|  |
| --- |
|  |
| BIFROST AVS Vacuum tank MOTION SAT |
|  |

|  | Name | Role/Title |
| --- | --- | --- |
| Owner | Anders Sandström | Electronics Engineer Motion Control & Automation |
| Owner | Federico Rojas | Motion Control Engineer |
| Reviewer | Thomas Gahl | Group Leader Motion Control & Automation |
| Approver | Liam Whitelegg | Instrument Lead Engineer for BIFROST |

Contents

[1. Results 4](#_Toc78195313)

[1.1. General inspection 4](#_Toc78195314)

[1.2. Initial motion test 5](#_Toc78195315)

[1.2.1. Switches 5](#_Toc78195316)

[1.2.2. Gear ratio 5](#_Toc78195317)

[1.2.3. Backlash 6](#_Toc78195318)

[1.3. Motion range and switch performance 7](#_Toc78195319)

[1.3.1. Motion range 7](#_Toc78195320)

[1.3.2. Switch performance 8](#_Toc78195321)

[1.4. High speed test 8](#_Toc78195322)

[1.5. Accuracy 10](#_Toc78195323)

[1.6. Bidirectional repeatability 12](#_Toc78195324)

[2. Differences before and after collision 12](#_Toc78195325)

[2.1. Backlash 12](#_Toc78195326)

[2.2. Motor position vs encoder position 14](#_Toc78195327)

[2.3. Accuracy and gear ratio 15](#_Toc78195328)

[3. CONCLUSIONS 17](#_Toc78195329)

[4. references 19](#_Toc78195330)

[5. Appendix A Switch performance 20](#_Toc78195331)

[6. Appendix B: Repeatability data (Before collision) 22](#_Toc78195332)

[7. Appendix C: Repeatability data (after collision) 28](#_Toc78195333)

[8. Appendix D: Backlash measurements after collision 32](#_Toc78195334)

# 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.

## 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

## Initial motion test

### Switches

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

### Gear ratio

Basic gear ratios were calculated for both encoder and motor.

Gear ratio motor: 8,10165\*10-5degtank/degmotor

Gear ratio encoder: 4.43610-5degtank/countsencoder

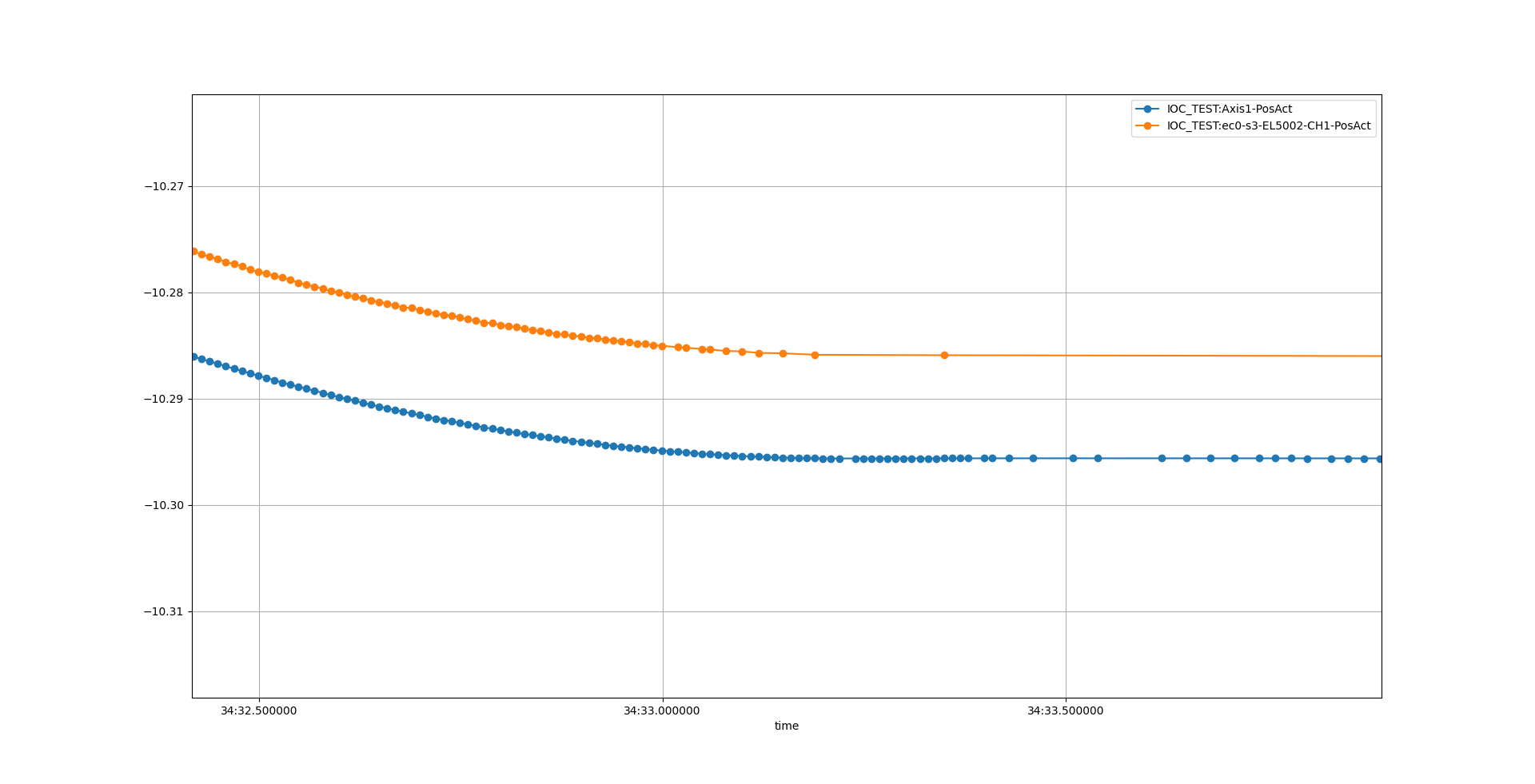
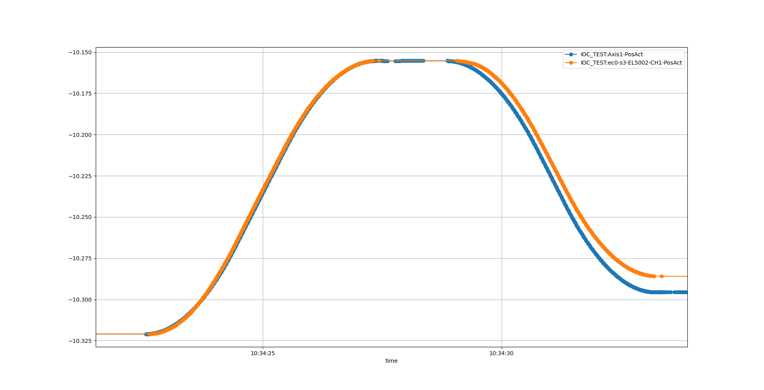
These gear ratios were used to generate setpoints for the further tests.

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.



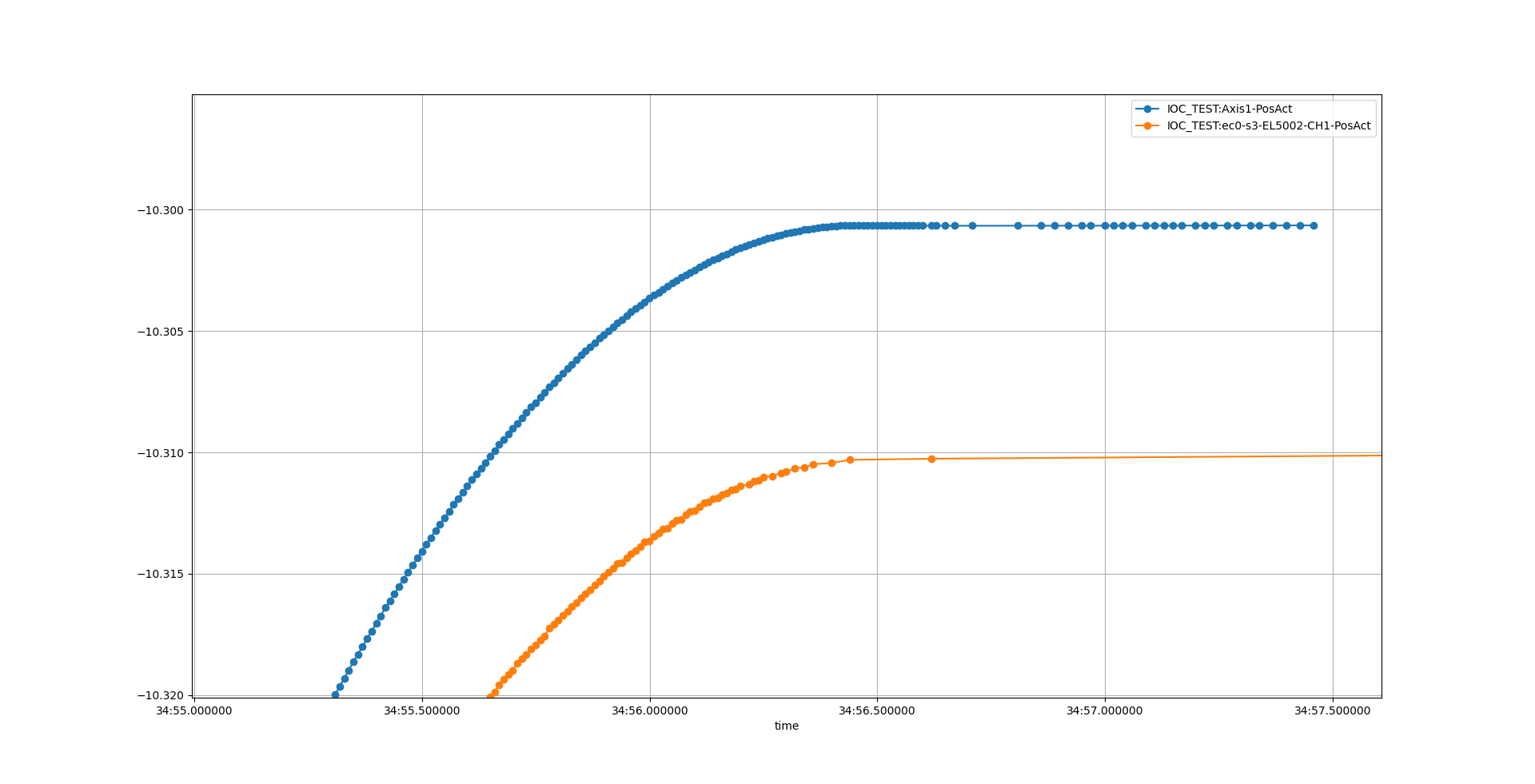
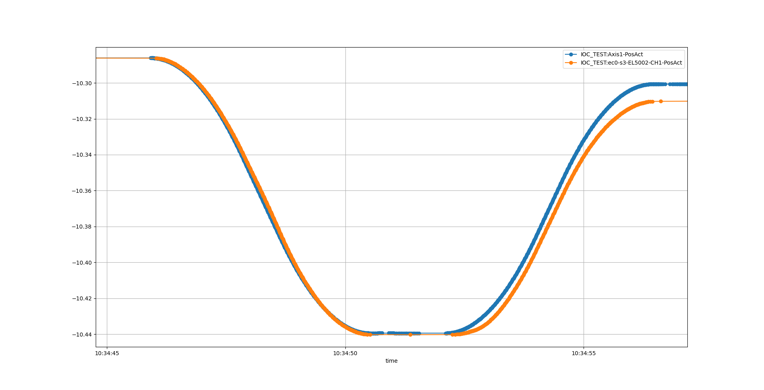
Tank angle

