

SAS Prealignment Platform V4 Test Results

Matthew Capstick

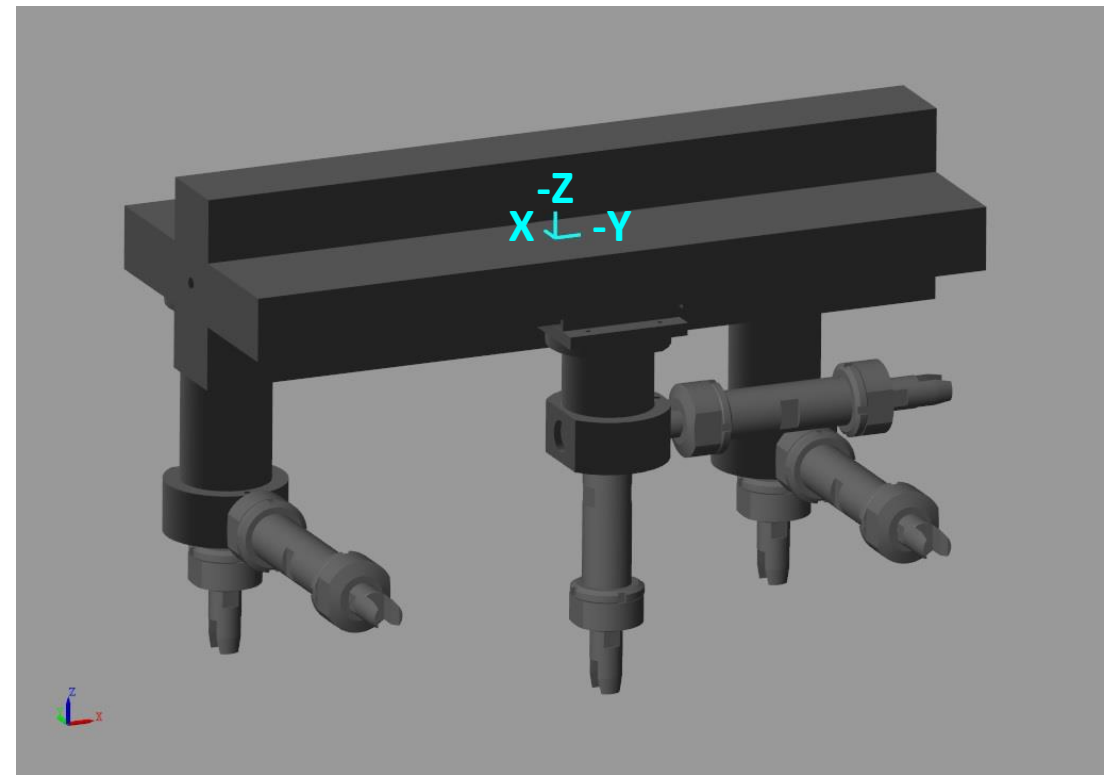
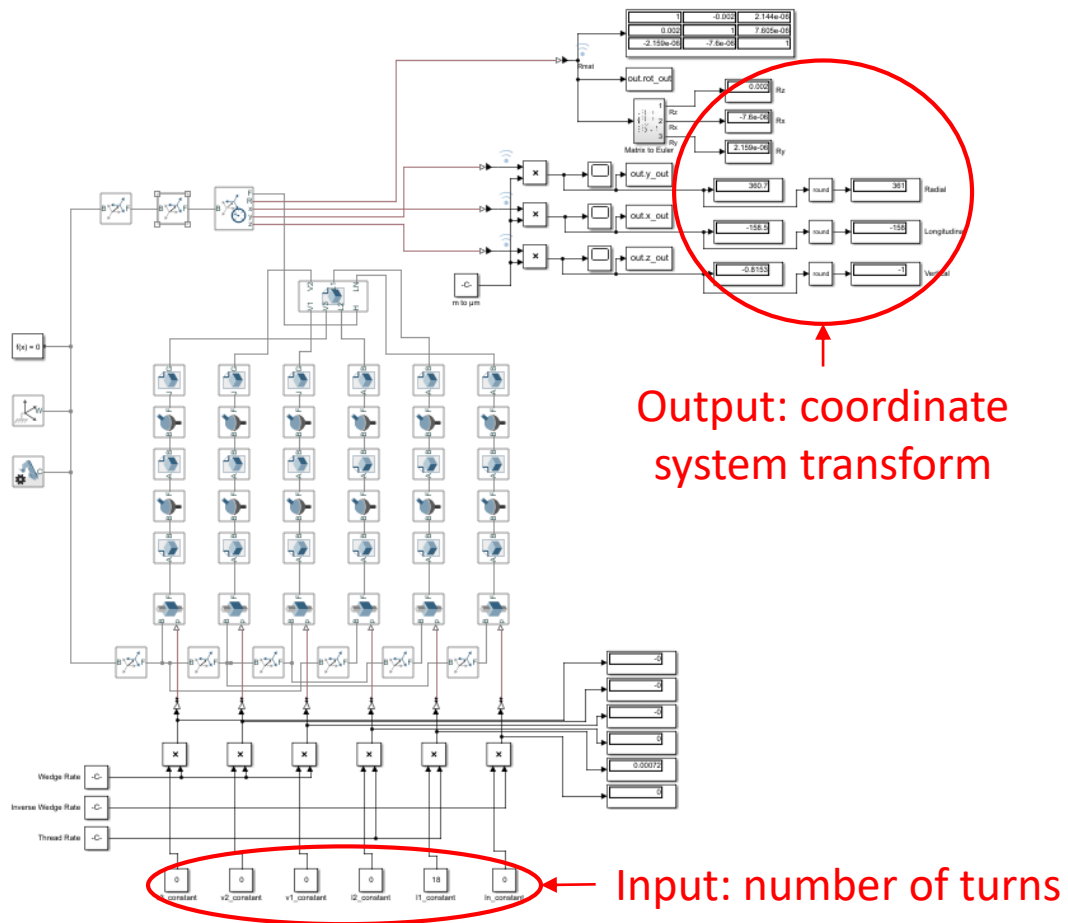
01/02/2023

