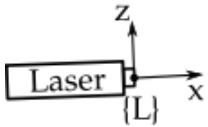


Ray-tracing model



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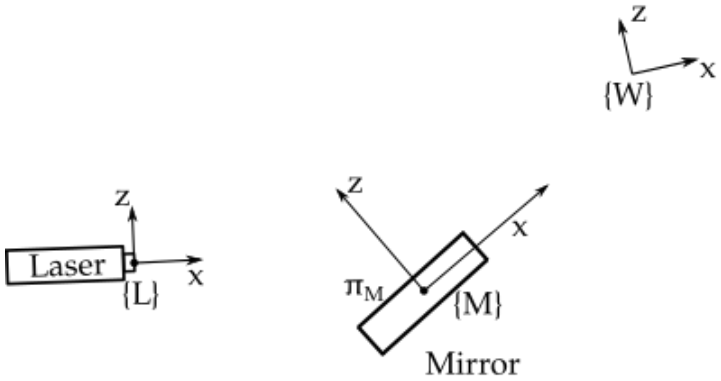
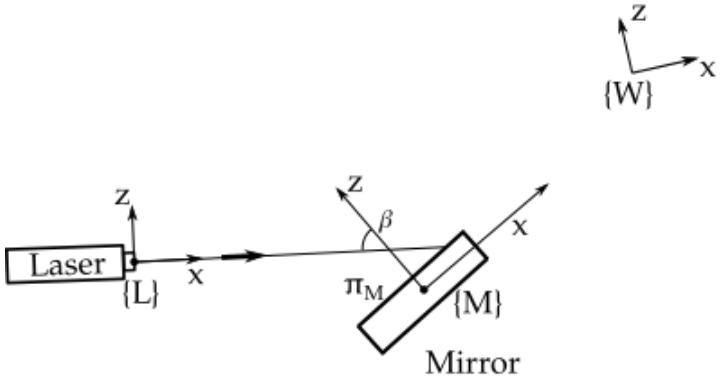


Ray-tracing model



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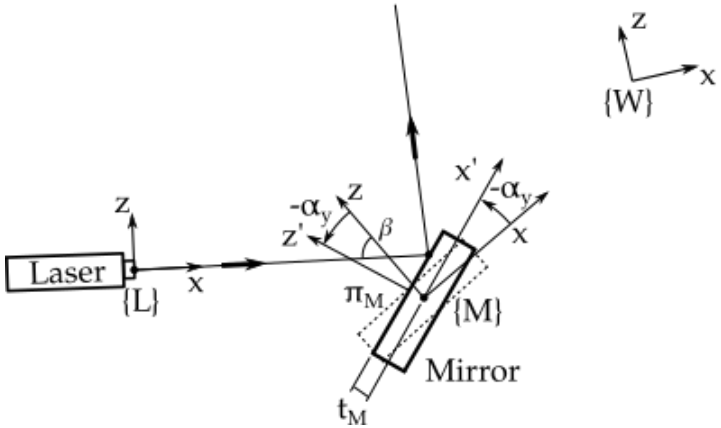
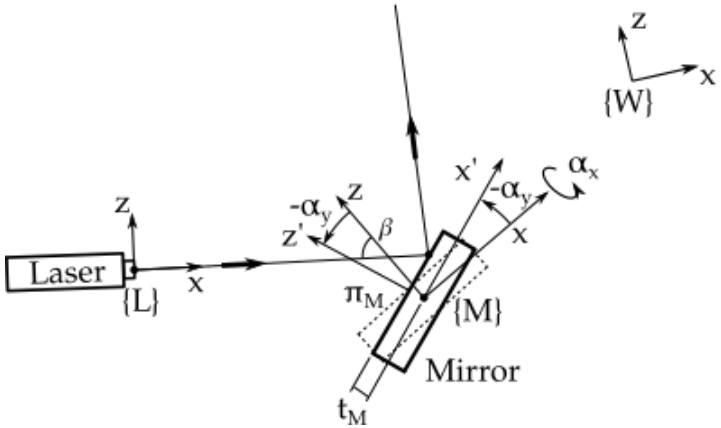


Ray-tracing model



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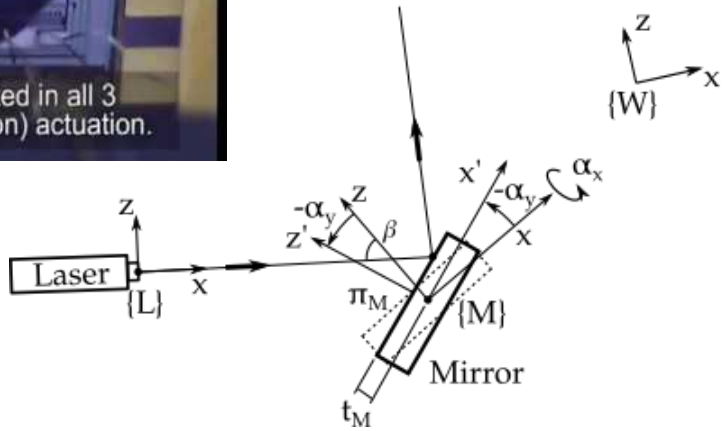

