

Gravity Model Report

DRAFT

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1 Abstract

This report aims to provide a general review on the performance of the gravity model used on the PR37 surgical 7DOF arm MS7. The gravity model is originally designed as a standalone feature offline on PC (named **JointWrench_PC** for convenience), and then integrated to real time system in robot base (named **JointWrench_Base**). In PR37 arm, torque sensor data from each actuator (named **Joint-Torque_Sensor**) will be used to evaluate gravity performance.

In this report, we will first compare JointWrench_Base and JointWrench_PC to confirm that the designed gravity model is well implemented in robot control system. After then, we will compare the component of torque along Z axis in JointWrench_Base with JointTorque_Sensor. Assuming that torque sensor reading is reliable, the difference between nominal and experimental joint torques should be below a certain threshold. This report will present all results and analysis regarding to the evaluation of gravity model.

The tests in this report are designed for a MS7 robot set, which includes the 7DOF arm and IDM, no extra load.

Robot configuration plays an important role in the gravity model. The pre-defined robot configurations can be divided in two groups. The first group includes robot configurations provided by Auris for different use cases. The second group includes robot configurations that maximize the load a certain joint. Therefore, the pre-defined robot configurations cover the general cases as well as the extreme cases.

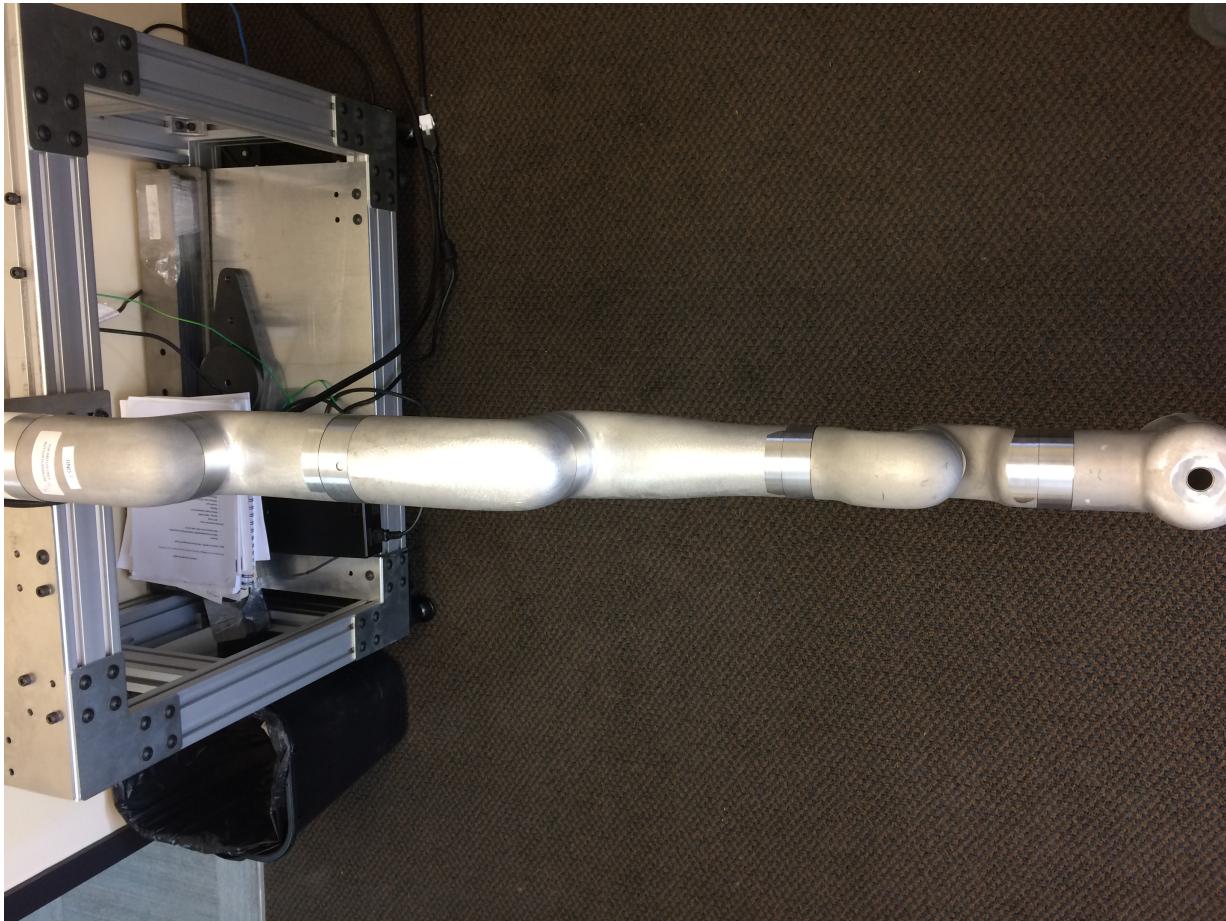


Figure 1: Test setup

2 Test Setup

2.1 Robot setup

The base of PR37 robot is horizontally attached to a vertical pole. At its initial position (also defined as Pose11 in pre-defined robot configurations), the robot is fully extended and the torque load at each actuator sensor is ideally zero. The user should reset joint torque sensor if the data from torque sensor is needed.

2.2 Pre-defined robot configurations