Test Data

The test programme from Vivien Rude and Maksymilian Kucharz (BE-GM):

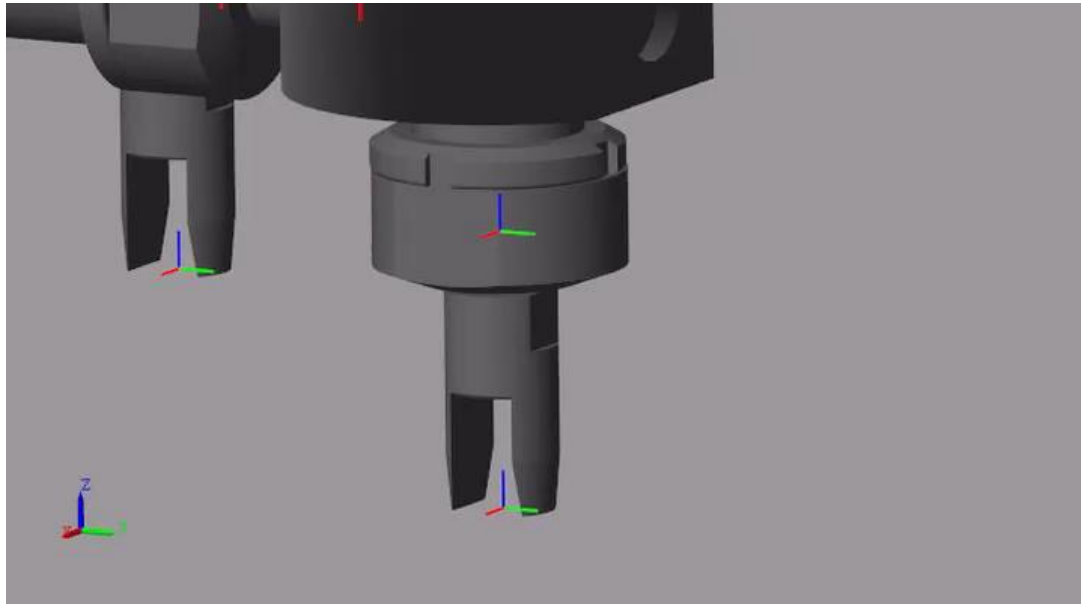
STATION	ACTION	ROTATION (NUMBER OF REVOLUTIONS)						MEASURED POSITION (mm/mrad)					
		K1	K2	K3	K4	K5	K6 (LN)	Tx	Ty	Tz	Rx	Ry	Rz
ST1.1	<i>O-MEASUREMENT</i>	-	-	-	-	-	-	0.003	0.004	0.005	-0.000049	-4.2E-05	0.000014
ST1.2	<i>RADIAL</i>	+9	0	0	0	+9	0	0.352	0.015	-0.013	-0.000084	0.000088	-6.9E-05
ST1.3	<i>YAW</i>	+9	0	0	0	-9	0	0.376	-0.104	-0.008	-0.000213	-9E-06	-0.00184
ST1.4	<i>READJUST</i>	-18	0	0	0	0	0	0.011	0.007	-0.002	-0.000048	-4E-06	0.000032
ST2.1	<i>O-MEASUREMENT</i>	-	-	-	-	-	-	0.01	0	-0.004	-0.000067	-1.1E-05	0.000034
ST2.2	<i>VERTICAL</i>	0	+8	+8	+8	0	0	0.003	0.009	-0.244	-0.000021	-5.2E-05	0.000021
ST2.3	<i>PITCH</i>	0	+8	0	-8	0	0	0	0.123	-0.244	-0.001343	-4.1E-05	-1E-06
ST2.4	<i>ROLL</i>	0	-8	+8	-8	0	0	-0.49	0.139	-0.248	-0.001373	-0.00309	0.000065
ST2.5	<i>READJUST</i>	0	-8	-16	+8	0	0	-0.037	0.012	-0.012	-0.000065	-9E-06	0.000019
ST3.1	<i>LONGITUDINAL</i>	0	0	0	0	0	+18	-0.036	-0.493	-0.004	-0.000117	-9.2E-05	0.000162
ST3.2	<i>READJUST</i>	0	0	0	0	0	-18	-0.03	-0.054	-0.011	-0.000066	-1.8E-05	0.000003
ST4.1	<i>RANDOM</i>	+9	+16	-16	+8	+18	0	1.361	0.085	0.045	-0.000714	0.005293	0.00093
ST4.2	<i>RANDOM</i>	+9	-8	+8	+8	-18	0	0.988	-0.273	-0.072	0.000548	0.003813	-0.00191
ST4.3	<i>RANDOM</i>	-9	-8	-8	-8	-9	0	0.633	-0.253	0.18	0.000465	0.003779	-0.00184
ST4.4	<i>READJUSTED</i>	-9	0	+16	-8	+9	0	0.013	-0.065	-0.006	-0.000019	0.000006	-9.1E-05

