UNIVERSITÀ DEGLI STUDI DI PADOVA

Development of non contact measurement techniques for 3D shape analysis

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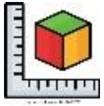
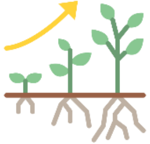
- 3D Measurements Methods
- Volume evaluation algorithms
- Uncertainty analysis



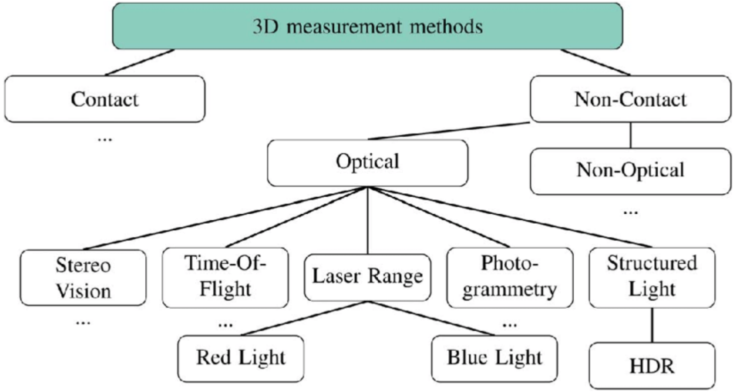
- Application 1: Simple geometry

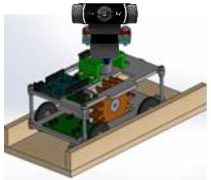


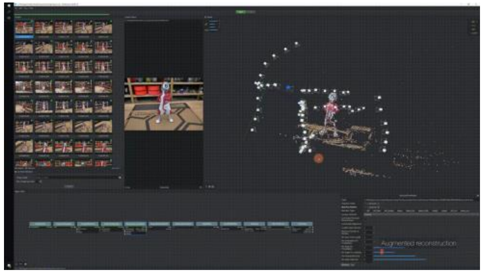
- Application 2: Slow modification of geometry
- Application 3: Complex geometry

- Application 4: Movement
- Conclusion

3D measurement method



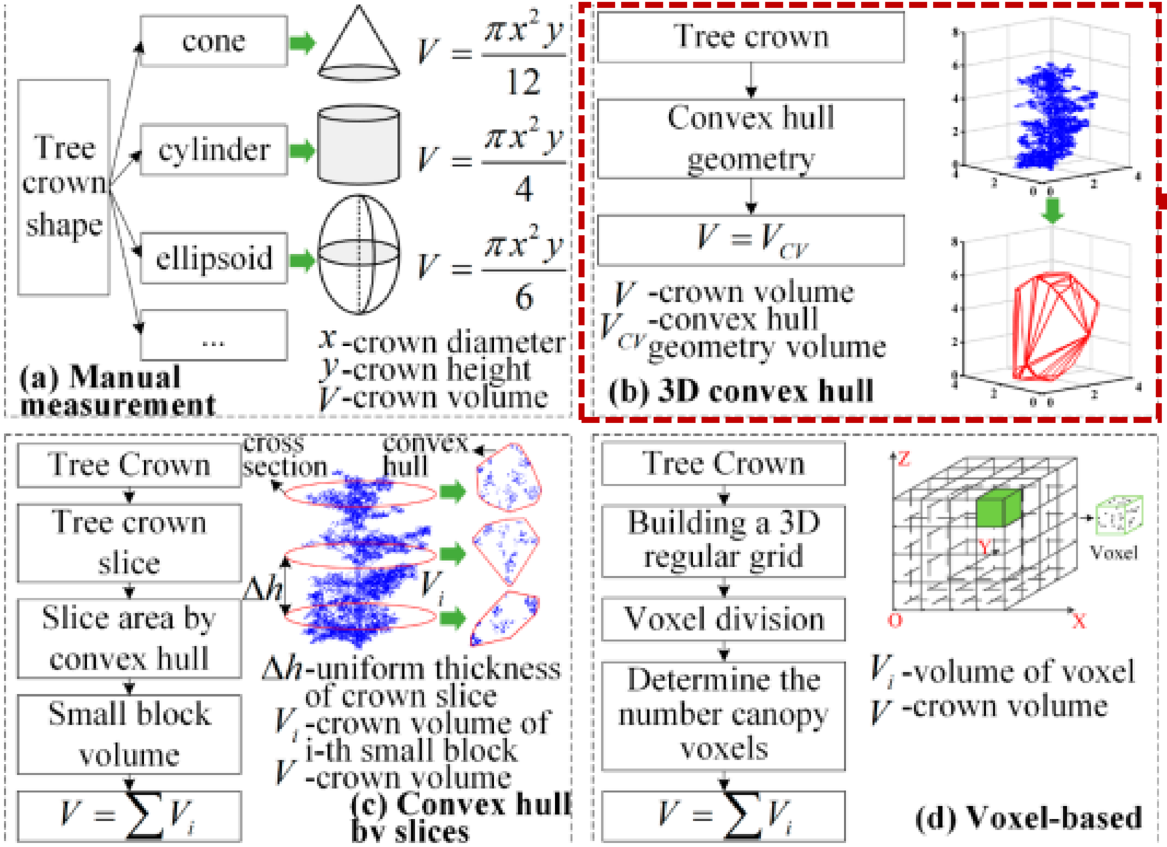


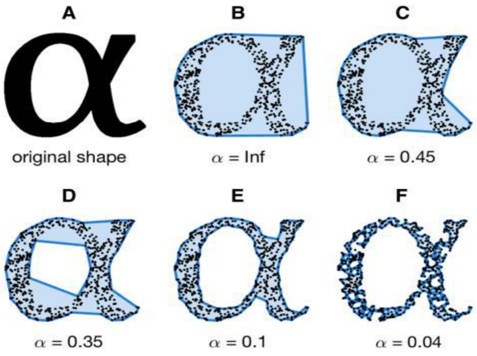


Measurement Problems

- Instrument
- Object geometry
- Object material
- External condition
- Standard

Volume measurement





(e) Alpha shape

- Alpha radius (A.R)
- Critical alpha (C.A.)
- Alpha spectrum (A.Sp)
- Alpha Optimal (A opt.)

Measurements

Term	Meaning	Equation
RMSE	The standard deviation of the prediction residuals	$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\hat{y}_i - y_i)^2}{n}}$ where $\hat{y}_i$ is the estimated value, y_i is the observed value and n is the sample size
RRMSE	RMSE relative to mean	$RRMSE = \frac{RMSE}{\bar{x}}$
MSE	The average squared errors of prediction residuals	$MSE = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2$
R^2	The proportion of the variance of one variable that can be explained by the variance of the second variable	$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \mu_y)^2}{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}$ where μ_y is the mean of observed values
MAE	The average of the absolute values of prediction residuals	$MAE = \frac{\sum_{i=1}^{n}\lvert\hat{y}_i - y_i\rvert}{n}$
MAPE	The average of the absolute values of prediction residuals divided by the actual values	$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left\lvert\frac{y_i - \hat{y}_i}{y_i}\right\rvert$
CCC	Interpreted similarly to R^2, but used to compare two methods predictions or to measure repeatability of repeats of a single method	$CCC = \frac{2\rho\sigma_y\sigma_{\hat{y}}}{\sigma_y^2 + \sigma_{\hat{y}}^2 + (\mu_y - \mu_{\hat{y}})^2}$ where σ_y represents the variability of either the observed value or another variable and $\sigma_{\hat{y}}$ and $\mu_{\hat{y}}$ the variability and the mean of either the estimated value or another variable
RCV	The minimal significant difference between temporally different measurements	$RCV = \pm q\sqrt{2\left(\sigma_y^2 + \sigma_{\hat{y}}^2\right)}$ where q is the quantile for the desired probability from a standard normal distribution
MCC	Measures the agreement of binary classifications	$MCC = \frac{TP \times TN - FP \times FN}{\sqrt{(TP+FP)(TP+FN)(TN+FP)(TN+FN)}}$ where TP is true positives, TN is true negatives, FP is false positives and FN is false negatives of binary classification

Uncertainty

(G.U.I.)

$$\bar{x} = \frac{1}{N}\sum_{k=1}^{N} x_k$$

$$\sigma(x) = \sqrt{\frac{1}{N-1}\sum_{k=1}^{N}(x_k - \bar{x})^\wedge 2}$$

$$u_R(\bar{x}) = \frac{\sigma(x)}{\sqrt{N}}$$

Application 1

Static objects : Volume Reconstruction Uncertainty analysis on simpler to more complex geometries

- Samples (Sphere, Cube, Pyramid)
- Convex object (FIFA WC, Human torso,…)
- Complex shape (Lettuce plant)

OBJECTIVE :

<u>Evaluate the effect of density, size and Alpha Radius, on the volume reconstruction of selected geometries</u>

Application 1: Samples

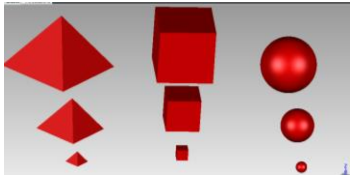
Objective: Influence of point density and object size on volume reconstruction uncertainty

Algorithms:

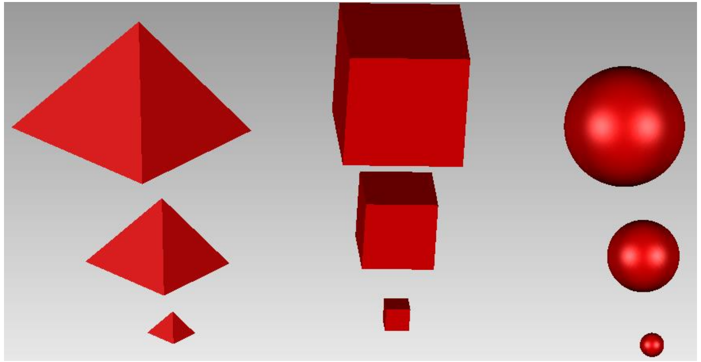
- Alpha shape → Alpha radius: radius ranging form 5 to 105 mm, with 10 mm steps
- Alpha critical
- Alpha optimal
- Convex hull

→ **Effect of size and point density on uncertainty**

Sample group 1: Np 9000, size 10 mm, 30mm, 50mm
Sample group 1: Np 9000, size 100 mm, 300mm, 500mm
Total test=18



Sample Group 1



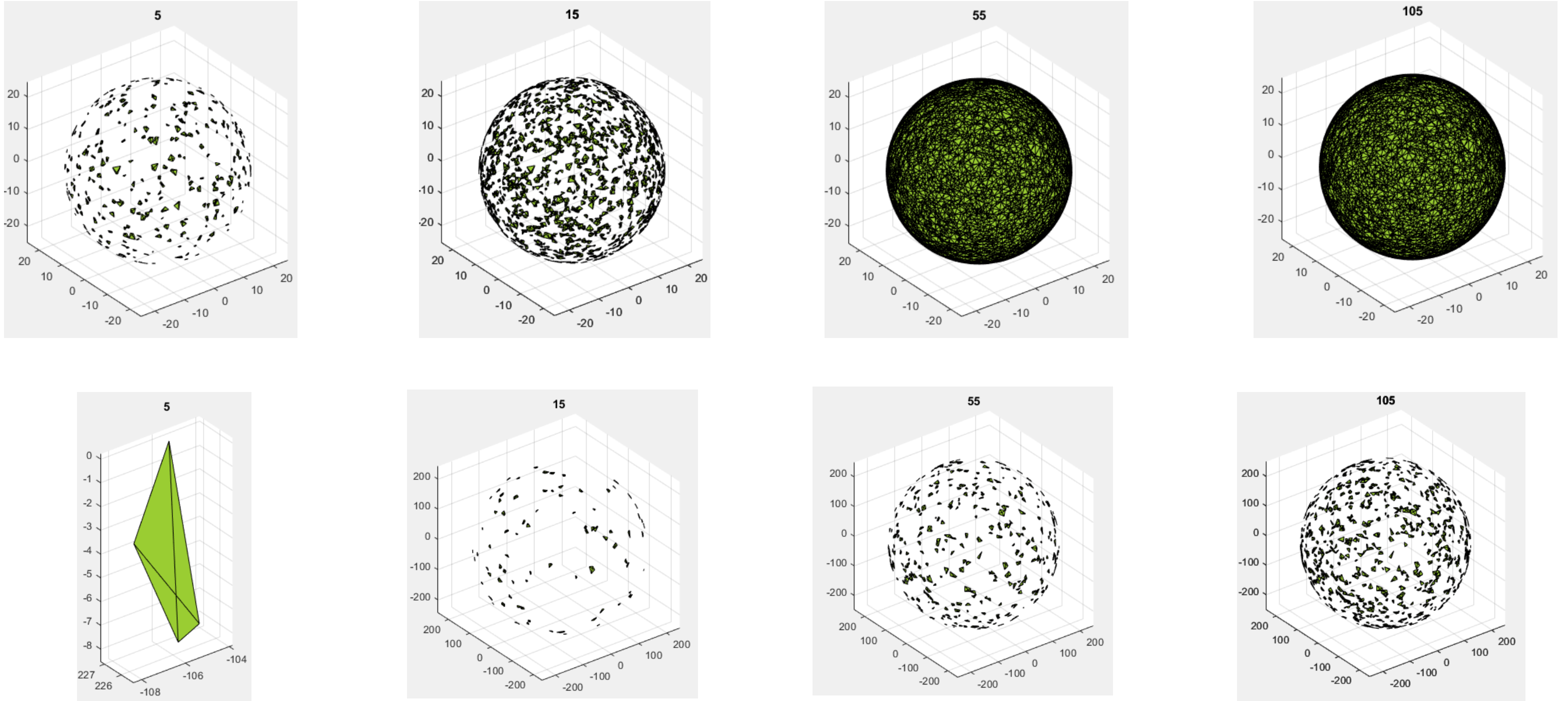
Sample Group 2

Application 1: Alpha Shape on Sphere

5 mm — **ALPHA SHAPE RADIUS RANGE** — **105 mm**

S 30 mm

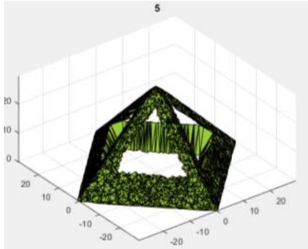
S 300 mm

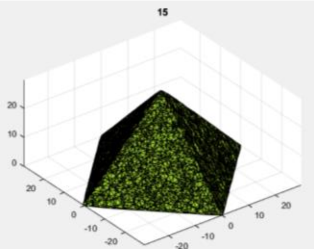


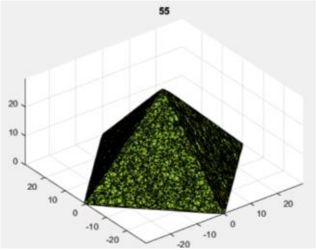
Application 1: Alpha Shape on Pyramid

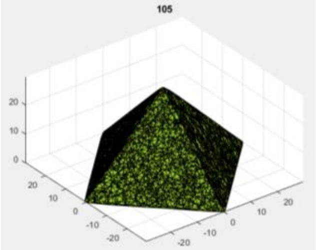
5 mm — **ALPHA SHAPE RADIUS RANGE** → **105 mm**