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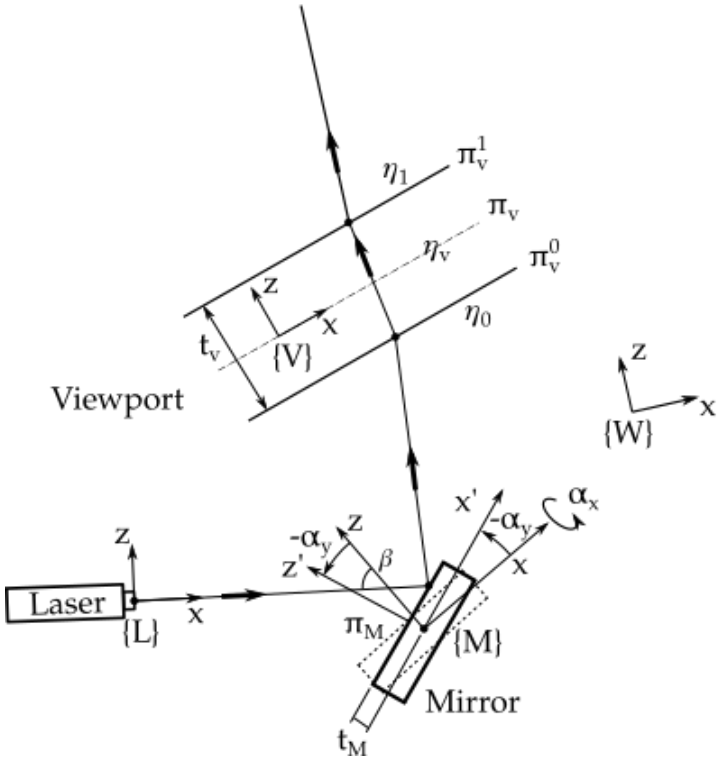
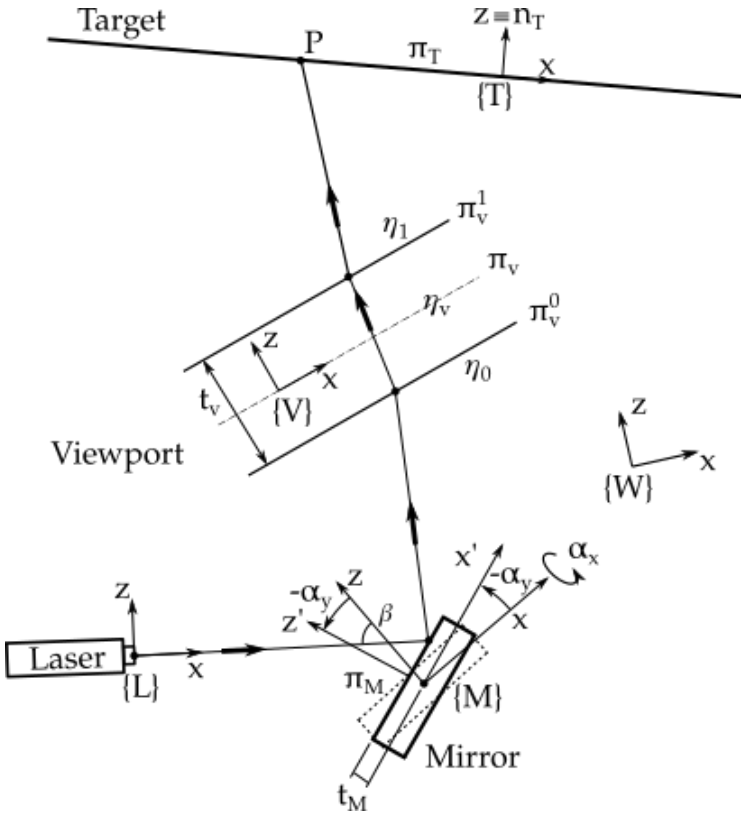
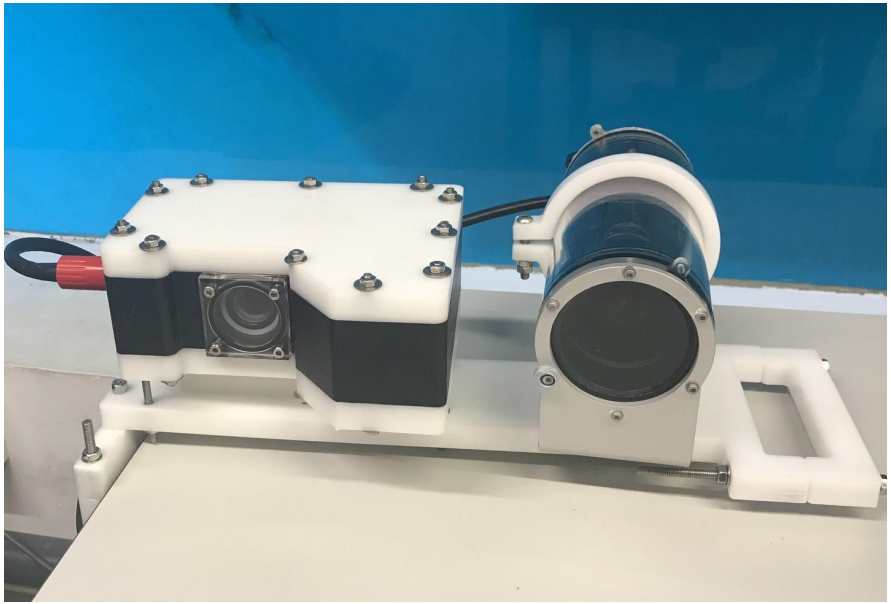


Ray-tracing model



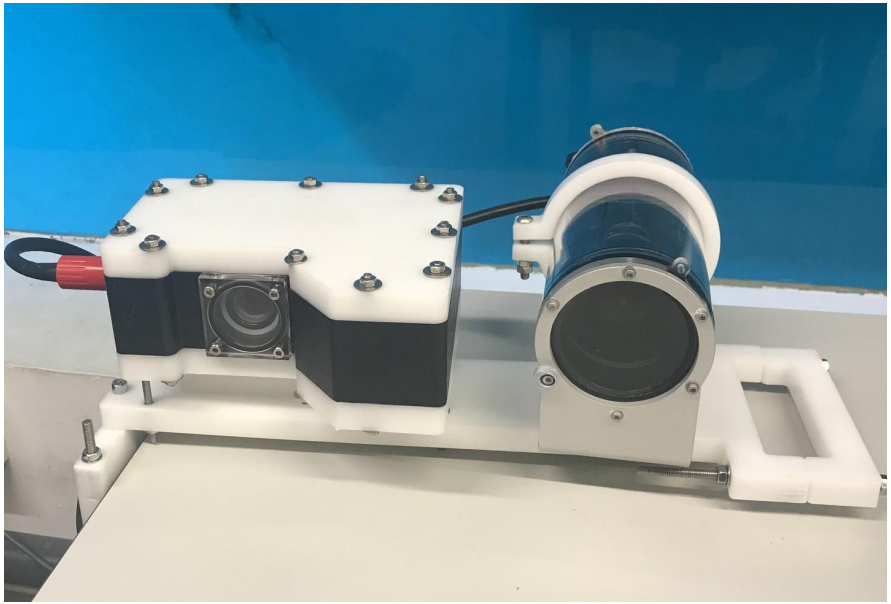
Underwater 3D scanner: prototype

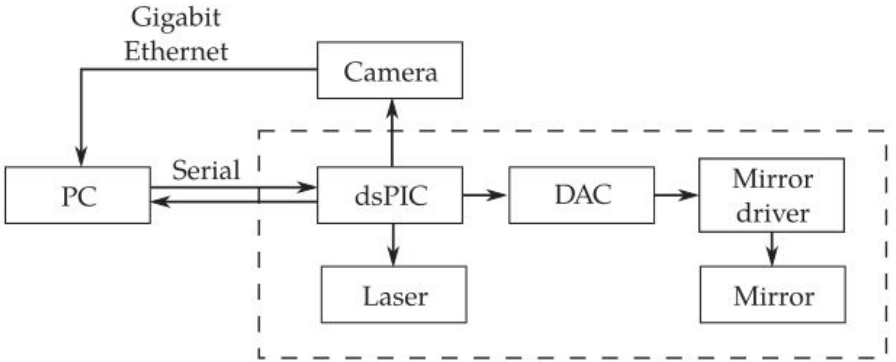


State-of-the-art performance:

- 50 lines/s (up to 100k points/s)
- Approx FoV: 30° x 30°
- Plane fitting accuracy:
  - 0.5mm @ 0.6m
  - 3mm @ 1.5m
- Range dependent on baseline and visibility conditions: 0.4m - 5m

Underwater 3D scanner: prototype





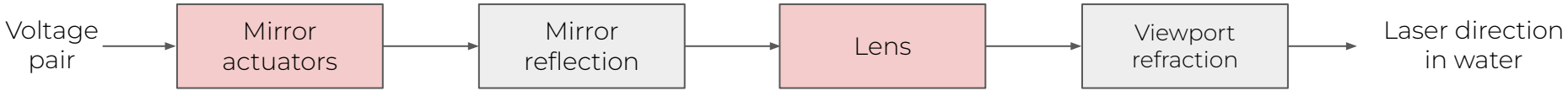
Challenges


Angle pair
Mirror reflection
Viewport refraction
Laser direction in water

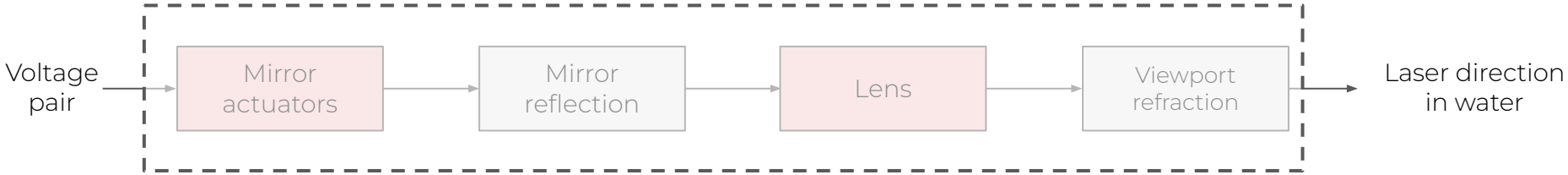
Challenges


Voltage pair
Mirror actuators
Mirror reflection
Viewport refraction
Laser direction in water

Challenges


Voltage pair
Mirror actuators
Mirror reflection
Lens
Viewport refraction
Laser direction in water

Challenges


Voltage pair
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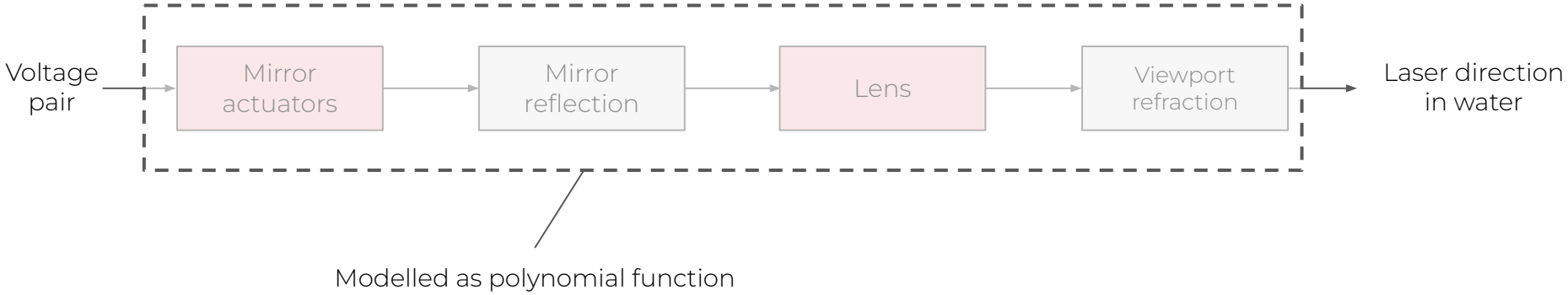
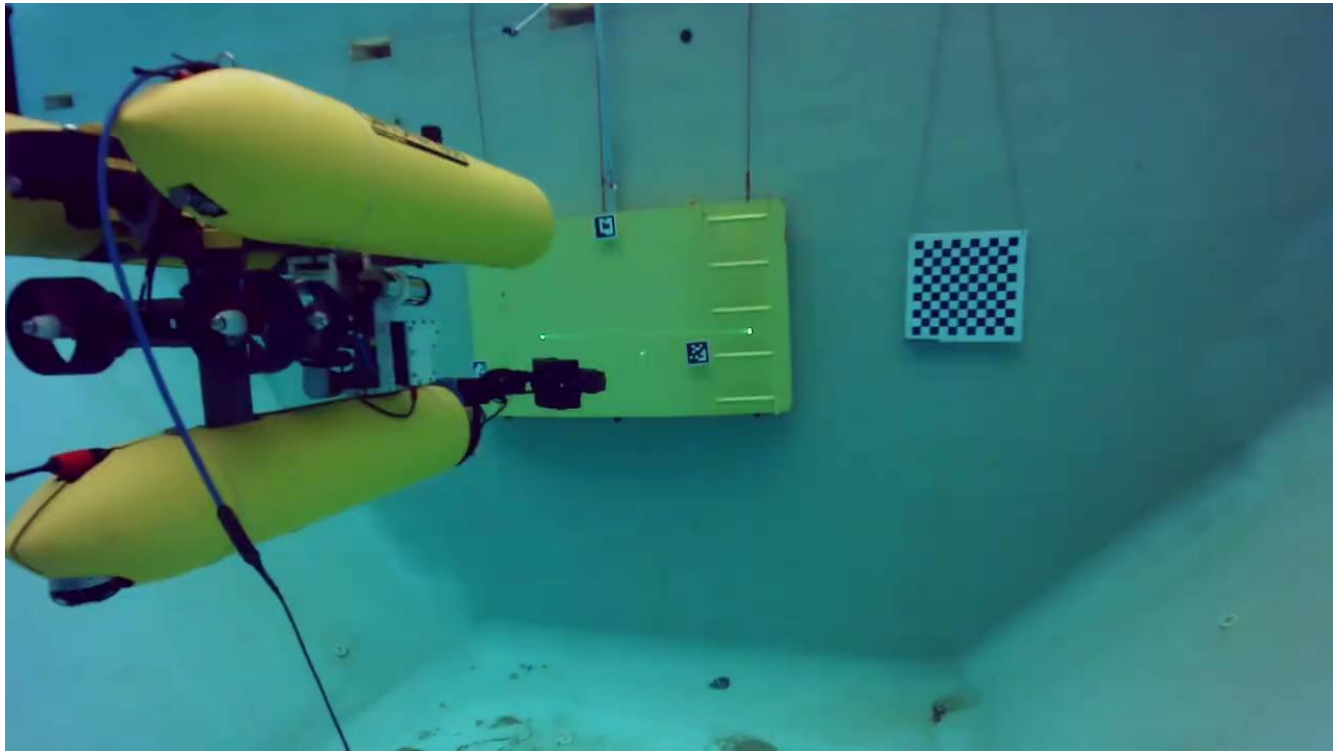
Challenges