MatLab/Simulink Model

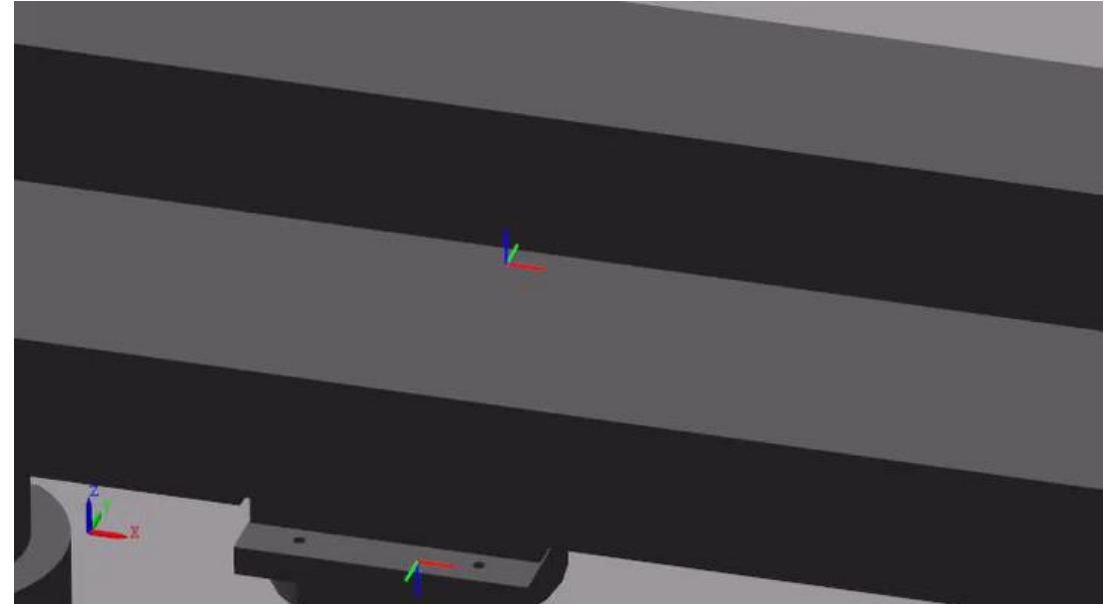


MatLab/Simulink Model

Input Vertical Translation



Output Coordinate System Translation



Comparison

STATION	ACTION	ROTATION (NUMBER OF REVOLUTIONS)						Measured			Predicted mm			Difference $\mu\text{m}/\mu\text{rad}$		
		K1	K2	K3	K4	K5	K6 (LN)	X	Y	Z	X	Y	Z	X	Y	Z
ST1.1	0-MEASUREMENT	-	-	-	-	-	-	0.003	0.004	0.005	0.000	0.000	0.000	3	4	5
								-0.000049	-0.000042	0.000014	0.000000	0.000000	0.000000	-0.049	-0.042	0.014
ST1.2	RADIAL	+9	0	0	0	+9	0	0.352	0.015	-0.013	0.360	0.001	0.000	-8	14.4535	-12.5643
								-0.000084	0.000088	-0.000069	-0.000003	-0.000003	0.000000	-0.08138	0.090873	-0.069
ST1.3	YAW	+9	0	0	0	-9	0	0.376	-0.104	-0.008	0.361	-0.159	-0.001	15.3	54.5	-7.1847
								-0.000213	-0.000009	-0.001836	-0.000008	0.000002	0.002000	-0.2054	-0.01116	-3.836
ST1.4	READJUST	-18	0	0	0	0	0	0.011	0.007	-0.002	0.000	0.000	0.000	11	7	-2
								-0.000048	-0.000004	0.000032	0.000000	0.000000	0.000000	-0.048	-0.004	0.032
ST2.1	0-MEASUREMENT	-	-	-	-	-	-	0.010	0.000	-0.004	0.000	0.000	0.000	10	0	-4
								-0.000067	-0.000011	0.000034	0.000000	0.000000	0.000000	-0.067	-0.011	0.034
ST2.2	VERTICAL	0	+8	+8	+8	0	0	0.003	0.009	-0.244	0.000	0.000	-0.240	3.2072	8.7562	-4
								-0.000021	-0.000052	0.000021	-0.000003	-0.000003	0.000000	-0.01841	-0.04909	0.021
ST2.3	PITCH	0	+8	0	-8	0	0	0.000	0.123	-0.244	0.000	0.131	-0.240	0.4479	-7.6	-3.9
								-0.001343	-0.000041	-0.000001	0.001331	-0.000003	-0.000002	-2.674	-0.03811	0.001294
ST2.4	ROLL	0	-8	+8	-8	0	0	-0.490	0.139	-0.248	-0.507	0.132	-0.241	17.2	7	-7.3
								-0.001373	-0.003086	0.000065	0.001331	0.002997	-0.000002	-2.704	-6.083	0.066577
ST2.5	READJUST	0	-8	-16	+8	0	0	-0.037	0.012	-0.012	0.000	0.000	0.000	-37	12	-12
								-0.000065	-0.000009	0.000019	0.000000	0.000000	0.000000	-0.065	-0.009	0.019
ST3.1	LONGITUDINAL	0	0	0	0	0	+18	-0.036	-0.493	-0.004	-0.001	-0.540	-0.001	-34.949	47	-3.0359
								-0.000117	-0.000092	0.000162	-0.000003	-0.000003	0.000000	-0.11436	-0.08915	0.162

