Calibration of 2D LiDAR sensors

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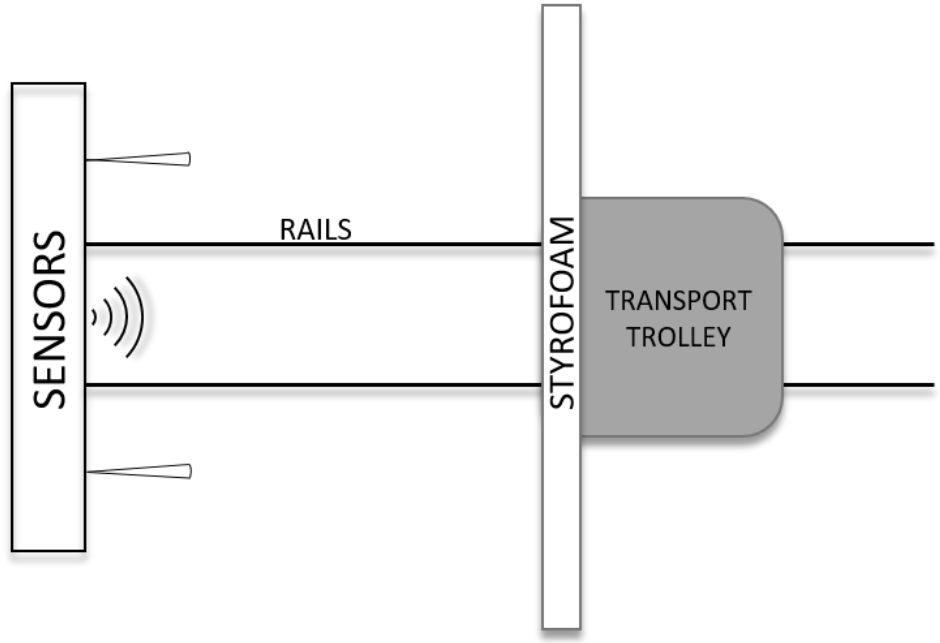
Agenda

- Experiment
- Gathered data
- Sensors’ data analysis
- Calibration results
- Conclusions
- Future research

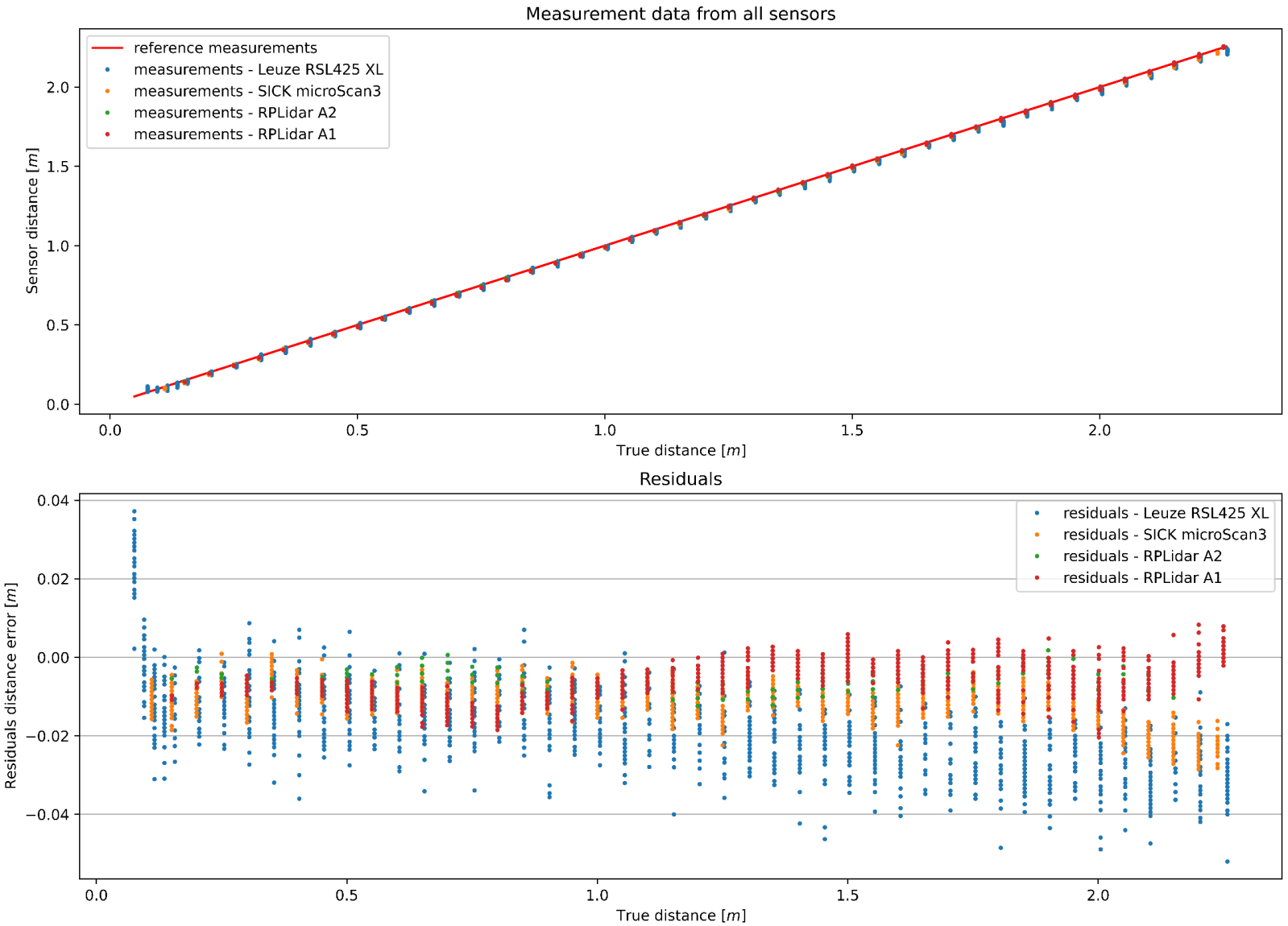
Experiment

- Sensors were connected to a PC
- Full test was performed in range of 0.07-2.25 m
  - From 0.07 m to 0.13 m mobile obstacle was shifted by 0.02 m
  - From 0.13 m to 2.25 m mobile obstacle was shifted by 0.05 m
- All sensors were tested separately to avoid mutual arousing

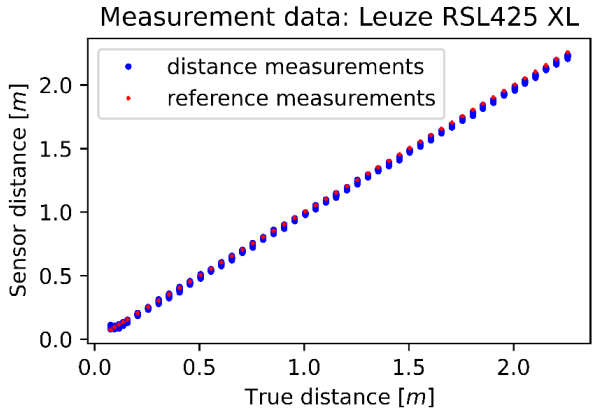
Type	Model	Range	Resolution	Measurement error	FOV
LiDAR 2D	Leuze RSL425 XL	0.05 – 50 m	1 mm	max 60 mm @ 0.3 – 6 m 1% @ >6 m	270 deg
LiDAR 2D	SICK microScan3	0.1 – 64 m	1 mm	max 60 mm @ 0.1 – 6 m 1% @ >6 m	275 deg
LiDAR 2D	RPLidar A1	0.15 – 12 m	1 mm	< 1%	360 deg
LiDAR 2D	RPLidar A2	0.15 – 16 m	1 mm	< 1%	360 deg
LiDAR 1D	Leica DISTO X4	0.05 – 150 m	0.1 mm	1 mm @ 0.05 – 10 m, 0.1 mm/m @ 10 – 30 m, 0.2 mm/m @ 30 – 100 m, 0.3 mm/m @ >100 m	0.034 deg

