
BIFROST AVS VACUUM TANK MOTION SAT

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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

All motions tests were performed with only the vacuum vessel as load. No extra load was added to simulate the full load of the system as it was done in the FAT done by AVS.

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: $8,10165 \cdot 10^{-5} \text{deg}_{\text{tank}}/\text{deg}_{\text{motor}}$

Gear ratio encoder: $4.43610^{-5} \text{deg}_{\text{tank}}/\text{counts}_{\text{encoder}}$

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.

1.2.3. 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.

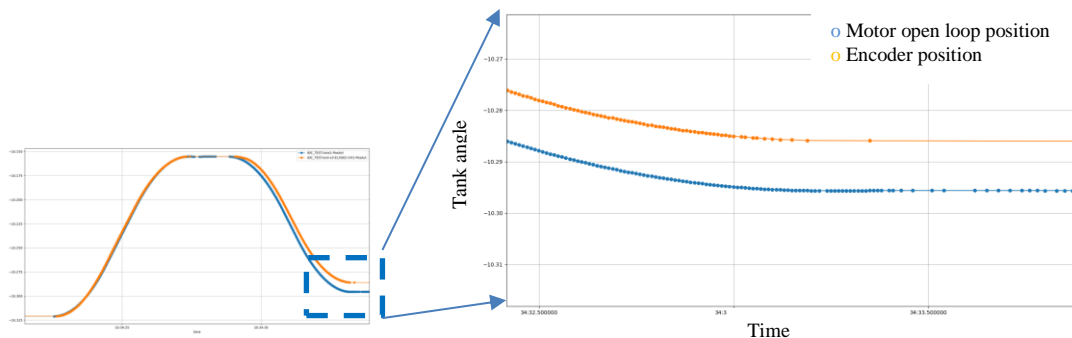


Figure 2: Backlash test in backward direction

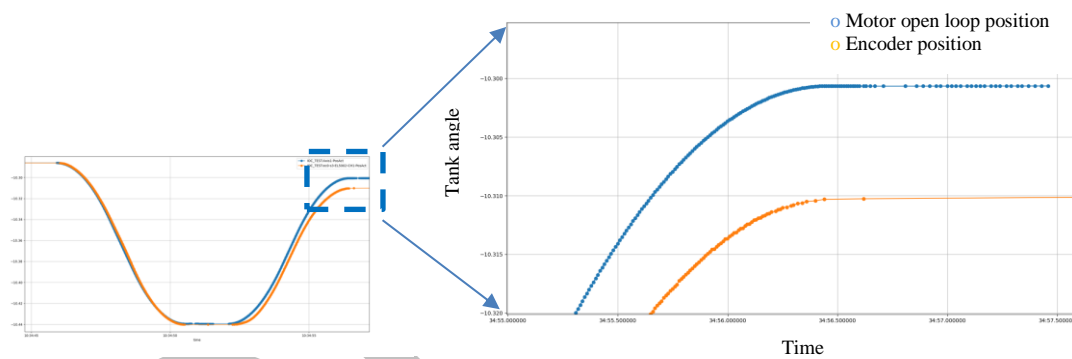


Figure 3: Backlash test in forward direction

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.

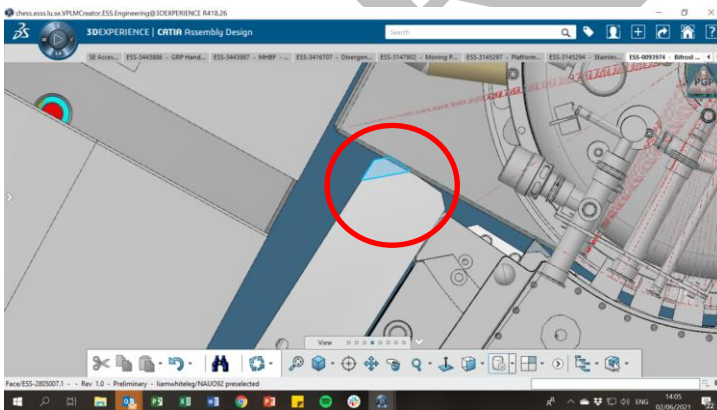


Figure 5: CAD drawing of tank in hard stop position (from above)

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.

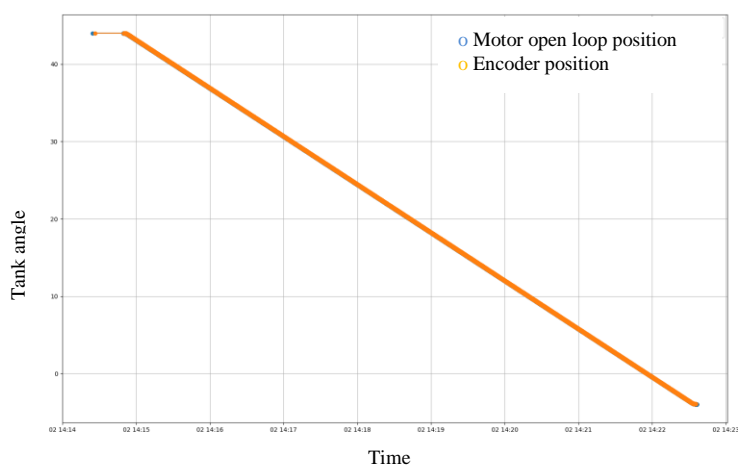


Figure 6: High speed test over entire stroke (backward direction)

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.