At each pre-defined robot configuration, the sensor data will be recorded and compared with the gravity model output. Their difference will be used to evaluate the gravity model performance. At different robot configurations, the torque at each actuator may vary widely. Therefore, the choice of robot configuration for gravity model evaluation is important. The pre-defined robot configurations used in this report can be categorized into two groups.

Group A In the first group (see in Table 1), the robot configurations are provided by Auris from some

Table 1: Pre-defined Robot Configuration of Group A (Degrees)

	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Pose 1	115	236.85	138.2	264.09	63	235.28	155.28
Pose 2	140	245.42	90.92	281.41	353.62	295.06	265.4
Pose 3	293	137.05	220.52	87.4	217.98	307	103.13
Pose 4	10	176.73	147.59	43.32	142.68	275	205.12
Pose 5	85	255.93	141.29	236.09	65.84	228.26	130.5
Pose 6	140	205.51	96.12	275.16	313.2	260.62	229.57
Pose 7	120	240.31	140.2	239.88	66.74	239.24	115.38
Pose 8	285	113.25	129.73	289.67	7.89	195.54	83.44
Pose 9	285	121.22	234.46	131.94	356.65	77.01	227.27
Pose 10	340	141.74	22.27	67.95	16.12	61.73	153.11

Table 2: Pre-defined Robot Configuration of Group B (Degrees)

	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7	Maximum Load
Pose 11	180	180	180	180	180	180	180	No load to all (Figure 1)
Pose 12	270	180	180	180	180	180	180	Joint 2, 4, 6, 7 (Figure 12)
Pose 13	180	180	180	180	180	90	180	Joint 5 (Figure 13)
Pose 14	180	180	180	90	180	180	180	Joint 3 (Figure 14)
Pose 15	180	90	180	180	180	180	180	Joint 1 (Figure 15)

real user cases. The robot is in a normal operating condition, and these statuses present most common cases. In Pose3, the position command for joint 6 should be 307.70. However, this value provided by Auris cannot be achieved, due to physical limit. In the test, command 307 degree is given instead. The test and computation regarding to Pose3 are subjected to this minor modification.

Group B In the second group (see in Table 2), the robot configurations are defined to have a maximum load on one or several joints. Since there is no extra load on the robot end-effector, the load only takes robot arm and IDM into account.