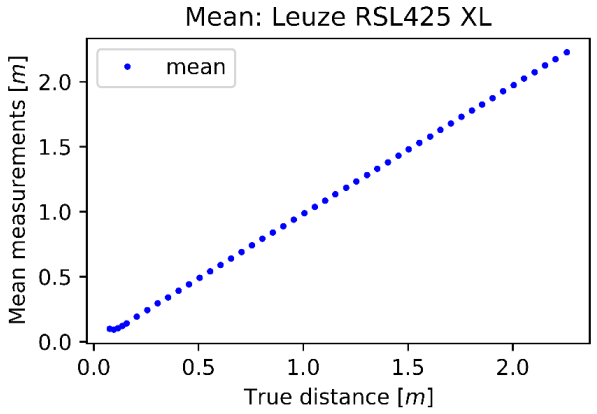


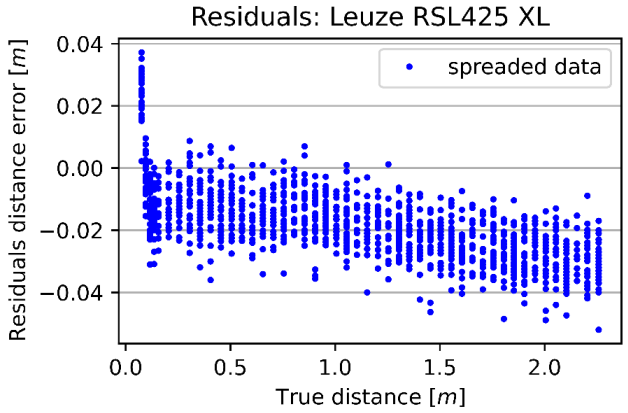
Gathered data

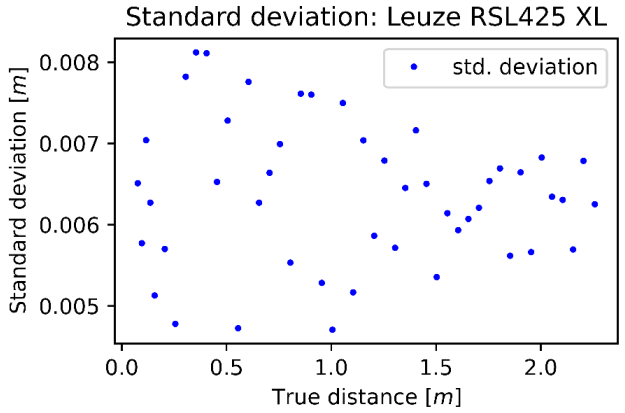


Leuze RSL425 XL





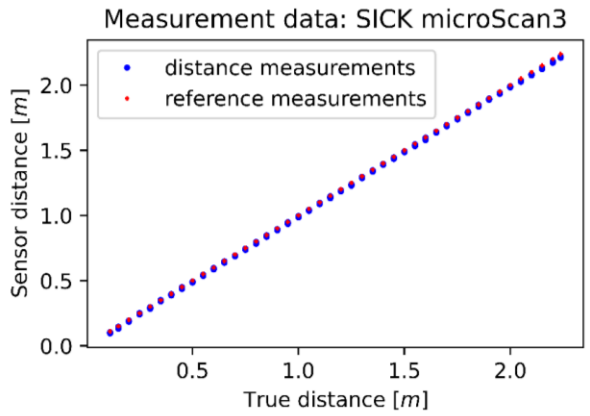


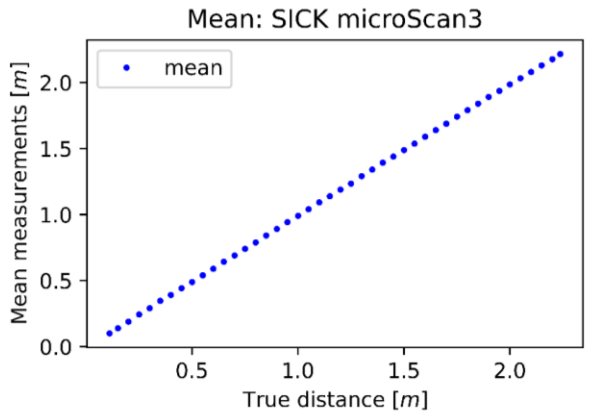


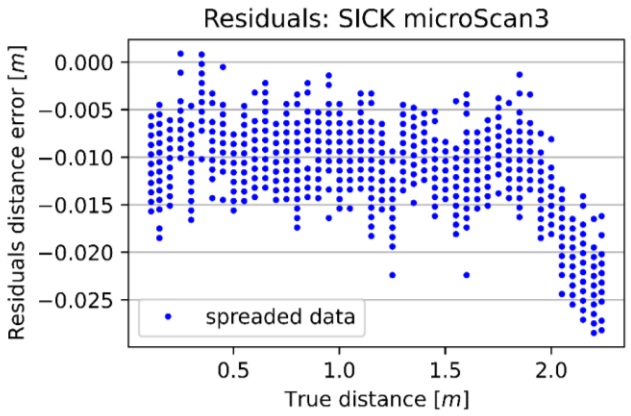
Sensors	Std. deviation [m] in range 0.095 – 2.25 m				Residuals [m]			
	Min.	Avg.	Max.	Max - Min	Min.	Avg.	Max.	RMSE
Leuze RSL425 XL	0.0047	0.0063	0.0081	0.0034	-0.0520	-0.0197	0.0096	0.0218

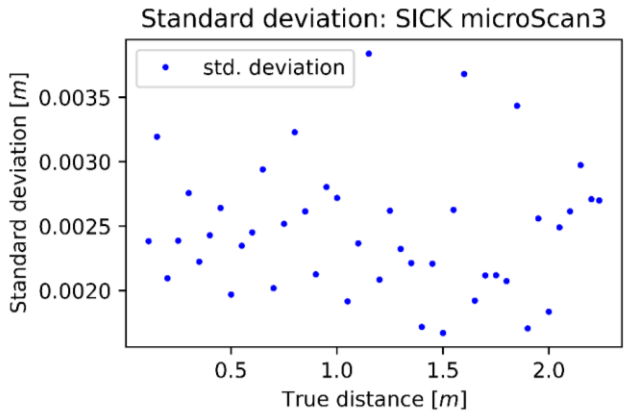
- ✓ Lowest accuracy
- ✓ Lowest precision