Voltage pair
Mirror actuators
Mirror reflection
Lens
Viewport refraction
Laser direction in water
Modelled as polynomial function

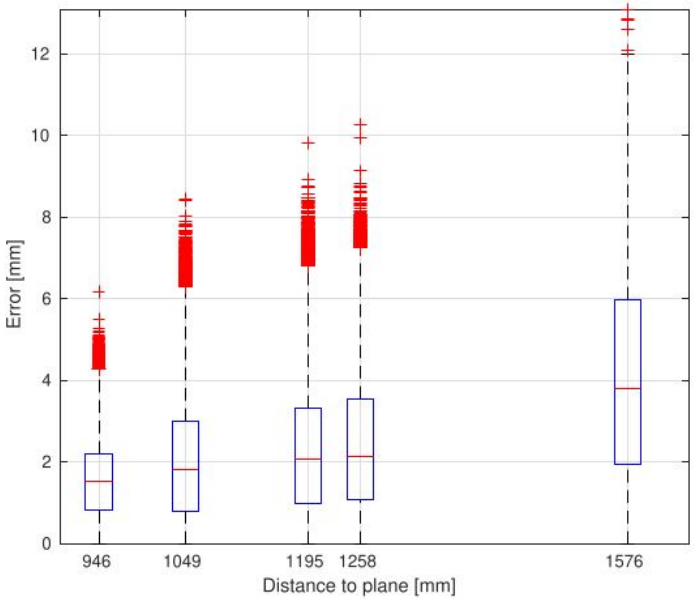
Calibration

Scanning

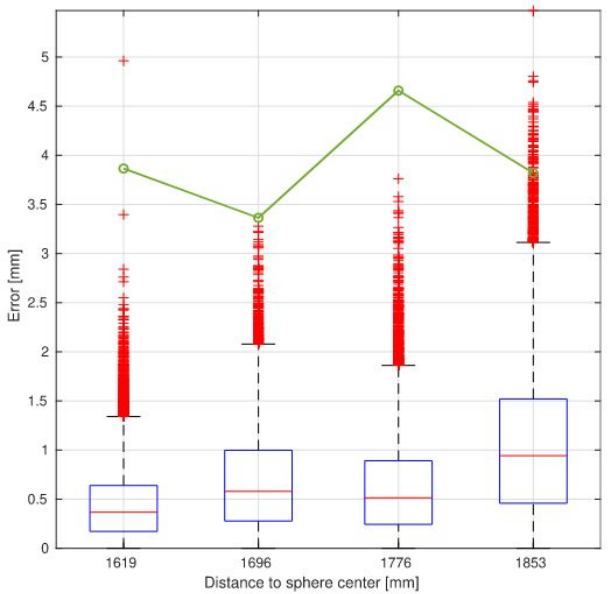


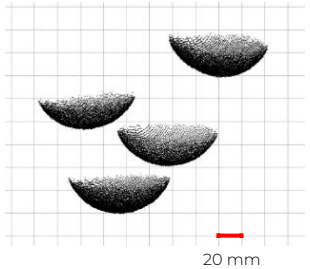
Results: accuracy characterization

Plane fitting

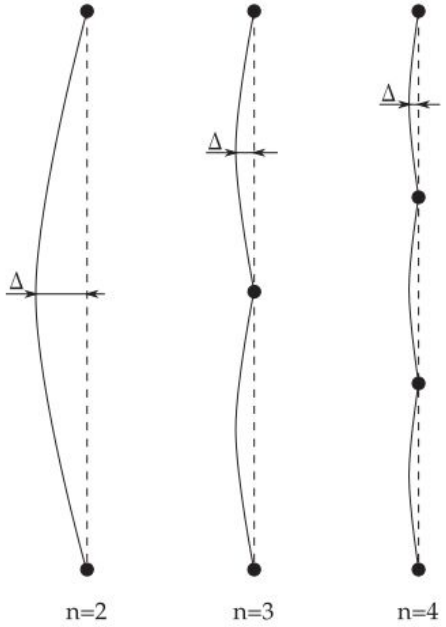


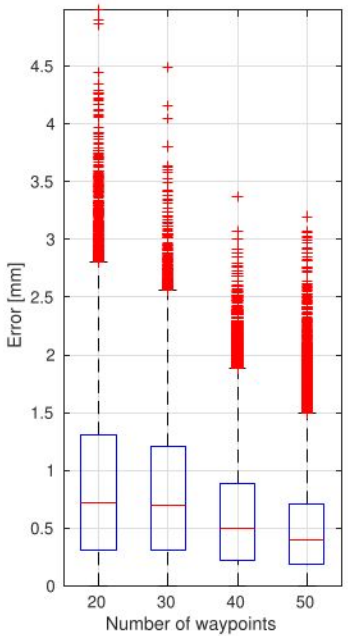
Sphere fitting

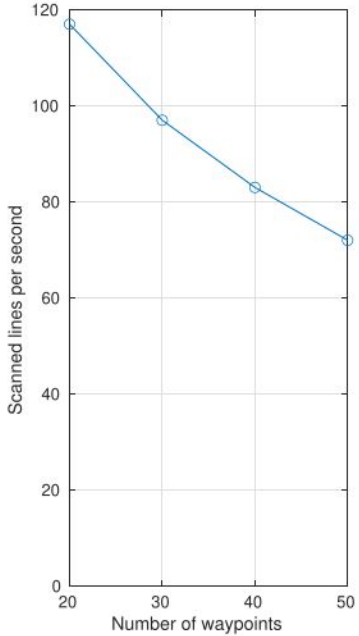