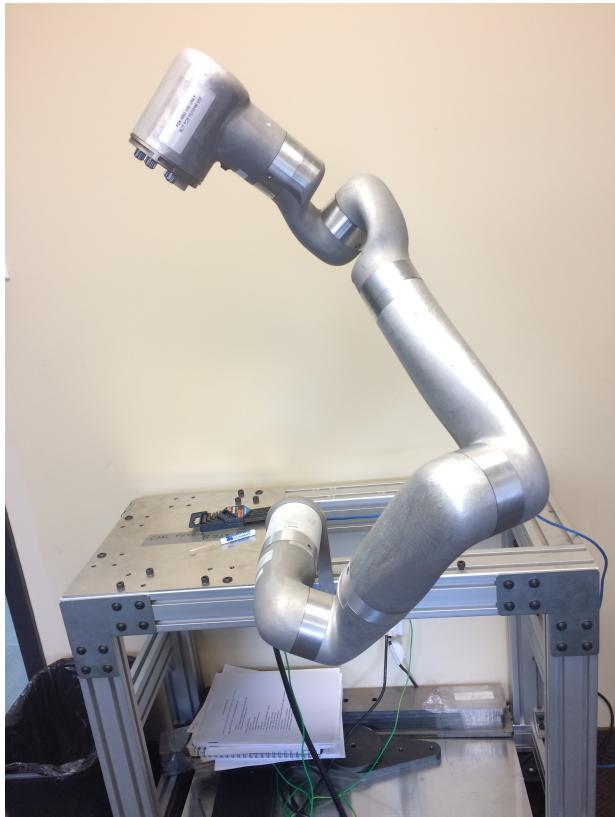


Figure 2: Pose1



Figure 3: Pose2



Figure 4: Pose3



Figure 5: Pose4



Figure 6: Pose5

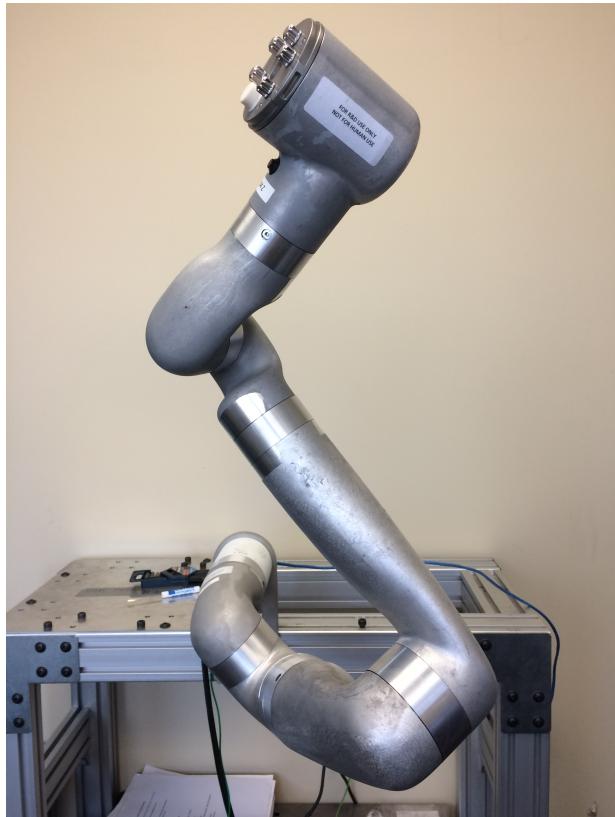


Figure 7: Pose6



Figure 8: Pose7



Figure 9: Pose8



Figure 10: Pose9



Figure 11: Pose10



Figure 12: Pose12

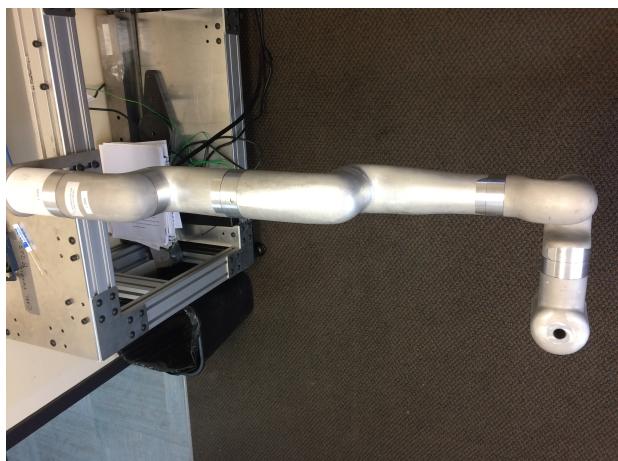


Figure 13: Pose13

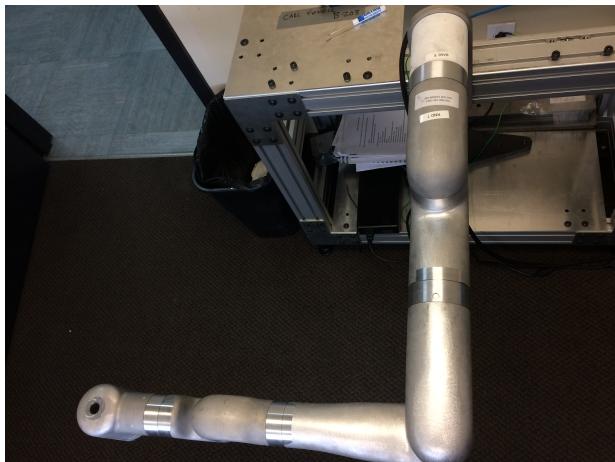


Figure 14: Pose14



Figure 15: Pose15

3 Test Procedure

3.1 Source Code Repository

PR37 MS7 arm uses a different architecture than MS5/6 arm. The branch of each repository is listed below:

- keos: release/1.9
- bitwin: release/1.1
- rtcontrol_nextgen: release/1.1
- sdk_assitive: temp_logButton*

temp_logButton is modified from release/1.1, with only one modification on the data log buttons. In this branch, "START LOG" and "STOP LOG" buttons will activate/deactivate the rtcontrol logger, instead of NOVA logger. This modification is a temporal change for this test only. Because at the moment of test, rtcontrol cannot log data when robot was in a static position.

3.2 Data acquisition

Make sure change the joint positions in "traj/mainTrajectories.csv" in NOVA installation folder to the predefined configurations shown in Section 2.

1. run executable rtcontrol on QNX
2. run sdk_assitive to get NOVA interface on PC (as in Figure 16)
3. select AURIS in NOVA
4. select AURIS Control in NOVA