SICK microScan3





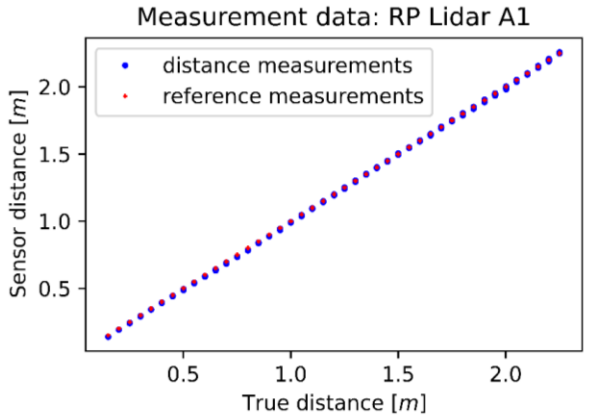


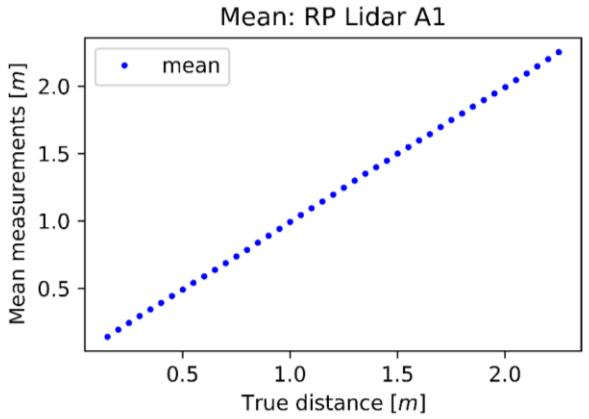


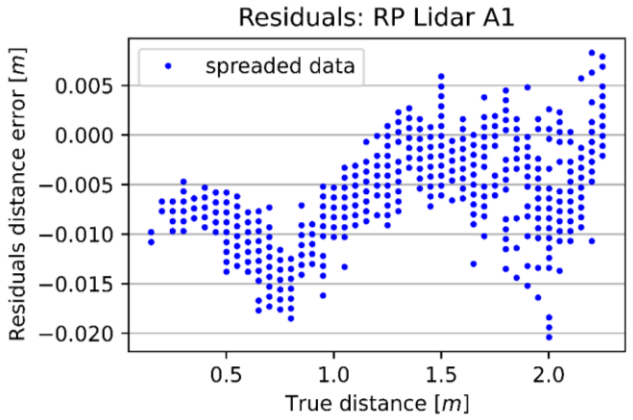
Sensors	Std. deviation [m] in range 0.11 – 2.24 m				Residuals [m]			
	Min.	Avg.	Max.	Max - Min	Min.	Avg.	Max.	RMSE
SICK microScan3	0.0017	0.0025	0.0038	0.0021	-0.0285	-0.0114	0.0009	0.0124

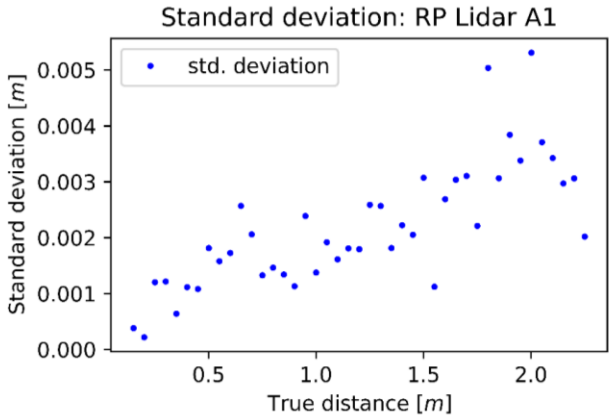
- ✓ Low accuracy
- ✓ Medium precision

RPLidar A1





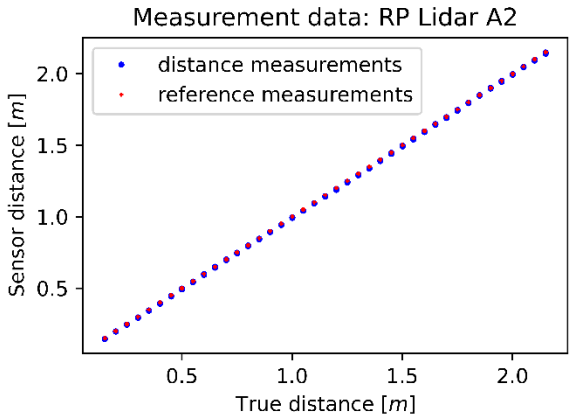


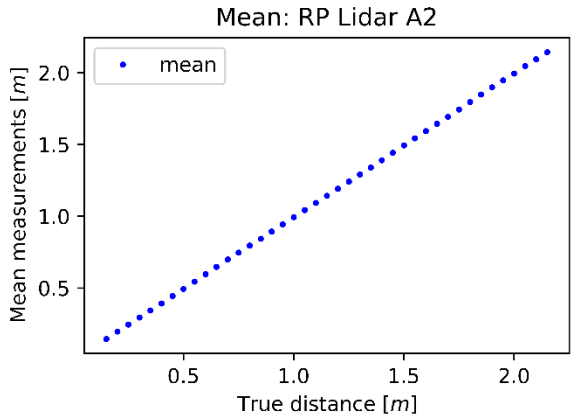


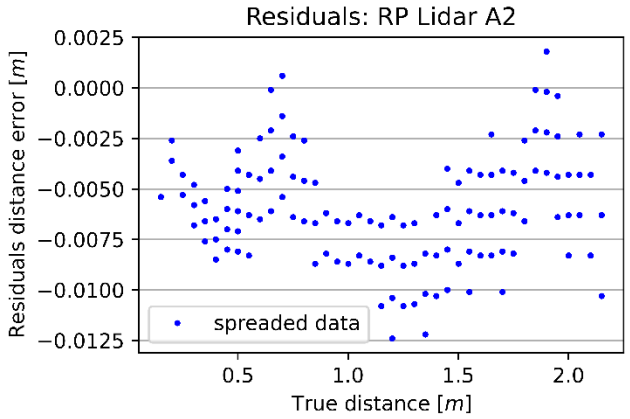
Sensors	Std. deviation [m] in range 0.15 – 2.25 m				Residuals [m]			
	Min.	Avg.	Max.	Max - Min	Min.	Avg.	Max.	RMSE
RPLidar A1	0.0002	0.0022	0.0053	0.0051	-0.0204	-0.0063	0.0083	0.0079

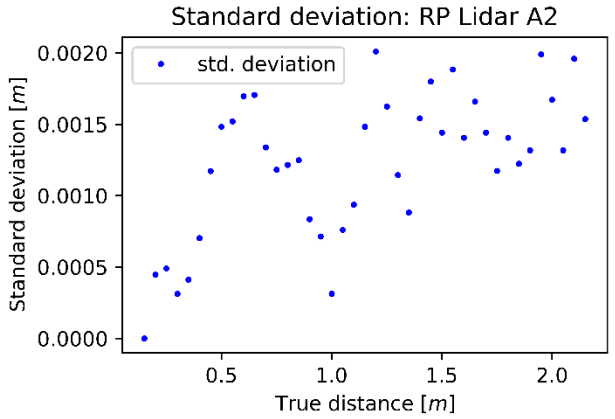
- ✓ Medium accuracy
- ✓ Medium precision

