BIFROST AVS VACUUM TANK MOTION SAT

	Name	Role/Title
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1. RESULTS

In general, the tests went well until the test measuring the total motion range. When approaching the upper hard limit, the tank collided with the center concrete block. Most tests were already done before the collision but some extra data was collected after in order to see if the collision had any impact on the motion performance of the movement. A comparison can be found in chapter 2.

1.1. General inspection

- Vacuum equipment was found to be connected and prevented motion and had to be disconnected.
- Grounding of crate vs the vacuum tank assembly was measured to be OK.
- A small dent on the Posital encoder housing was identified, Figure 1.

Figure 1: Posital encoder dent

1.2. Initial motion test

1.2.1.Switches

All switches except the anti-collision switch was found to be engaging properly. The anti-collision switch was therefore adjusted.

1.2.2.Gear ratio

Basic gear ratios were calculated for both encoder and motor.
Gear ratio motor: $8{,}10165*10^{-5} deg_{tank}/deg_{motor}$
Gear ratio encoder: $4.43610^{-5} deg_{tank}/counts_{encoder}$

These gear ratios were used to generate setpoints for the further tests.
For analysis of the data, gear ratios calculated from the accuracy test are used.

Backlash

A simple backlash tests was performed at approx. -10deg (only at one position). The test measures only the backlash between encoder and motor shaft.

Figure 2 shows a graph for the backlash test in forward direction and Figure 3 shows the backlash test in backward direction.

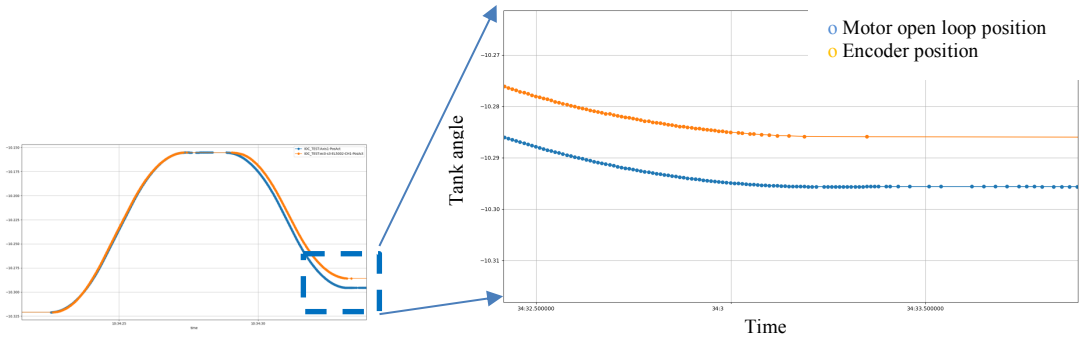

Figure 2: Backlash test in backward direction

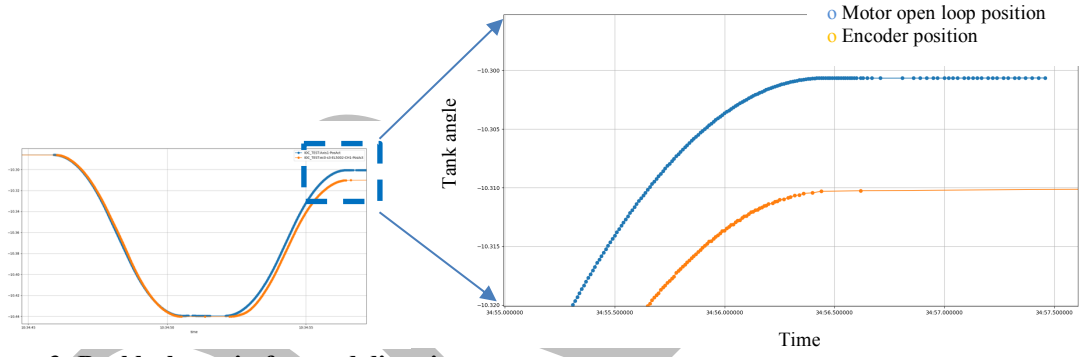

Figure 3: Backlash test in forward direction

Both tests indicate a backlash of 0.01deg between motor and encoder.

1.3. Motion range and switch performance

1.3.1.Motion range

The low hard stop was measured to be at approx. -10.98deg. and the upper hard stop could not be reached.
When approaching the upper hard limit, the tank collided with the center concrete block, Figure 4.