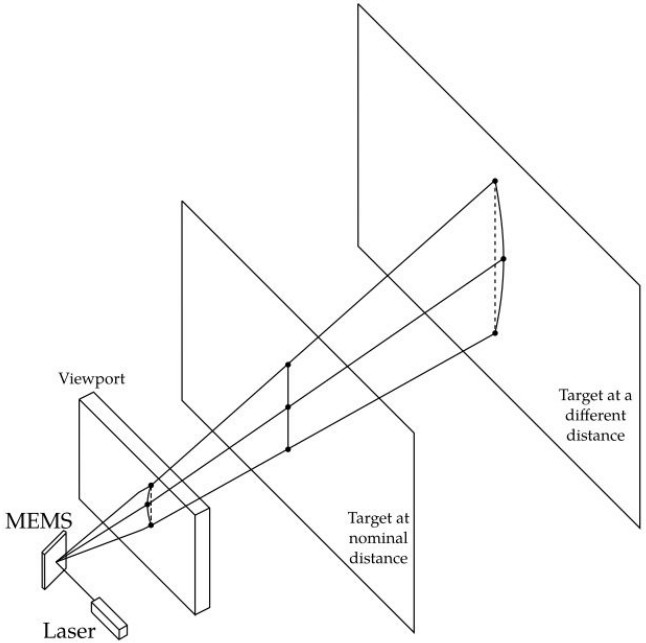
Results: Number of waypoints per line

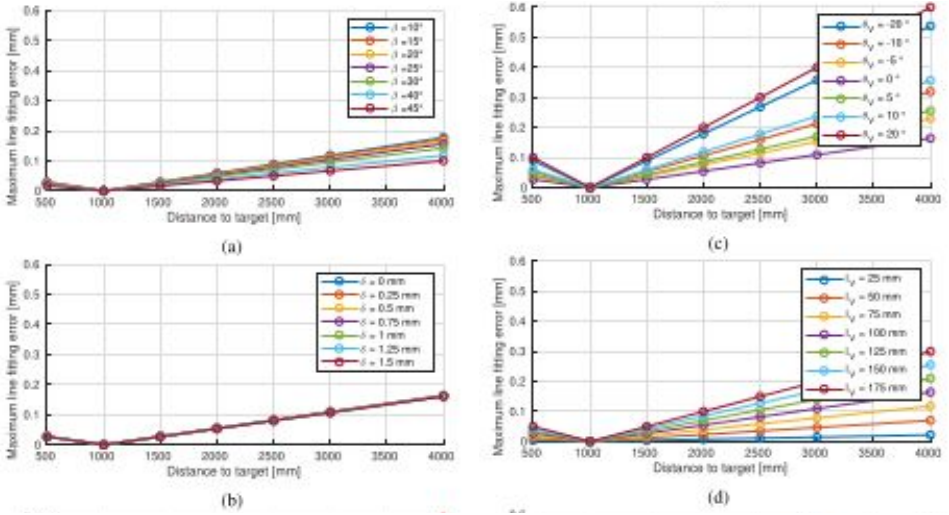




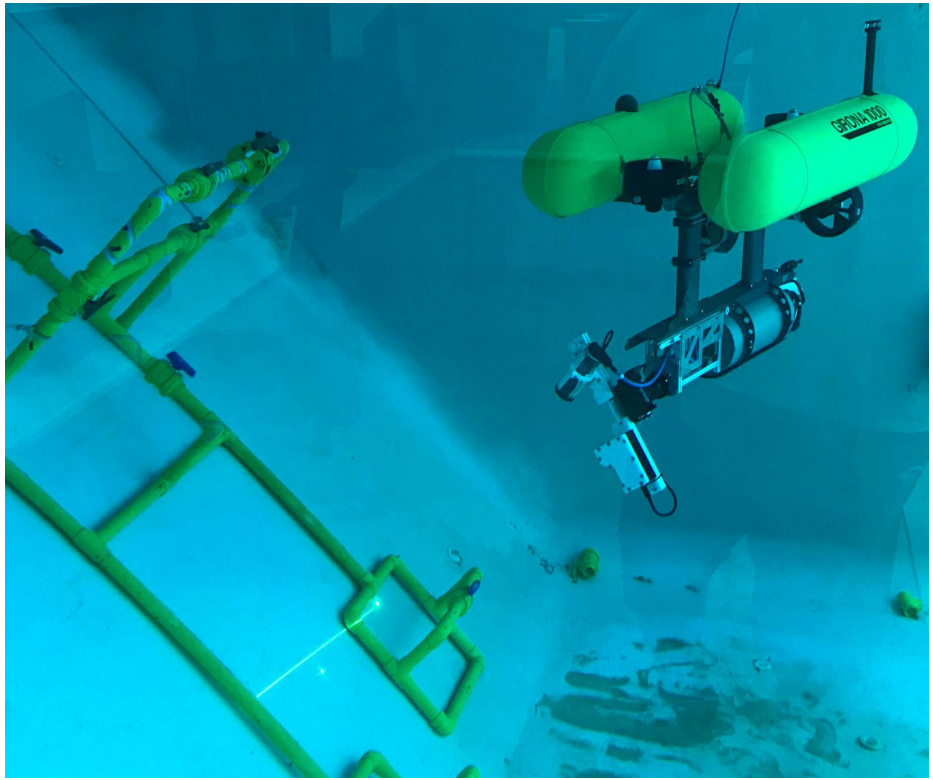


Scanning at different distances

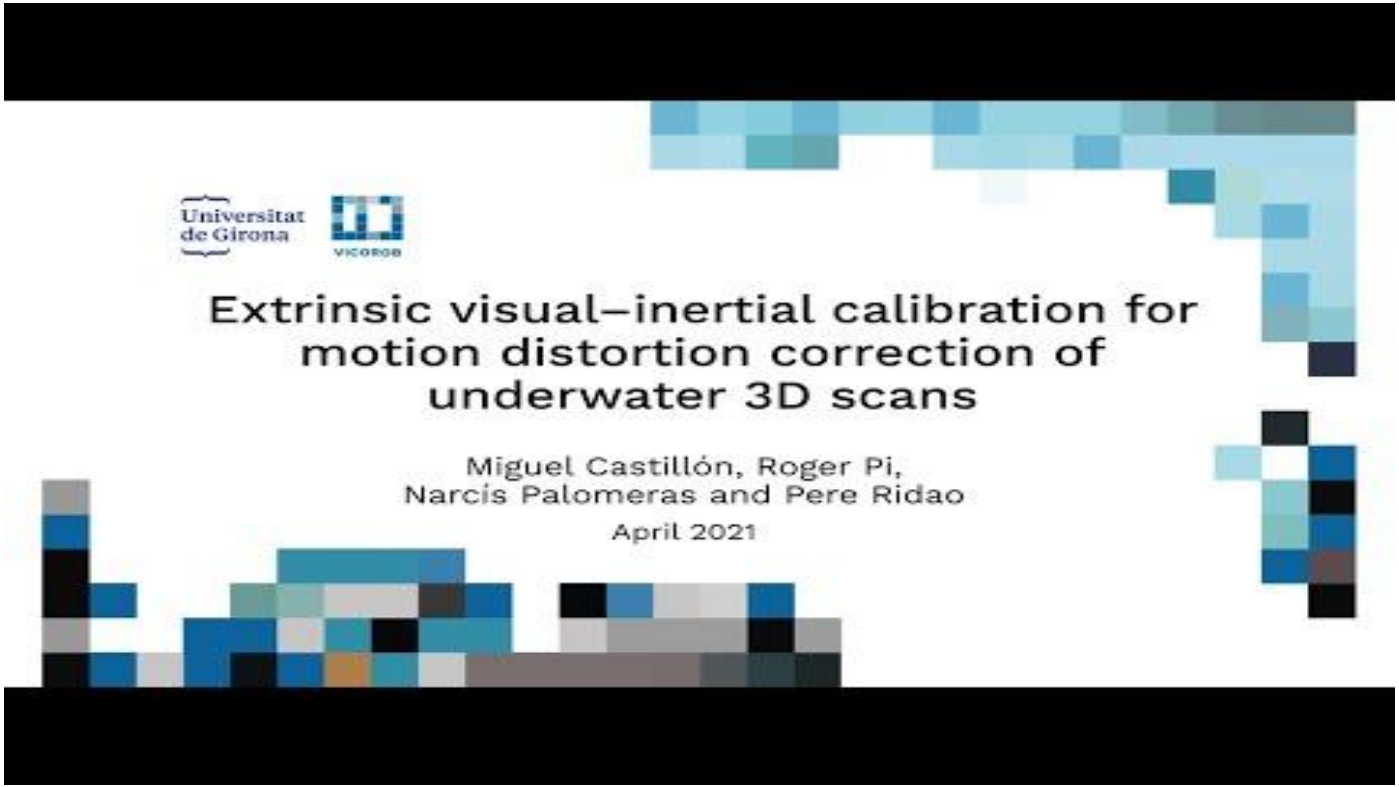




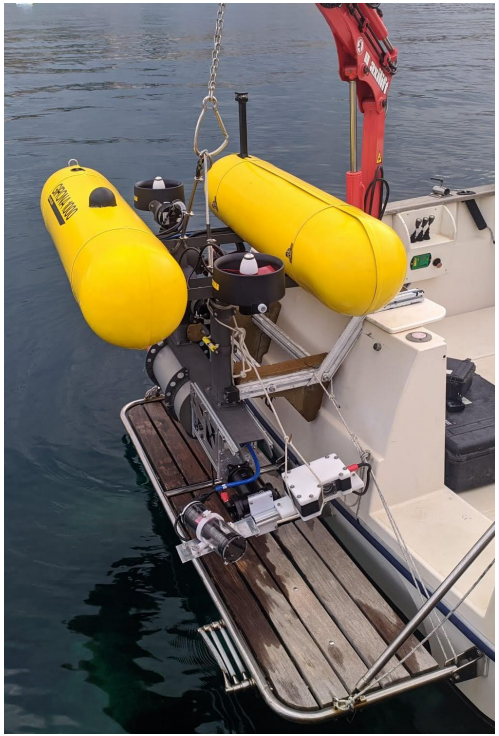
Dynamic scanning

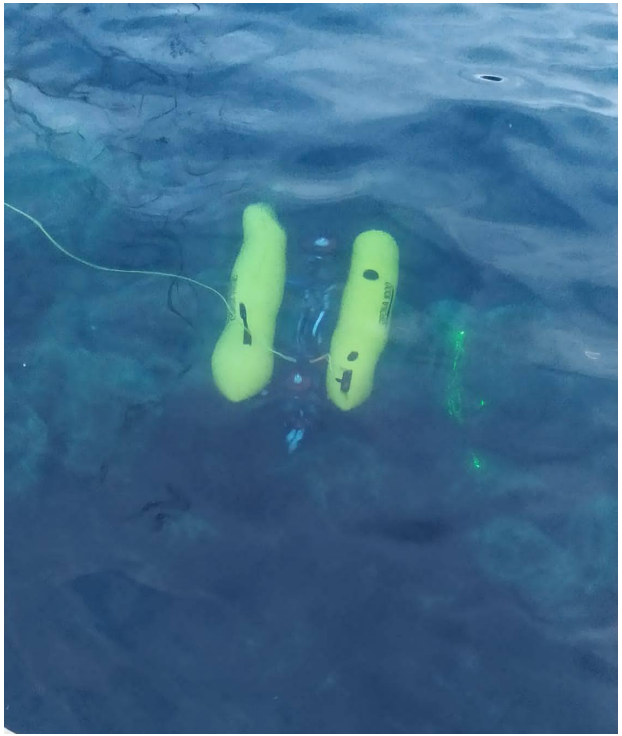


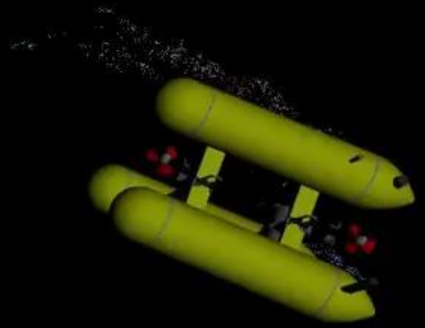
Dynamic scanning



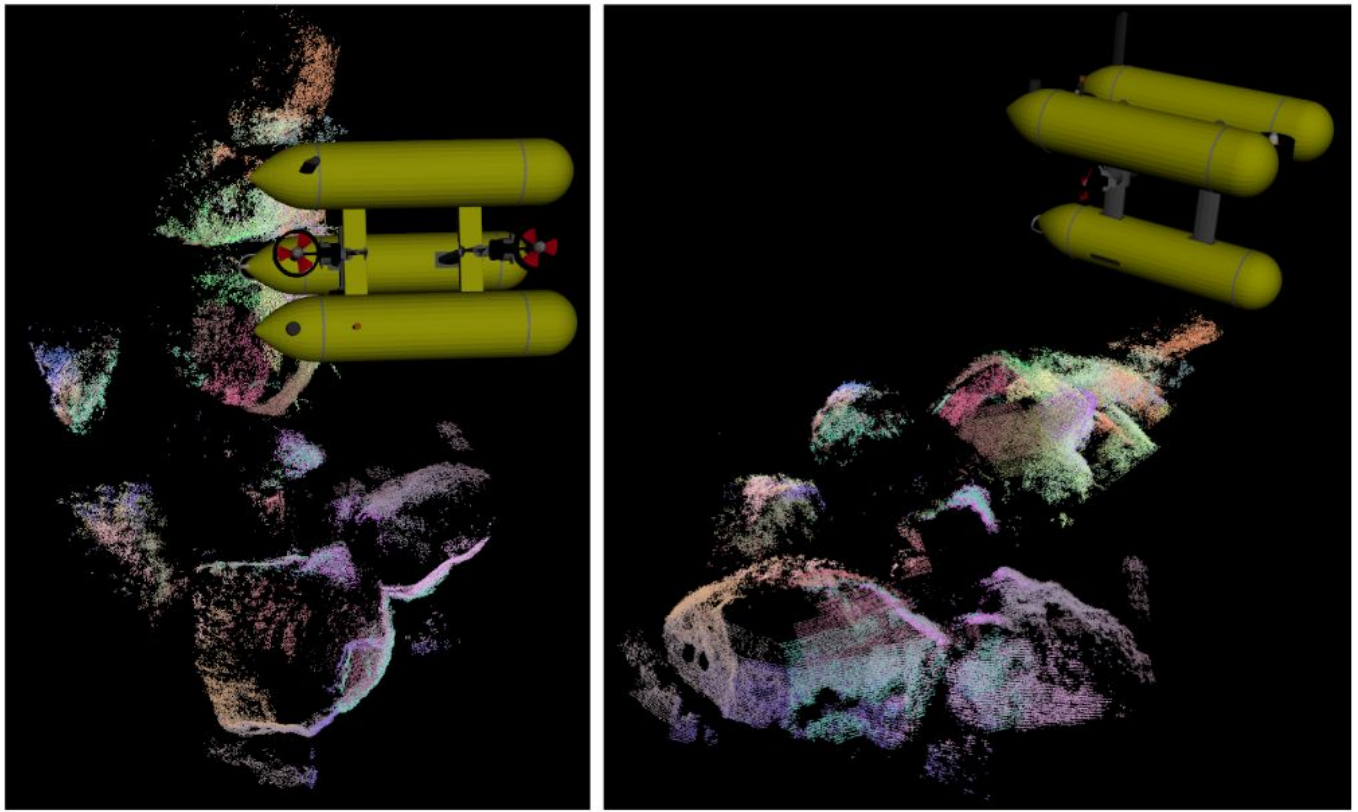