Comparison

STATION	ACTION	ROTATION (NUMBER OF REVOLUTIONS)							Measured (mm)			Predicted (mm)			Difference ($\mu\text{m}/\mu\text{rad}$)			
		K1	K2	K3	K4	K5	K6 (LN)		X	Y	Z	X	Y	Z	X	Y	Z	
ST1.2	RADIAL	+9	0	0	0	+9	0		T	0.352	0.015	-0.013	0.36	0.000547	-0.00044	-8	14.4535	-12.5643
									R	-8.4E-05	0.000088	-6.9E-05	-2.6E-06	-2.9E-06	7.66E-12	-0.08138	0.090873	-0.069

- Adjusted radially by turning the two lateral adjustment points 9 turns each.
- Predicted 360 μm translation (360 $\mu\text{m}/9 = 40\mu\text{m}/\text{turn}$), measured 352 μm .
- Error in direction of motion 8 $\mu\text{m} = <1\mu\text{m}/\text{turn}$.
- Maximum error (LN) 14 $\mu\text{m} = <2\mu\text{m}/\text{turn}$.

STATION	ACTION	ROTATION (NUMBER OF REVOLUTIONS)							Measured (mm)			Predicted (mm)			Difference ($\mu\text{m}/\mu\text{rad}$)			
		K1	K2	K3	K4	K5	K6 (LN)		X	Y	Z	X	Y	Z	X	Y	Z	
ST1.3	YAW	+9	0	0	0	-9	0		T	0.376	-0.104	-0.008	0.3607	-0.1585	-0.00082	15.3	54.5	-7.1847
									R	-0.00021	-9E-06	-0.00184	-7.6E-06	2.16E-06	0.002	-0.2054	-0.01116	-3.836

- Yawed by adjusting the lateral adjustment points +9 and -9 turns.
- Stacked on the previous adjustment. Resulting position is both translated radially and yawed.
- Maximum error 54.5 μm in the longitudinal direction.
- Error in direction of motion 8 $\mu\text{m} = <3\mu\text{m}/\text{turn}$.
- Angular error 4 $\mu\text{rad} = <0.25\mu\text{rad}/\text{turn}$

Comparison

STATION	ACTION	ROTATION (NUMBER OF REVOLUTIONS)							Measured (mm)			Predicted (mm)			Difference ($\mu\text{m}/\mu\text{rad}$)			
		K1	K2	K3	K4	K5	K6 (LN)		X	Y	Z	X	Y	Z	X	Y	Z	
ST2.2	VERTICAL	0	+8	+8	+8	0	0		T	0.003	0.009	-0.244	-0.00021	0.000244	-0.24	3.2072	8.7562	-4
									R	-2.1E-05	-5.2E-05	0.000021	-2.6E-06	-2.9E-06	4.22E-11	-0.01841	-0.04909	0.021

- Translated purely vertically by moving all vertical axes 8 turns upwards.
- Z axis error is $4\mu\text{m} = <0.5\mu\text{m}/\text{turn}$.
- Maximum error $8\mu\text{m}$ again in the longitudinal direction.