Figure 4: Collision with center concrete block.

After the collision, the CAD drawings were checked and there it was clear that it would not be possible to reach the hard stop, Figure 5, unfortunately this was not realized before it happened.

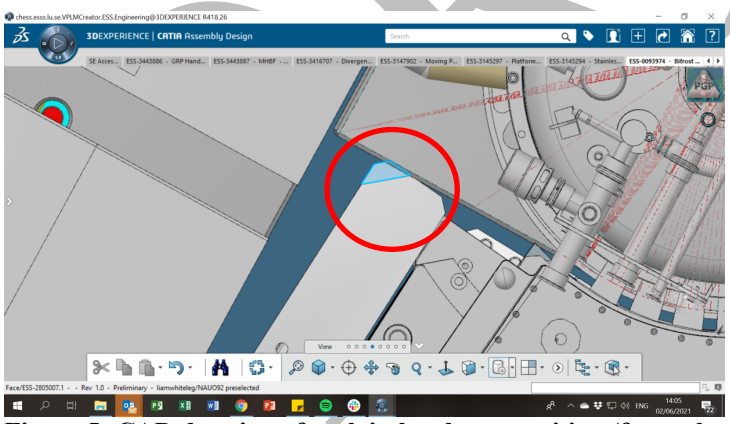

Figure 5: CAD drawing of tank in hard stop position (from above)

As can be seen in the cad drawing, the edge of the upper tank frame collides with the concrete block and after analysis it was concluded that both the concrete block and the tank frame was displaced. An analysis of the motion performance differences before and after the collision can be found in chapter 2.

1.3.2.Switch performance

Data acquired in the switch performance test are presented in Appendix A Switch performance. The data switch position data is based on encoder position that have been calibrated with laser tracker measurements from the accuracy tests described in chapter 1.5.
The data is summarized in Table 1.

Table 1: Switch performance

	Engage		Disengage	
Switch	**Position [deg]**	**Range [deg]**	**Position [deg]**	**Range [deg]**
Low kill	-4,606	0,001	-4,574	0,000
Low limit	-4,281	0,001	-4,253	0,001
Anti-collision	32,863	0,000	32,831	0,000
High limit	44,965	0,000	44,923	0,000
High kill	45,350	0,000	45,321	0,000

1.4. High speed test

No problem was encountered when running in 0.1 deg/s. The whole stroke was measured and the encoder and motor position follow like expected, see Figure 6.

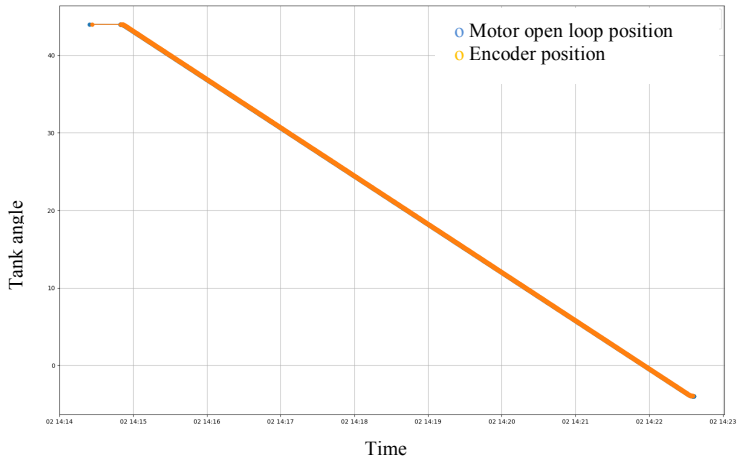

Figure 6: High speed test over entire stroke (backward direction)

By removing the linear component of the encoder position data, the error of encoder position versus the motor position can be analyzed, see Figure 7.