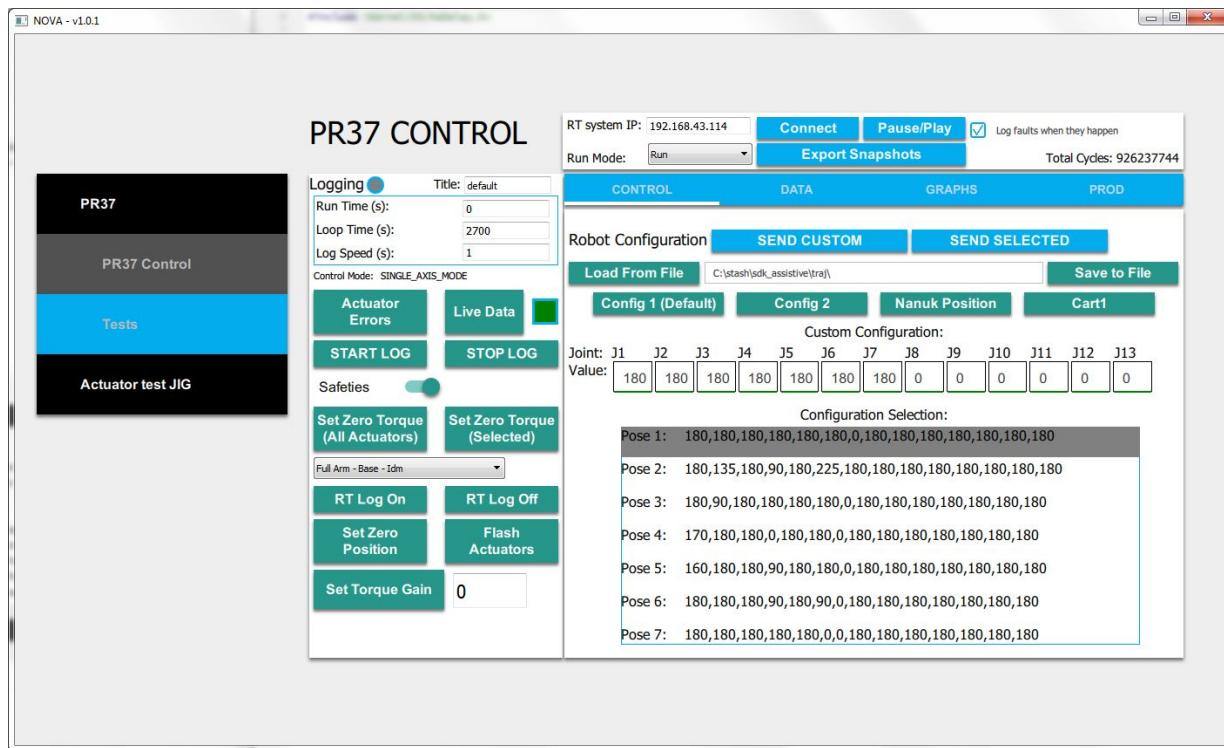


Figure 16: NOVA interface

5. set IP of QNX, Run Mode in "run", and then click Connect
6. release robot break
7. select a pose in the list of "Configuration Selection" and press "SEND SELECTED" button
8. when robot motion finished, click "START LOG", and then click "STOP LOG" approximately 2 seconds later
9. copy and rename the log file according to the index of pre-defined configuration
10. input a new pre-defined robot configuration and repeat the steps to get data log for all pre-defined robot configurations

4 Gravity Model Test Results

With the predefined poses in Table 1 and Table 2, we obtained the computed JointWrench_PC. The JointWrench_Base is obtained while sending the same joint position command, as described in Section 3. The i^{th} joint wrench contains force and torque along x, y and z axis of i^{th} joint frame. The difference of these two joint wrench values are defined as $\text{abs}(\text{JointWrench_PC} - \text{JointWrench_Base})$.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Actuator7	0.0000	0.0006	0.0004	0.0005	0.0002	0.0004	0.0001	0.0007	0.0003	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator6	0.0001	0.0003	0.0001	0.0001	0.0003	0.0006	0.0009	0.0000	0.0001	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator5	0.0002	0.0003	0.0001	0.0003	0.0002	0.0003	0.0007	0.0005	0.0012	0.0004	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator4	0.0000	0.0004	0.0005	0.0003	0.0004	0.0002	0.0006	0.0008	0.0011	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator3	0.0008	0.0003	0.0001	0.0001	0.0002	0.0001	0.0001	0.0003	0.0006	0.0005	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator2	0.0012	0.0009	0.0014	0.0000	0.0006	0.0005	0.0001	0.0007	0.0010	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator1	0.0000	0.0000	0.0021	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Base	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Figure 17: Error of Force along X axis in N

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Actuator7	0.0001	0.0000	0.0002	0.0000	0.0002	0.0001	0.0005	0.0001	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator6	0.0001	0.0007	0.0001	0.0003	0.0006	0.0006	0.0009	0.0000	0.0005	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator5	0.0001	0.0004	0.0003	0.0002	0.0003	0.0000	0.0001	0.0008	0.0007	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator4	0.0001	0.0004	0.0003	0.0003	0.0005	0.0003	0.0003	0.0008	0.0007	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator3	0.0000	0.0001	0.0006	0.0000	0.0003	0.0006	0.0008	0.0004	0.0006	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator2	0.0008	0.0004	0.0009	0.0002	0.0001	0.0010	0.0000	0.0003	0.0006	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator1	0.0000	0.0000	0.0050	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Base	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001