STATION	ACTION	ROTATION (NUMBER OF REVOLUTIONS)							Measured (mm)			Predicted (mm)			Difference ($\mu\text{m}/\mu\text{rad}$)			
		K1	K2	K3	K4	K5	K6 (LN)		X	Y	Z	X	Y	Z	X	Y	Z	
ST2.3	PITCH	0	+8	0	-8	0	0		T	0.000	0.123	-0.244	0.000	0.131	-0.240	0.4479	-7.6	-3.9
									R	-1.3E-03	-4.1E-05	-1.0E-06	1.33E-03	-2.9E-06	-2.3E-06	-2.674	-0.03811	0.001294

- Pitched by adjusting the end vertical adjustment points +8 turns and -8 turns.
- 'True' positions are now +16, +8, +0. Resulting position is both translated vertically and pitched.
- Maximum error $8\mu\text{m}$ again in the longitudinal direction.
- Angular error $3\mu\text{rad} = <0.25\mu\text{rad}/\text{turn}$

Comparison

STATION	ACTION	ROTATION (NUMBER OF REVOLUTIONS)							Measured (mm)			Predicted (mm)			Difference ($\mu\text{m}/\mu\text{rad}$)			
		K1	K2	K3	K4	K5	K6 (LN)		X	Y	Z	X	Y	Z	X	Y	Z	
ST2.4	ROLL	0	-8	+8	-8	0	0		T	-0.490	0.139	-0.248	-0.507	0.132	-0.241	17.2	7	-7.3
									R	-1.4E-03	-3.1E-03	6.50E-05	1.33E-03	3.00E-03	-1.6E-06	-2.704	-6.083	0.066577

- Rolled by adjusting the end vertical adjustment points -8 turns and the middle point +8 turns.
- 'True' positions are now +8, +16, -8. Resulting position is both translated vertically, pitched, and rolled.
- Maximum error $17\mu\text{m}$ radially.
- Angular error in roll $6\mu\text{rad} = <0.3\mu\text{rad}/\text{turn}$

STATION	ACTION	ROTATION (NUMBER OF REVOLUTIONS)							Measured (mm)			Predicted (mm)			Difference ($\mu\text{m}/\mu\text{rad}$)			
		K1	K2	K3	K4	K5	K6 (LN)		X	Y	Z	X	Y	Z	X	Y	Z	
ST3.1	LONGITUDINAL	0	0	0	0	0	+18		T	-0.036	-0.493	-0.004	-0.001	-0.540	-0.001	-34.949	47	-3.0359
									R	-1.2E-04	-9.2E-05	1.62E-04	-2.6E-06	-2.9E-06	1.62E-10	-0.11436	-0.08915	0.162

- Pure longitudinal translation +18 turns.
- Error in direction of motion is $47\mu\text{m} = 2.5\mu\text{m}/\text{turn}$, possibly indicating some play in the longitudinal adjustment.
- Off axis error is $35\mu\text{m}$ vertically, $2\mu\text{m}/\text{turn}$.

Comparison Summary

A simplified summary of the single axis adjustments. Note the largest error does not necessarily occur in the direction of adjustment, many of these adjustments were made consecutively, without readjustment, and we do not know that the platform was perfectly centred at the start of the testing.

STATION	ACTION	PREDICTED TRANSLATION/ ROTATION (mm/mrad)	MEASURED TRANSLATION/ ROTATION (mm/mrad)	LARGEST ERROR ($\mu\text{m}/\mu\text{rad}$)	LARGEST ERROR ($\mu\text{m}/\mu\text{rad}$)/turn
ST2.2	VERTICAL	-0.244	-0.240	8.756	1.0945
ST1.2	RADIAL	0.352	0.360	14.454	1.6059
ST3.1	LONGITUDINAL	-0.493	-0.540	47.000	2.6111
ST2.4	ROLL	-0.003086	0.002997	-6.083	-0.7604
ST2.3	PITCH	-0.001343	0.001331	-2.674	-0.1671
ST1.3	YAW	-0.001836	0.002000	-3.836	-0.4262

The per-turn errors are 1-3 μm , and <1 μrad . The smallest errors are close the measurable limit of the laser tracker (per turn), there will also be some error in the manual counting on whole revolutions.

Our testing indicated a 1-2 μm variation in the adjustment rate when backlash was eliminated. Here backlash was not eliminated.

However, the longitudinal error is often greater regardless of the axis of adjustment.