Time

o Motor open loop position

o Encoder position

Figure 2: Backlash test in backward direction



o Motor open loop position

o Encoder position

Tank angle

Time

Figure 3: Backlash test in forward direction

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

## Motion range and switch performance

### 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.

### 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.

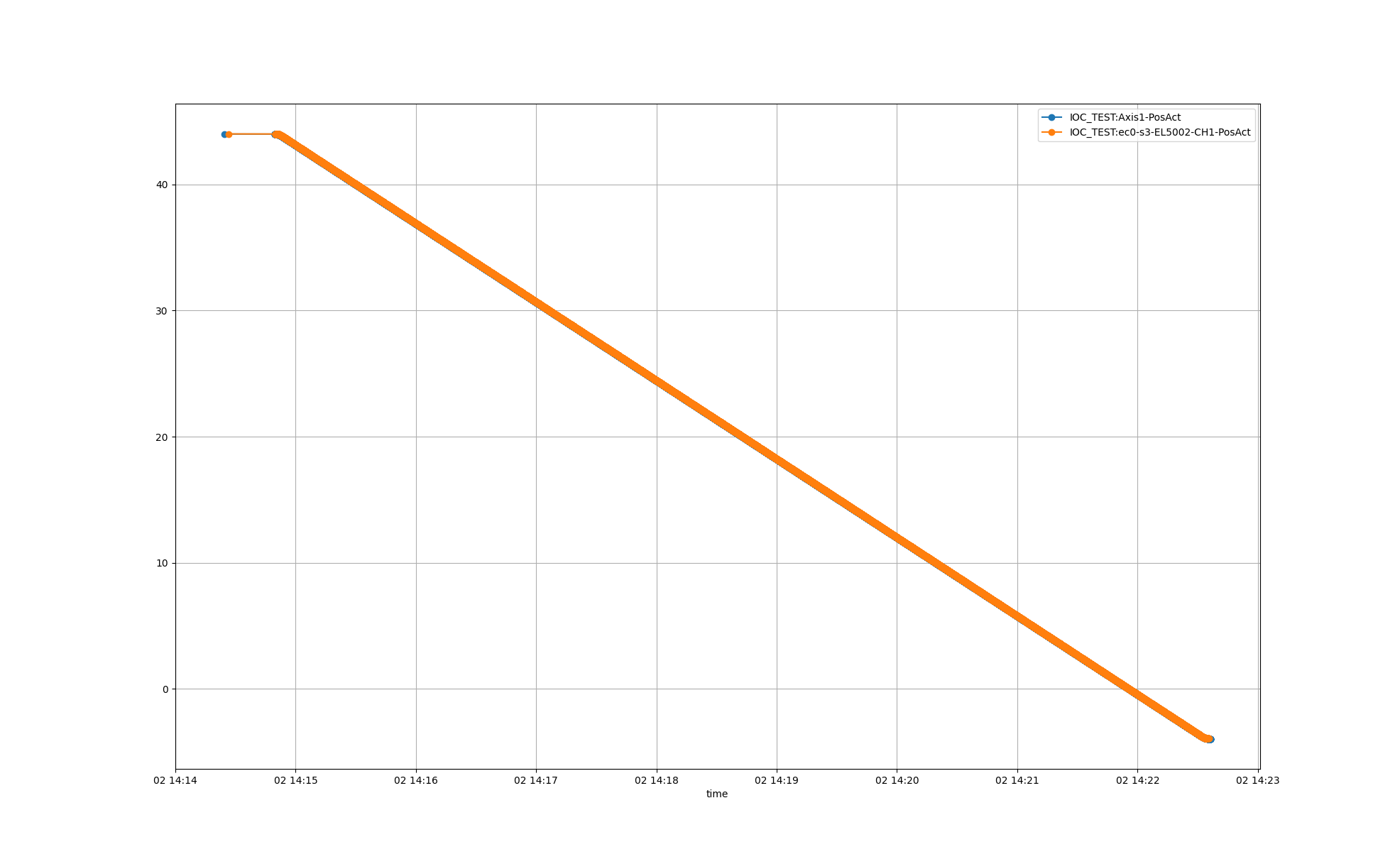
The data is summarized in Table 1.

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 |

## 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.



Time

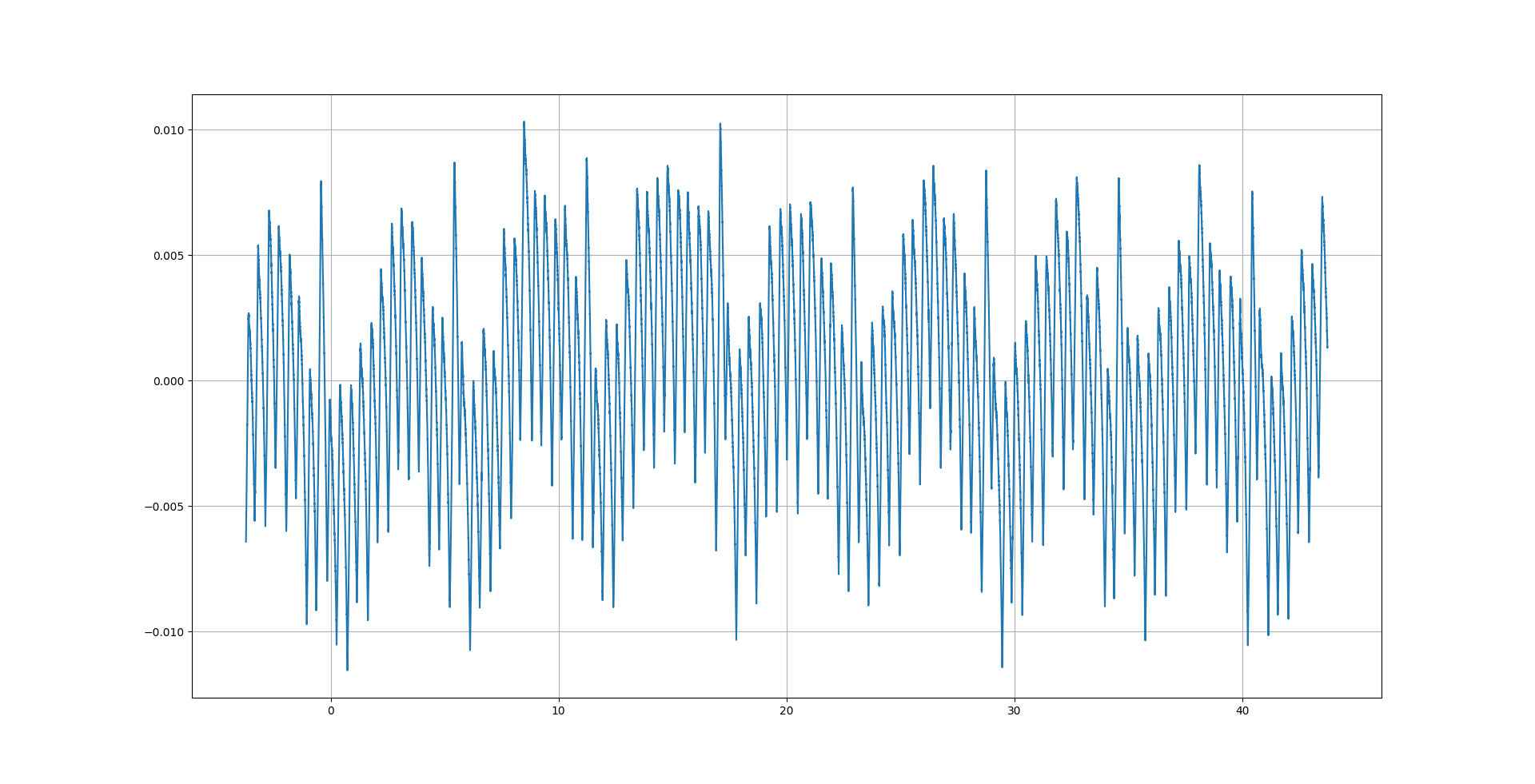
o Motor open loop position

o Encoder position

Tank angle

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.



Tank angle

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).