RPLidar A2





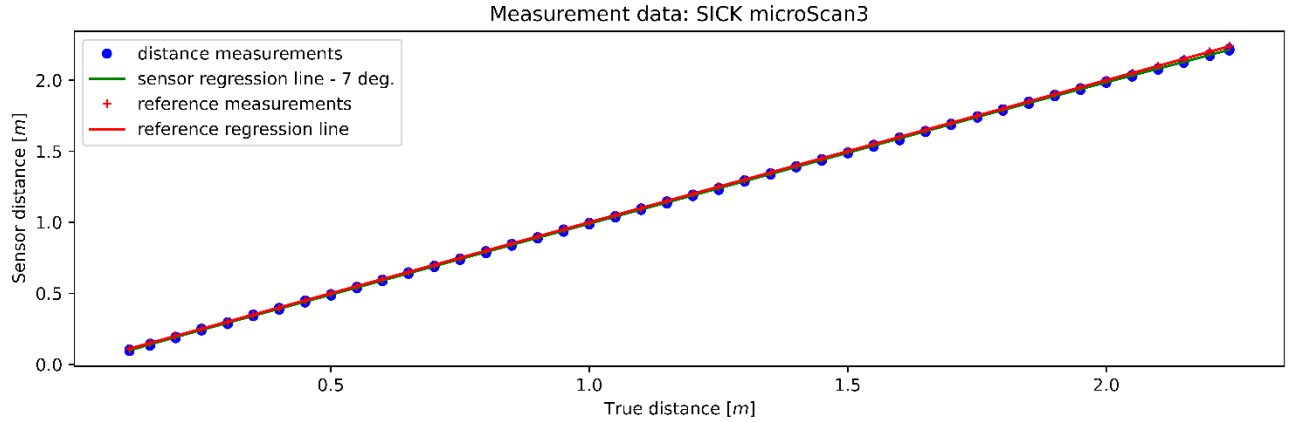


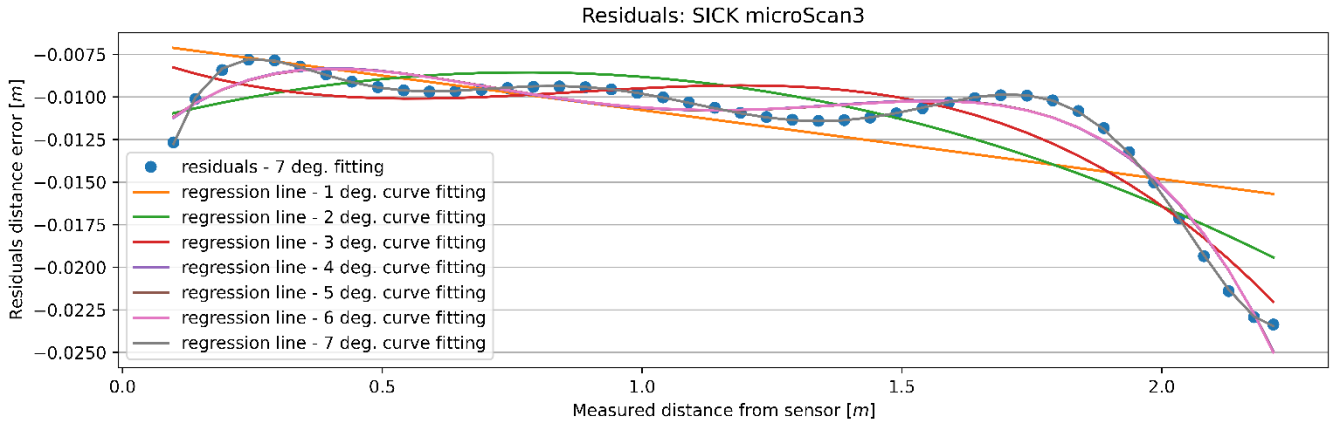


Sensors	Std. deviation [m] in range 0.15 – 2.25 m				Residuals [m]			
	Min.	Avg.	Max.	Max - Min	Min.	Avg.	Max.	RMSE
RPLidar A2	0	0.0012	0.0020	0.0020	-0.0124	-0.0059	0.0018	0.0064

- ✓ Highest accuracy
- ✓ Highest precision

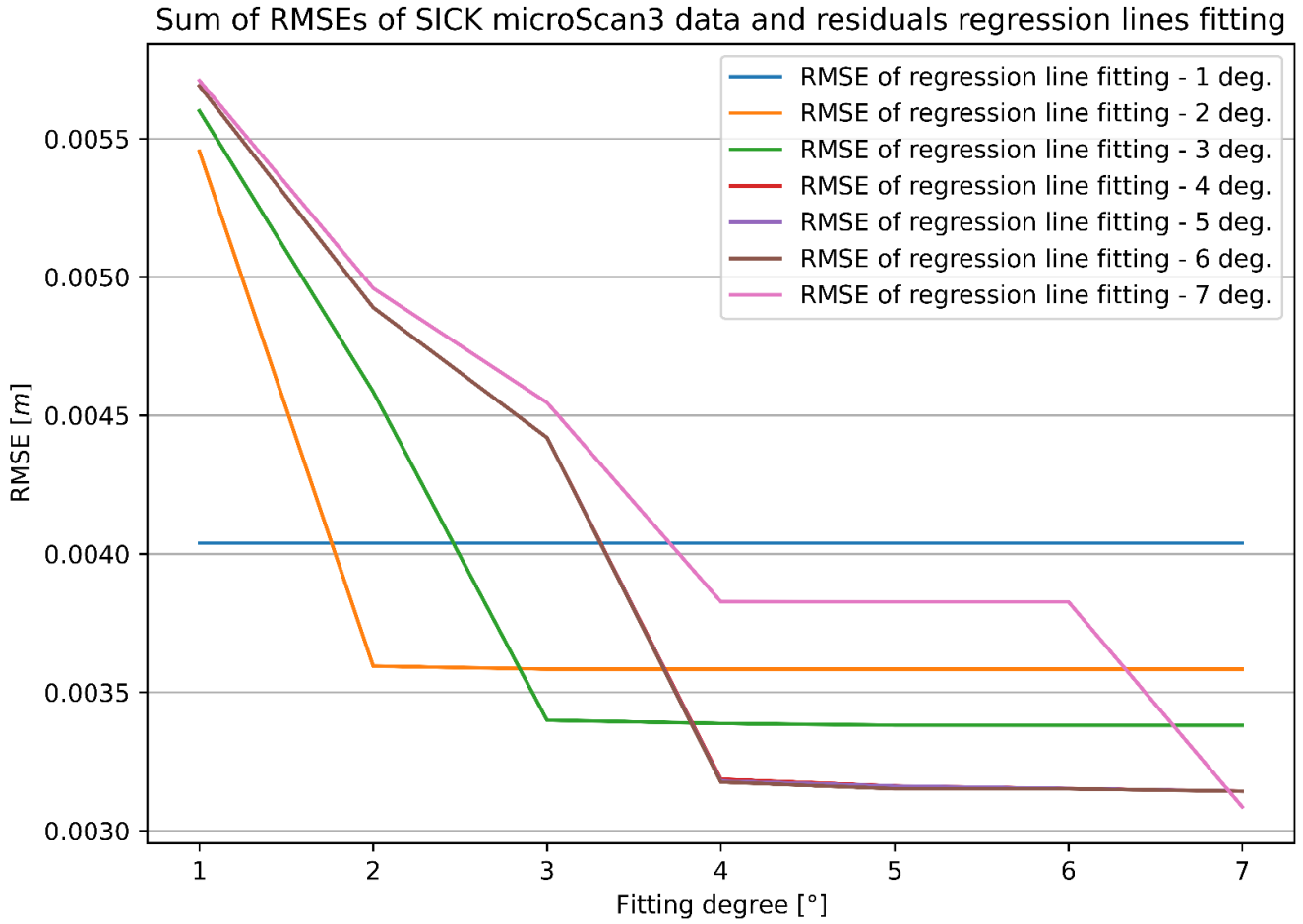
Single section calibration





	Single section curve fitting		
Sensors	RMSE [m]		Percentage of improvement [%]
	Before calibration	After calibration	
SICK microScan3	0.0124	0.0031	75.11

Single section calibration



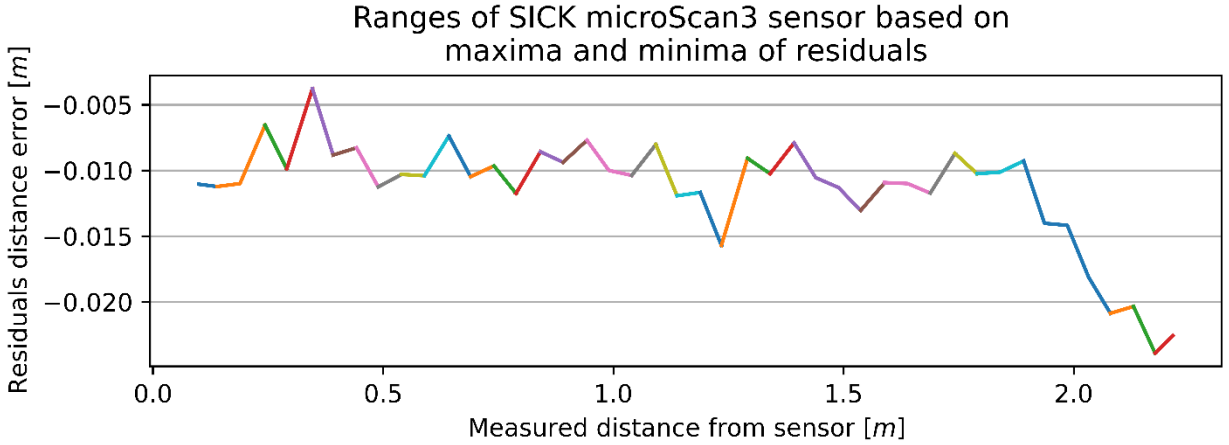
	Single section curve fitting		
Sensors	RMSE [m]		Percentage of improvement [%]
	Before calibration	After calibration	
SICK microScan3	0.0124	0.0031	75.11