Comparison Summary

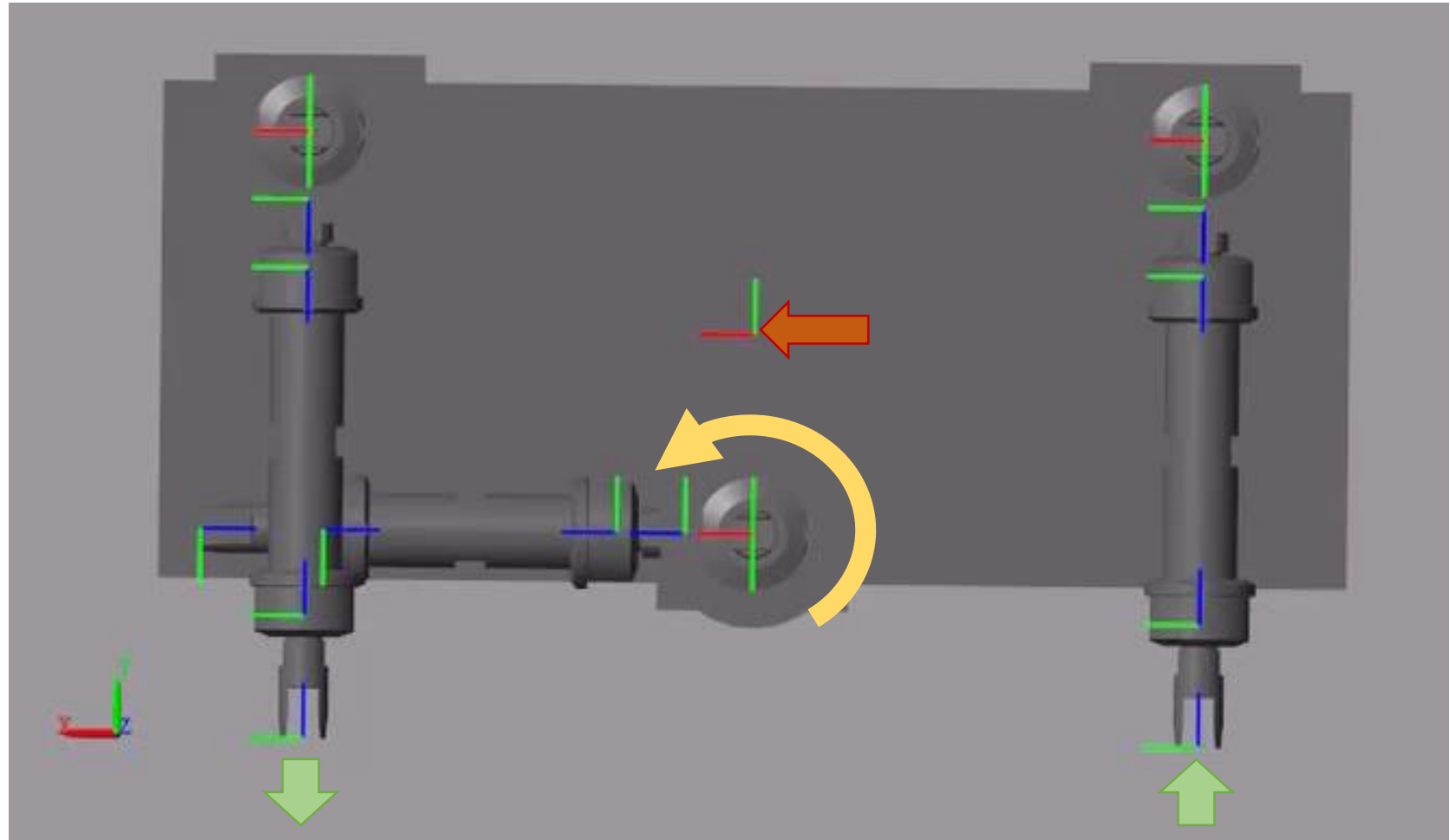


STATION	ACTION	ROTATION (NUMBER OF REVOLUTIONS)						Measured			Predicted mm			Difference $\mu\text{m}/\mu\text{rad}$		
		K1	K2	K3	K4	K5	K6 (LN)	X	Y	Z	X	Y	Z	X	Y	Z
ST1.1	0-MEASUREMENT	-	-	-	-	-	-	0.003	0.004	0.005	0.000	0.000	0.000	3	4	5
								-0.000049	-0.000042	0.000014	0.000000	0.000000	0.000000	-0.049	-0.042	0.014
ST1.2	RADIAL	+9	0	0	0	+9	0	0.352	0.015	-0.013	0.360	0.001	0.000	-8	14.4535	-12.5643
								-0.000084	0.000088	-0.000069	-0.000003	-0.000003	0.000000	-0.08138	0.090873	-0.069
ST1.3	YAW	+9	0	0	0	-9	0	0.376	-0.104	-0.008	0.361	-0.159	-0.001	15.3	54.5	-7.1847
								-0.000213	-0.000009	-0.001836	-0.000008	0.000002	0.002000	-0.2054	-0.01116	-3.836
ST1.4	READJUST	-18	0	0	0	0	0	0.011	0.007	-0.002	0.000	0.000	0.000	11	7	-2
								-0.000048	-0.000004	0.000032	0.000000	0.000000	0.000000	-0.048	-0.004	0.032
ST2.1	0-MEASUREMENT	-	-	-	-	-	-	0.010	0.000	-0.004	0.000	0.000	0.000	10	0	-4
								-0.000067	-0.000011	0.000034	0.000000	0.000000	0.000000	-0.067	-0.011	0.034
ST2.2	VERTICAL	0	+8	+8	+8	0	0	0.003	0.009	-0.244	0.000	0.000	-0.240	3.2072	8.7562	-4
								-0.000021	-0.000052	0.000021	-0.000003	-0.000003	0.000000	-0.01841	-0.04909	0.021
ST2.3	PITCH	0	+8	0	-8	0	0	0.000	0.123	-0.244	0.000	0.131	-0.240	0.4479	-7.6	-3.9
								-0.001343	-0.000041	-0.000001	0.001331	-0.000003	-0.000002	-2.674	-0.03811	0.001294
ST2.4	ROLL	0	-8	+8	-8	0	0	-0.490	0.139	-0.248	-0.507	0.132	-0.241	17.2	7	-7.3
								-0.001373	-0.003086	0.000065	0.001331	0.002997	-0.000002	-2.704	-6.083	0.066577
ST2.5	READJUST	0	-8	-16	+8	0	0	-0.037	0.012	-0.012	0.000	0.000	0.000	-37	12	-12
								-0.000065	-0.000009	0.000019	0.000000	0.000000	0.000000	-0.065	-0.009	0.019
ST3.1	LONGITUDINAL	0	0	0	0	0	+18	-0.036	-0.493	-0.004	-0.001	-0.540	-0.001	-34.949	47	-3.0359
								-0.000117	-0.000092	0.000162	-0.000003	-0.000003	0.000000	-0.11436	-0.08915	0.162
ST3.2	READJUST	0	0	0	0	0	-18	-0.030	-0.054	-0.011	0.000	0.000	0.000	-30	-54	-11
								-0.000066	-0.000018	0.000003	0.000000	0.000000	0.000000	-0.066	-0.018	0.003
ST4.1	RANDOM	+9	+16	-16	+8	+18	0	1.361	0.085	0.045	1.428	0.149	0.055	-67	-64	-10
								-0.000714	0.005293	0.000930	0.000657	0.000000	0.000000	-1.3707	5.293	0.93
ST4.2	RANDOM	+9	-8	+8	+8	-18	0	0.988	-0.273	-0.072	0.994	-0.222	-0.063	-6.4	-51.1	-9.1
								0.000548	0.003813	-0.001907	-0.000659	-0.003758	0.002001	1.2071	7.571	-3.908
ST4.3	RANDOM	-9	-8	-8	-8	-9	0	0.633	-0.253	0.180	0.634	-0.223	0.179	-1.4	-29.9	1.4
								0.000465	0.003779	-0.001840	-0.000664	-0.003758	0.002000	1.1289	7.537	-3.84
ST4.4	READJUSTED	-9	0	+16	-8	+9	0	0.013	-0.065	-0.006	0.000	0.000	0.000	13	-65	-6
								-0.000019	0.000006	-0.000091	0.000000	0.000000	0.000000	-0.019	0.006	-0.091