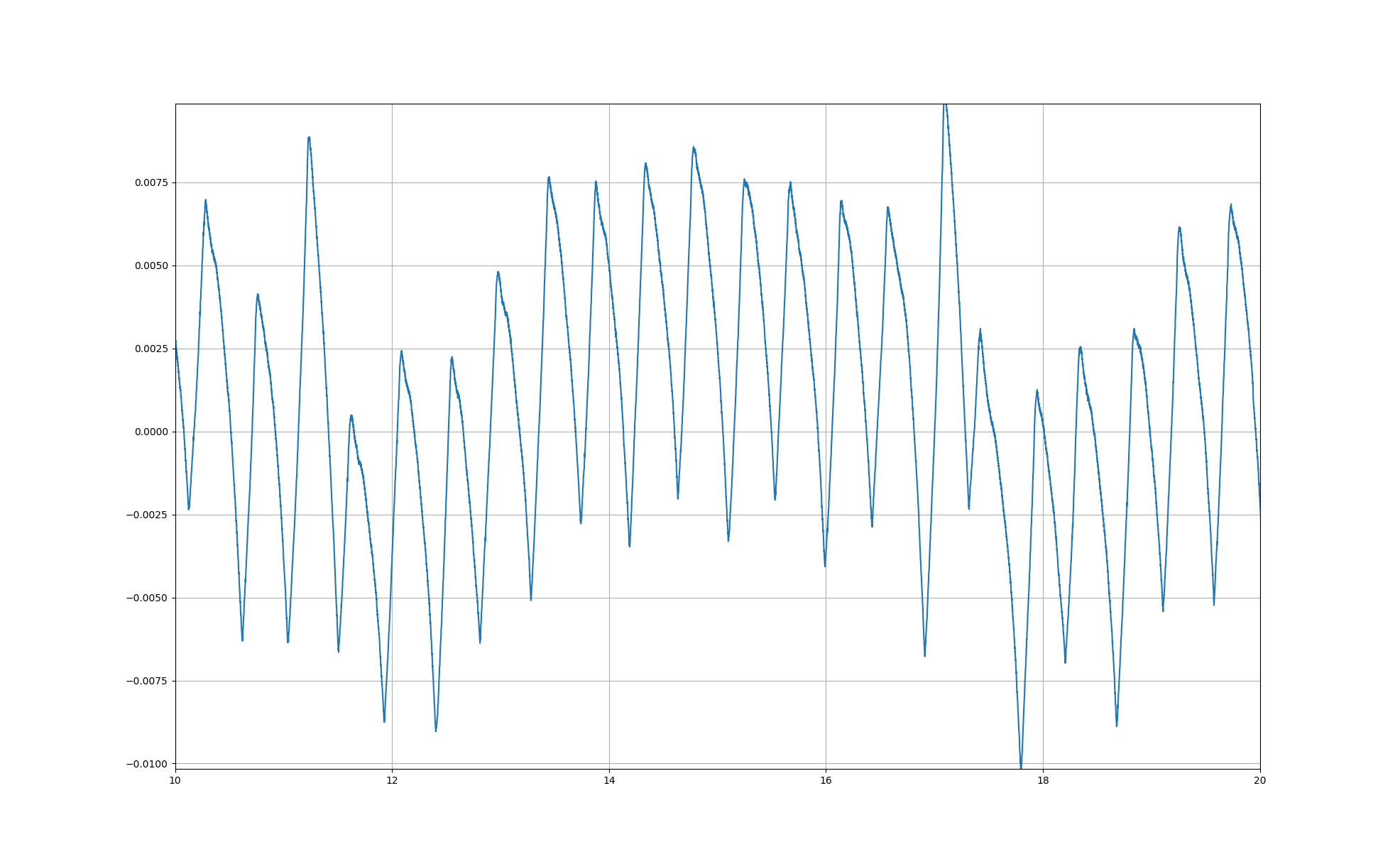


Figure 8: Encoder error vs tank angle, zoom 10..20 deg (without backlash)

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).

## 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 degtank/degmotor | -0,0081 | 0,0273 |
| **Encoder position** | -4,45114E-05 degtank/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 |

## 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.

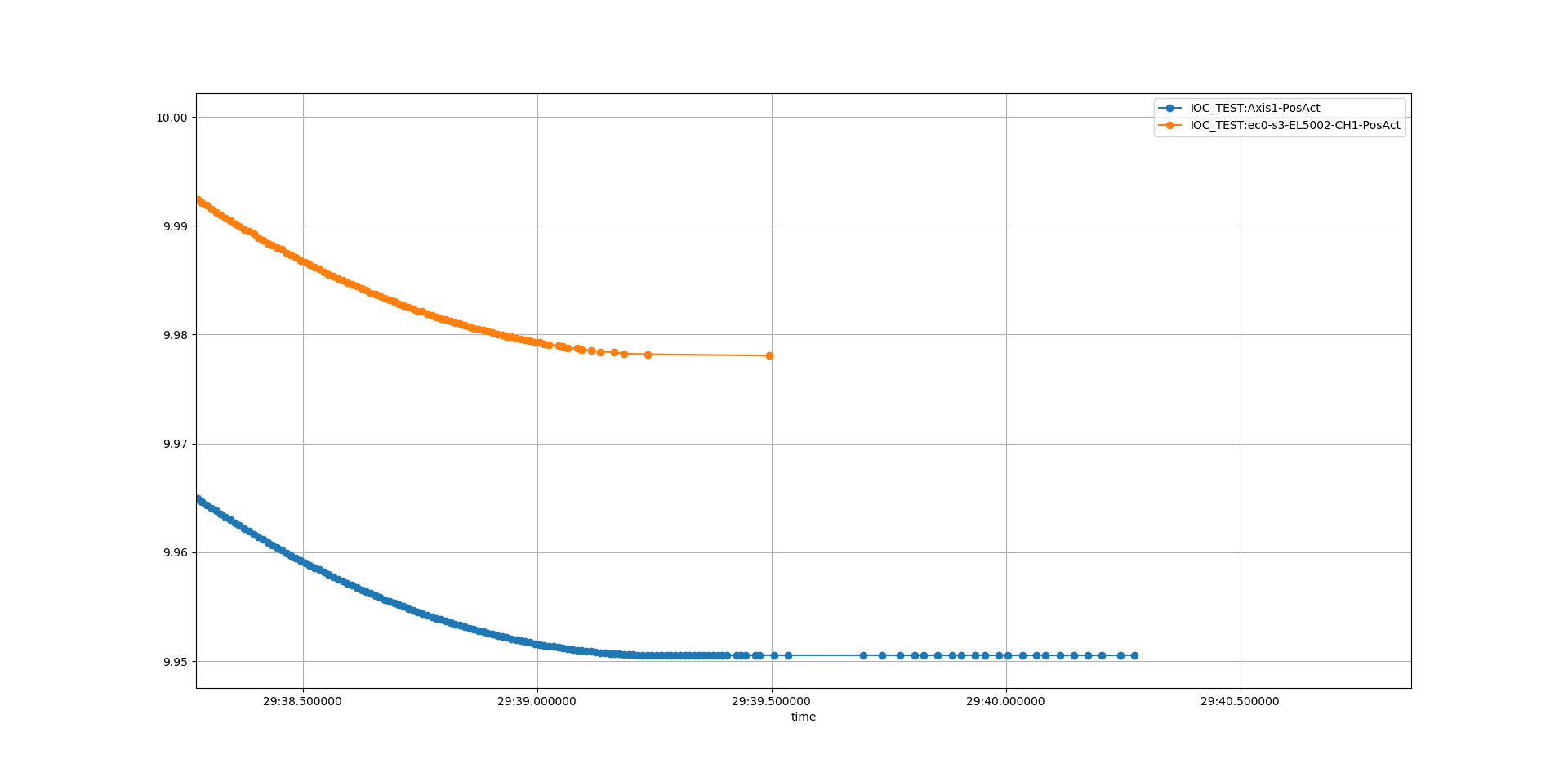
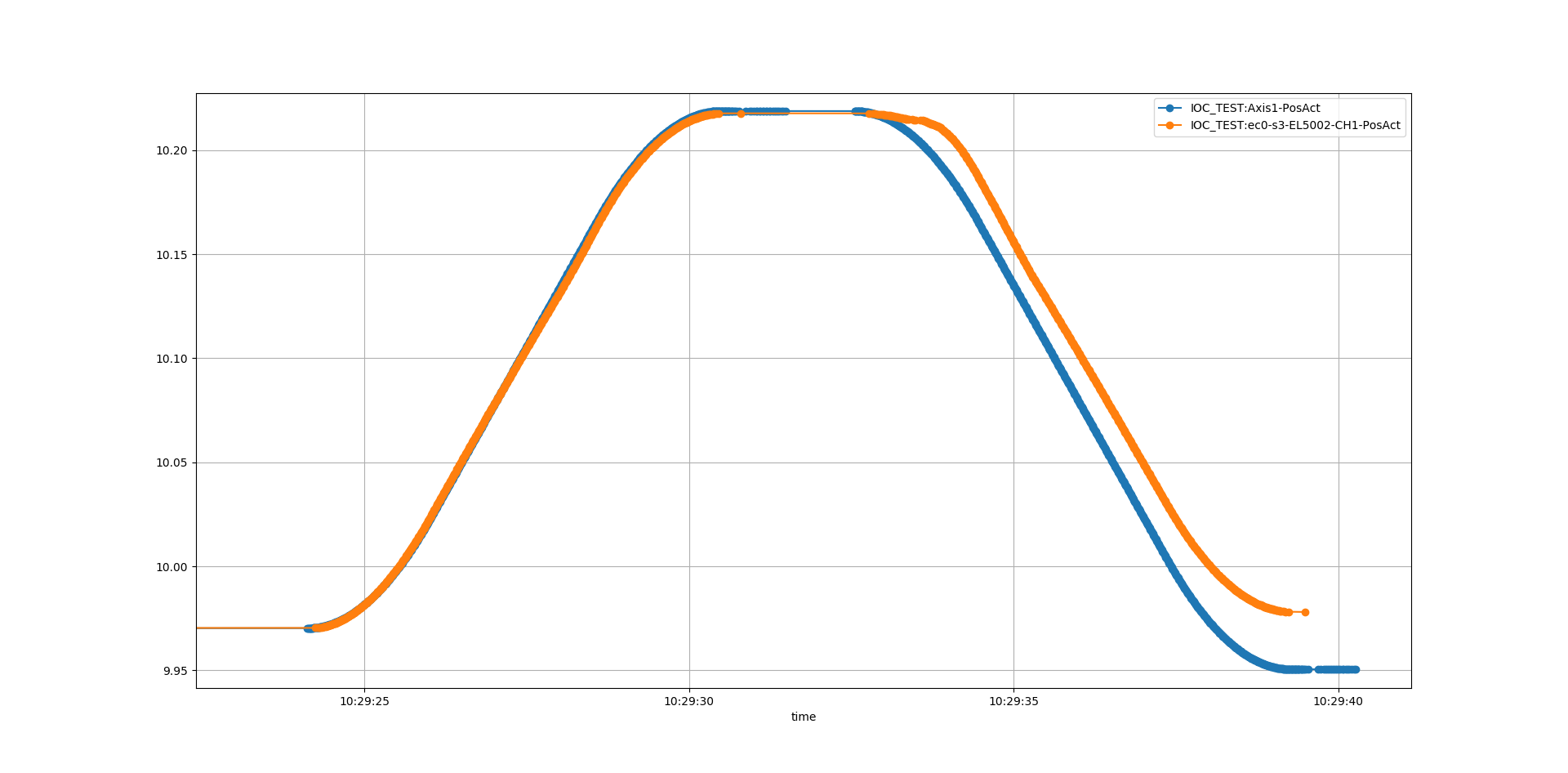
# Differences before and after collision