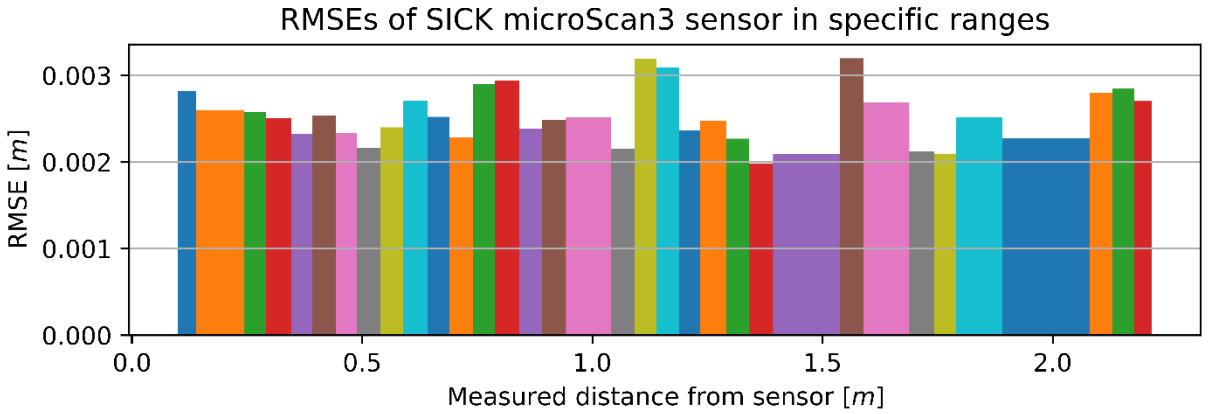
Single section calibration results

		Range		Best fitting degree	Parameters							
		From	To		a	b	c	d	e	f	g	h
1	Data	0.1107	2.2382	7	0.0469	-0.3852	1.2664	-2.1387	1.9784	-0.9855	1.2373	-0.0292
	Residuals	0.0980	2.2148	7	0.0484	-0.3927	1.2726	-2.1144	1.9182	-0.9330	0.2178	-0.0268

$$\boldsymbol{Corrected\ distance = measured\ distance\ - f(measured\ distance)}$$

Adaptive curve fitting





	Single section curve fitting			Adaptive curve fitting			
Sensors	RMSE [m]		Percentage of improvement [%]	RMSE [m]	Percentage of improvement [%]	Difference between calib. methods [m]	Difference between calib. methods [%]
	Before calibration	After calibration		After calibration			
SICK microScan3	0.0124	0.0031	75.11	0.0025	79.52	-0.0006	4.84

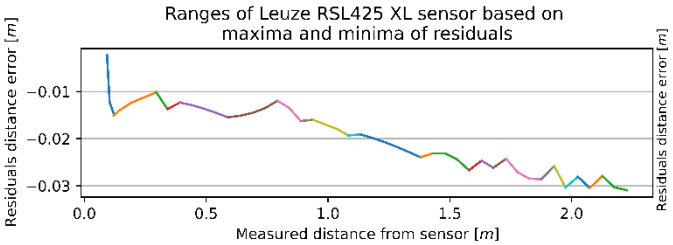
Adaptive curve fitting calibration results

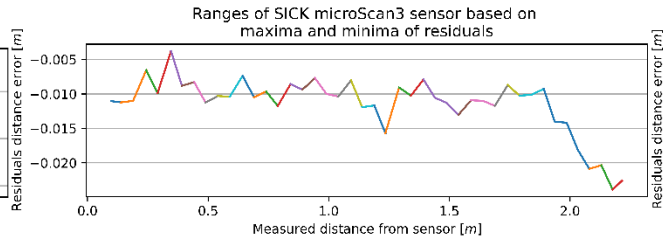
		Range		Best fitting degree	Parameters				
		From	To		a	b	c	d	e
1	Data	0.1107	0.1505	1	0.9956	-0.0106			
	Residuals	0.0996	0.1393	1	-0.0044	-0.0106			
2	Data	0.1505	0.2501	2	0.8480	0.7072	0.0136		
	Residuals	0.1393	0.2436	2	0.7405	-0.2386	0.0076		
3	Data	0.2501	0.3006	1	0.9342	0.0099			
	Residuals	0.2436	0.2907	1	-0.0705	0.0106			
4	Data	0.3006	0.3502	2	1.1320	0.3862	0.0723		
	Residuals	0.2907	0.3464	1	0.1095	-0.0417			
5	Data	0.3502	0.4003	1	0.8992	0.0315			
	Residuals	0.3464	0.3915	1	-0.1121	0.0351			
6	Data	0.4003	0.4505	1	1.0110	-0.0132			
	Residuals	0.3915	0.4422	1	0.0108	-0.0131			
7	Data	0.4505	0.5006	2	-2.8213	3.6240	-0.6178		
	Residuals	0.4422	0.4893	1	-0.0631	0.0196			
8	Data	0.5006	0.5506	2	2.6612	-1.7785	0.7128		
	Residuals	0.4894	0.5403	1	0.0186	-0.0204			
9	Data	0.5506	0.6002	3	2.0556	2.0666	-3.4232	1.4555	
	Residuals	0.5403	0.5898	1	-0.0020	-0.0092			
10	Data	0.6002	0.6502	3	0.3753	4.1800	-4.6066	1.7677	
	Residuals	0.5898	0.6428	1	0.0570	-0.0440			

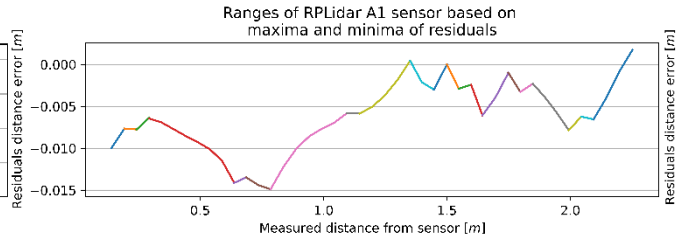
		Range		Best fitting degree	Parameters				
		From	To		a	b	c	d	e
11	Data	0.6502	0.7005	1	0.9384	0.0327			
	Residuals	0.6428	0.6900	1	-0.0657	0.0348			
12	Data	0.7005	0.7504	1	1.0165	-0.0221			
	Residuals	0.6900	0.7408	1	0.0163	-0.0217			
13	Data	0.7504	0.8004	2	-2.9367	5.5123	-1.7420		
	Residuals	0.7408	0.7887	1	-0.0438	0.0228			
14	Data	0.8004	0.8502	3	1.1763	0.5360	-2.2253	1.6232	
	Residuals	0.7886	0.8416	1	0.0599	-0.0590			
15	Data	0.8502	0.9003	1	0.9840	0.0050			
	Residuals	0.8416	0.8909	1	-0.0162	0.0051			
16	Data	0.9003	0.9504	4	4.4140	-2.8599	-3.2164	0.3343	2.3840
	Residuals	0.8909	0.9427	1	0.0324	-0.0382			
17	Data	0.9504	1.0504	2	0.3850	0.2029	0.4021		
	Residuals	0.9427	1.0400	2	0.4178	-0.8558	0.4278		
18	Data	1.0504	1.1003	3	0.3823	-1.3510	2.6260	-0.6709	
	Residuals	1.0400	1.0923	1	0.0450	-0.0572			
19	Data	1.1003	1.1503	3	-0.4185	2.4895	-3.0908	2.0366	
	Residuals	1.0923	1.1384	1	-0.0846	0.0844			
20	Data	1.1503	1.2005	1	1.0050	-0.0177			
	Residuals	1.1384	1.1888	1	0.0050	-0.0176			
... [34]									