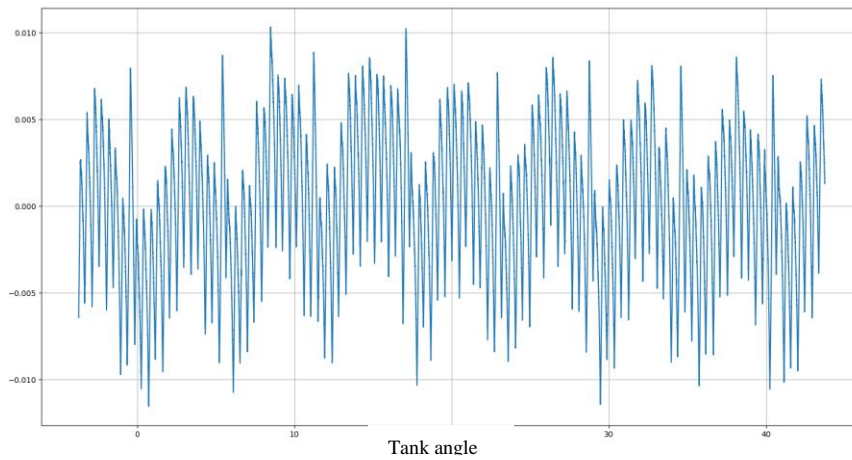


Figure 7: Encoder error vs tank angle (without backlash)

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).

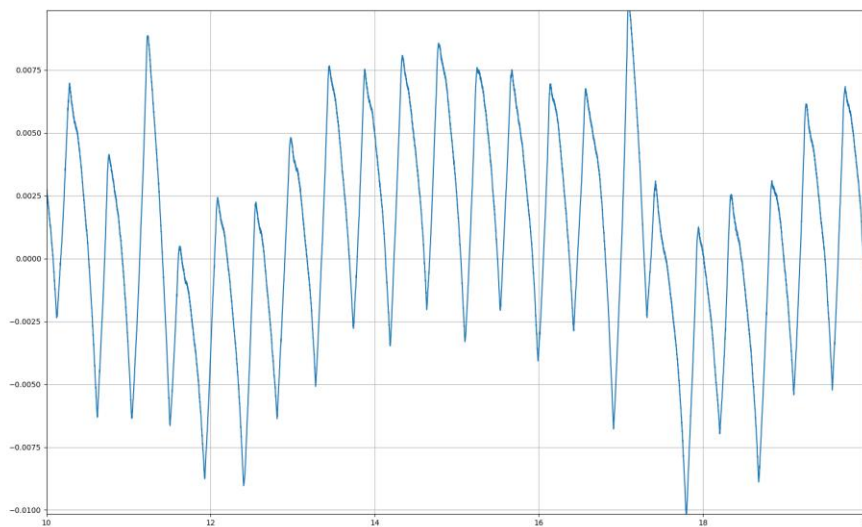


Figure 8: Encoder error vs tank angle, zoom 10..20 deg (without backlash)

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	$8,10412\text{E-}05 \text{ deg}_{\text{tank}}/\text{deg}_{\text{motor}}$	-0,0081	0,0273
Encoder position	$-4,45114\text{E-}05 \text{ deg}_{\text{tank}}/\text{encoder count}$	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

2. DATA ACQUIRED DURING THE REPEATABILITY TEST ARE LISTED IN APPENDIX B: REPEATABILITY DATA (BEFORE COLLISION)

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		

Appendix C: Repeatability data.

Based on these data sets the repeatability can be calculated to be 0.010 deg.

3. 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
4. Repeatability

3.1. Backlash

Data for backlash was taken at 5 different positions after collision but only at one position before. Figure 9 shows motor open loop counter and encoder position for a movement when reversing direction.

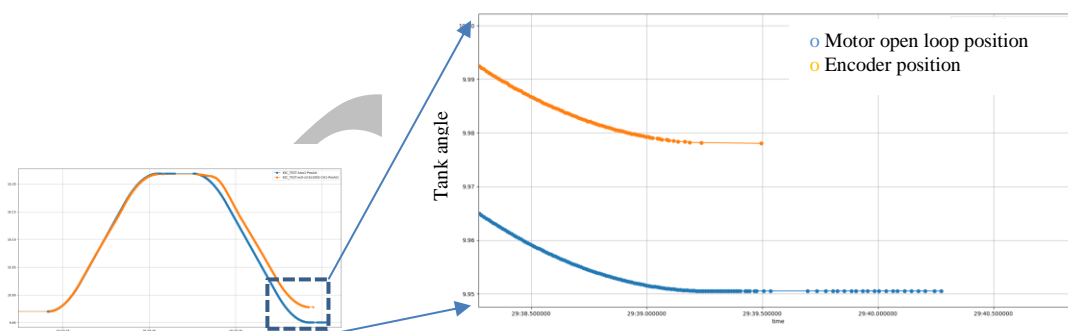


Figure 9: Backlash after collision at 10 deg tank angle

For this move the backlash seems to be approx. 0.025deg compared to 0.01deg before. The other data is presented in “**Error! Reference source not found.**”. From these graphs it can be concluded that backlash between motor shaft and encoder shaft is in the range of 0.02..0.03 deg_{tank}.