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

## Backlash

Data for backlash was taken at 5 different positions after collision but only at one position before. Figure 10 shows motor open loop counter and encoder position for a movement when reversing direction.



o Motor open loop position

o Encoder position

Tank angle

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 “Appendix C: Backlash measurements after collision”. From these graphs it can be concluded that backlash between motor shaft and encoder shaft is in the range of 0.02..0.03 degtank.

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.

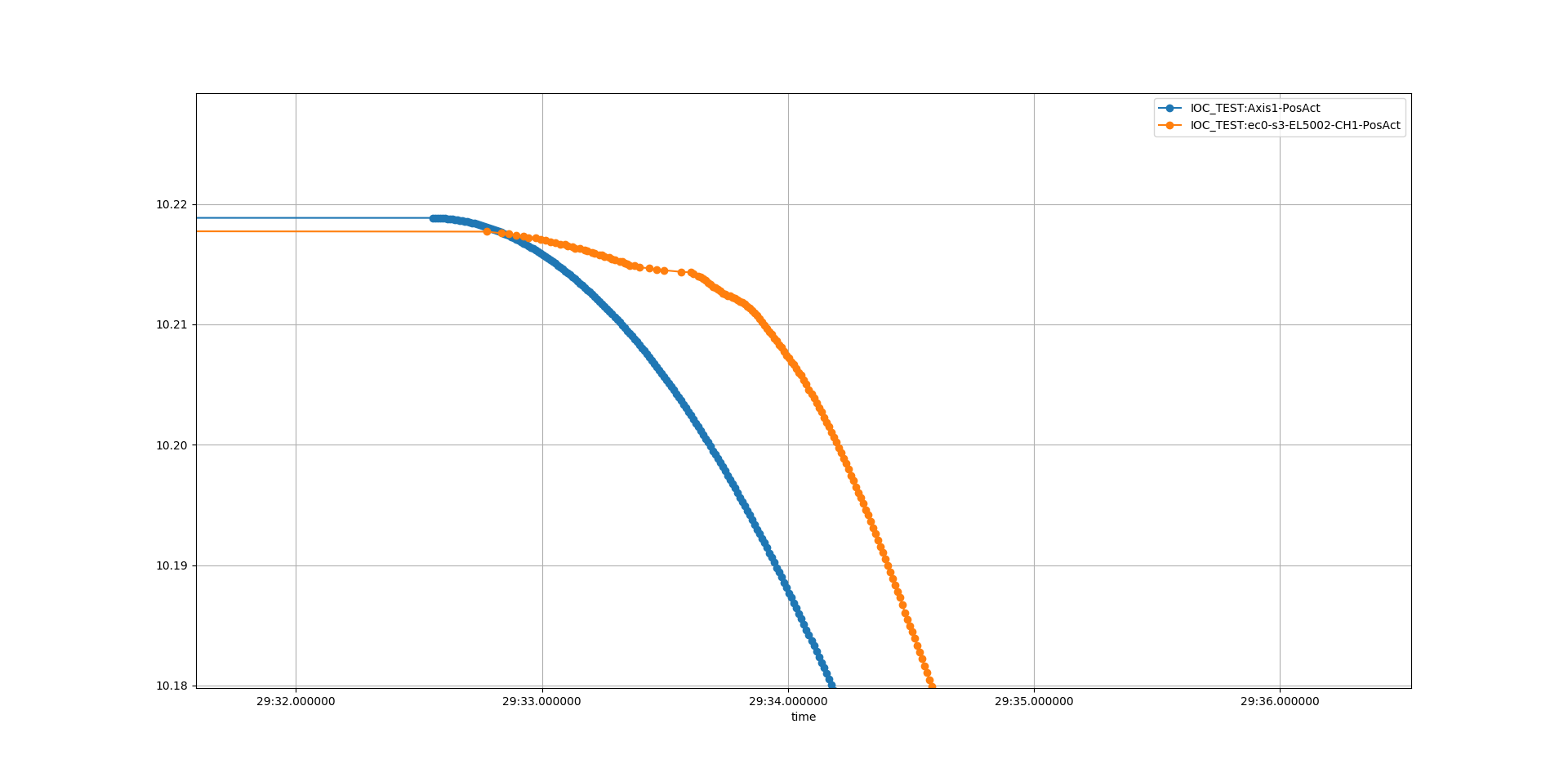
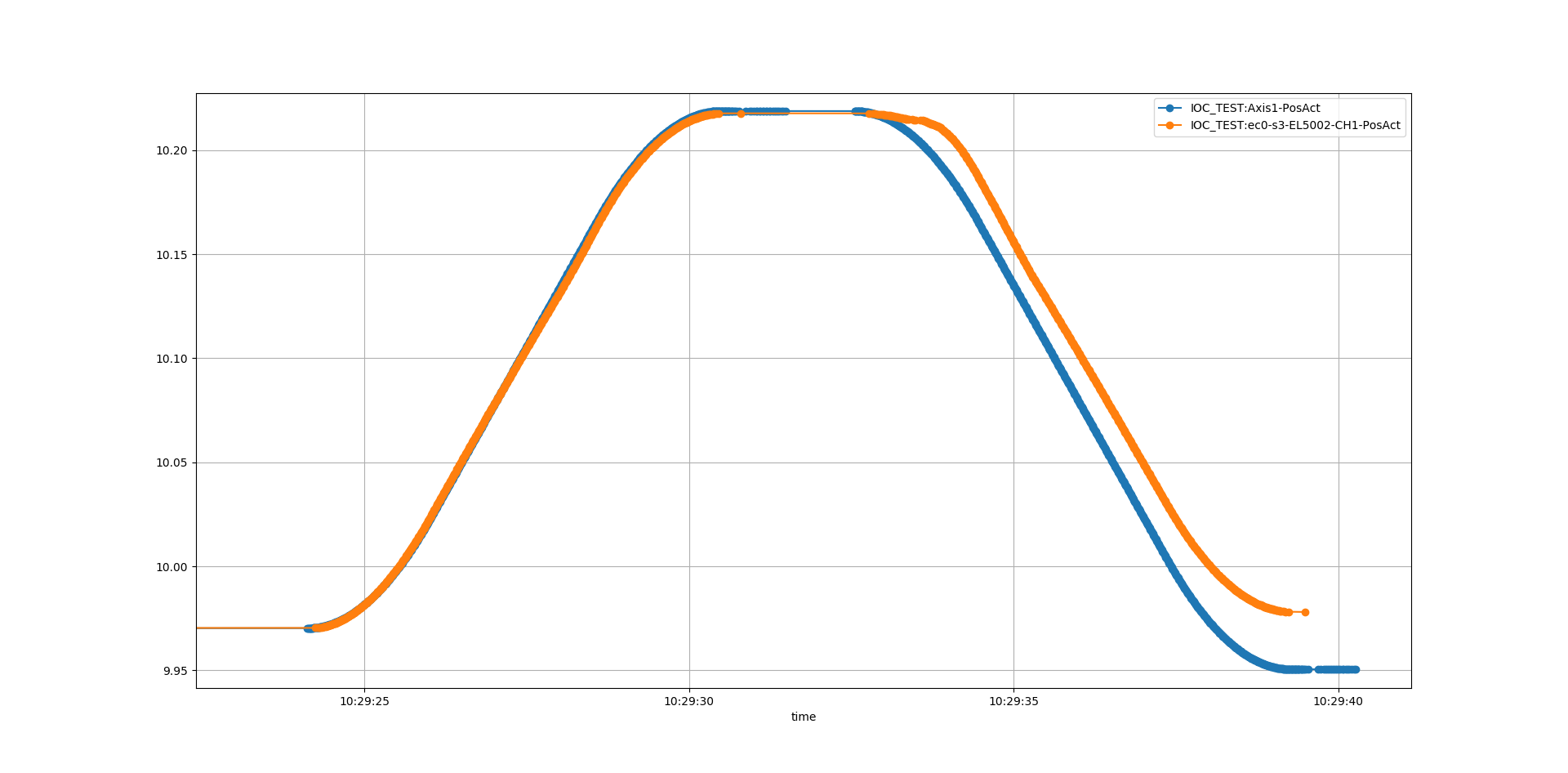


Figure 10: Acceleration phase when reverse direction.

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

## 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 688degmotor/s
* after collision 1280degmotor/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 688degmotor/s). Figure 11 shows the same data but acquired after the collision but at a higher velocity (1280degmotor/s). In both graphs the backlash is not shown.