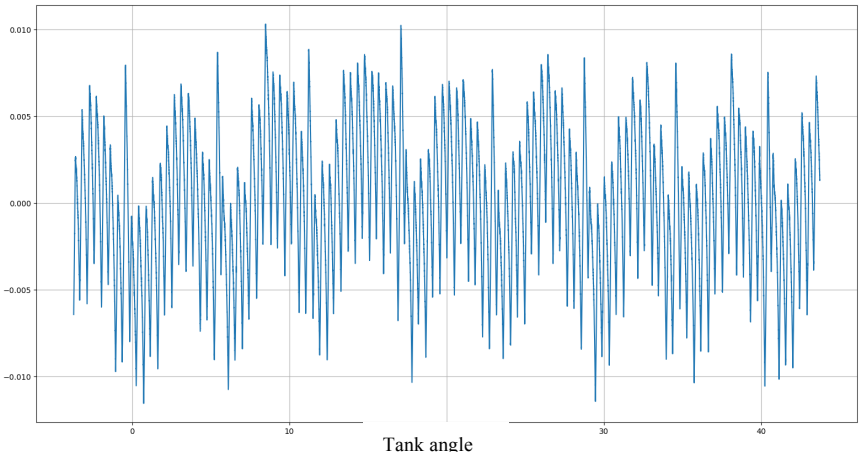

Figure 7: Encoder error vs tank angle (without backlash)

The data shows a repeated oscillation, each 5-6 degrees, in the error between the motor position and encoder position. Also, a shorter wavelength disturbance can be identified, Figure 8. The source of these errors can probably be found in the mechanical design, like frame design and motion system (gears and chains).

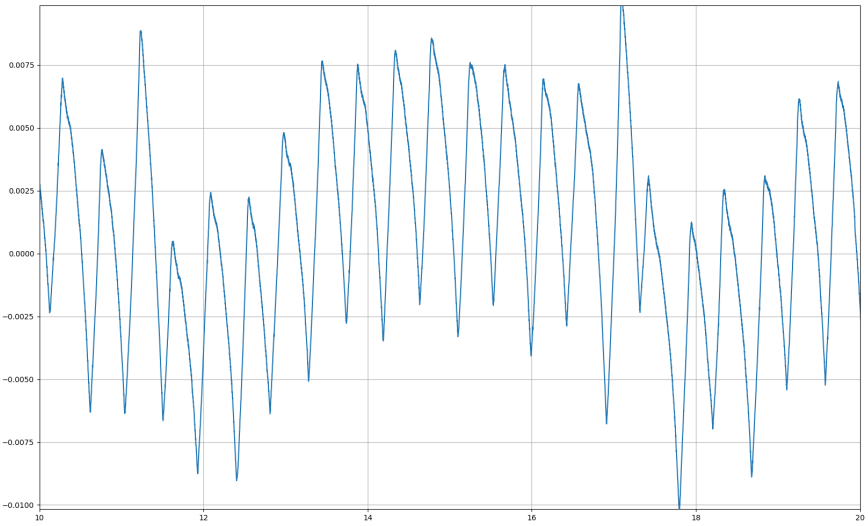

Figure 8: Encoder error vs tank angle, zoom 10..20 deg (without backlash)

Both these disturbances will lead to a maximum error over the stroke of +-0.01 degrees between the motor position and the encoder position (excluding backlash).

1.5. Accuracy

Table 2, shows the data collected during the accuracy test.

Table 2: Accuracy test data

Position	Laser tracker position [deg]	Open loop position [deg]	Open loop diff abs [deg]	Encoder [deg]	Encoder Diff abs [deg]
hardstop low	-10,98	-10,97821038	0,001789625	-10,97441724	0,005582764
-5	-5,0177	-5,0097	0,0080	-5,0102	0,0075
0	0,0192	-0,0081	0,0273	-0,0117	0,0309
5	4,9862	4,9934	0,0072	4,9956	0,0094
10	9,9888	9,9949	0,0061	9,9986	0,0098
15	14,9897	14,9964	0,0067	15,0016	0,0119
20	19,9951	19,9980	0,0029	19,9979	0,0028
25	24,9998	24,9995	0,0003	24,9971	0,0027
30	29,9965	30,0010	0,0045	29,9951	0,0014
35	35,0005	35,0025	0,0020	34,9974	0,0031
40	40,0095	40,0041	0,0054	40,0049	0,0046
45	45,0127	45,0056	0,0071	45,0114	0,0013
hardstop high	48,5000				

From the data the optimal gear ratio and accuracy can be calculated, see Table 3.