S 30 mm

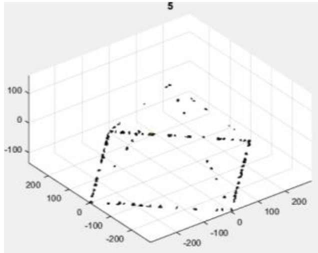


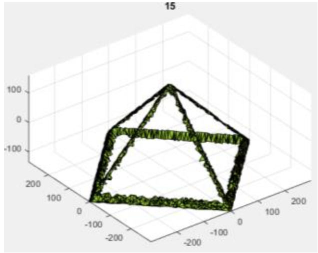


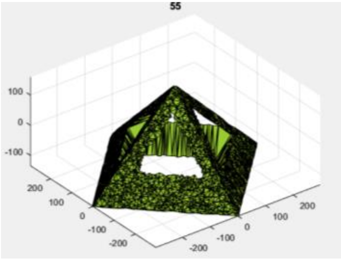


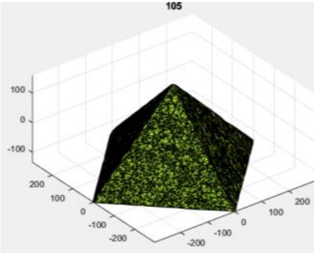


S 300 mm







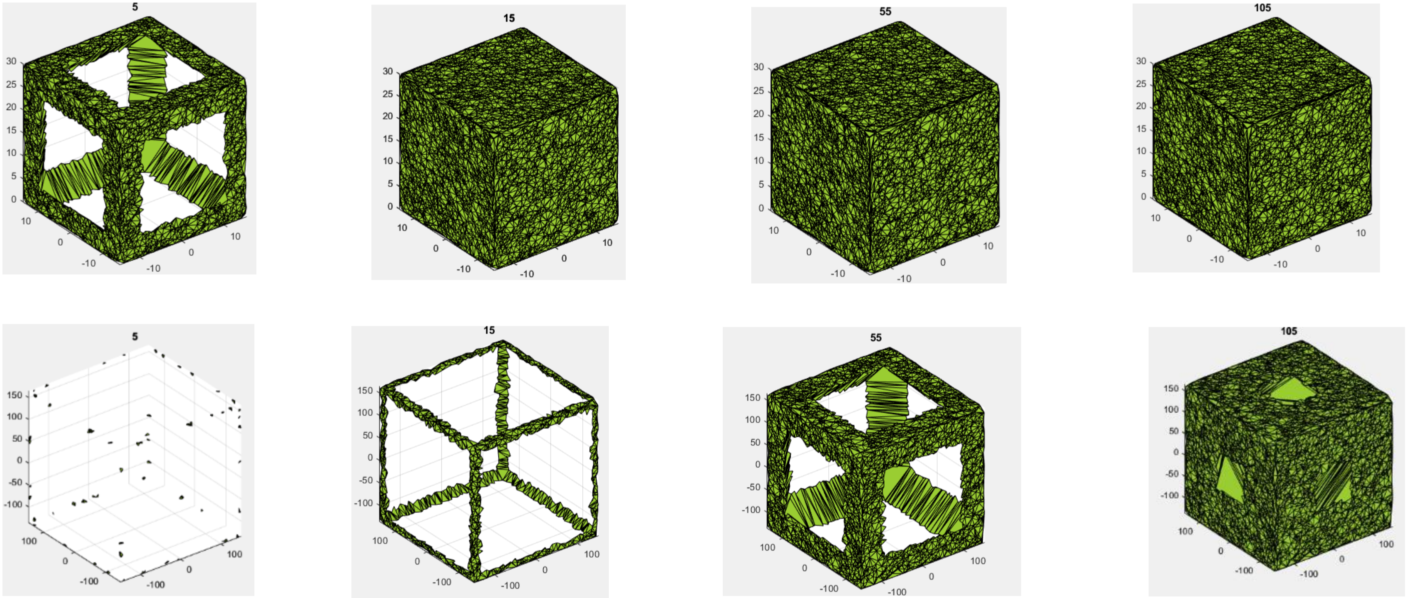


Application 1: Alpha Shape on Cube

5 mm **ALPHA SHAPE RADIUS RANGE** **105 mm**

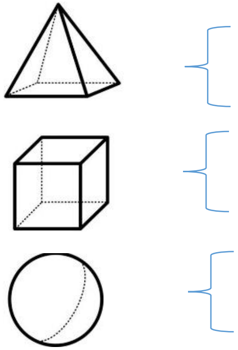
S 30 mm

S 300 mm



Applications Samples Rsult

- **Generally, smaller geometries allow better reconstruction**
- **The spherical geometry is the hardest to reconstruct, especially for bigger sizes**
- **For smaller geometries a minimum alpha radius of 15 mm is found**
- **For bigger geometries a minimum alpha radius of 75 mm is found**
- **The uncertainty ratio between the biggest and smallest geometry is found**



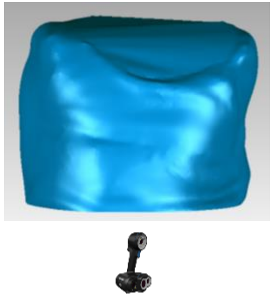
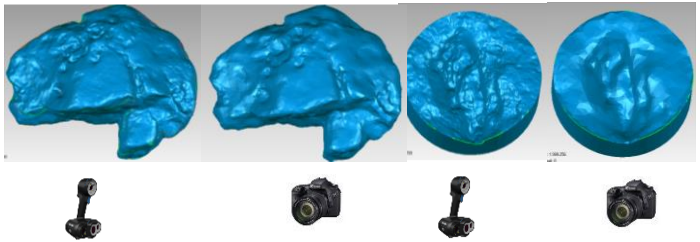
Unc %	un unc %	U/u2
2,28	8,58	3,765716
2,49	21,07	8,470613
0,61	25,38	41,30696
6,05	13,38	2,211269
6,43	23,12	3,596139
6,21	24,71	3,978492
40,68	25,82	0,634596
40,63	29,86	0,734965
40,67	18,41	0,452535

Applications on CH, B, ST, D

Cultural Heritage (CH) **Biomedicine (B)** **Sport training (ST)** **Design (D)**

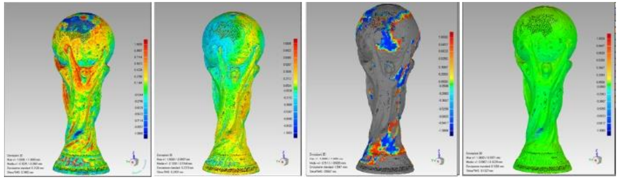
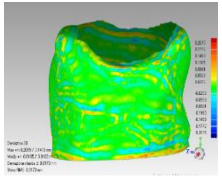
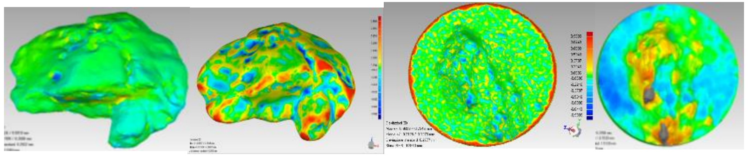
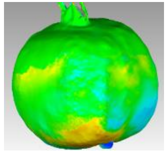
Test

Part


Comparison acquisition with final model

10 samples different size

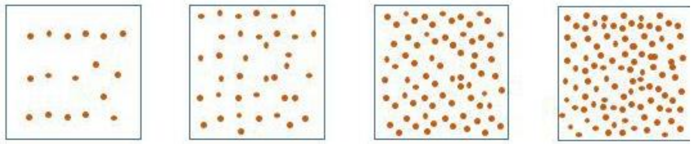
X 4 X 1 X 2 X 2 X 1

Parameters

More complex object

	Volume [mm^3]	Area [mm^2]	N points [adm]	Density np/[mm^2]
1 CH SL 0.5 mm	3299339,06	152197,39	1620374,00	10,65
2 CH SL 2 mm	3312267,49	165294,72	34236,00	0,21
3 CH Ph1_High	3133700,88	157195,16	33603,00	0,21
4 CH L2_Low	2934166,68	137706,91	4273,00	0,03
5 Biomedicine	3472976,28	127480,56	33816,00	0,27
6 ST SL 2 mm	366927,51	41986,66	330254,00	7,87
7 ST Ph1_High	394650,11	41404,28	1000127,00	24,16
8 ST test SL 0.5	203778,98	28028,55	98060,00	3,50
9 ST test SL 2	206576,03	22696,45	5237,00	0,23
10 Design (D)	396066,94	27462,17	519457,00	18,92

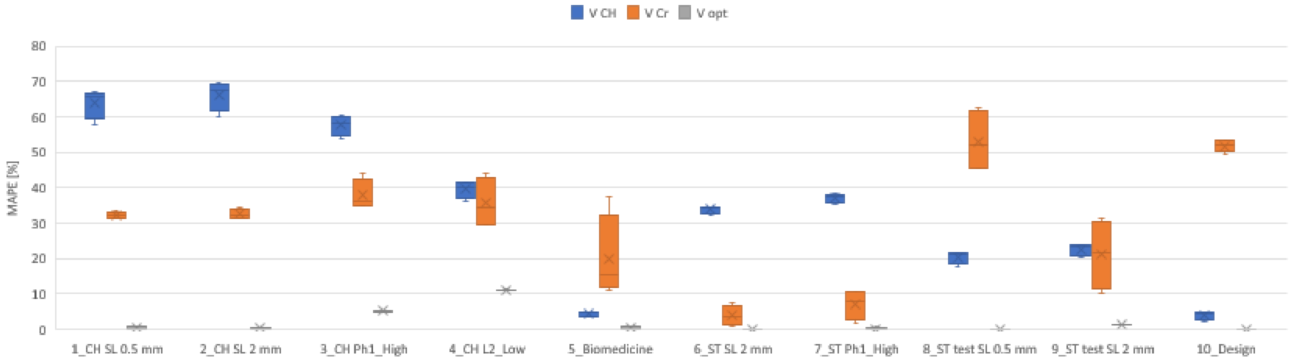
The point cloud original is to heavy to compute. Hence, it is necessary to reduce the number o points for the reconstruction. Resampling the acquisition, it is possible to investigate the influence of resolution on the reconstructions.

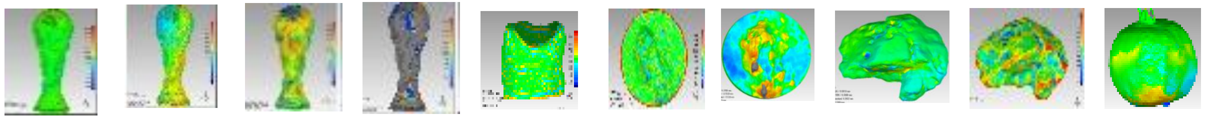


Np 1000, 3000, 6000, 9000

Results Algorithms

- For bigger geometries (FIFA World Cup) a similar minimum alpha radius is found. The correspondance is not found for smaller geometries (fruits), even if they are more similar to reference shapes (sphere).
- Considering the Structured Light reconstruction as the reference model (after processing with Geomagic Wrap), it is possible to find the distances (MAPE) with the models obtained by Convex Hull, Alpha Critical, Alpha Optimal algorithms

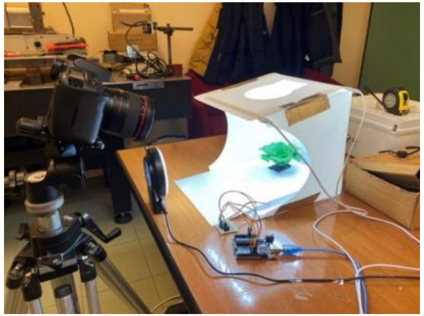




Convex Hull MAPE:

- **37%-67% (FIFA WC)**
- **About 20 % for small objects**

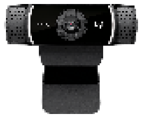
More Complex Geometry: Plant

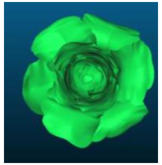


A more complex object, lettuce plant, is scanned using 4 different methods, each one with different resolution and cost :

- **Structured light scanner (5 scans)**
- **Photogrammetry with high cost Canon DSLR (3 scans)**
- **Photogrammetry with low cost Webcam (3 scans)**
- **Laser sheet (1 scan)**