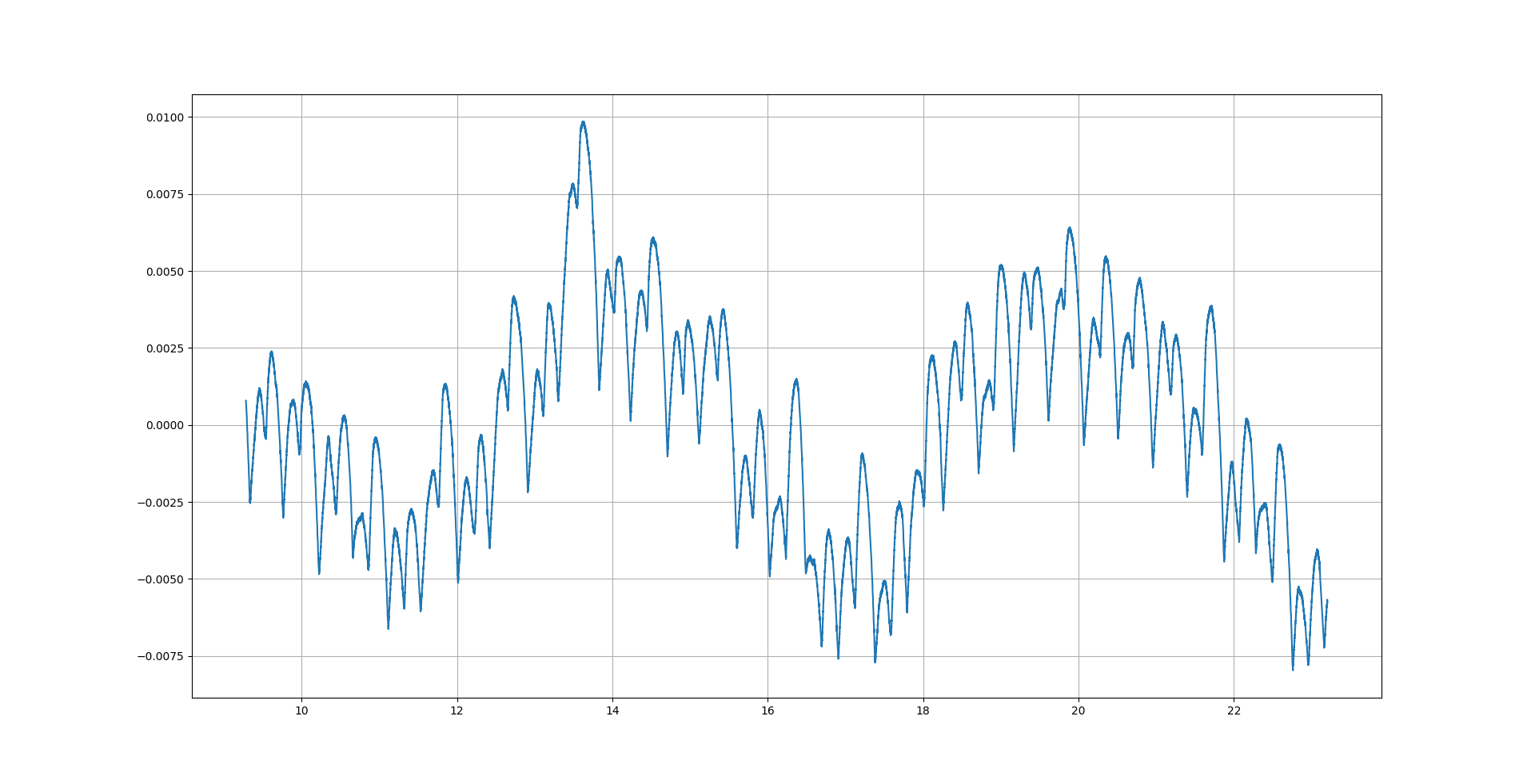


Figure 11: Before collision: Encoder position error (without backlash) at 688degmotor/s

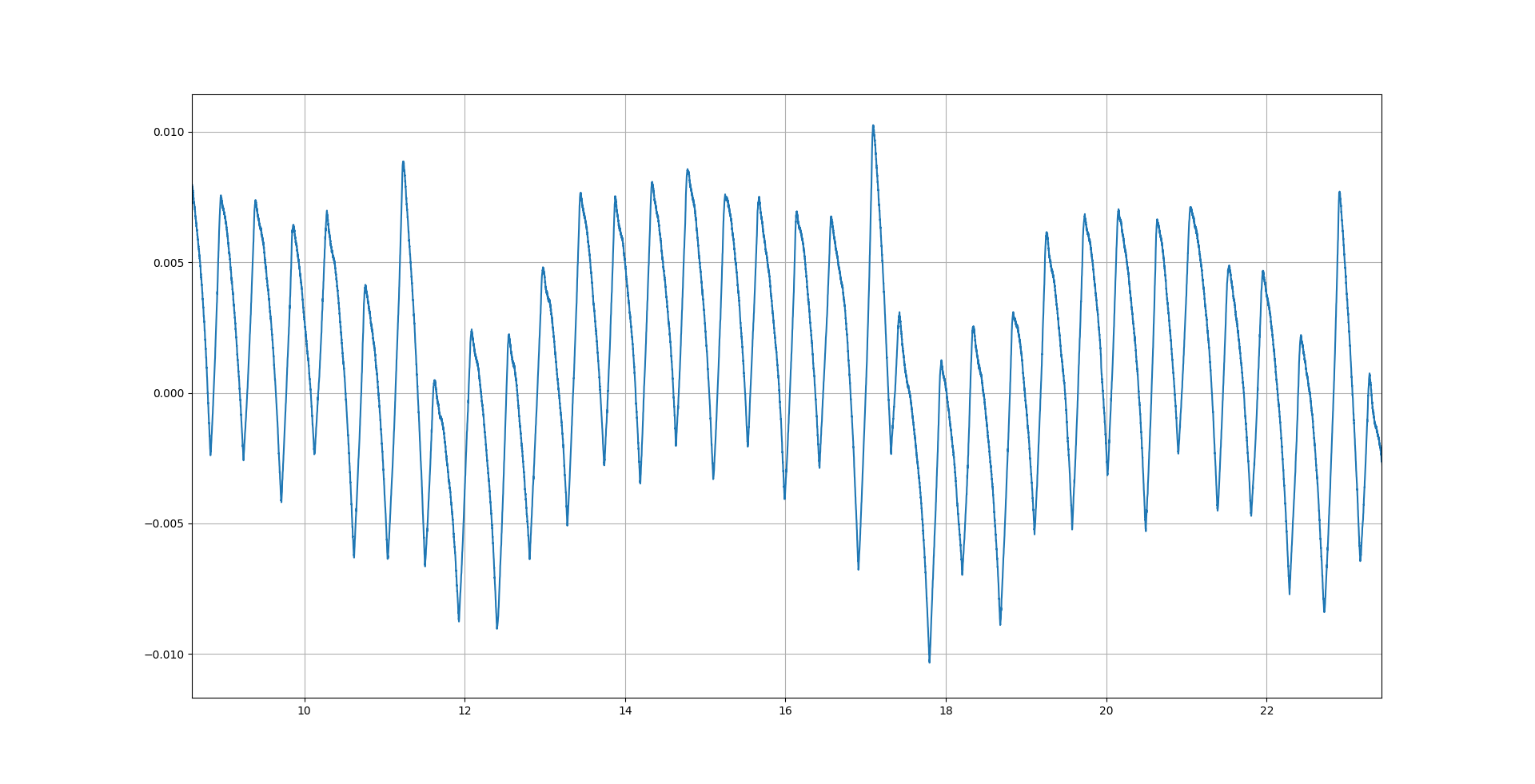


Figure 12: After collision: Encoder position error (without backlash) at 1280degmotor/s

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.

## 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.

## 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, it is safe to say that the repeatability values in both cases show a better value and fulfils the requirement.

# 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 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 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]** | 0,0044 | OK | Similar to before collision but based on fewer measurements, see chapter 2 for detailed comparison. |
| **6** | **Bidirectional repeatability [deg]** | 0,00093 | Check | Shows and improvement. But it is very unlikely that is true. See chapter 2 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.