Table 3: Accuracy

Source	Gear ratio []	Offset [deg]	Accuracy [deg]
Open loop position	8,10412E-05 deg_{tank}/deg_{motor}	-0,0081	0,0273
Encoder position	-4,45114E-05 deg_{tank}/encoder count	30,7267	0,0309

Note: Since only one data point per target position was measured, the maximum deviation from target position is considered to be the accuracy.

In Table 2, the value at 0 degrees is clearly standing out with high deviation. If the values at zero is considered as an outlier and thereby excluded the updated accuracy values can be found in Table 4 and Table 5.

Table 4: Accuracy test data with position zero excluded

Position	Laser tracker [deg]	Open loop position [deg]	Open loop diff abs [deg]	Encoder [deg]	Encoder Diff abs [deg]
hardstop low					
-5	-5,0177	-5,0194	0,0017	-5,02125	0,0036
0	Excluded	Excluded	Excluded	Excluded	Excluded
5	4,9862	4,9862	0,0000	4,9875	0,0013
10	9,9888	9,9890	0,0002	9,9920	0,0032
15	14,9897	14,9919	0,0022	14,9964	0,0067
20	19,9951	19,9947	0,0004	19,9942	0,0009
25	24,9998	24,9975	0,0023	24,9949	0,0049
30	29,9965	30,0004	0,0039	29,9944	0,0021
35	35,0005	35,0032	0,0027	34,9981	0,0024
40	40,0095	40,0060	0,0035	40,0071	0,0024
45	45,0127	45,0089	0,0038	45,0150	0,0023
hardstop high	48,5000				

Table 5: Accuracy with position 0 excluded

Source	Gear ratio	Offset [deg]	Accuracy [deg]
Open loop position	8,1062E-05	-0,0166	0,0039
Encoder position	-4,4525E-05	30,7262	0,0067

1.6. Bidirectional repeatability

Data acquired during the repeatability test are listed in Appendix B: Repeatability data.
Based on these data sets the repeatability can be calculated to be 0.010 deg.

2. DIFFERENCES BEFORE AND AFTER COLLISION

In order to judge if the collision have impacted the performance of the motion system some comparisons can be made by looking at data collected before and after. Unfortunately, only a few comparable datasets have been identified but in total three comparisons can be made based on the recorded data:

1. Backlash
2. Encoder error (vs linear open loop counter)
3. Accuracy and gear ratio

2.1. Backlash

From the data acquired during the high-speed tests also backlash in one direction can be checked. Figure 9 shows motor open loop counter and encoder position during the acceleration phase.

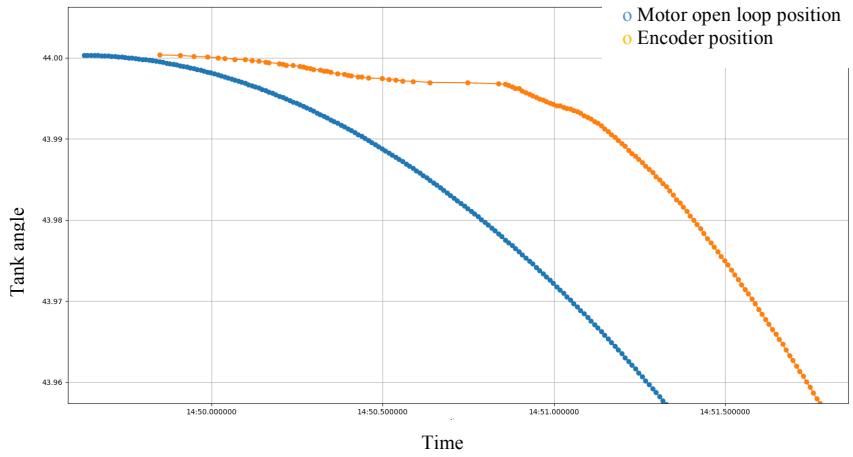

Figure 9: Backlash after collision

For this move the backlash seems to be approx. 0.02deg compared to 0.01deg before. Another thing worth noting is the behavior of the encoder position curve where the value seems to update unpredictable in the acceleration phase

Note: Before the collision, no data was recorded at this tank angle. Therefore, it's hard to judge if the increase in backlash is related to the collision.