REFERENCE: STL model of the lettuce plant

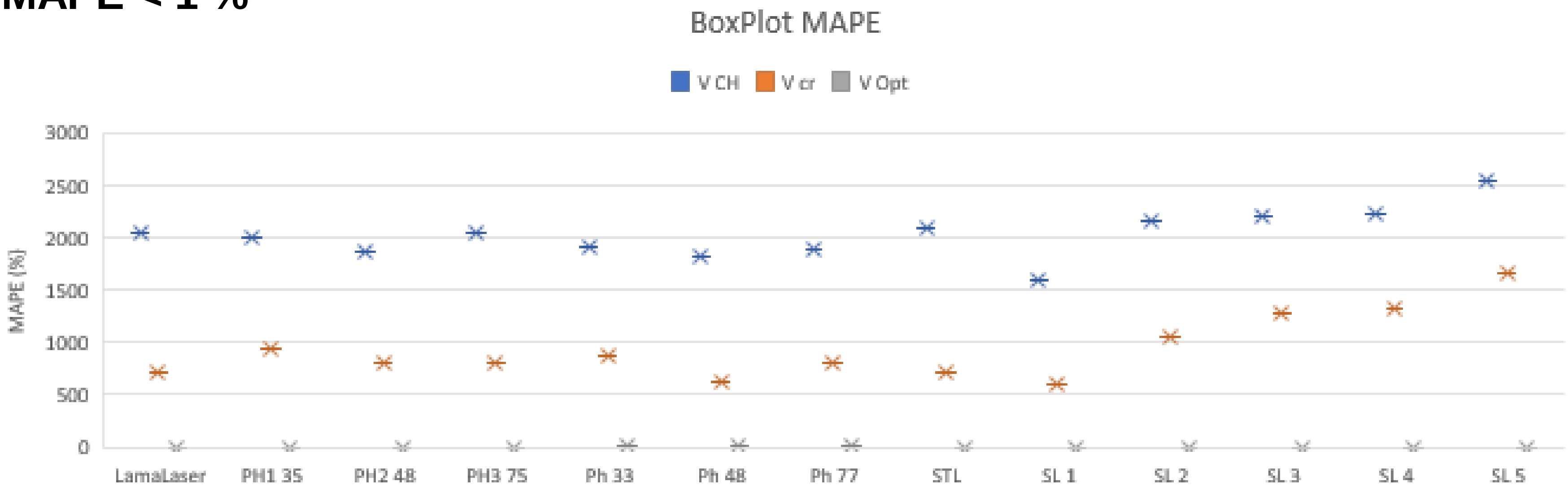




Analisys

- **The distance of the CH and AC reconstructions from the reference model, ranges from 500 % to 2000 %**

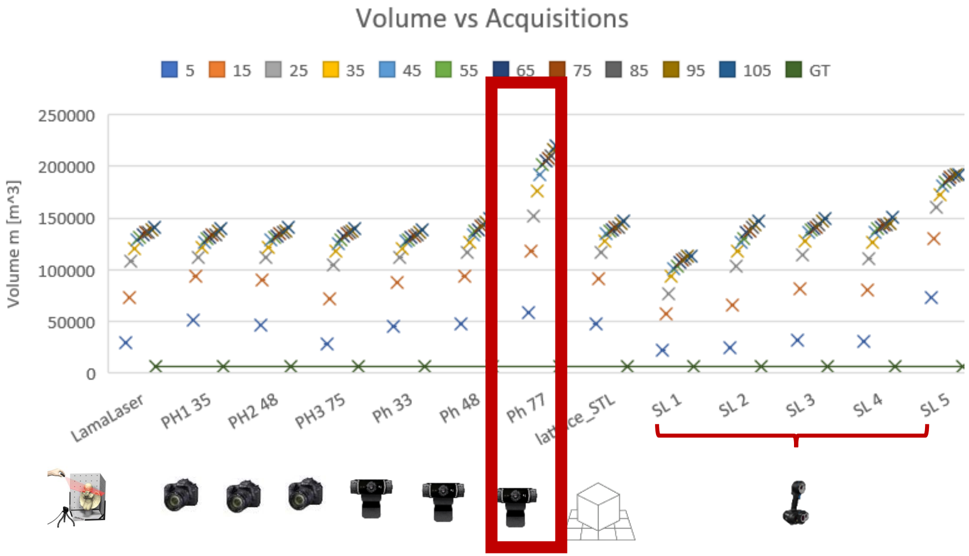
- **A better performance is obtained using the Alpha Optimal radius algorithm: MAPE < 1 %**

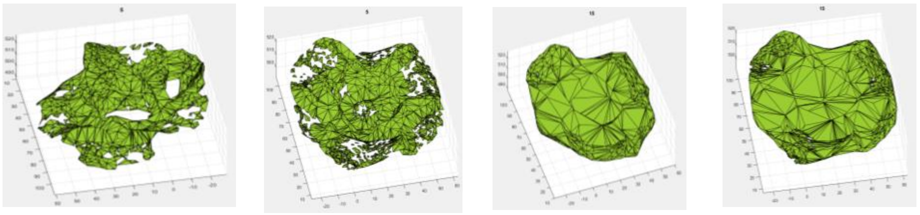


Complex geometry: Result

Varying the Alpha radius, a similar performance is obtained using different sensors.

Using the proposed algorithms, the reconstruction can be achieved even with cheaper scanning techniques





Application 2

Object with slow modification of geometry:

Artificial tree

Application 2

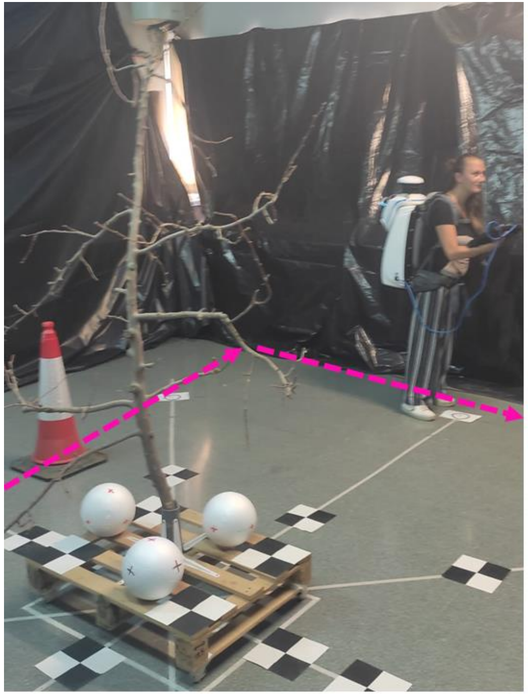
OBJECTIVE :

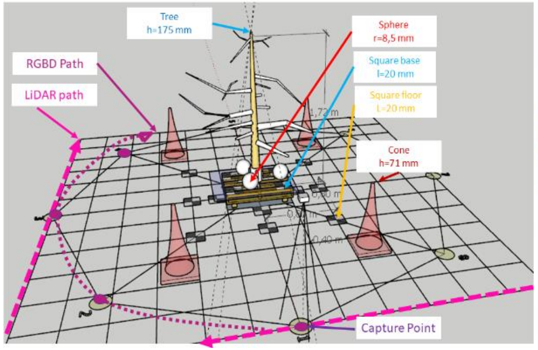
<u>Find the relation between leaves area and reconstructed volume</u>

Set-up

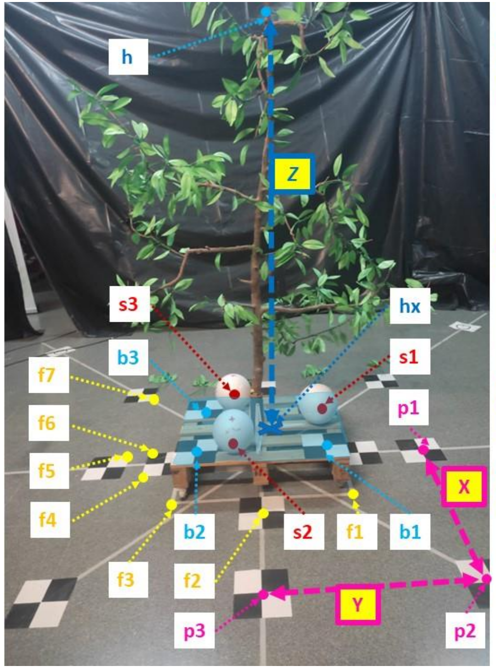
Scanning techniques used:

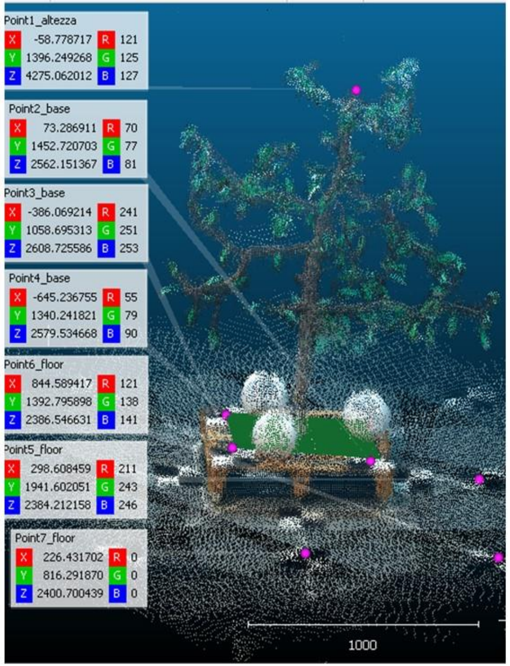
- **LiDAR : high cost (15 scans)**
- **Azure-Kinect : low cost (15 scans)**