# 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 |
|  |  |  |  |
|  |  |  |  |

# 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 |  |  |

# 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 (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 |  |

# Appendix D: Backlash measurements after collision

**0 degtank**

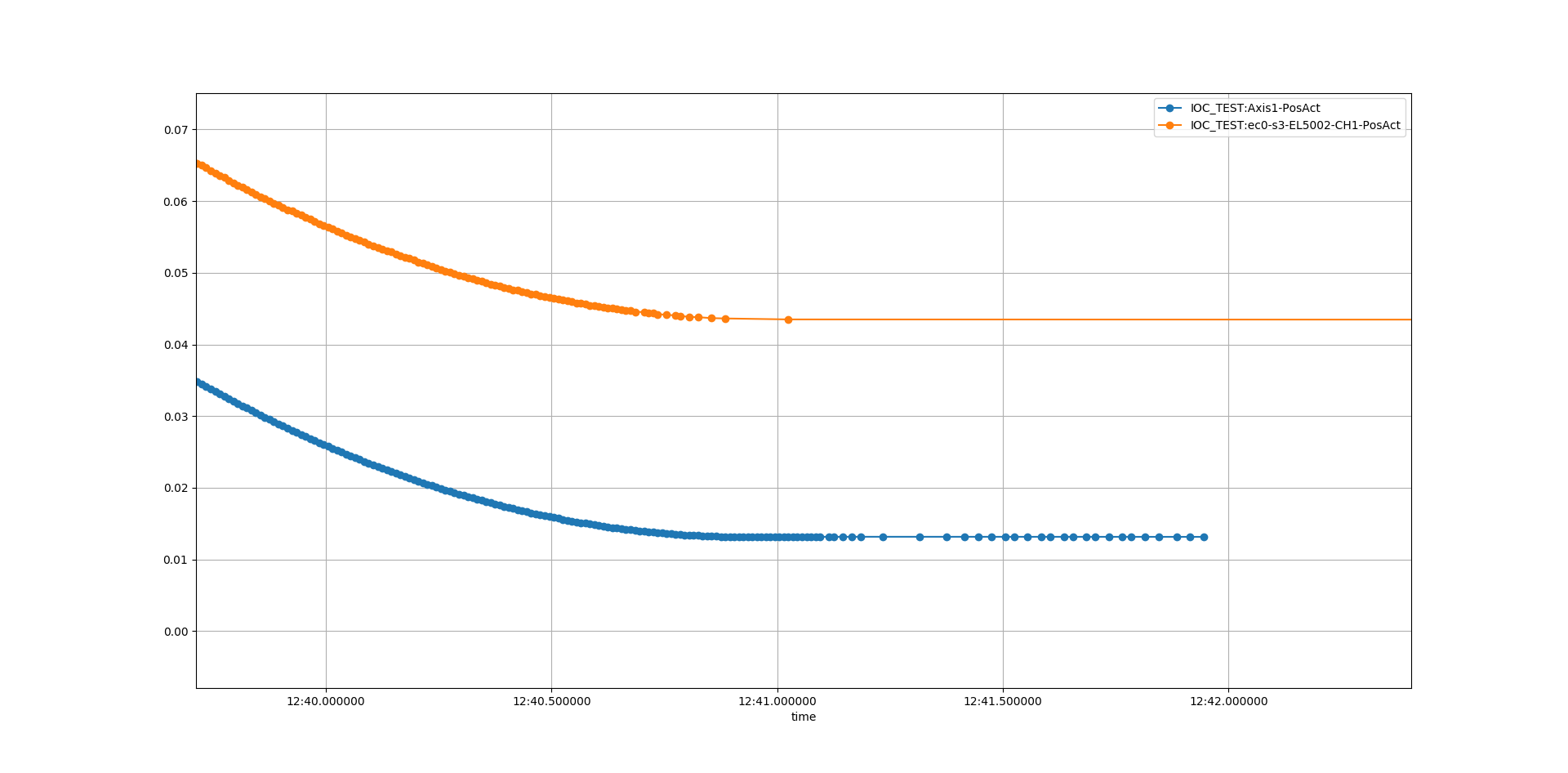


Figure 13: Backward backlash between motor and encoder shaft