2.2. Motor position vs encoder position

Data for open loop counter position and encoder position was acquired for angles between 9 and 23 degrees both before and after collision. Unfortunately, the velocity was different at the two tests:

- before collision 688deg$_{motor}$/s
- after collision 1280deg$_{motor}$/s

Figure 10 shows the deviation of the encoder position from the motor open loop position at angles between 9 to 23 degrees (at a velocity of 688deg$_{motor}$/s). Figure 11 shows the same data but acquired after the collision but at a higher velocity (1280deg$_{motor}$/s). In both graphs the backlash is not shown.

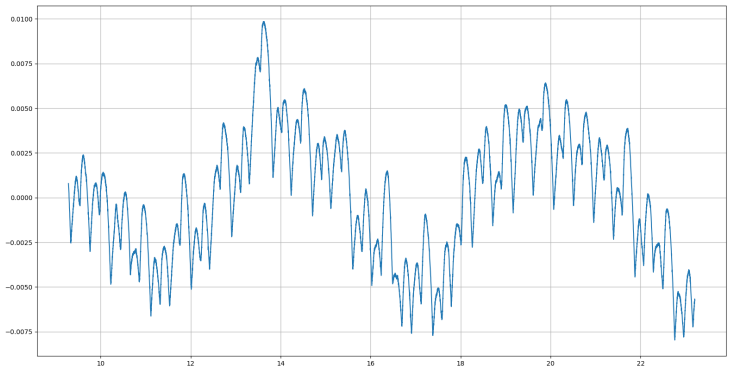

Figure 10: Before collision: Encoder position error (without backlash) at 688deg$_{motor}$/s

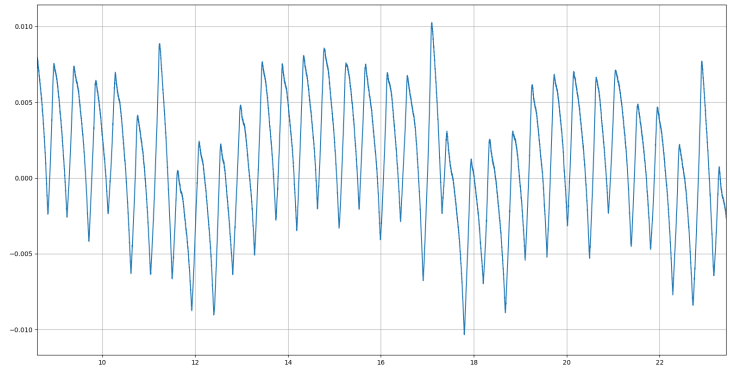

Figure 11: After collision: Encoder position error (without backlash) at 1280deg$_{motor}$/s

The same cyclic error with a frequency of approx. 6 degrees and an amplitude 0.01deg can be identified in both graphs. However, the amplitude of the lower wavelength error has increased after the collision.

2.3. Accuracy and gear ratio

A reduced accuracy test was performed after the collision. In this test, some of the measurement positions were excluded, Table 6. The values for position 0 is excluded in the comparison since data for this position was considered a outlier in the dataset acquired before collision.

Table 6: After collision: Accuracy measurements

Position	Laser tracker [deg]	Open loop position [deg]	Open loop diff abs [deg]	Posital Encoder [deg]	Posital Diff abs [deg]
hardstop low	10.98				
-5	-5,0017	-5,0164	0,0147	-5,0039	0,0022
0	0,0000	-0,0165	excluded	0,0013	excluded
5	4,9725	4,9834	0,0109	4,9737	0,0012
10	9,9755	9,9833	0,0078	9,9784	0,0029
15					
20					
25					
30					
35	34,9801	34,9826	0,0025	34,9763	0,0038
40					
45	44,9890	44,9824	0,0066	44,9908	0,0018
hardstop high					

The calculated accuracy values based on these data are shown in Table 7. These values can be compared with the accuracies calculated based on the data from the same positions before collision, Table 8. Note that the data for position 0 have also been excluded from the data taken from before collision since this data set seems to be an outlier.