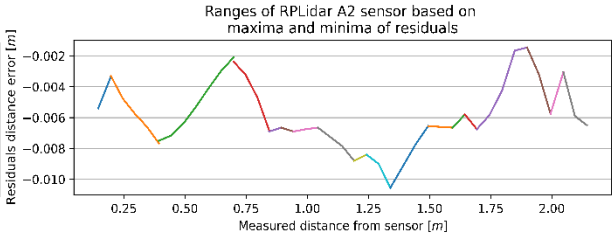
$$Corrected\ distance = measured\ distance - f(measured\ distance)$$

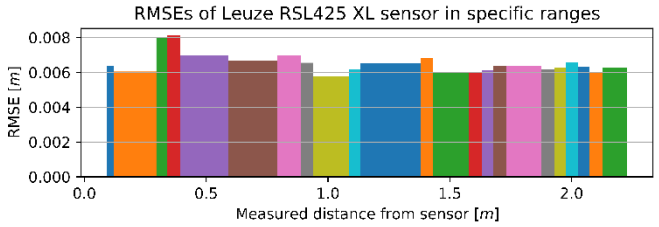
Calibration results

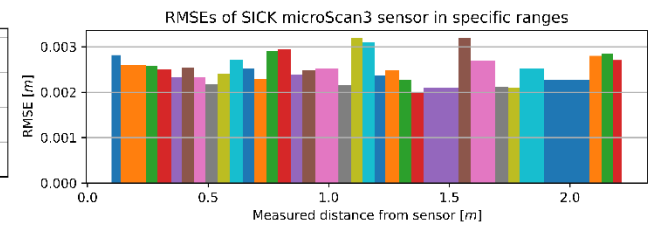


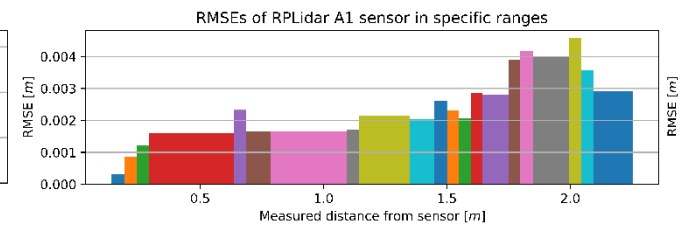


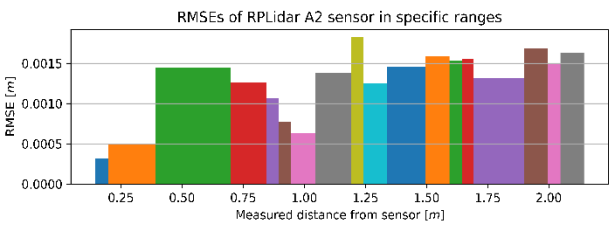










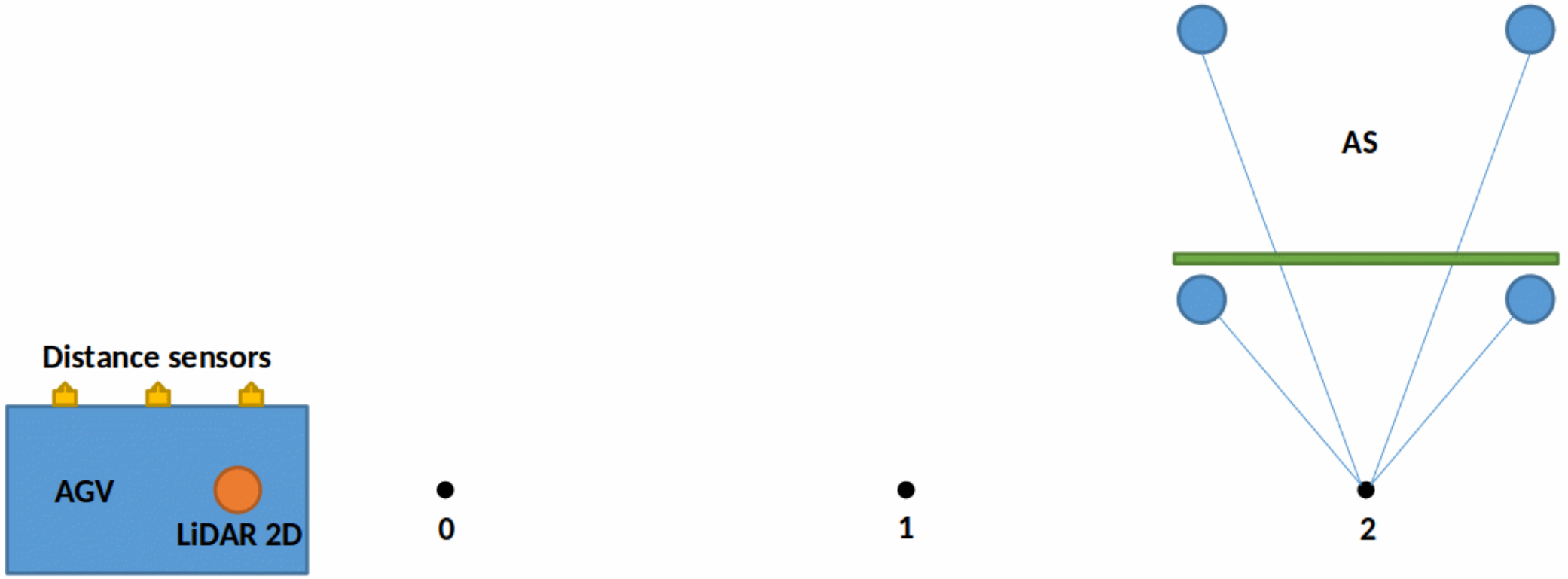


Sensors	Single section curve fitting			Adaptive curve fitting		Difference between calib. methods [m]	Difference between calib. methods [%]
	RMSE [m]		Percentage of improvement [%]	RMSE [m]	Percentage of improvement [%]		
	Before calibration	After calibration		After calibration			
For range 0.095 – 2.25m							
Leuze RSL425 XL	0.0218	0.0067	69.37	0.0069	68.50	+0.0002	-0.92
For range 0.1160 – 2.25m							
Leuze RSL425 XL	0.0220	0.0066	70.20	0.0065	70.35	-0.0001	0.45
For range 0.1359 – 2.25m							
Leuze RSL425 XL	0.0221	0.00654	70.48	0.00648	70.73	-0.00006	0.27
For range 0.11 – 2.24m							
SICK microScan3	0.0124	0.0031	75.11	0.0025	79.52	-0.0006	4.84
For range 0.15 – 2.25m							
RPLidar A1	0.0079	0.0028	64.26	0.0024	69.12	-0.0004	0.50
For range 0.15 – 2.15m							
RPLidar A2	0.0064	0.0018	72.57	0.0013	79.14	-0.0005	7.81