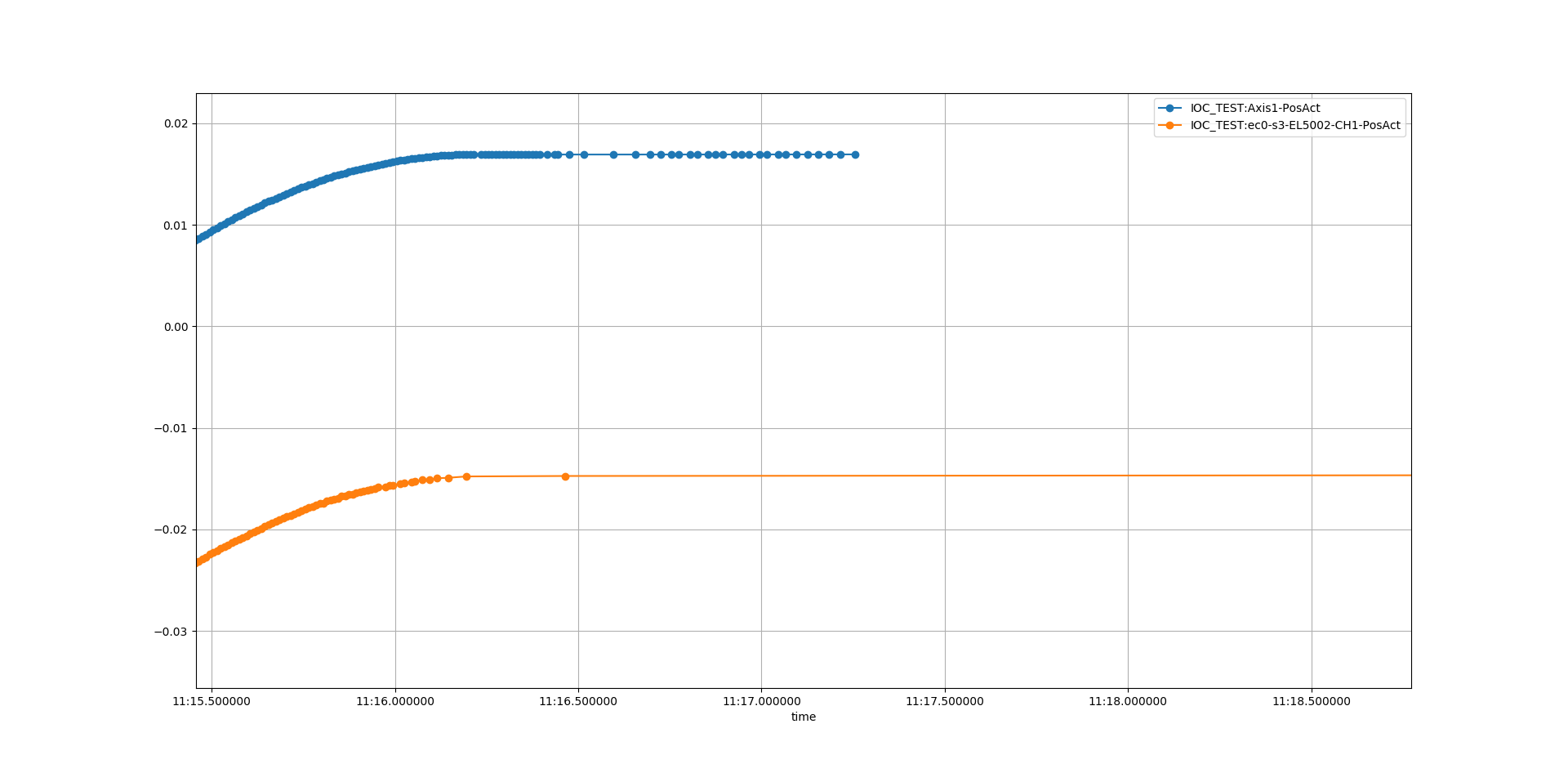


Figure 14: Forward backlash between motor and encoder shaft

**10 degtank**

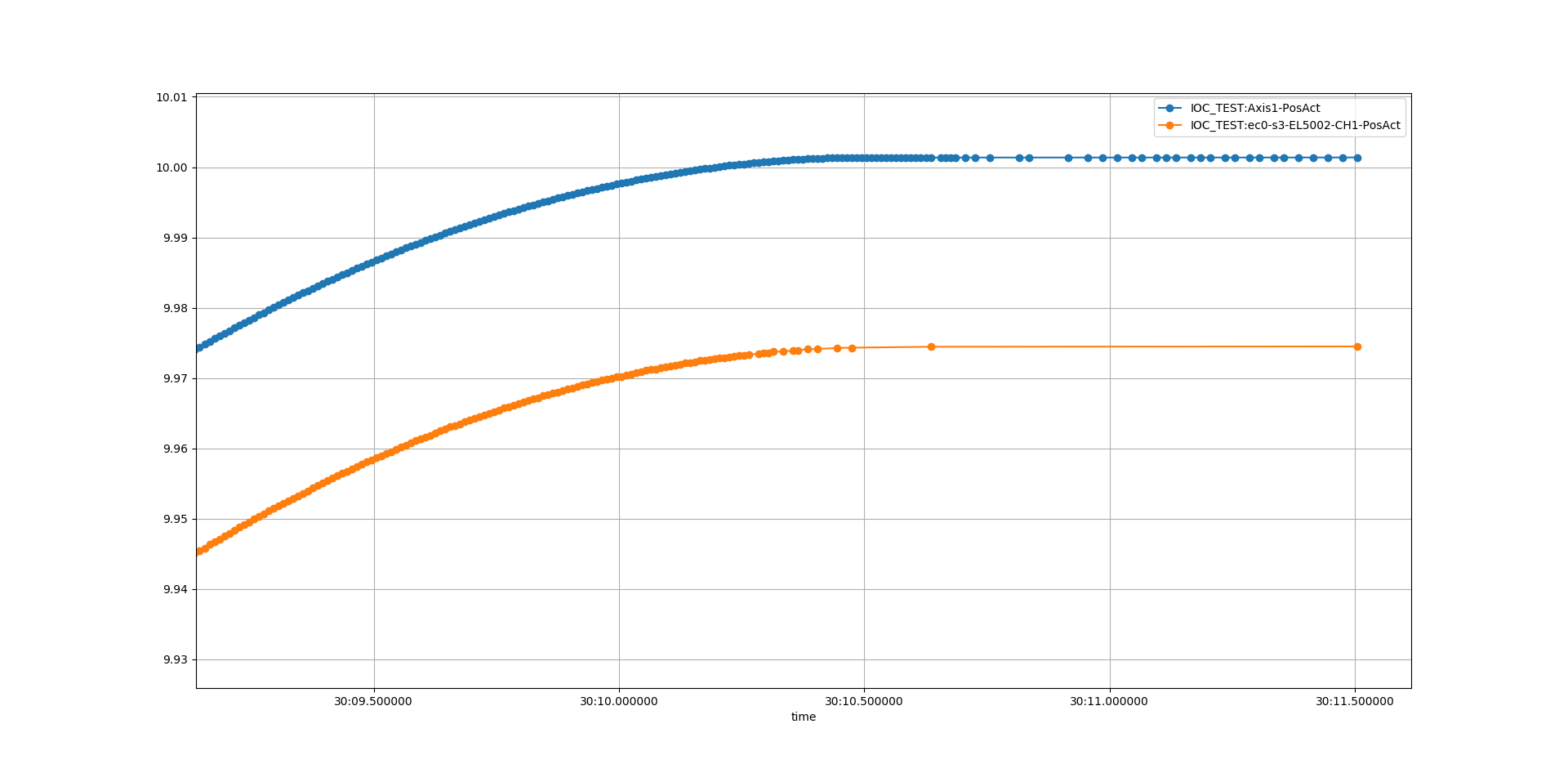


Figure 15: Backward backlash between motor and encoder shaft

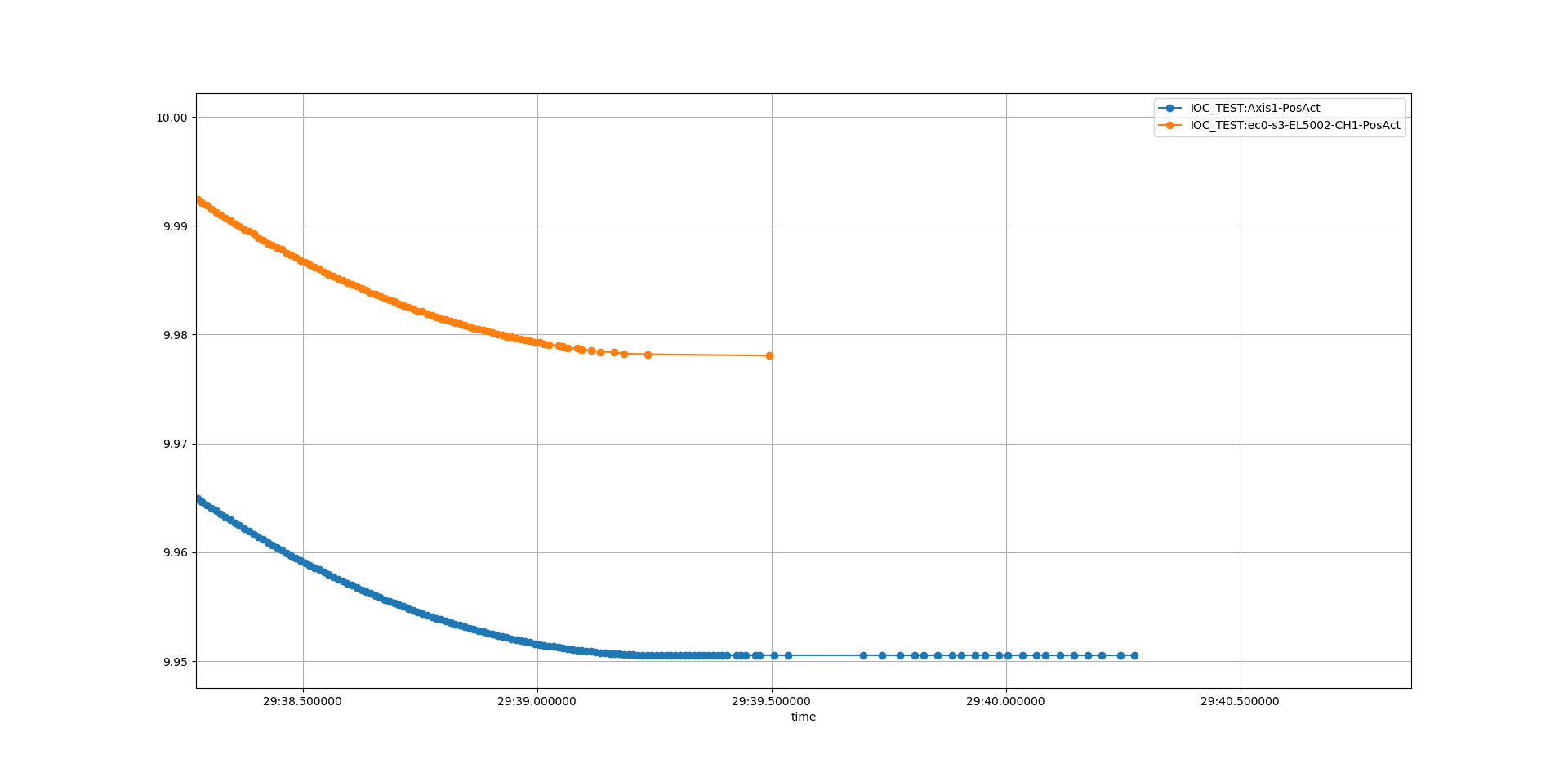


Figure 16: Forward backlash between motor and encoder shaft

**20 degtank**

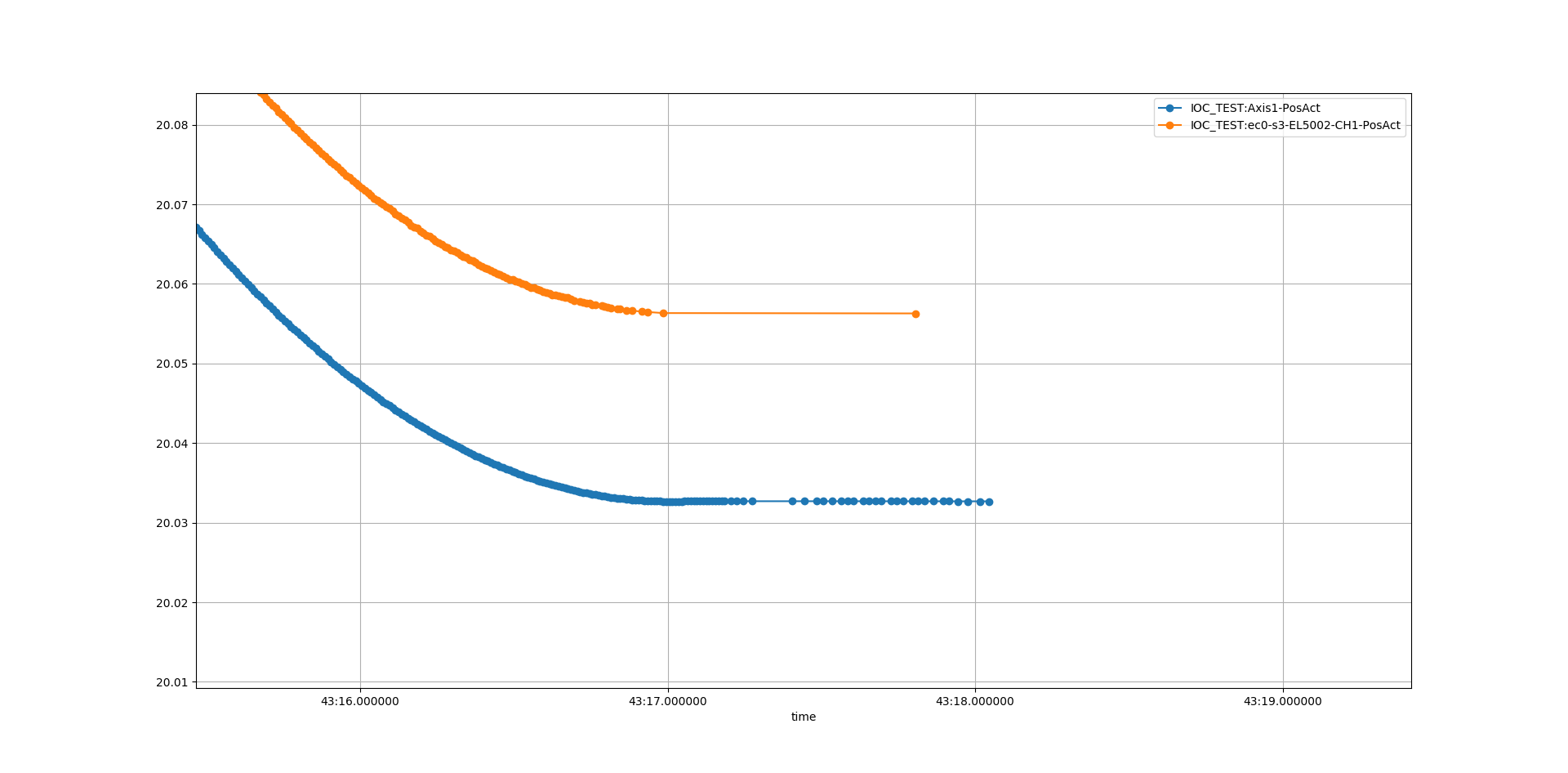


Figure 17: Backward backlash between motor and encoder shaft