Table 7: After collision: Accuracy and gear ratio

Source	Gear ratio	Offset [deg]	Accuracy [deg]
Open loop position	8,10623E-05	0,0001	0,0147
Encoder position	-4,45245E-05	30,7262	0,0038

Table 8: Before collision: Accuracy measurements (same points as after collision but excluding 0 position)

Position	Laser tracker [deg]	Open loop position [deg]	Open loop diff abs [deg]	Posital Encoder [deg]	Posital Diff abs [deg]
hardstop low					
-5	-5,0177	-5,0188	0,0011	-5,0202	0,0025
	Excluded	Excluded		Excluded	
5	4,9862	4,9866	0,0004	4,9878	0,0016
10	9,9888	9,9893	0,0005	9,9919	0,0031
35	35,0005	35,0027	0,0022	34,9961	0,0044
45	45,0127	45,0080	0,0047	45,0123	0,0004
hardstop high					

Table 9: Before collision: Accuracy and gear ratio

Source	Gear ratio	Offset [deg]	Accuracy [deg]
Open loop position	8,10599E-05	-0,0161	0,0047
Encoder position	4,45212E-05	30,7245	0,0044

The accuracy of the motor open loop position has degraded from 0.0047deg to 0.0147 deg. The accuracy of the Posital encoder have not changed significantly, 0.0044 deg before collision compared to 0.0038 after collision.

Worth noting is that the optimal gear ratio has changed slightly mainly for the motor shaft.

3. CONCLUSIONS

Results from the tests are summarized in the below tables. Table 10 shows general results and Table 11 and Table 12 shows motion performance before and after collision.

Table 10: General results

Test:	Description:	Value	Status:	Comment:
1	General Inspection			
1.1	Mechanical			
1.1.1	Observations		OK	Dent on Posital encoder housing. Encoder was concluded to work correct.
1.2	Electrical			
1.2.1	Observations			
1.2.2	Grounding		OK	
1.2.3	Motor Phase A		OK	
1.2.4	Motor Phase B		OK	
1.2.5	Low Limit Switch		OK	
1.2.6	High Limit Switch		OK	
1.2.7	Anti-Collision Switch		OK	Needed adjustment
1.2.8	Low Kill Switch		OK	
1.2.8	High Kill Switch		OK	

Table 11: Results from data acquired before collision

2	Initial Motion Test			
2.1	Gera ratio posital encoder []	-4,4525E-05	OK	
2.1	Gera ratio open loop []	8,1062E-05	OK	
2.1	Backlash [deg]	0,01	OK	Based on one measurement at -10 deg
	Motion Performance			
3	Range and switch performance			
3.1	Range (hard stop to hardstop)		Not ok	Could not reach upper hard limit
3.2	Low Kill Engage [deg]	-4,61	OK	
3.2	Low Kill Disengage [deg]	-4,57	OK	
3.3	Low Limit Engage [deg]	-4,28	OK	
3.3	Low Limit Disengage [deg]	-4,25	OK	
3.4	Anti -Collision Engage [deg]	32,86	OK	
3.4	Anti -Collision Disengage [deg]	32,83	OK	
3.5	High Limit Engage [deg]	44,97	OK	
3.5	High Limit Disengage [deg]	44,92	OK	
3.6	High Kill Engage [deg]	45,35	OK	
3.6	High Kill Disengage [deg]	45,32	OK	

5	**Accuracy open loop [deg]**	0,0039	OK	Zero position was treated as an outlier and therefore excluded.
5	**Accuracy Posital encoder [deg]**	0,0067	OK	Zero position was treated as an outlier and therefore excluded. If analysis is made on only the data points collected after collision the accuracy would be 0,0044
6	**Bidirectional repeatability [deg]**	0,0088	OK	Zero position was treated as an outlier and therefore excluded.

Table 12: Results from after collision

2	**Initial Motion Test**			
2.1	**Gera ratio posital encoder []**	-4,4525E-05	OK	Seems to have changed slightly
2.1	**Gera ratio open loop []**	8,1062E-05	OK	
2.1	**Backlash [deg]**	0,02	Check	Based on high speed test at 45 deg. Need more data to conclude, see chapter 2 for detailed comparison.
	Motion Performance			
4	**High speed test**		OK	
5.1	**Accuracy open loop [deg]**	0,0147	Check	Open loop accuracy seems to be worse after collision. But data is based on only a few measurements, see chapter 2 for detailed comparison
5.2	**Accuracy Posital encoder[deg]**	0,0038	OK	Even better than before collision but fewer measurements, see chapter 2 for detailed comparison.
6	**Bidirectional repeatability [deg]**		Check	Not measured after collision.