Figure 18: Error of Force along Y axis in N

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Actuator7	0.0001	0.0004	0.0000	0.0002	0.0004	0.0004	0.0006	0.0000	0.0004	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator6	0.0001	0.0003	0.0001	0.0001	0.0003	0.0000	0.0000	0.0006	0.0005	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator5	0.0000	0.0003	0.0003	0.0002	0.0004	0.0002	0.0001	0.0005	0.0004	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator4	0.0000	0.0001	0.0005	0.0000	0.0002	0.0004	0.0007	0.0002	0.0004	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator3	0.0006	0.0004	0.0008	0.0001	0.0001	0.0007	0.0000	0.0002	0.0005	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator2	0.0000	0.0000	0.0041	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Base	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Figure 19: Error of Force along Z axis in N

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Actuator7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator6	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0000	0.0001	0.0000	0.0001	0.0001	0.0001
Actuator5	0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	0.0001	0.0002	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator4	0.0000	0.0001	0.0001	0.0000	0.0001	0.0001	0.0003	0.0000	0.0002	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator3	0.0000	0.0001	0.0001	0.0001	0.0001	0.0000	0.0003	0.0000	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator2	0.0000	0.0001	0.0007	0.0002	0.0001	0.0002	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator1	0.0001	0.0001	0.0009	0.0000	0.0000	0.0001	0.0001	0.0000	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
Base	0.0003	0.0001	0.0003	0.0001	0.0002	0.0001	0.0002	0.0001	0.0007	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Figure 20: Error of Torque along X axis in Nm

	Actuator7	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
	Actuator6	0.0000	0.0000	0.0001	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
	Actuator5	0.0000	0.0001	0.0000	0.0001	0.0001	0.0001	0.0002	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	
	Actuator4	0.0000	0.0001	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	
	Actuator3	0.0001	0.0001	0.0000	0.0001	0.0000	0.0002	0.0002	0.0001	0.0003	0.0001	0.0000	0.0000	0.0000	0.0000	
	Actuator2	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0000	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	
	Actuator1	0.0003	0.0001	0.0007	0.0000	0.0001	0.0001	0.0002	0.0000	0.0007	0.0000	0.0000	0.0000	0.0000	0.0000	
	Base	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		Index of Pre-defined Robot Configuration														

Figure 21: Error of Torque along Y axis in Nm

	Actuator7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	
	Actuator6	0.0000	0.0000	0.0001	0.0000	0.0000	0.0001	0.0001	0.0000	0.0001	0.0001	0.0000	0.0001	0.0000	0.0000	
	Actuator5	0.0001	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0001	0.0000	0.0000	
	Actuator4	0.0000	0.0002	0.0001	0.0001	0.0000	0.0002	0.0001	0.0003	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	
	Actuator3	0.0000	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	
	Actuator2	0.0002	0.0001	0.0005	0.0000	0.0001	0.0000	0.0001	0.0001	0.0006	0.0001	0.0000	0.0000	0.0000	0.0000	
	Actuator1	0.0000	0.0002	0.0007	0.0002	0.0001	0.0005	0.0001	0.0001	0.0001	0.0000	0.0000	0.0001	0.0000	0.0000	
	Base	0.0000	0.0002	0.0007	0.0003	0.0001	0.0004	0.0002	0.0002	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		Index of Pre-defined Robot Configuration														

Figure 22: Error of Torque along Z axis in Nm

The Figure 17 to Figure 22 shows the error distribution of all the tests in 15 poses (horizontal axis). The vertical axis indicates the joint index, with base with index 1 and joint 7 with index 8. The color of each cell demonstrates the error of the corresponding test (the darker, the worse). In worst cases, the error of joint force reach 0.005N and torque is around 0.001Nm.