Figure 18: Forward backlash between motor and encoder shaft

**30 degtank**

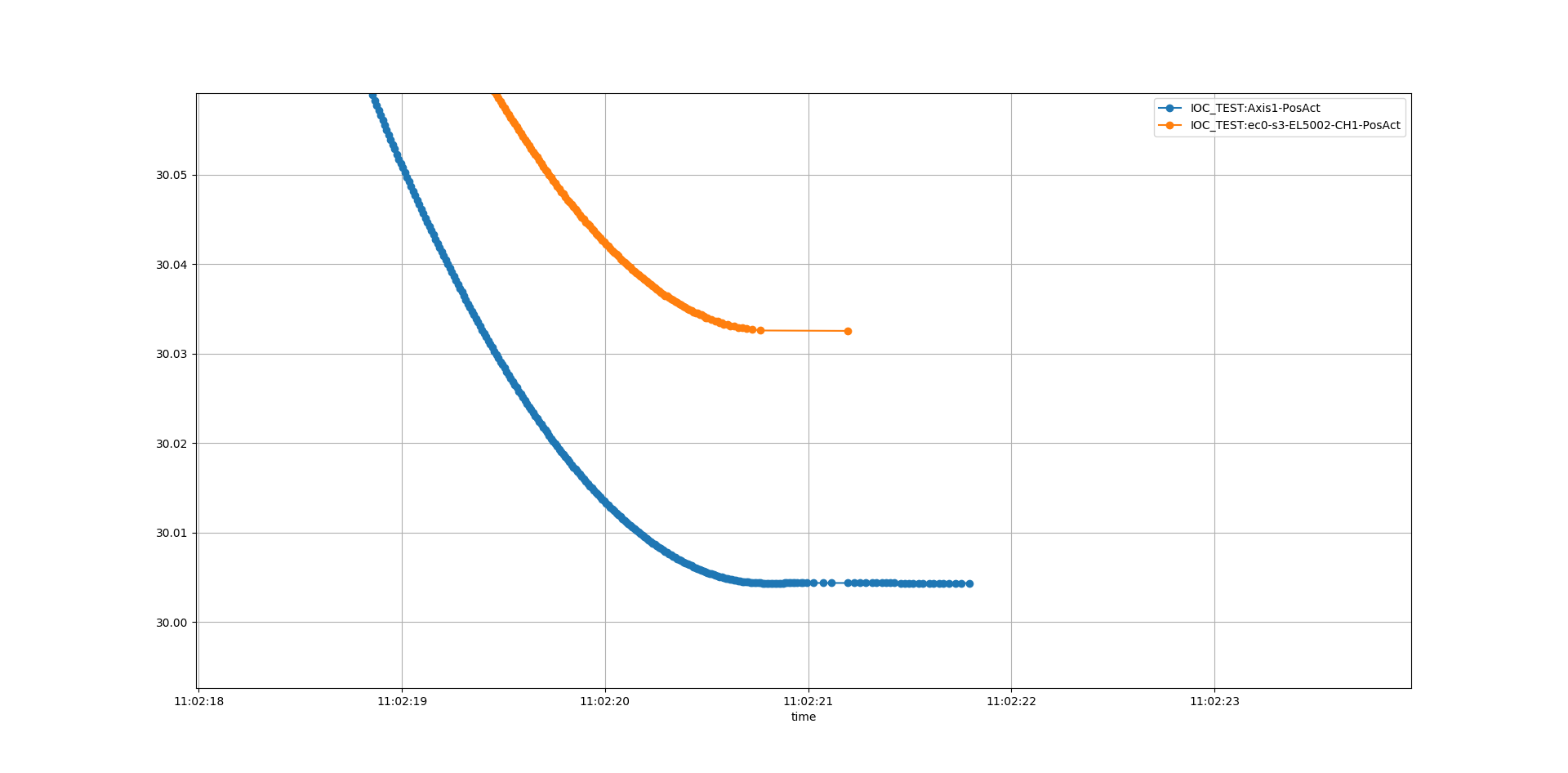


Figure 19: Backward backlash between motor and encoder shaft

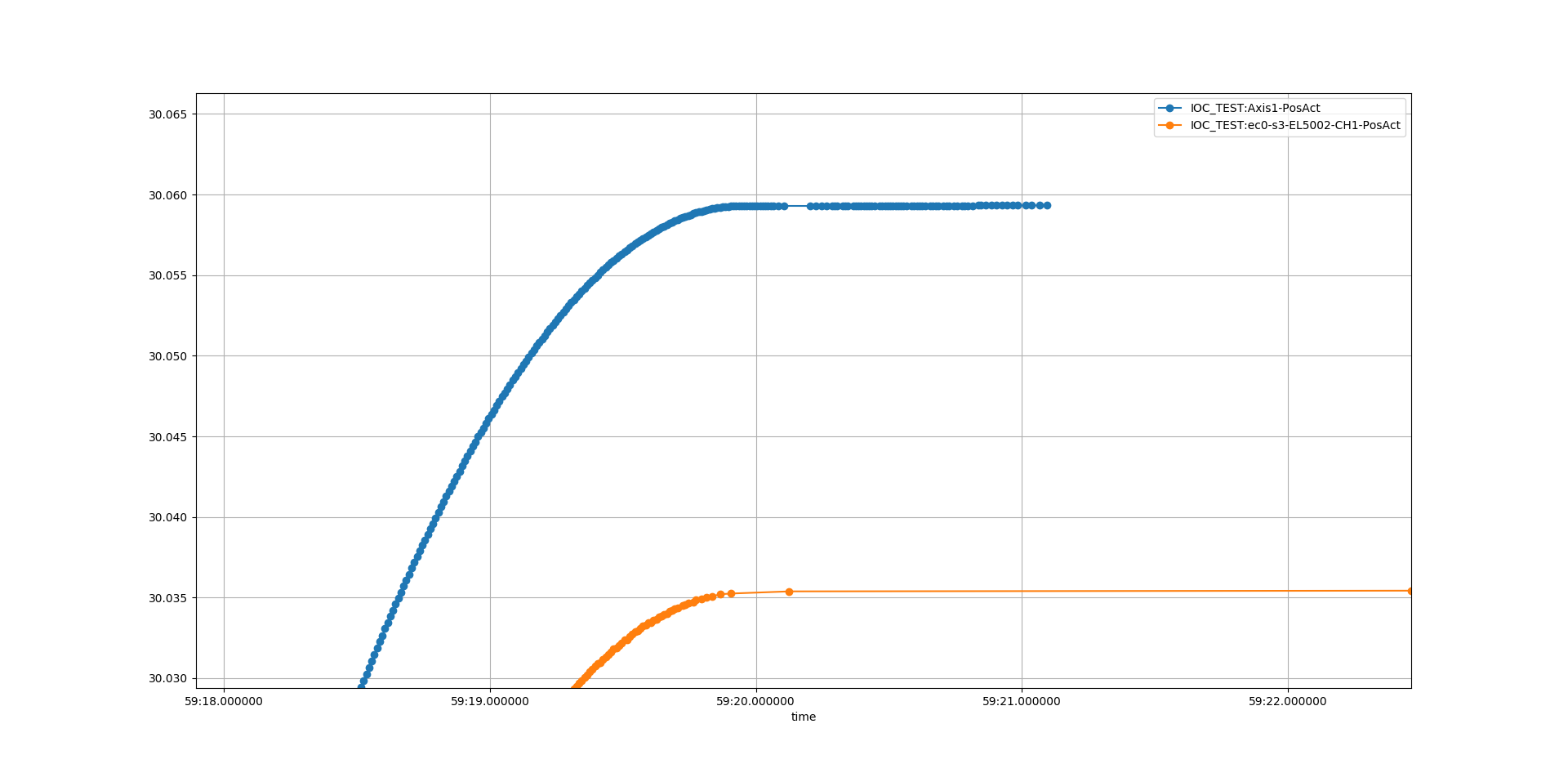


Figure 20: Forward backlash between motor and encoder shaft

**40 degtank**

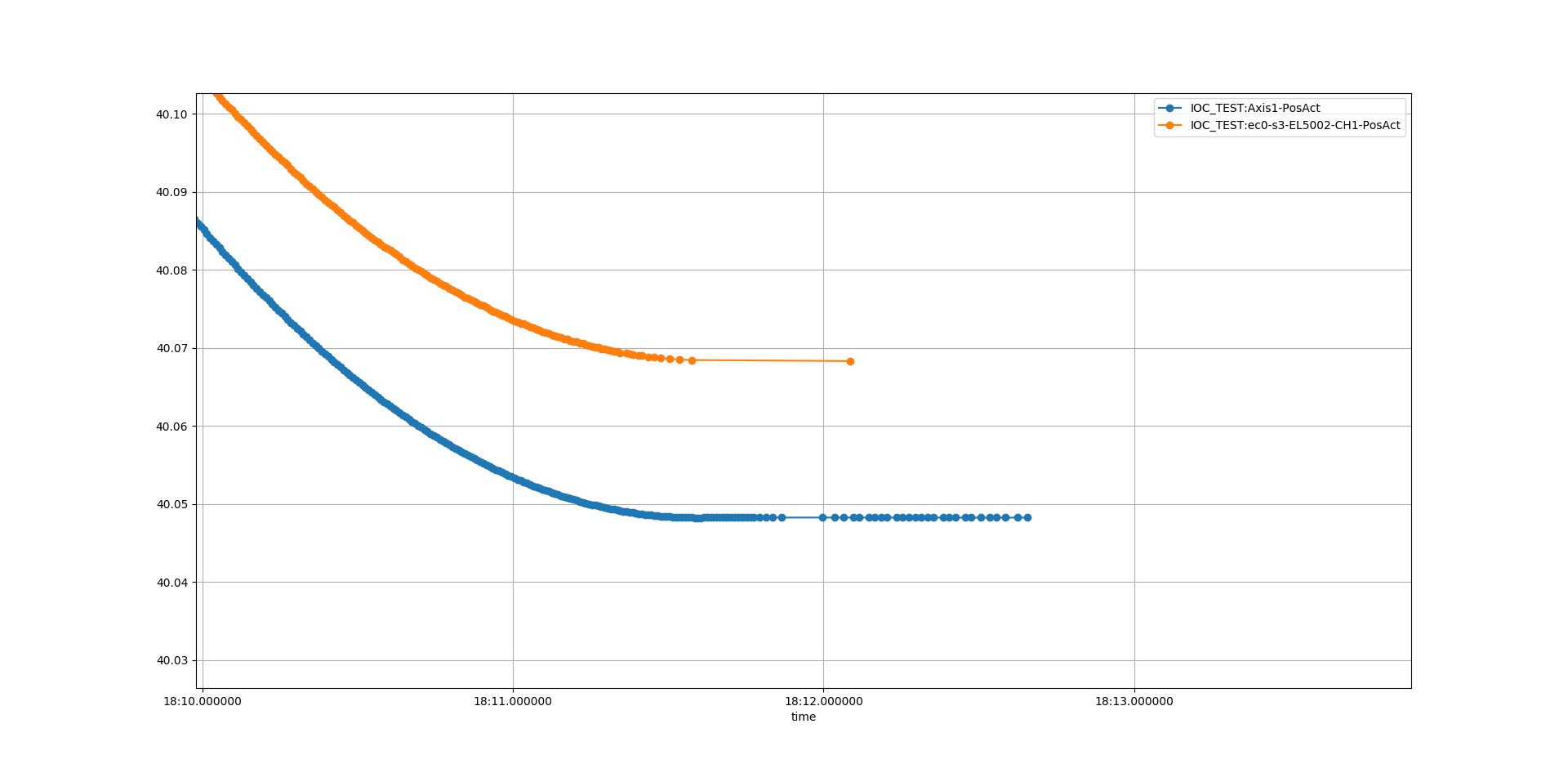


Figure 21: Backward backlash between motor and encoder shaft



Figure 22: Forward backlash between motor and encoder shaft