- The largest errors almost all occurred in the Y (longitudinal) axis.
- Possibly indicating play within the longitudinal adjustment.
- Could possibly be improved by increasing the stiffness of the spring, the lubrication, or another change to the longitudinal wedge/fork.
- Compound errors occur in 'random' adjustments.

Unintended Longitudinal Translation

Noticeable longitudinal displacement is predicted and measured even when the longitudinal adjustment is unused. This is because the longitudinal joint is not centred. Shown here in a pure yawing motion.



Stability

- The stability of the platform was also tested by readjusting the structure, manually shaking it, and re-measuring the position.
- This was repeated twice, and the structure was returned to it's original position.

STATION	ACTION	ROTATION (NUMBER OF REVOLUTIONS)						MEASURED POSITION (mm/mrad)					
		K1	K2	K3	K4	K5	K6 (LN)	Tx	Ty	Tz	Rx	Ry	Rz
ST4.4	READJUSTED	-9	0	+16	-8	+9	0	0.013	-0.065	-0.006	-1.9E-05	0.000006	-9.1E-05
ST5.1	STABILITY (VESSEL SHAKEN)	-	-	-	-	-	-	-0.032	-0.069	-0.021	-7.7E-05	0.000054	-0.00017
ST5.2	STABILITY	+27	+24	-24	+24	-27	0	1.45	-0.491	0.021	-0.00022	0.008705	-0.00576
ST5.3	STABILITY (VESSEL SHAKEN)	-	-	-	-	-	-	1.414	-0.513	0.01	-0.00019	0.008765	-0.00599
ST5.4	READJUSTED	-27	-24	+24	-24	+27	0	-0.011	-0.075	0.005	-4.7E-05	0.000025	-0.00019

- Relative position change due to the shaking:

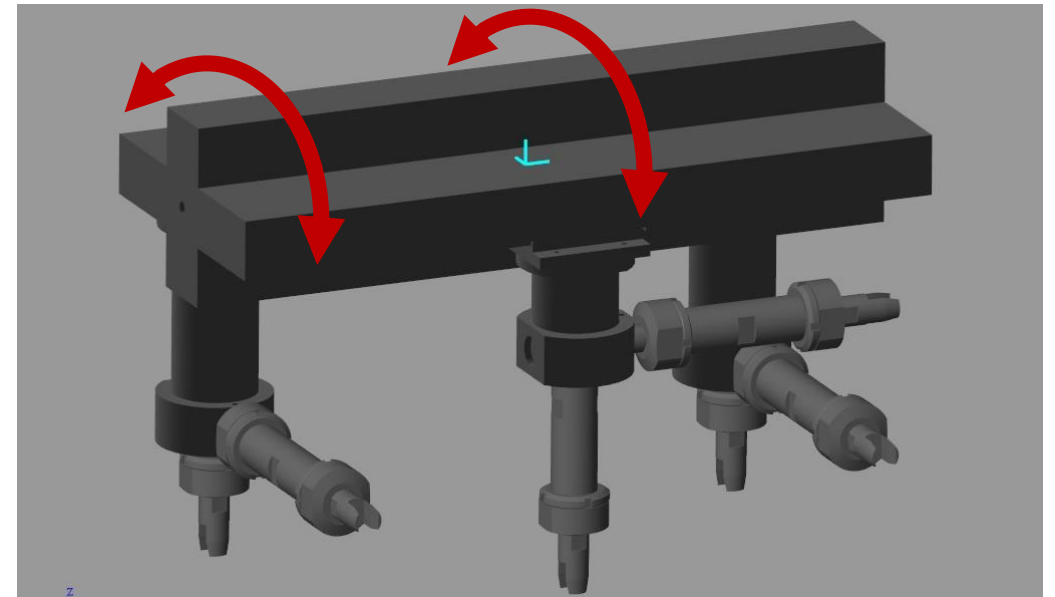
STATION	ACTION	RELATIVE POSITION ($\mu\text{m}/\mu\text{rad}$)					
		Tx	Ty	Tz	Rx	Ry	Rz
ST5.1	STABILITY (VESSEL SHAKEN)	-45	-4	-15	-0.058	0.048	-0.082
ST5.3	STABILITY (VESSEL SHAKEN)	-36	-22	-11	0.026	0.06	-0.225