Another thing worth noting is the behavior of the encoder position curve where the value seems to update unpredictable in the acceleration phase, Figure 10.

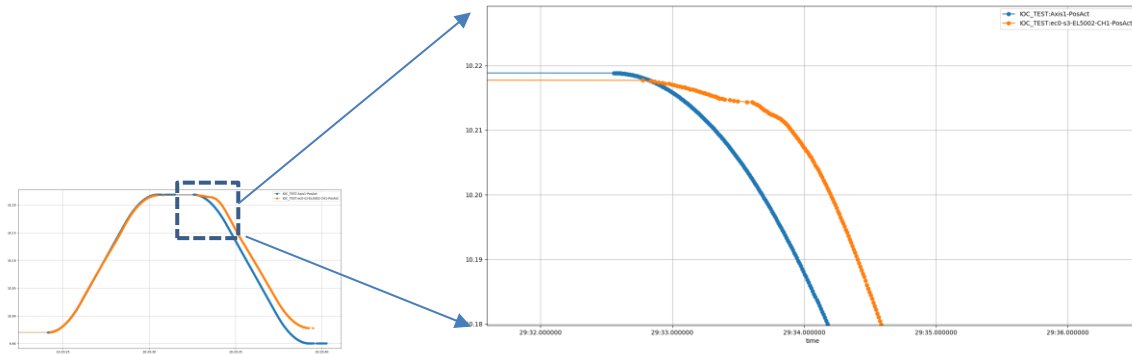


Figure 10: Acceleration phase when reverse direction.

This could be an indication of that something is slipping or more loose, maybe the motor chain, than before but hard to draw conclusions.

3.2. 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 $688\text{deg}_{\text{motor}}/\text{s}$
- after collision $1280\text{deg}_{\text{motor}}/\text{s}$

Figure 11 shows the deviation of the encoder position from the motor open loop position at angles between 9 to 23 degrees (at a velocity of $688\text{deg}_{\text{motor}}/\text{s}$). Figure 12 shows the same data but acquired after the collision but at a higher velocity ($1280\text{deg}_{\text{motor}}/\text{s}$). In both graphs the backlash is not shown.

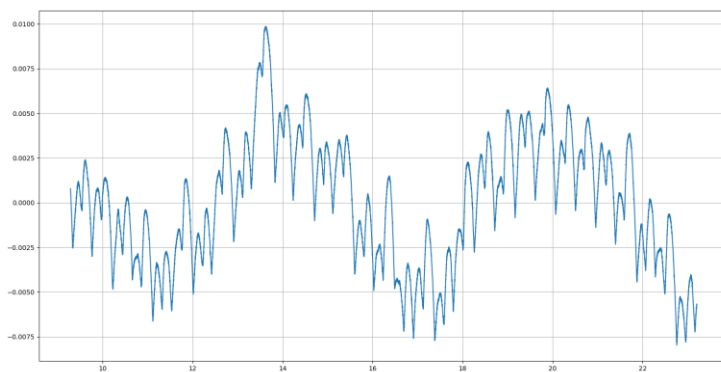


Figure 11: Before collision: Encoder position error (without backlash) at $688\text{deg}_{\text{motor}}/\text{s}$

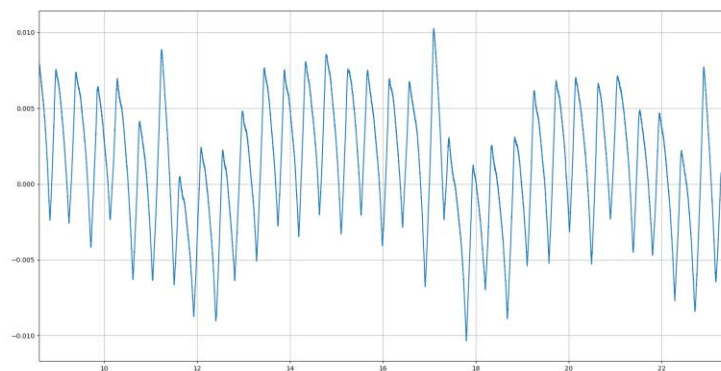


Figure 12: After collision: Encoder position error (without backlash) at $1280\text{deg}_{\text{motor}}/\text{s}$

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.

3.3. Accuracy and gear ratio

A reduced accuracy test was performed after the collision. The results can be seen in Table 6. The test was performed without a laser tracker, therefore the accuracy this time is measured with the encoder.

Table 6: After collision: Accuracy measurements

Position	Open loop	Posital Encoder	Diff OL Posital
0	0,0000	0,0000	0,0000
10	10,0000	10,0065	0,0065
20	20,0000	20,0065	0,0065
30	30,0000	29,9959	0,0041
40	40,0000	40,0006	0,0006

The gear ratios were recalculated too for the comparison. 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.