Measurements





REFERENCE:

- **X-Y PLANE: planar distance between targets**
- **Z AXIS: Tree height**
- **Spheres diameters placed on the base**

Artificial Tree Set-up

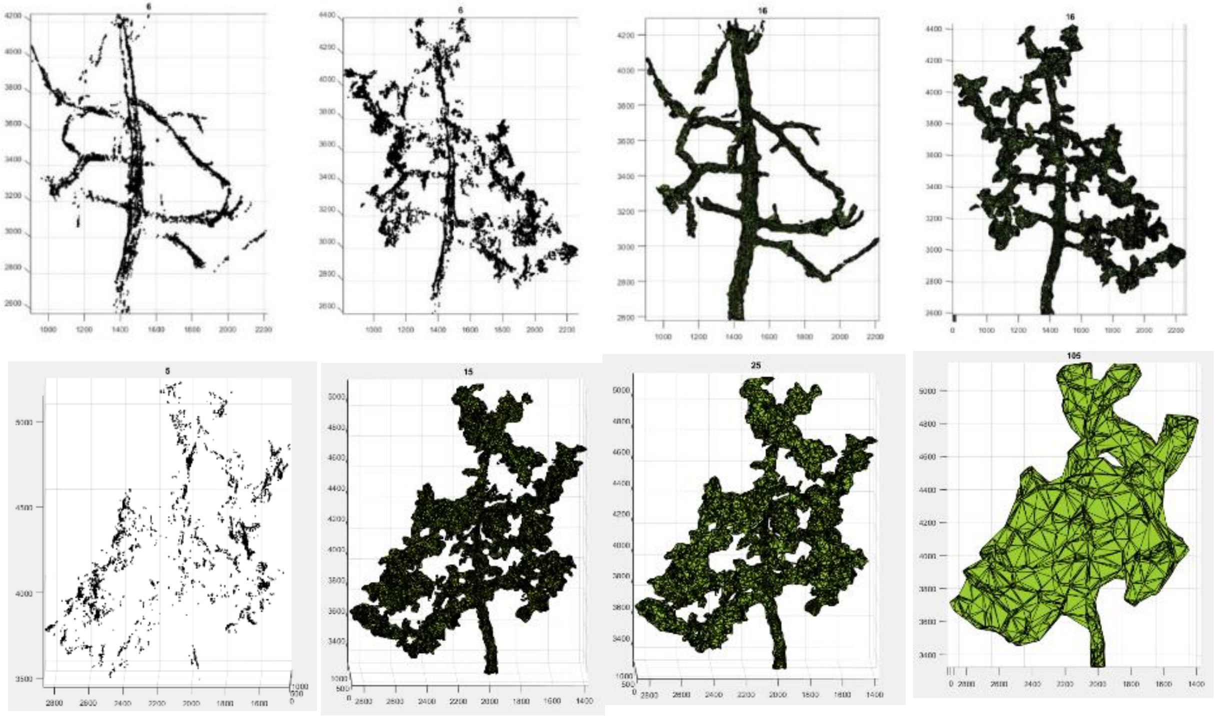


Figure alpha variation of tree, acquisition 7 with 300 leaves: From alpha=5 mm to alpha=105 mm with a step of 10 mm

The starting tree has a total of 700 artificial leaves.

In each of the acquisitions performed, 50 leaves are removed.

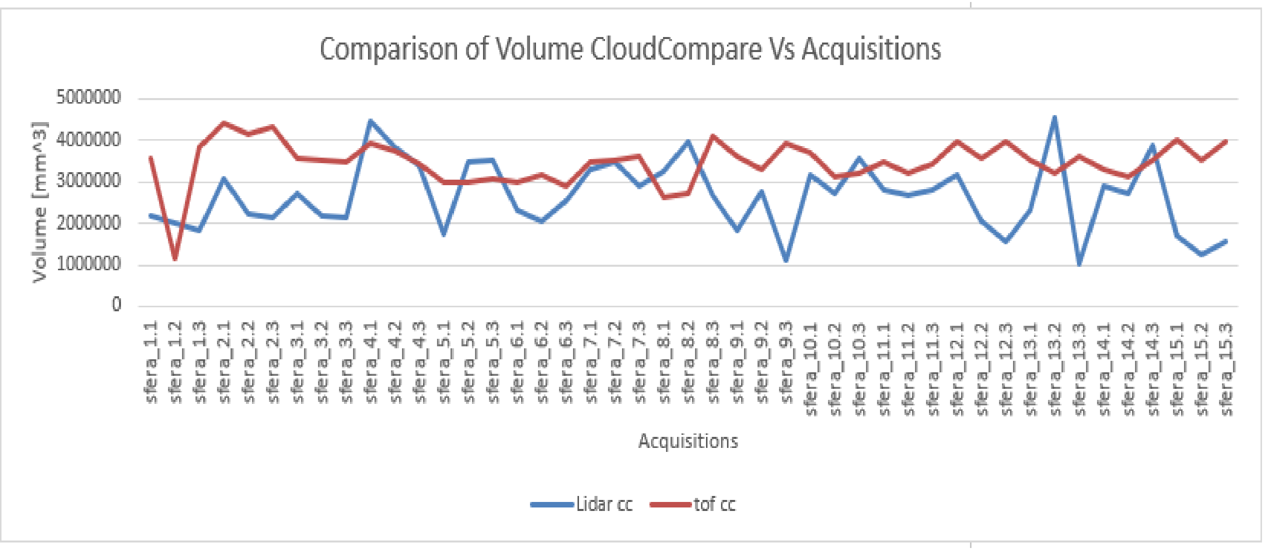
In the final acquisition the tree is completely defoliated.

Applications

Analyzing by CloudCompare of the reference spheres, the scans made using Azure-Kinect allow a more stable volume reconstructions. Hence, the following results are based only on the acquisition using this technology, neglecting the LiDAR scans.

RGB-D

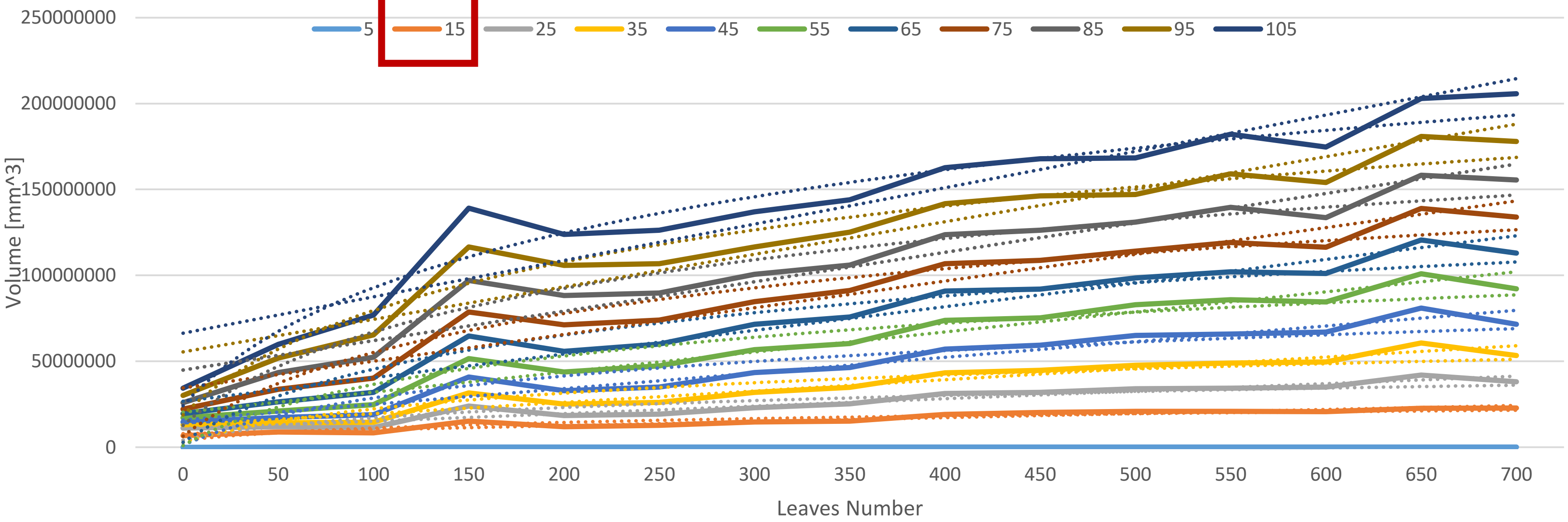
LiDAR



Volume evaluation

Volume reconstructed over the 15 scans, with Alpha varying in 5-105 mm range

Best reconstruction in linear field



Relation measure Volume/Number Leaf

For Alpha lower than 75 mm, the relation between the leaves area and the reconstructed volume is LINEAR. If an Alpha radius over 75 mm is selected, this relation becomes LOGARITHMIC

- **Alpha Radius < 75 mm   R^2lin = 0,95   R^2log = 0,86**
- **Alpha Radius > 75 mm   R^2lin = 0,82   R^2log = 0,96**

Using Convex Hull (Alpha Radius=∞), the relation becomes even more LOGARITHMIC, with R^2log=0.97. The linear variance reaches a value of R^2 = 0.73 as maximum value of uncertainty.