Stability

- Relative position change due to the shaking:

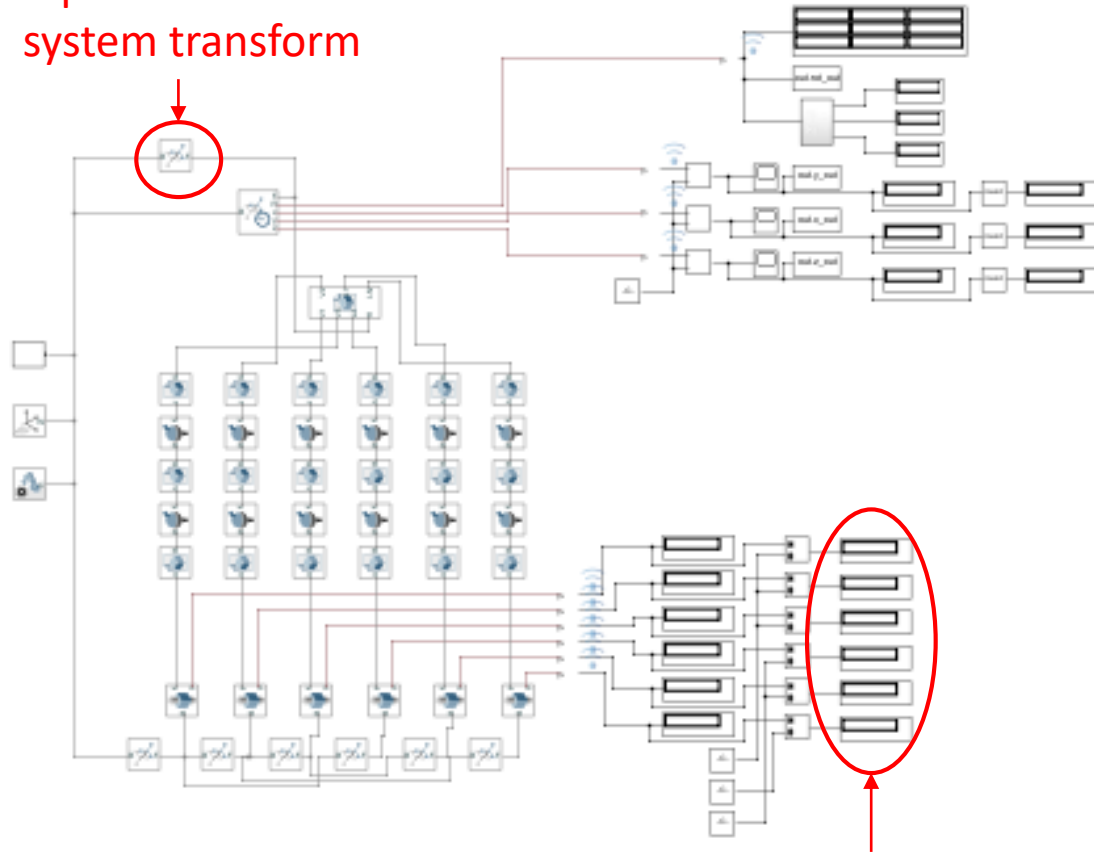
STATION	ACTION	RELATIVE POSITION ($\mu\text{m}/\mu\text{rad}$)					
		Tx	Ty	Tz	Rx	Ry	Rz
ST5.1	STABILITY (VESSEL SHAKEN)	-45	-4	-15	-0.058	0.048	-0.082
ST5.3	STABILITY (VESSEL SHAKEN)	-36	-22	-11	0.026	0.06	-0.225

- Maximum change in position = $45\mu\text{m}$ in the lateral (x) direction.
 - Possibly due to the orientation of the structure when it was shaken
- Nearly all the changes are enough to put the structure out of the prealignment tolerance.
- Exactly how much it was shaken is unknown.



Inverse Kinematics

Input: coordinate system transform



Output: number of turns