Table 7: After collision: Accuracy and gear ratio

	Gearratio	Offset
Openloop	8,10165E-05	-0,000003
Posital	4,45032E-05	30,7613

	Accuracy
Max value=	0,0065
Average=	0,0044

Table 8: Before collision: Accuracy measurements

Position	Laser tracker [deg]	Open loop position [deg]	Open loop diff abs [deg]	Posital Encoder [deg]	Posital Diff abs [deg]
0	0,0192	-0,0081	0,0273	-0,0117	0,0309
10	9,9888	9,9949	0,0061	9,9986	0,0098
20	19,9951	19,9980	0,0029	19,9979	0,0028
30	29,9965	30,0010	0,0045	29,9951	0,0014
40	40,0095	40,0041	0,0054	40,0049	0,0046

Table 9: Before collision: Accuracy and gear ratio

Source	Gear ratio	Offset [deg]	Accuracy [deg]
Open loop position	8,10599E-05	-0,0161	0,00473
Encoder position	4,45212E-05	30,7245	0,00466

As mentioned in chapter 1.5 the zero measurement is considered an outlier and is not taken into account for the accuracy calculation and comparison. The accuracy of the system is calculated as the average of all the measurements. Without the laser tracker measurement as reference is hard to do a proper comparison of the measurements. Specially because the measurement at 10 degrees is increasing the average of the measurement before collision. However, we can see in both cases the average accuracy is 0,00466 before and 0,0044 after. We can conclude that the accuracy of the system was not affected by the collision and it is still fulfilling the set requirement.

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

3.4. Repeatability

Reduced repeatability tests were done after the collision. The same as with the accuracy, there was no laser tracker in this measurements and those data cannot be compared. Appendix C: Repeatability data (after collision) shows all the measurements done in the test.

Table 10. After collision Repeatability

	System repeatability
Max. value	0,00093457
Average	0,00060079

Table 10 shows the calculated repeatability after collision. The repeatability of the system before collision and not counting the laser tracker is 0,00129deg. Showing an unlikely apparent improvement of repeatability after collision. In the test before collision 6 measurements were used and some of those measurements have a bigger standard deviation compared to the measurements

after collision. Because of this it is hard to really know the exact difference in repeatability before and after collision. However, the value after collision is similar to the value calculated by AVS. It is safe to say that the repeatability fulfils the requirement.

4. CONCLUSIONS

Results from the tests are summarized in the below tables. Table 11 shows general results and Table 12 and Table 13 shows motion performance before and after collision.

Table 11: 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 12: 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 13: 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..0,03	Check	Based on measurements made at 5 positions in both directions. See chapter 3 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 3 for detailed comparison
5.2	Accuracy Posital encoder[deg]	0,0044	OK	Similar to before collision but based on fewer measurements, see chapter 3 for detailed comparison.
6	Bidirectional repeatability [deg]	0,00093	OK	Shows and improvement compare to before collision. But it is a similar value to the AVS repeatability tests. See chapter 3 for detailed comparison.

In general, the equipment fulfills all of the requirements. The tests performed after the collision were done without the laser scanner as an absolute reference. The overall performance of the system has not change much after the collision. Some data sets show a big standard deviation compare to other data sets and it is not clear if was a measurement error or a strange behavior of the system. Even with all that into account no data set performed worse than the set requirements. However, from the results it can be concluded that the backlash has increased after the collision.

5. 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

6. 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		

7. APPENDIX B: REPEATABILITY DATA (BEFORE COLLISION)

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		

8. APPENDIX C: REPEATABILITY DATA (AFTER COLLISION)

Position	0deg	from below
Test	Open loop counter	Posital encoder
1	0,000000	0
2	0,000000	0,00013351
3	-0,000001	0,00013351
4	-0,000001	0,00013351
Range	0,000001	0,00013351
STD	0,004059494	6,67548E-05
Repeatability	0,00013351	

Position	0deg	from above
Test	Open loop counter	Posital encoder
1	0,000007	0,030929716
2	0,000007	0,031285742
3	0,000007	0,031330245
4	0,000007	0,031508258
Range	0,000001	0,000578541
STD	0,003515625	0,000242396
Repeatability	0,000578541	

Position	10deg	from below
Test	Open loop counter	Posital encoder
1	9,999999	10,00645296
2	9,999999	10,00712051
3	9,999999	10,00680899
4	9,999999	10,00663098
Range	0,000000	0,000667548
STD	0	0,00028467
Repeatability	0,000667548	

Position	10deg	from above
Test	Open loop counter	Posital encoder
1	10,000006	10,03297686
2	10,000006	10,03315488
3	10,000006	10,03333289
4	10,000007	10,0335109
Range	0,000001	0,000534038
STD	0,0035	0,000229813
Repeatability	0,000534038	

Position	20deg	from below
Test	Open loop counter	Posital encoder
1	19,999999	20,00645296
2	19,999999	20,00680899
3	19,999999	20,00649747
4	19,999999	20,00627495
Range	0,000001	0,000534038
STD	0,0035	0,000222145
Repeatability	0,000534038	