Application 3

Object with slow modification of geometry:

Greenhouse lettuce plants

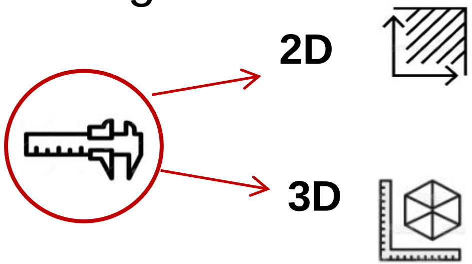
Howard. Conference paper: Anomaly detection in plant growth in a controlled environment using 3D scanning techniques and deep learning
2021 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor)

OBJECTIVE :

<u>Select the best techniques to scan complex geometries, used to train a Deep Learning algorithm</u>

Anomaly detection in plant growth in a controlled environment using 3D scanning techniques and deep learning

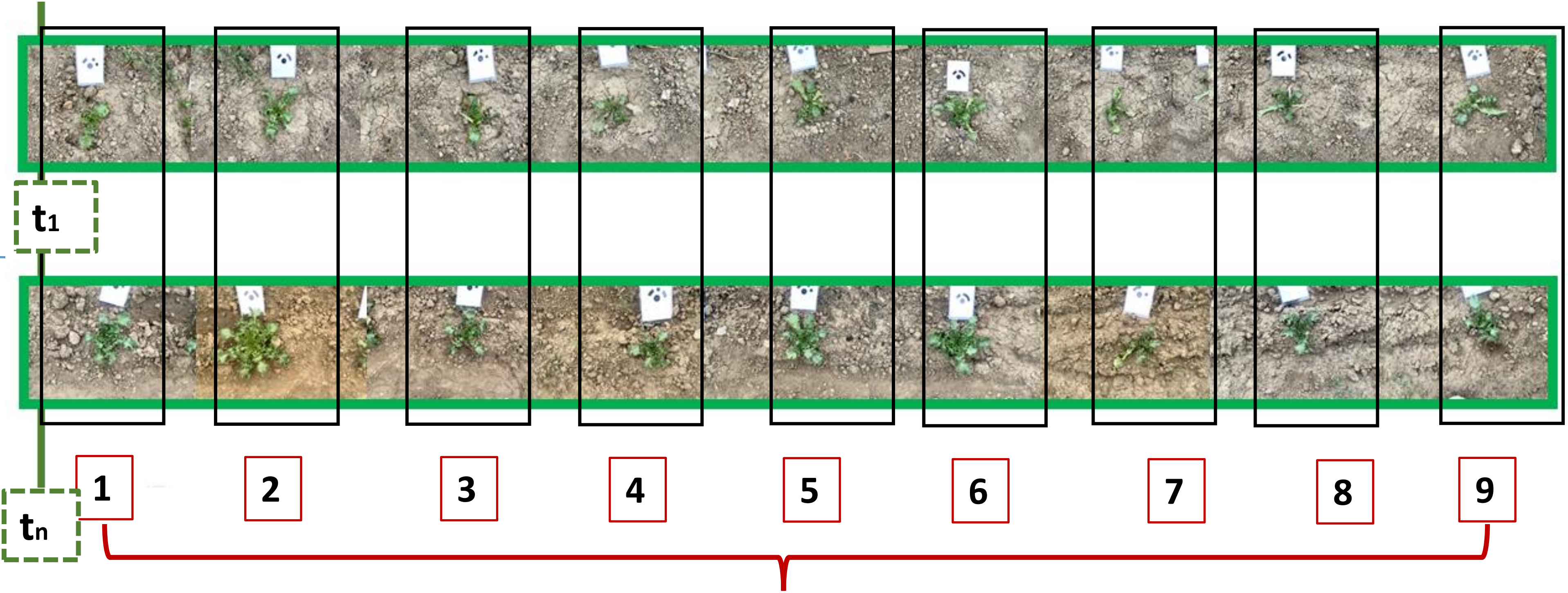
Input — **Contactless monitoring systems**



Deep Learning — **Anomaly recognition**

Output — **Accuracy**

Lettuce Plant Measurements

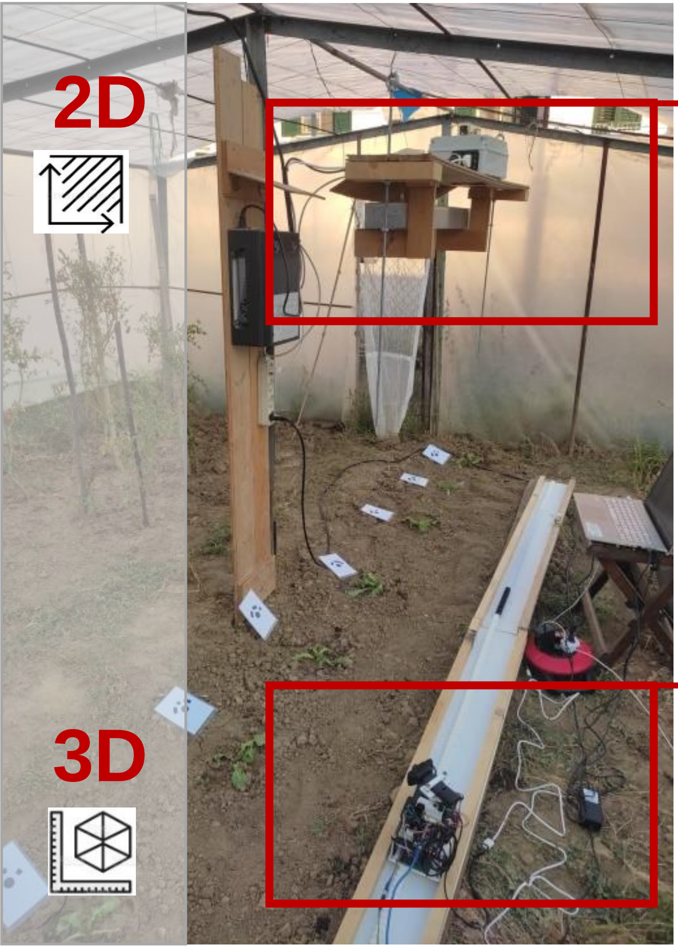


Time (t): 2 week

9 Chicorium endivia plants

- **Measurements: 126**
- **Time: 17:00 to 19:00**
- **Days: 15**

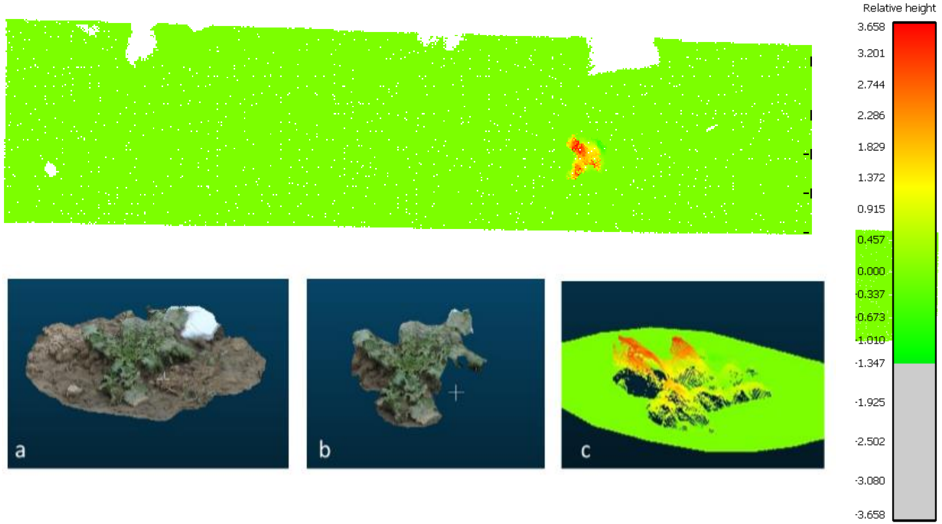
Instruments and Set-up

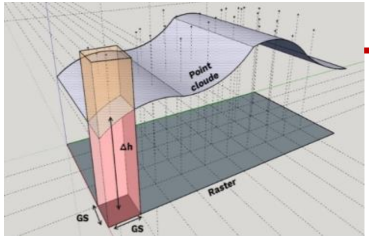


	Cost	Resolution
Full-HD camera, Sony IMX219 (G)	−	−
Go! SCAN 50 by Creaform (SL)	+	+
- Automated 3D printed low-cost scanner(PI)	−	−
- Canon Eos 7D(Pc)	+	−
c) i-Pad 20 pro (L)	−	−

3D Volume evaluation

- Segmentation and raster





Volume calculation parameters used in Cloud Compare	
Parameters	Values
Grid Step (Raster)	1 mm
Grid Step (Volume)	1 mm
Projection direction	Z
Matching Cells	90%
Point Cloud density	1000 points/cm^2

V

Segmentation and 2.5D raster image

RGB

H3D

Panel a: isolating each plant from the total mesh, with a portion of soil. **Panel b**: isolating the plant from the soil. **Panel c:** generation of the reference plane, used for the 2.5D raster for the plant volume evaluation.