Conclusions

- Adaptive curve fitting calibration method enables to:
  - divide the measuring range for a given sensor into sections based on the determination of the minima and maxima points of residuals
  - increase sensors' accuracy and obtain the smallest possible measurement error for a given measuring section
- After adaptive curve fitting all sensors improved their measurement accuracy to their level of standard deviation
- The proposed solution enables to calibrate a given batch of sensors or a single sensor
- Due to the requirement to use many polynomials to perform calculations, it is advisable to tabulate the calibration results

Docking procedure



Thank you

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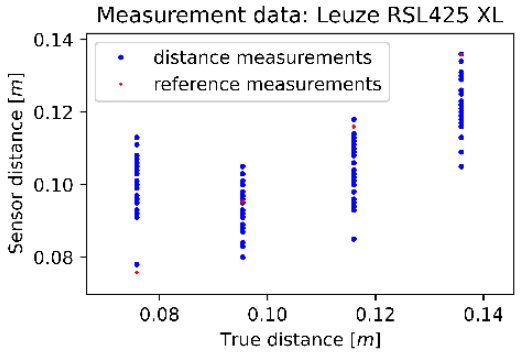
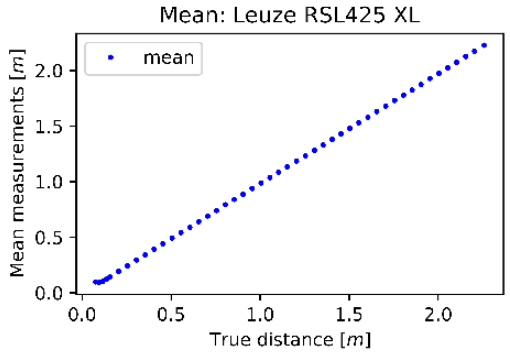
Comparison

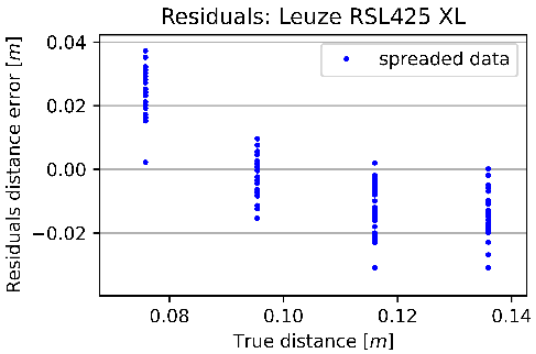
Sensors	Std. deviation [m]				Residuals [m]			
	Min.	Avg.	Max.	Max - Min	Min.	Avg.	Max.	RMSE
Leuze RSL425 XL	0.0047	0.0063	0.0081	0.0034	-0.0520	-0.0197	0.0096	0.0218
SICK microScan3	0.0017	0.0025	0.0038	0.0021	-0.0285	-0.0114	0.0009	0.0124
RPLidar A1	0.0002	0.0022	0.0053	0.0051	-0.0204	-0.0063	0.0083	0.0079
RPLidar A2	0	0.0012	0.0020	0.0020	-0.0124	-0.0059	0.0018	0.0064

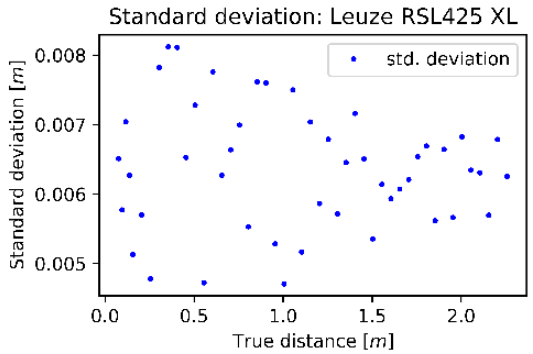
	Single section curve fitting			Adaptive curve fitting			
Sensors	RMSE [m]		Percentage of improvement [%]	RMSE [m]	Percentage of improvement [%]	Improvement between calib. methods [m]	Improvement between calib. methods [%]
	Before calibration	After calibration		After calibration			
For range 0.095 – 2.25m							
Leuze RSL425 XL	0.0218	0.0067	69.37	0.0069	68.50	+0.0002	-0.92
For range 0.1160 – 2.25m							
Leuze RSL425 XL	0.0220	0.0066	70.20	0.0065	70.35	-0.0001	0.45
For range 0.1359 – 2.25m							
Leuze RSL425 XL	0.0221	0.00654	70.48	0.00648	70.73	-0.00006	0.27
For range 0.11 – 2.24m							
SICK microScan3	0.0124	0.0031	75.11	0.0025	79.52	-0.0006	4.84
For range 0.15 – 2.25m							
RPLidar A1	0.0079	0.0028	64.26	0.0024	69.12	-0.0004	0.50
For range 0.15 – 2.15m							
RPLidar A2	0.0064	0.0018	72.57	0.0013	79.14	-0.0005	7.81