Position	20deg	from above
Test	Open loop counter	Posital encoder
1	20,000006	20,02745847
2	20,000006	20,02763648
3	20,000006	20,02781449
4	20,000006	20,02799251
Range	0,000000	0,000534038
STD	0	0,000229813
Repeatability	0,000534038	

Position	30deg	from below
Test	Open loop counter	Posital encoder
1	29,999998	29,9958612
2	29,999998	29,99670676
3	29,999999	29,99652875
4	29,999999	29,99652875
Range	0,000001	0,000845561
STD	0,004041452	0,000373005
Repeatability	0,000845561	

Position	30deg	from above
Test	Open loop counter	Posital encoder
1	30,000006	30,02576735
2	30,000006	30,02594536
3	30,000006	30,02625688
4	30,000006	30,0264794
Range	0,000001	0,000712051
STD	0,0035	0,000317557
Repeatability	0,000712051	

Position	40deg	from below
Test	Open loop counter	Posital encoder
1	39,999998	40,00062304
2	39,999999	40,00155761
3	39,999998	40,00120159
4	39,999999	40,00102357
Range	0,000001	0,000934567
STD	0,004041452	0,000388607
Repeatability	0,000934567	

Position	40deg	from above
Test	Open loop counter	Posital encoder
1	40,000005	40,02732496
2	40,000005	40,02754747
3	40,000005	40,02768098
4	40,000005	40,027859
Range	0,000000	0,000534038
STD	0	0,000225097
Repeatability	0,000534038	