Sea trials





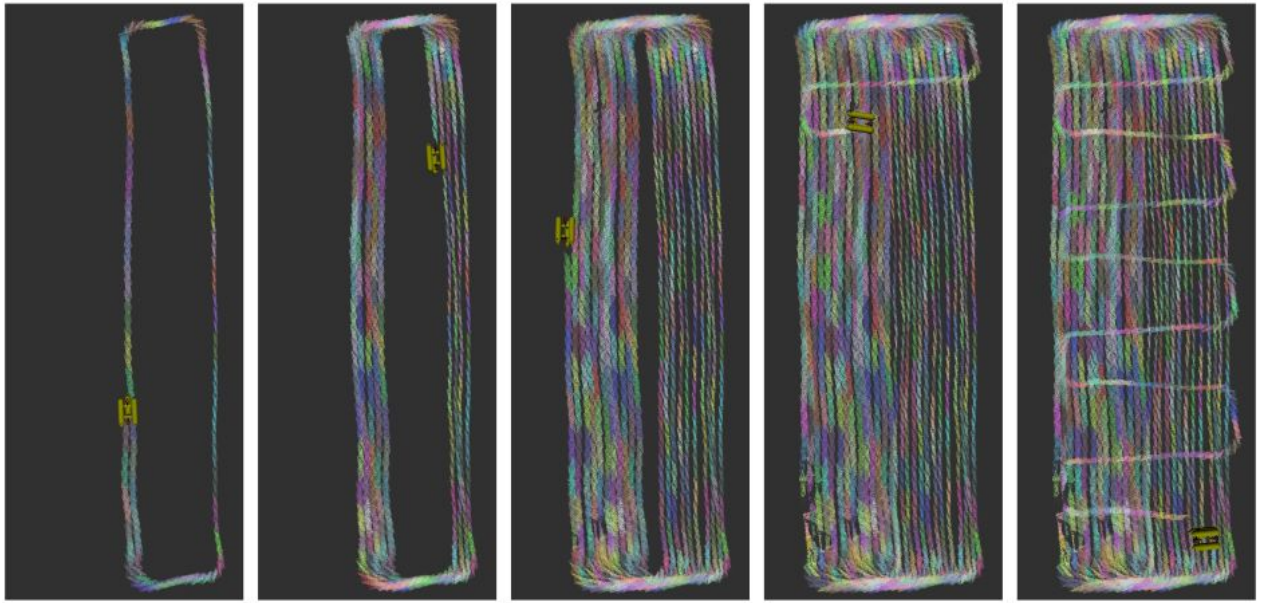


Sea trials: rocks

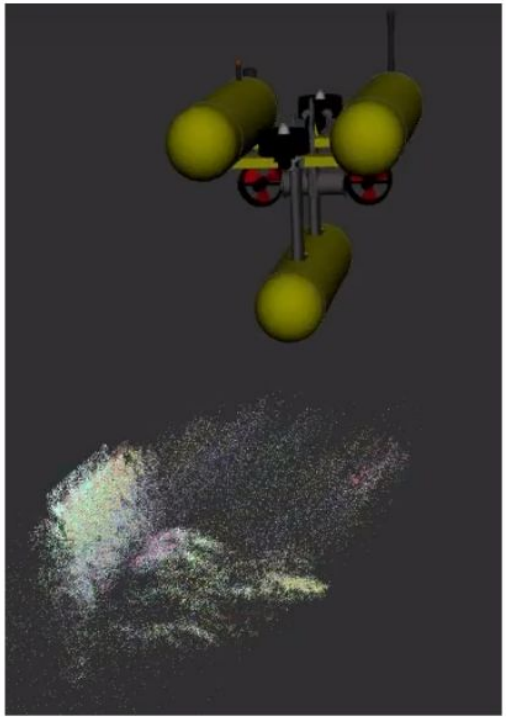


Sea trials: autonomous inspection

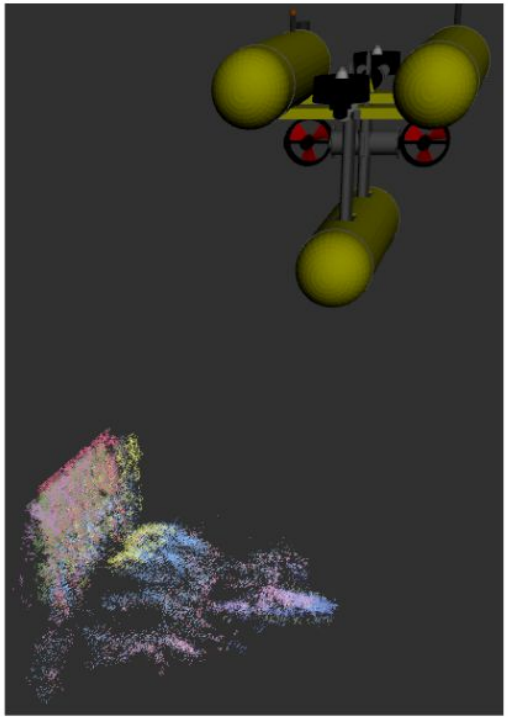
30 m x 8 m, 10m deep



Sea trials: backscatter



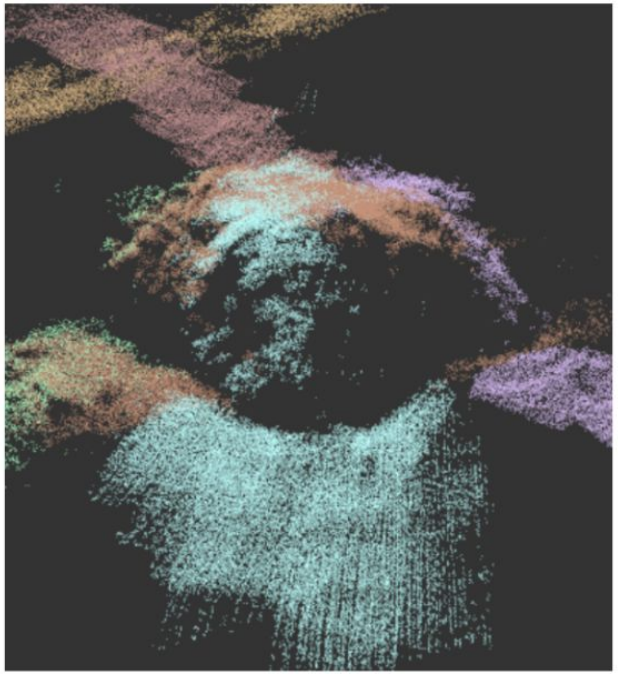
(a) Without outlier removal



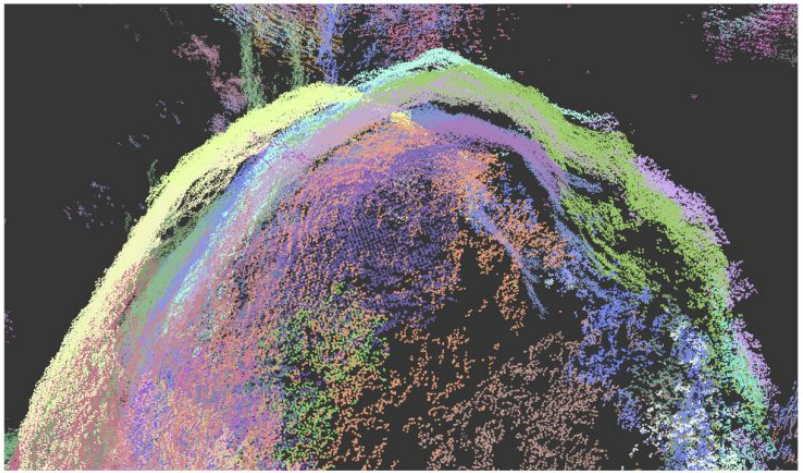
(b) With outlier removal

`pcl::StatisticalOutlierRemoval`
[Rusu 2007]

Sea trials: navigation drift



(a) Aggregated scans at the flat area of the seafloor (low drift).



(b) Aggregated scans at the rocky area of the seafloor (high drift).

Conclusions

Contributions

- Underwater 3D laser scanner
  - Literature survey
  - Counteracting refraction at light projection
  - Simple calibration based on projection functions

Future work

- Laser scanner
  - Higher laser power and backscatter, larger baseline, range gating
  - Study influence of the water refraction index
  - Increase scanning speed (better dynamic control of the mirror)
  - Automatic calibration
  - Multimodal perception (RGB cameras, sonar).
  - Explore Event-Based cameras

Future work

Thank-you very much for your attention...

- Higher laser power and backscatter, larger baseline, range gating
- Study influence of the water refraction index
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- Explore Event-Based cameras

Any questions ??