It is noticed that the robot cannot perfectly reach the predefined configurations. It is more meaningful to

compute JointWrench_PC based on robot joint position feedback for the comparison, as shown in Figure 23to Figure 28. It is obvious that differences are ten times smaller, in the scale of 10^{-4} N (Force) or Nm(Torque). This difference may due to the provided data precision in the code or computation round up.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Index of Pre-defined Robot Configuration														
Actuator7	0.0000	0.0000	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator6	0.0001	0.0000	0.0002	0.0001	0.0000	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator5	0.0001	0.0000	0.0001	0.0002	0.0002	0.0000	0.0000	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator4	0.0001	0.0000	0.0000	0.0000	0.0001	0.0000	0.0002	0.0002	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator3	0.0001	0.0000	0.0007	0.0001	0.0002	0.0000	0.0001	0.0003	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator2	0.0001	0.0001	0.0002	0.0000	0.0006	0.0001	0.0001	0.0006	0.0002	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator1	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Base	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Figure 23: Error of Force along X axis in N

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Index of Pre-defined Robot Configuration														
Actuator7	0.0000	0.0000	0.0001	0.0000	0.0001	0.0000	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator6	0.0000	0.0000	0.0003	0.0001	0.0000	0.0001	0.0001	0.0002	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator5	0.0000	0.0001	0.0002	0.0000	0.0000	0.0001	0.0001	0.0002	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator4	0.0000	0.0000	0.0004	0.0000	0.0001	0.0000	0.0000	0.0001	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator3	0.0002	0.0001	0.0001	0.0000	0.0003	0.0001	0.0001	0.0004	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator2	0.0001	0.0000	0.0002	0.0000	0.0001	0.0001	0.0000	0.0003	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator1	0.0000	0.0000	0.0003	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Base	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001

Figure 24: Error of Force along Y axis in N

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Actuator7	0.0000	0.0000	0.0002	0.0001	0.0000	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator6	0.0000	0.0001	0.0001	0.0000	0.0000	0.0001	0.0002	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator5	0.0001	0.0001	0.0004	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator4	0.0001	0.0000	0.0001	0.0000	0.0002	0.0000	0.0001	0.0003	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator3	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator2	0.0000	0.0000	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Base	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Figure 25: Error of Force along Z axis in N

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Actuator7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator6	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0001	0.0001	0.0001
Actuator5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator4	0.0001	0.0000	0.0001	0.0001	0.0001	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator2	0.0000	0.0000	0.0001	0.0000	0.0000	0.0001	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Actuator1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Base	0.0001	0.0000	0.0001	0.0000	0.0002	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Figure 26: Error of Torque along X axis in Nm

	Actuator7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
	Actuator6	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
	Actuator5	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
	Actuator4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
	Actuator3	0.0001	0.0000	0.0002	0.0000	0.0001	0.0001	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
	Actuator2	0.0001	0.0000	0.0001	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	
	Actuator1	0.0001	0.0000	0.0001	0.0000	0.0002	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
	Base	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		Index of Pre-defined Robot Configuration														

Figure 27: Error of Torque along Y axis in Nm

	Actuator7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	
	Actuator6	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	
	Actuator5	0.0001	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	
	Actuator4	0.0000	0.0000	0.0001	0.0000	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
	Actuator3	0.0000	0.0000	0.0001	0.0000	0.0001	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
	Actuator2	0.0001	0.0001	0.0001	0.0000	0.0002	0.0001	0.0001	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	
	Actuator1	0.0000	0.0001	0.0001	0.0001	0.0000	0.0001	0.0000	0.0000	0.0001	0.0000	0.0000	0.0001	0.0000	0.0000	
	Base	0.0001	0.0000	0.0002	0.0000	0.0001	0.0000	0.0001	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		Index of Pre-defined Robot Configuration														

Figure 28: Error of Torque along Z axis in Nm

Therefore, we can conclude that the joint wrench data from robot base matches with the data from offline PC. The computed joint wrench in robot base performs as designed.