9. APPENDIX D: BACKLASH MEASUREMENTS AFTER COLLISION

0 deg_{tank}

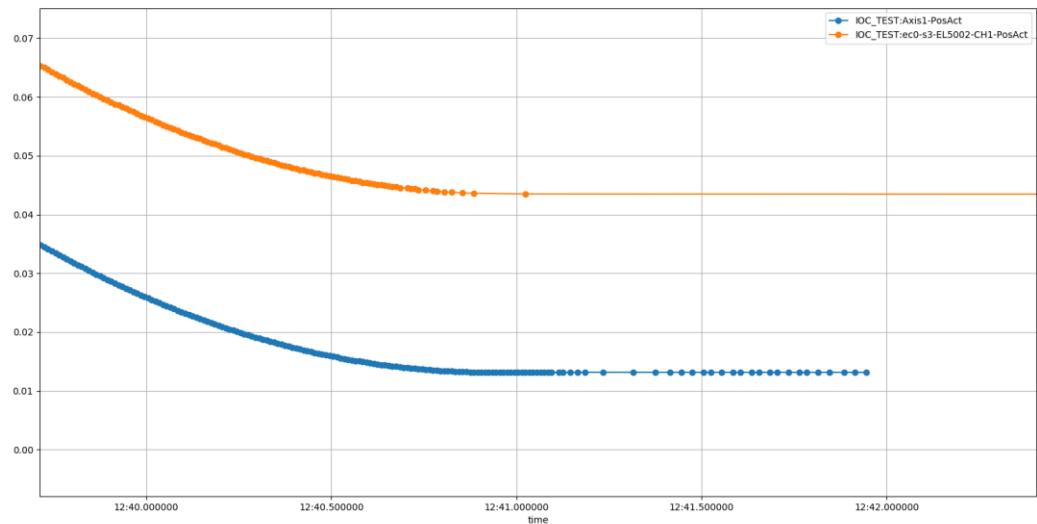


Figure 13: Backward backlash between motor and encoder shaft

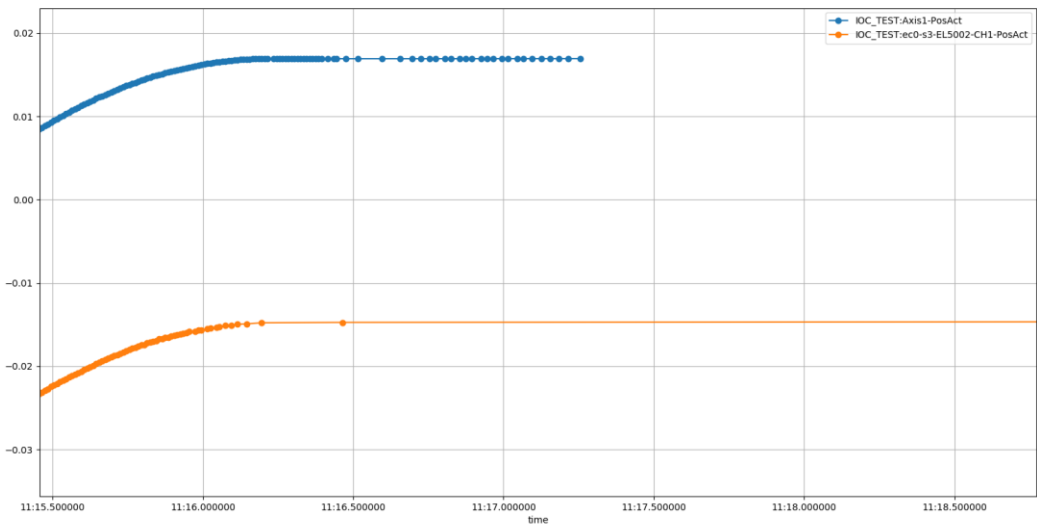


Figure 14: Forward backlash between motor and encoder shaft

10 deg_{tank}

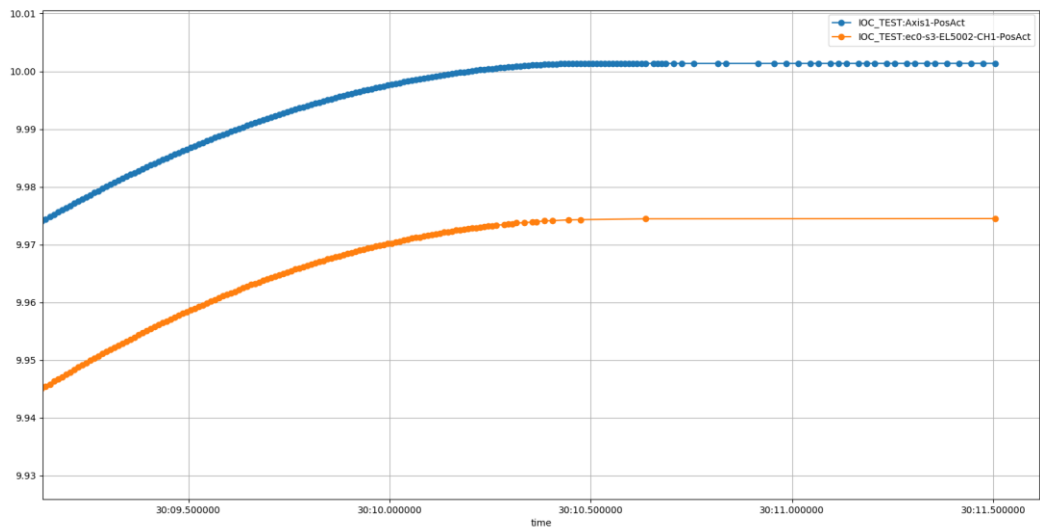


Figure 15: Backward backlash between motor and encoder shaft