In general, the equipment fulfills all of the requirements. However, based on the above analysis it would be good to make a few further tests to at least verify some of the parameters again after collision. One alternative would be to use the Posital encoder as a reference instead of the Laser tracker since it has shown to correspond well to the laser tracker both before and after the collision. Using the Posital encoder as reference system would allow a simpler test setup and faster tests.

4. REFERENCES

[1] EtherCAT organization, https://www.ethercat.org
[2] ecmc, open source motion control, https://accelconf.web.cern.ch/icalepcs2017/talks/mocpl05_talk.pdf

DOCUMENT REVISION HISTORY

Revision	Reason for and description of change	Author	Date
1	First issue	Anders Sandström	2020-12-17

5. APPENDIX A SWITCH PERFORMANCE

Low Kill Switch	Posital encoder			
L1	Engage	Disengage	Engage range	Disengage Range
1	-4,606081958	-4,573677657	0,000712182	0,00031158
2	-4,605681355	-4,573855703		
3	-4,605859401	-4,573855703		
4	-4,606393537	-4,573811191		
5	-4,605903912	-4,573989237		

Low Limit Switch	Posital encoder			
L2	Engage	Disengage	Engage range	Disengage Range
1	-4,280436542	-4,252973007	0,000845716	0,000756694
2	-4,281282258	-4,253329098		
3	-4,280970678	-4,253729701		
4	-4,281104213	-4,253551655		
5	-4,281104213	-4,253729701		

Anticollision Switch	Posital encoder			
L3	Engage	Disengage	Engage range	Disengage Range
1	32,86241426	32,83125629	0,00031158	0,000356091
2	32,86272584	32,8309002		
3	32,86259231	32,83103373		
4	32,8625478	32,83107824		
5	32,86259231	32,83103373		

High Limit Switch	Posital encoder			
L4	Engage	Disengage	Engage range	Disengage Range
1	44,96484186	44,92268956	0,0004006	0,000400602
2	44,96519795	44,92264505		
3	44,96484186	44,92228896		
4	44,96524246	44,92251152		
5	44,96488637	44,92251152		

Switch	Posital encoder			
L5	Engage	Disengage	Engage range	Disengage Range
1	45,34999902	45,32097758	0,00031158	0,00035609
2	45,34982098	45,32133367		
3	45,34999902	45,32128916		
4	45,34995451	45,32097758		
5	45,35013256	45,32111112		

6. APPENDIX B: REPEATABILITY DATA

Position **-5deg** **from below**

Test	Laser Scanner	Open loop counter	Posital encoder
1	-5,0168	-5,009677375	-5,01002292
2	-5,0185	-5,009676806	-5,01020097
3	-5,0184	-5,009677375	-5,01042353
4	-5,0197	-5,009676806	-5,01091315
5	-5,0196	-5,009677375	-5,01055706
6	-5,0196	-5,009677375	-5,01077962
Range	0,00290	0,00000057	0,00089
STD	0,001125463	2,94192E-07	0,0003386
Repeatabilty	0,00290		

Position **-5deg** **from above**

Test	Laser Scanner	Open loop counter	Posital encoder
1	-5,0073	-5,00966996	-4,9966695
2	-5,0064	-5,00966996	-4,99707011
3	-5,0065	-5,00966996	-4,99684755
4	-5,006	-5,00966996	-4,99671401
5	-5,0062	-5,00966996	-4,99653597
6	-5,0044	-5,00966996	-4,99649146
Range	0,00290	0,00000000	0,00058
STD	0,000958471	0	0,000213315
Repeatabilty	0,00290		

Position **0deg** **from below**

Test	Laser Scanner	Open loop counter	Posital encoder
1	0,0173	-0,008148729	-0,010012653
2	0,0171	-0,008149299	-0,010324233
3	0,0173	-0,008149299	-0,010190699
4	0,0166	-0,008149299	-0,010680324
5	0,0164	-0,008149299	-0,010502279
6	0,017	-0,008148729	-0,01085837
Range	0,00090	0,00000057	0,00085
STD	0,000372827	2,94295E-07	0,000314323
Repeatabilty	0,00090		

Position **0deg** **from above**

Test	Laser Scanner	Open loop counter	Posital encoder
1	0,0006	-0,008141321	0,007079725
2	0,0015	-0,00814189	0,005877917
3	0,0011	-0,008141321	0,006367542
4	0,0001	-0,00814189	0,006412054
5	0,0002	-0,00814189	0,0065901
6	0,001	-0,008141321	0,006768145
Range	0,00140	0,00000057	0,00120
STD	0,000546809	3,11654E-07	0,000406657
Repeatabilty	0,00140		