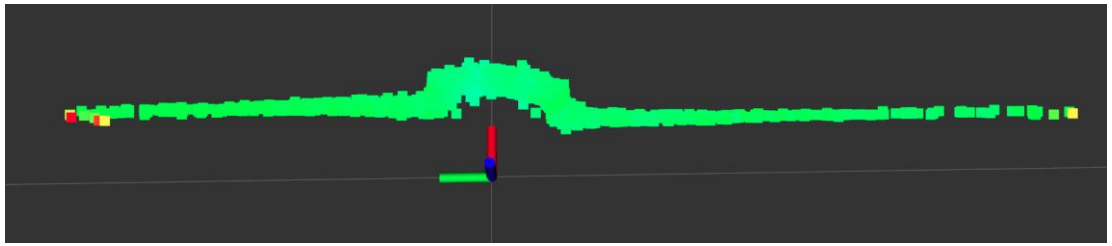
Leuze RSL425 XL

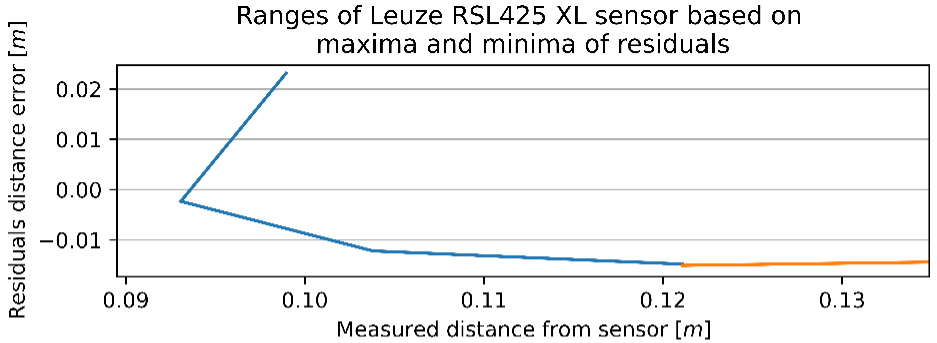


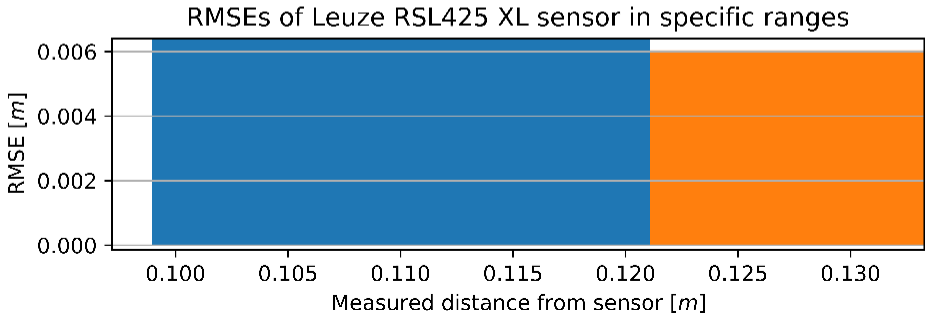


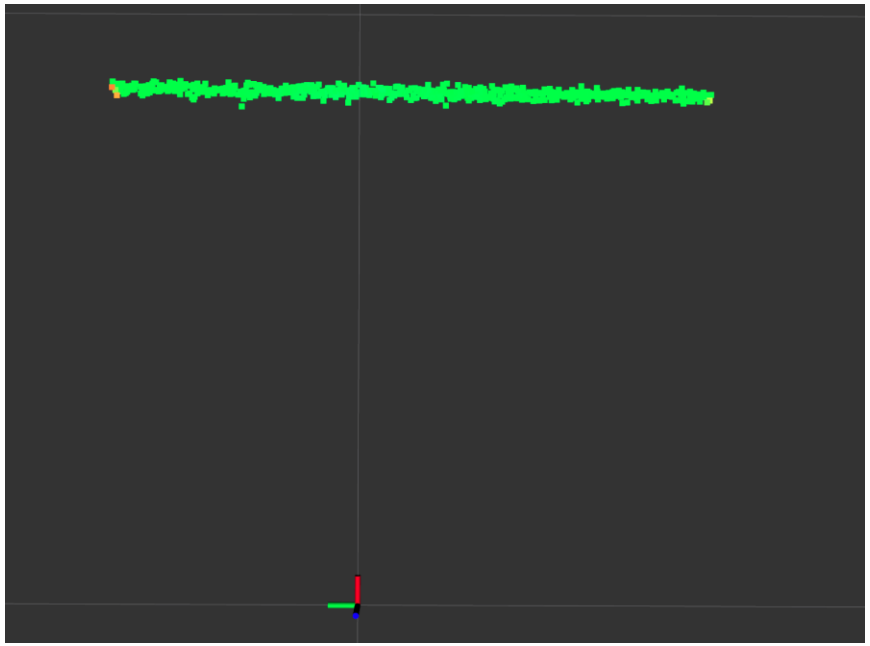




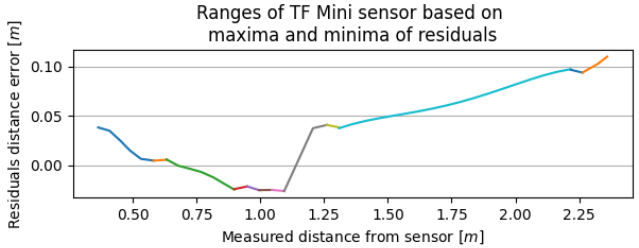


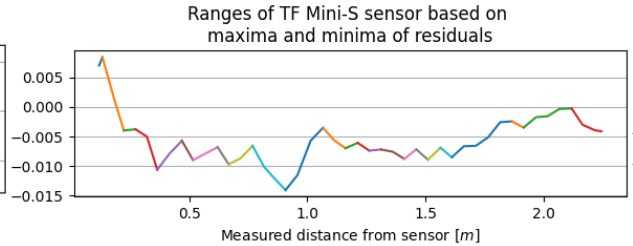


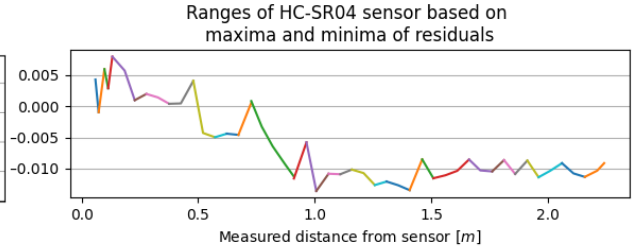


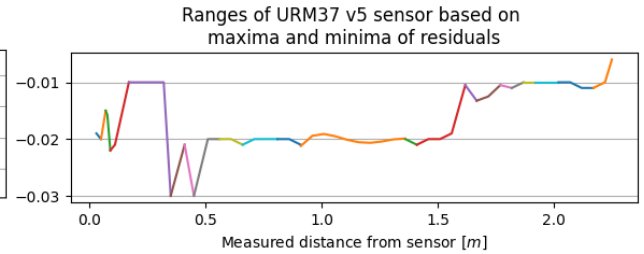


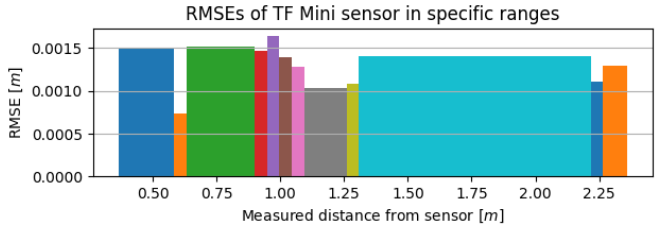
Single-beam distance sensors - calibration results

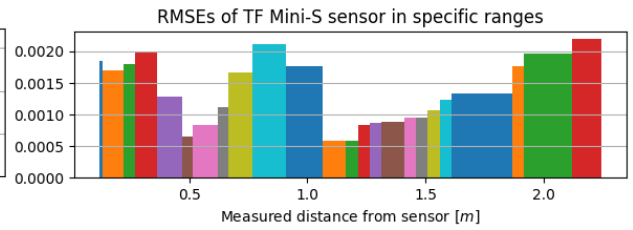


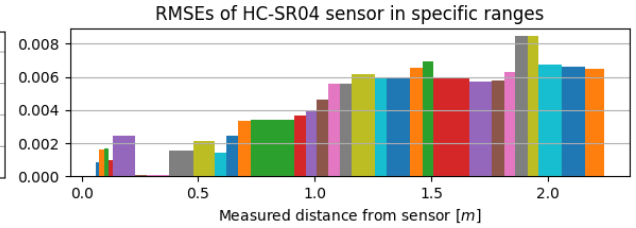


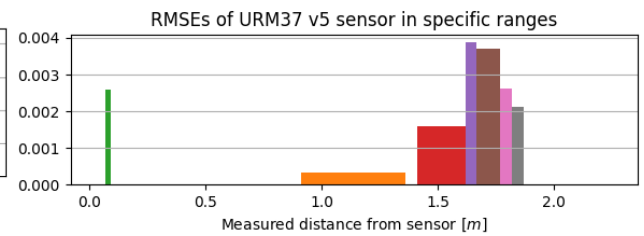












	Single section curve fitting			Adaptive curve fitting			
Sensors	**RMSE [m]**		**Percentage of improvement [%]**	**RMSE [m]**	**Percentage of improvement [%]**	**Improvement between calib. methods [m]**	**Improvement between calib. methods [%]**
	Before calibration	**After calibration**		**After calibration**			
TF Mini	0.0560	0.0103	81.58	0.0014	97.48	-0.0089 m	15.90 %
TF Mini-S	0.0072	0.0025	65.83	0.0016	78.31	-0.0009 m	12.48 %
HC-SR04	0.0100	0.0054	46.28	0.0050	49.69	-0.0004 m	3.41 %
URM37 v5	0.0177	0.0035	80.38	0.0014	92.30	-0.0021 m	11.92 %

Used methods of calibration

Single section

1. Reference sensor measurements curve fitting,
2. Assessment goodness of curve fitting to reference sensor measurements,
3. Curve fitting of not calibrated sensor measurements,
4. Assessment goodness of curve fitting to not calibrated sensor measurements,
5. Measurement of differences between reference regression line and the curve of not calibrated sensor (residuals),
6. Curve fitting of differences determined in step 5,
7. Assessment goodness of the final fitting.

Adaptive curve fitting

1. Reference sensor measurements curve fitting,
2. Assessment goodness of curve fitting to reference sensor measurements,
3. Averaging of all measurement series of not calibrated sensor,
4. Measurement of differences between reference regression line and the mean points of not calibrated sensor,
5. Finding a minima and maxima points of differences from step 4 and determination of descending and ascending sections,
6. Performing single section calibration for every section determined in step 5