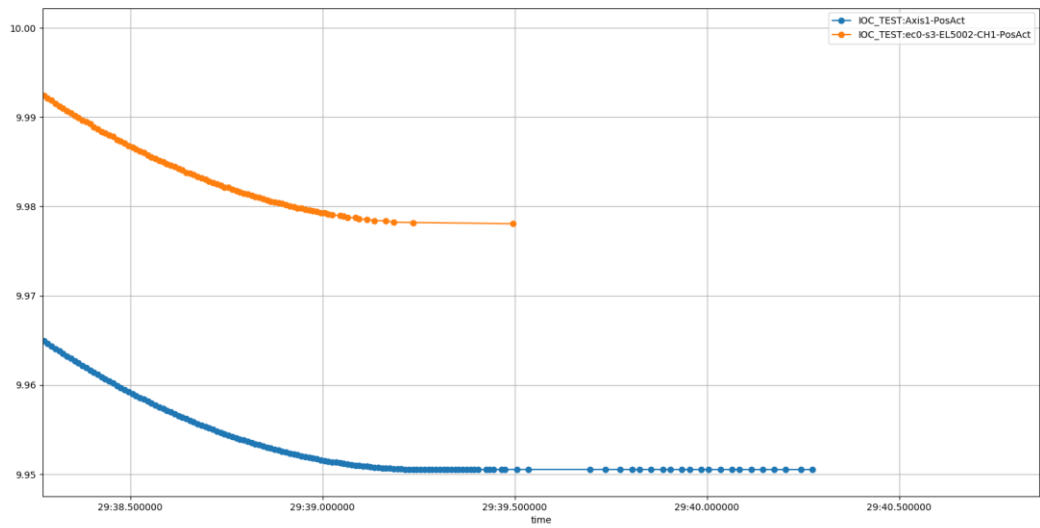


Figure 16: Forward backlash between motor and encoder shaft

20 deg_{tank}

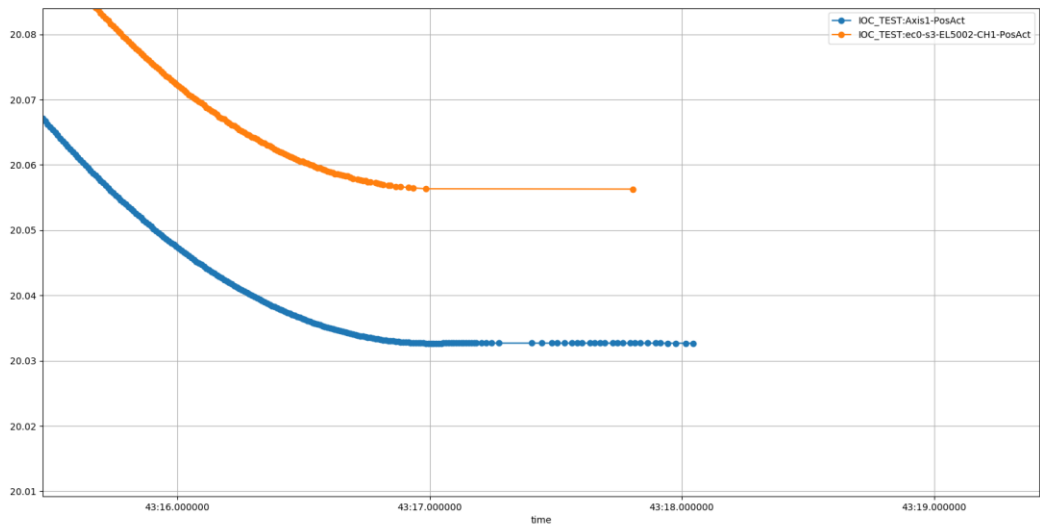


Figure 17: Backward backlash between motor and encoder shaft

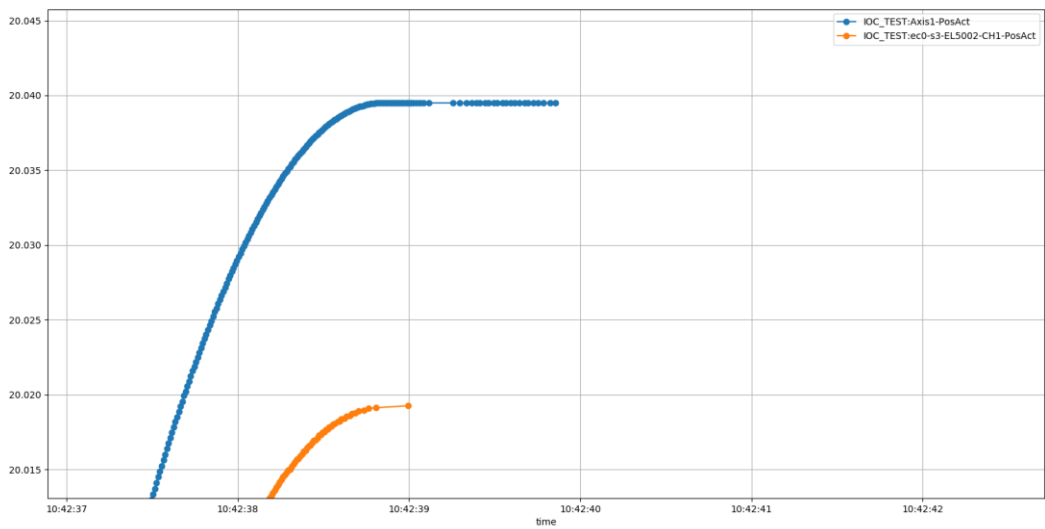


Figure 18: Forward backlash between motor and encoder shaft

30 deg_{tank}

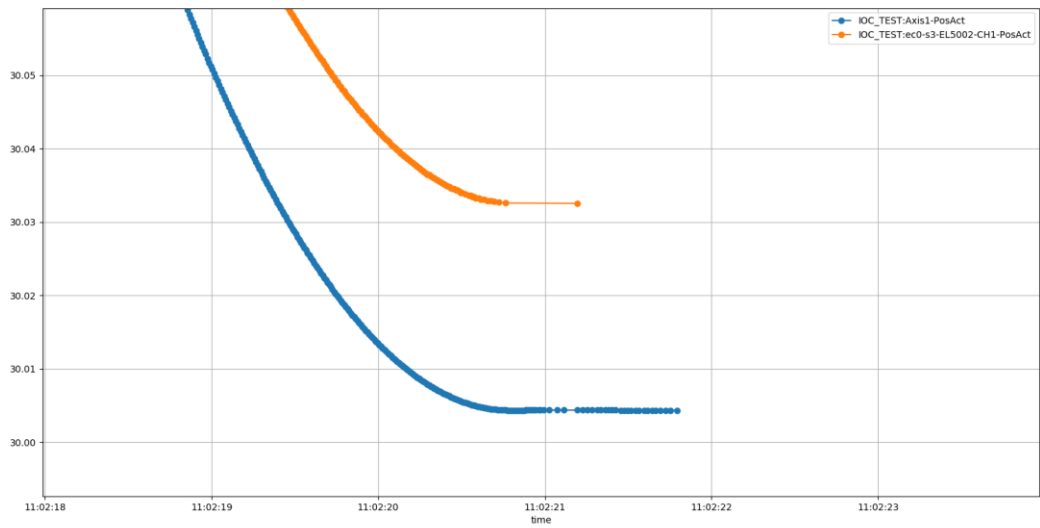