Position **10deg** **from below**

Test	Laser Scanner	Open loop counter	Posital encoder
1	9,9904	9,994907425	9,99935529
2	9,99	9,994907425	9,99904371
3	9,9896	9,994907425	9,99882115
4	9,9987	9,994907425	9,99850957
5	9,989	9,994907992	9,99846506
6	9,9886	9,994907425	9,99828701
Range	0,01010	0,00000057	0,00107
STD	0,003804077	2,31477E-07	0,000402742
Repeatabilty	0,01010		

Position **10deg** **from above**

Test	Laser Scanner	Open loop counter	Posital encoder
1	10,0046	9,994914832	10,01524586
2	10,0047	9,994914832	10,01435563
3	10,0051	9,994914832	10,01466721
4	10,0046	9,994914832	10,01484526
5	10,0048	9,994914265	10,0150233
6	10,0054	9,994914832	10,01520135
Range	0,00080	0,00000057	0,00089
STD	0,000320416	2,31477E-07	0,000340156
Repeatabilty	0,00089		

Position **20deg** **from below**

Test	Laser Scanner	Open loop counter	Posital encoder
1	19,9969	19,9979635	19,99910877
2	19,9954	19,9979635	19,99861914
3	19,9948	19,9979635	19,9984411
4	19,9948	19,9979635	19,99826305
5	19,995	19,9979635	19,9980405
6	19,9949	19,9979635	19,99790696
Range	0,00210	0,00000000	0,00120
STD	0,000814862	0	0,0004343
Repeatabilty	0,00210		

Position **20deg** **from above**

Test	Laser Scanner	Open loop counter	Posital encoder
1	20,016	19,99797098	20,0129963
2	20,011	19,99797098	20,0132188
3	20,0113	19,99797098	20,0133969
4	20,0117	19,99797098	20,0135749
5	20,0114	19,99797098	20,013753
6	20,0115	19,99797098	20,0130408
Range	0,00500	0,00000000	0,00076
STD	0,001900263	0	0,000300246
Repeatabilty	0,00500		

Position **30deg** **from below**

Test	Laser Scanner	Open loop counter	Posital encoder
1	29,9964	30,0010203	29,99623608
2	29,9968	30,00101974	29,99659217
3	29,9974	30,0010203	29,99641413
4	29,9969	30,00101974	29,99623608
5	29,9963	30,00101974	29,99605803
6	29,9964	30,00101974	29,99601352
Range	0,00110	0,00000057	0,00058
STD	0,000419524	2,92798E-07	0,000217607
Repeatabilty	0,00110		

Position **30deg** **from above**

Test	Laser Scanner	Open loop counter	Posital encoder
1	30,0162	30,00102771	30,0163107
2	30,0168	30,00102714	30,0166668
3	30,0167	30,00102714	30,0168893
4	30,0167	30,00102714	30,0172009
5	30,017	30,00102771	30,017379
6	30,0174	30,00102771	30,0176015
Range	0,00120	0,00000057	0,00129
STD	0,000394968	3,12202E-07	0,000478294
Repeatabilty	0,00129		

Position **40deg** **from below**

Test	Laser Scanner	Open loop counter	Posital encoder
1	40,0132	40,00407645	40,0059156
2	40,0078	40,00407645	40,0066723
3	40,0078	40,00407702	40,0064942
4	40,0044	40,00407645	40,0063162
5	40,0069	40,00407702	40,0060936
6	40,0055	40,00407702	40,0059601
Range	0,00880	0,00000057	0,00076
STD	0,003052212	3,12202E-07	0,000304071
Repeatabilty	0,00880		

Position **40deg** **from above**

Test	Laser Scanner	Open loop counter	Posital encoder
1	40,0172	40,00408386	40,01931354
2	40,0221	40,00408386	40,01949158
3	40,0176	40,00408329	40,01966963
4	40,0224	40,00408386	40,01984767
5	40,0186	40,00408386	40,01998121
6	40,0249	40,00408386	40,02015925
Range	0,00770	0,00000057	0,00085
STD	0,003112341	2,32702E-07	0,000314322
Repeatabilty	0,00770		