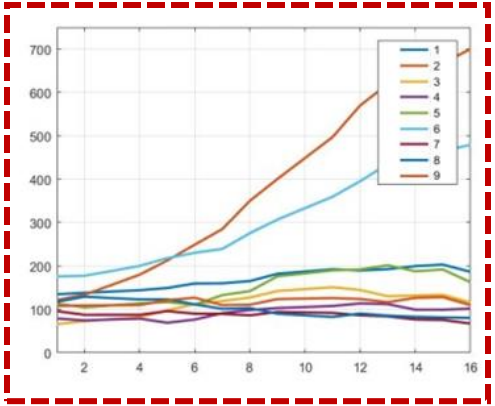
3D Dataset evaluation

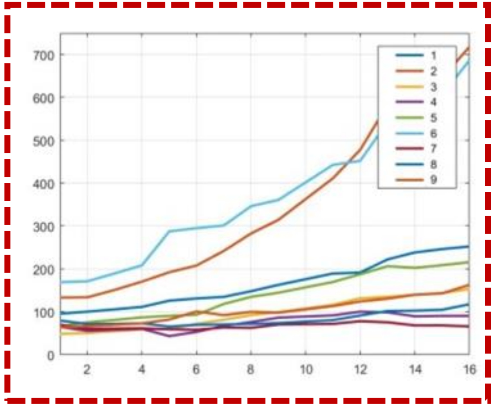
Experimental data

Data					
Field Height	/		/	/	/
2D Area		/	/	/	/
Height	/	/			
Volume		/			
RGB		/			

3D Volume by low cost photogrammetry

3D Volume by Lidar

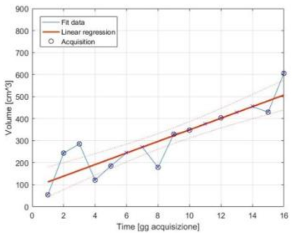




Indicators of health status and anomalies

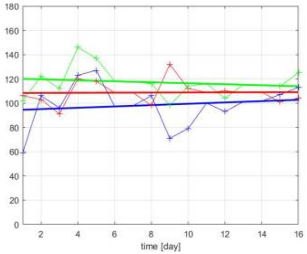
- Growth trend

  α, σ



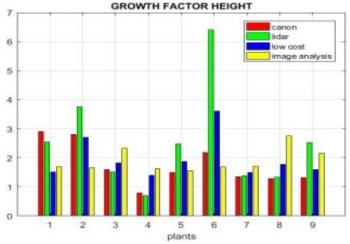
Has to be constantly increasing

- RGB trend



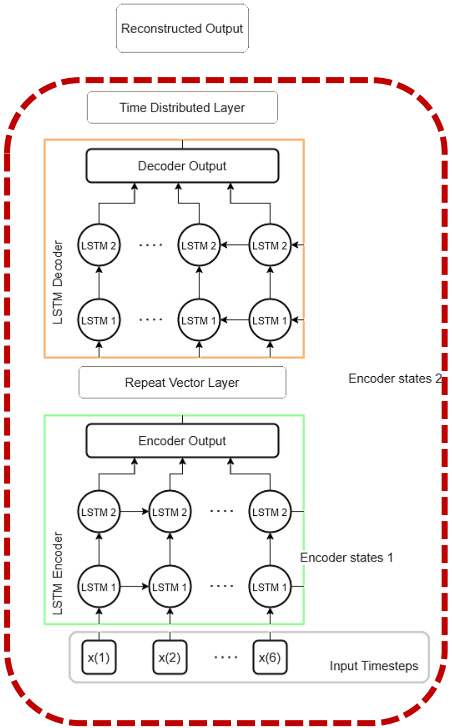
Green has to be the predominant color

- Growth factor



Deep learning input

LSTM Encoder-Decoder for anomaly detection



Input
t

126 x 3 x 5

Dataset

Height (field)

2D Area

Height (3D)

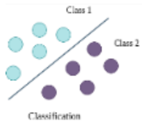
3D Volume

RGB

Deep Learning

Encoder Decoder

Error Reconstruction



Input tensor

Anomaly Detection

Encoder - Decoder

Input t

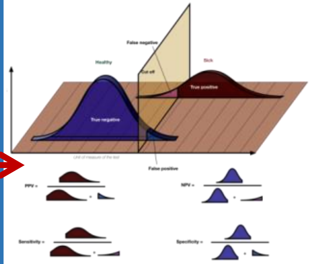
126 x 3 x 5

Dataset

anomaly

normality

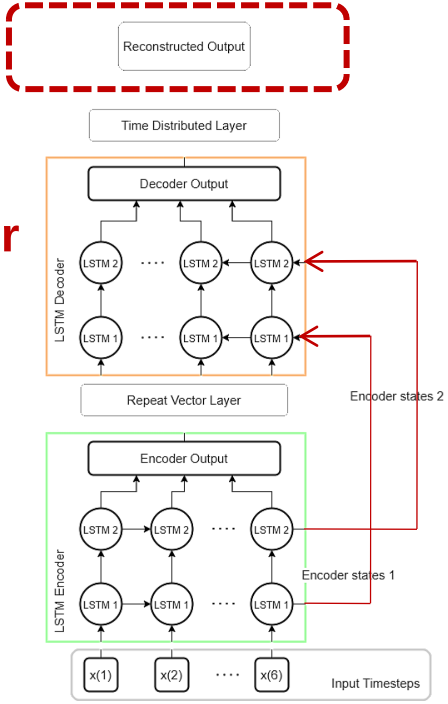
Deep Learning



Input tensor

Anomaly Detection

LSTM Encoder-Decoder for anomaly detection



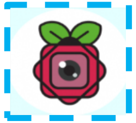
Reconstruction Error

Reconstruction error (MAE) distribution on normality and anomaly dataset

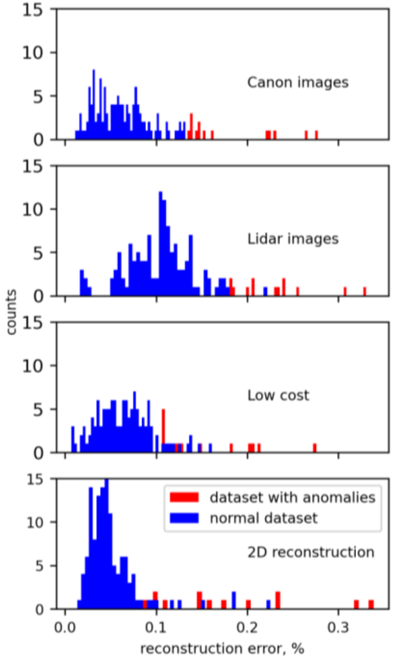
Pc

L

Pl



G



Confusion Matrix for LSTM per each model

Pc		Pred N	Pred A
Meas	N	1.00	0.00
Meas	A	0.64	0.36

L		Pred N	Pred A
Meas	N	0.99	0.01
Meas	A	0.07	0.93

Pl		Pred N	Pred A
Meas	N	0.95	0.05
Meas	A	0.36	0.64

G		Pred N	Pred A
Meas	N	0.97	0.03
Meas	A	0.50	0.50

Performance Indices for LSTM per each model

	Precision	Recall	F1 score
Pc	1.00	0.36	0.52
L	0.93	0.93	0.93
Pl	0.6	0.64	0.62
G	0.63	0.5	0.56

Conclusion

- Select the most suitable scanning technique for the acquisition of data
- The first analysis performed with Deep Learning returns promising results
- Results can be foreseen and the proposed approach could be convenient in large greenhouse settings or in vertical farms

Application 4

Objects with significant modification of geometry over small periods of time:

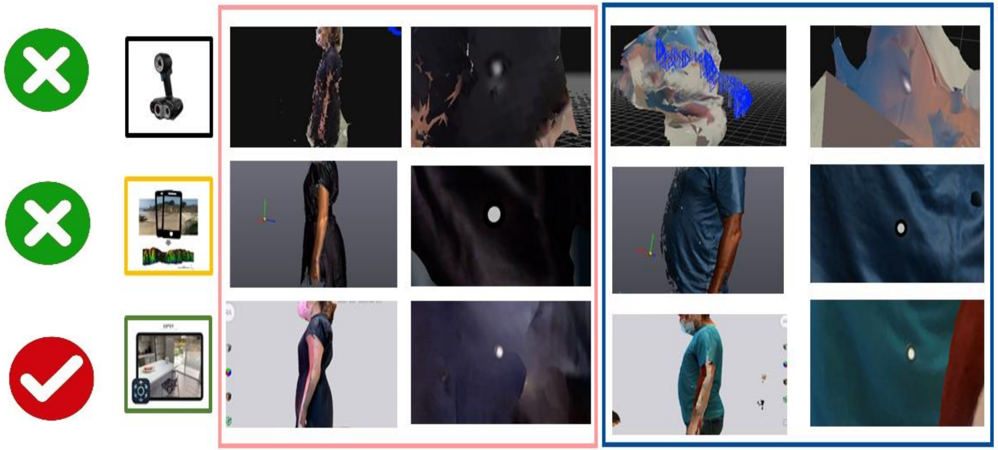
Human body

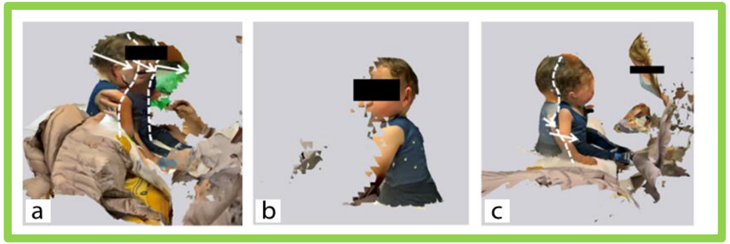
OBJECTIVE :