Figure 19: Backward backlash between motor and encoder shaft

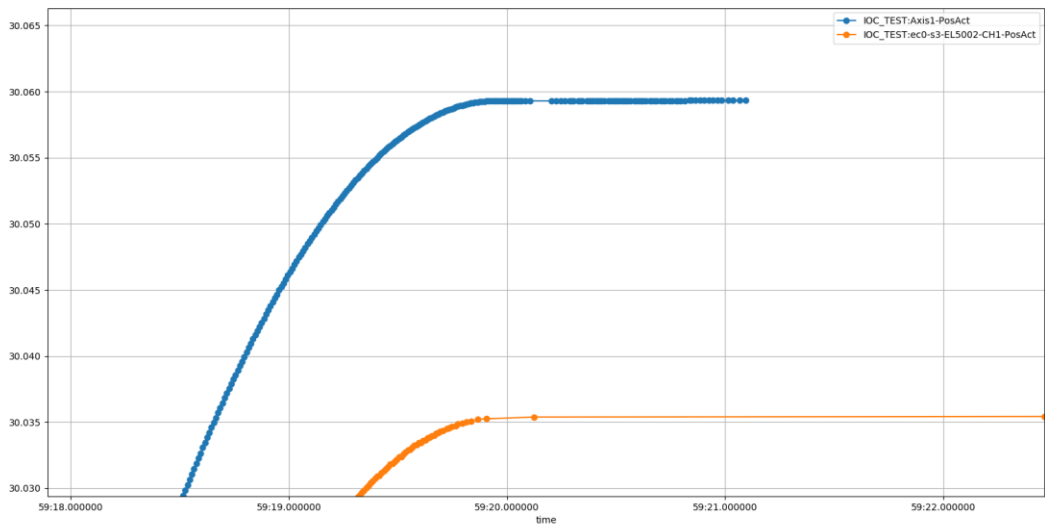


Figure 20: Forward backlash between motor and encoder shaft

40 deg tank

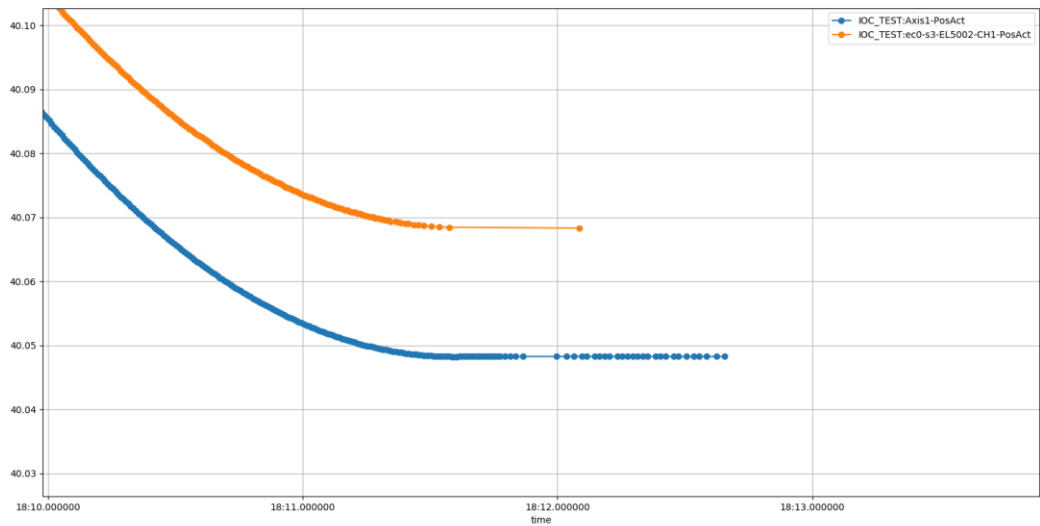


Figure 21: Backward backlash between motor and encoder shaft

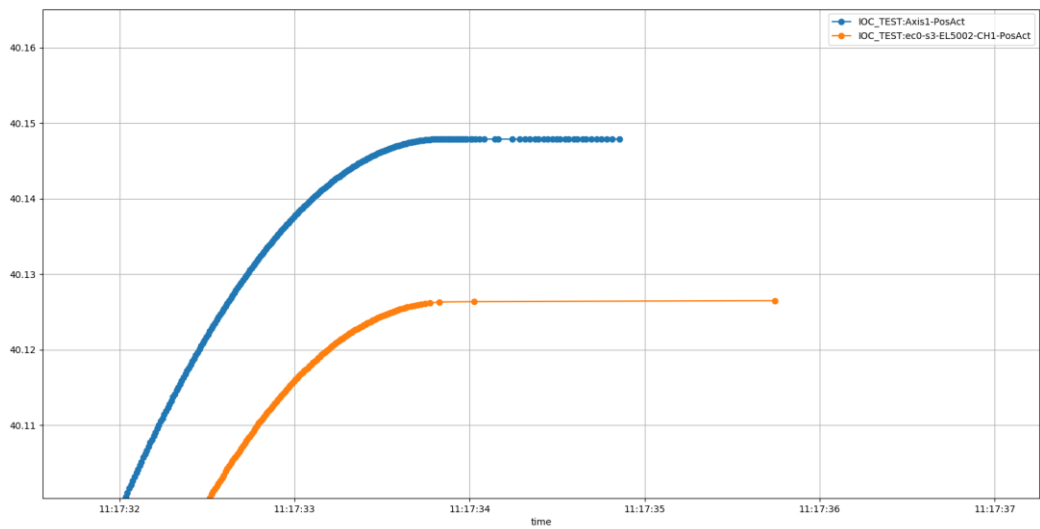


Figure 22: Forward backlash between motor and encoder shaft