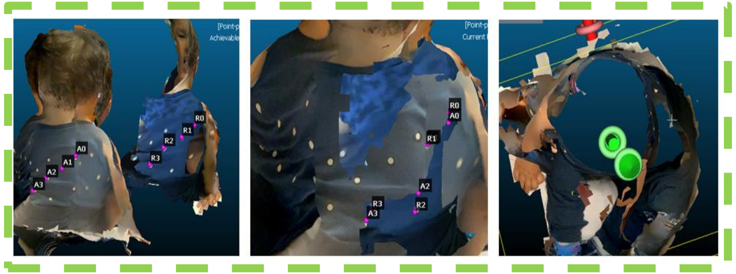
Human body shape reconstruction with a non-collaborative patient

Instruments and analysis

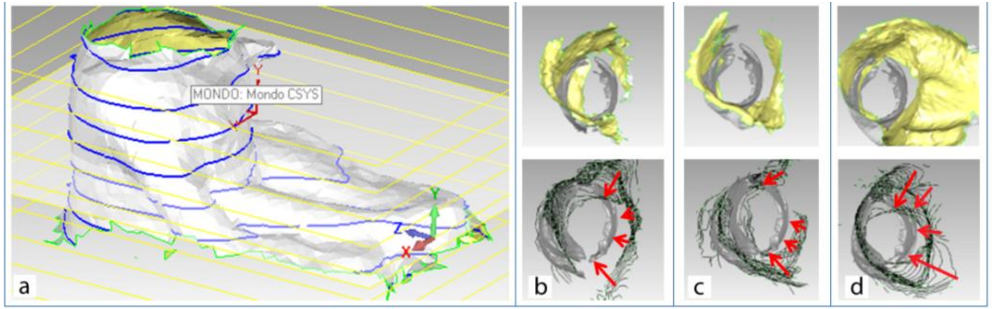
- Performances of three different techniques for 3D scanning have been investigated (LiDAR, Photogrammetry, Structured Light)
- Three different subjects have been scanned with the three different techniques and the obtained 3D model were analysed: two adults and one young boy.

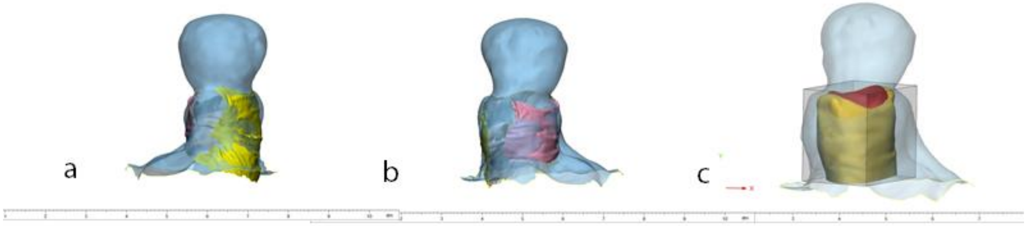






Multiscanning Approach

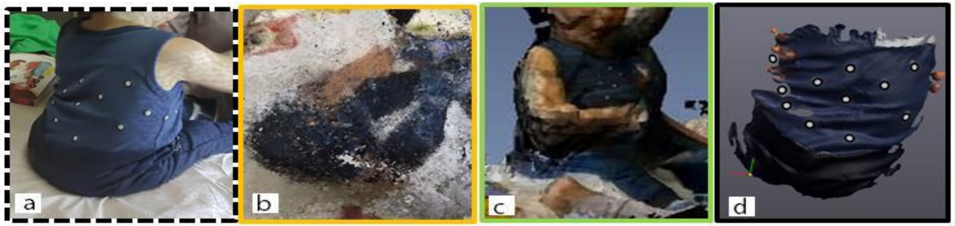




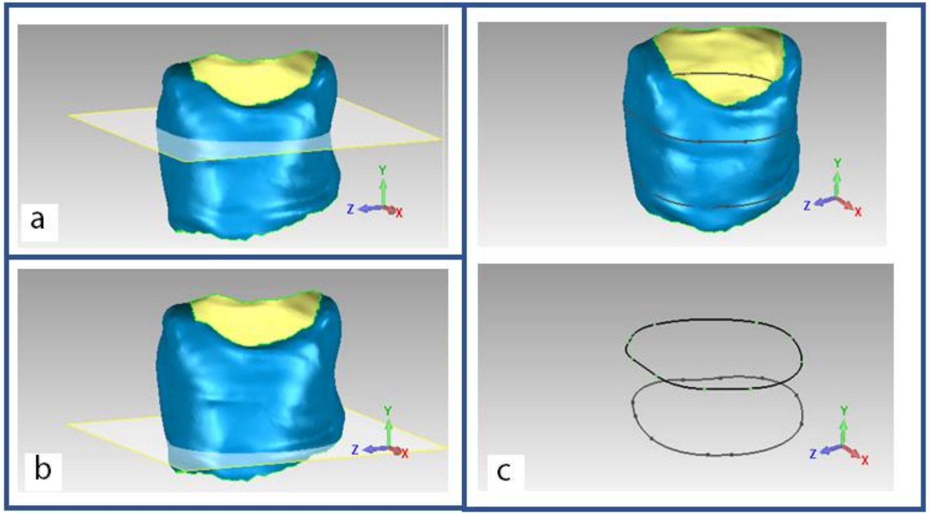
- To understand how movement affects the measurements, using LiDAR, two single shot scans from the side of the body and a third complessive scan were performed. The Reconstruction of the torso was performed in 3-Matic Materialise.
- This way it was possible to allign the structured light scan.

Results

- From the reconstructed model, the following measurements were extracted and compared to the manual measurements:
- a) circumferences at chest and waist levels
- b) Intersection between plane and model.



a) Body Child reconstruction with: b) Photogrammetry c) LiDAR and SL



Torso reconstruction and measurements

Conclusions

The shape of the human torso of a child was finally reconstructed, 3D printed and used for the creation of a patient-specific brace.

A final uncertainty of 0,8 mm was achieved. This result is valid, as in medical plasters applications the required uncertainty is 1,5 mm.

Future developments will focus on combining fast and low-cost techniques and algorithms with low-cost measurement systems for orthopaedic applications.

FINAL DISCUSSION:

- Different geometries in different scenarios were analyzed, using different scanning techniques (low and high cost)

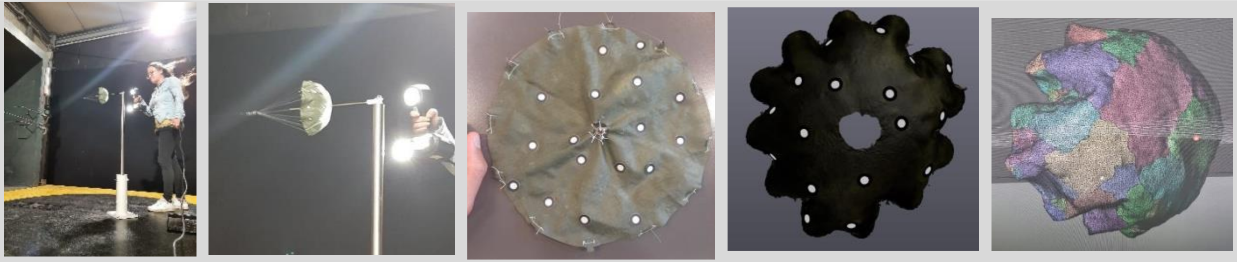
- New methods were defined to evaluate the uncertainty of contactless 3D shape measurements

- New methods suitable to perform scanning of moving objects were developed, reaching performances that allow the techniques to be applied not only in laboratory applications.

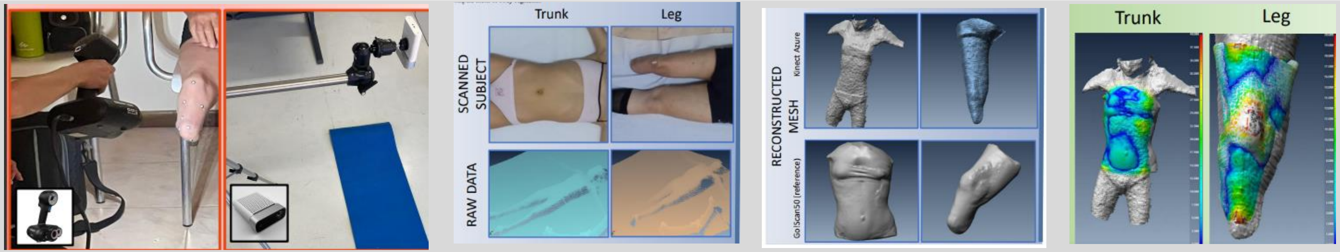
Side Project

Other projects

Motorbike helmet wind tunnel testing



Evaluation of parachute opening for different wind speeds



Comparison of body segment surfaces and volume by low ang high cost sensors

Thanks for the attention

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