The joint torque sensors are used to validate the performance of gravity model. Since joint torque sensors only measure the torque along joint axis, only the components of TorqueZ of JointWrench_Base are used for the comparison. The differences are demonstrated in Figure 29

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Actuator7	0.4499	0.5362	0.2731	0.6222	0.3185	0.4835	0.2944	0.4275	0.4742	0.3397	0.5346	0.4777	0.5234	0.5240	0.5248
Actuator6	0.1656	0.8826	0.8415	1.0358	0.8636	0.8976	0.8756	1.0222	0.0629	0.8742	0.0124	0.1181	1.1820	0.1295	0.0526
Actuator5	0.7387	0.0933	0.7990	0.2683	0.6207	0.0658	0.0235	1.0334	0.1022	0.1442	0.0135	0.0737	0.0965	0.0013	0.0025
Actuator4	0.0599	1.4153	0.1451	1.9160	0.3001	1.5813	1.4602	1.6632	0.3195	1.5084	0.0247	0.2214	0.0234	1.7405	0.3027
Actuator3	0.8300	1.1204	0.1430	0.2168	0.6232	1.0906	1.0769	1.0487	0.2945	0.6394	0.0209	0.2411	0.0620	0.3877	0.0569
Actuator2	0.3280	1.6240	1.4366	2.9140	0.4362	1.7881	1.2899	1.1313	3.4228	3.0148	0.0047	0.7404	0.0235	0.0042	2.1460
Actuator1	0.4286	1.3471	0.7387	0.4701	1.1096	1.5038	1.4300	0.8587	2.5682	2.6022	0.0074	2.7257	0.1335	0.4881	1.1272
Base	NaN														

Figure 29: Error of Torque along Z axis in Nm

The row for Base in Figure 29 is all NaN since there is no torque sensor on the robot base. The difference between joint torque sensor and TorqueZ of JointWrench_Base are quite evident, approximately 3.5Nm in worst cases. However, this is not enough to conclude that gravity model does not function well. The torque sensor is noisy and the seal at each joint may provide additional torque besides gravity torque. We already estimated that the seal may contribute around 2Nm to the joint. The estimation of torque sensor noise will be discussed in the Section 5.

5 Sensor Reliability Analysis

Torque sensors are often quite noisy. Since we use joint torque sensor to evaluate the gravity model. It is necessary to know the noise level when robot is in static. We record approximately one thousand samples for each joint torque sensor at each pre-defined robot configuration. The mean value of recorded data is submitted for the gravity model evaluation in Section 4. We also analyze the variation of the torque sensors in each test, and conclude the result in Figure 30. It is clear that torque sensors in the big actuators have more variations than the ones in small actuators. The test data with most variation is presented in 31.

	Actuator7	0.2261	0.2588	0.2231	0.2515	0.2451	0.2278	0.2354	0.2226	0.2046	0.2078	0.2296	0.2594	0.2811	0.2368	0.2714
Actuator6		0.2262	0.2465	0.2158	0.2158	0.2475	0.1940	0.2263	0.2132	0.2046	0.1965	0.2374	0.2563	0.2578	0.2061	0.1992
Actuator5		0.2122	0.2072	0.2514	0.1954	0.2184	0.2365	0.2534	0.2188	0.2174	0.2362	0.2245	0.2154	0.2372	0.2217	0.2171
Actuator4		1.1254	1.1192	1.1434	1.1421	0.9196	1.2089	1.1292	1.3911	0.9999	1.0590	1.2254	1.2201	1.0603	1.4440	1.1013
Actuator3		1.4144	1.3791	1.2939	1.3417	1.2134	1.2295	1.1074	1.1903	1.2622	1.2658	1.2444	1.1723	1.2596	1.2854	1.1051
Actuator2		1.1363	1.3141	1.0583	0.9579	0.9922	1.0929	1.1382	0.9848	1.0676	1.0886	1.0663	1.2399	1.0281	1.1676	1.1839
Actuator1		1.0724	1.0028	1.3847	0.8863	1.1261	0.9529	1.0520	1.0449	0.9332	1.0903	0.8507	1.0618	1.0360	0.9187	1.0451
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		Index of Pre-defined Robot Configuration														

Figure 30: Variation of Sensor Noise

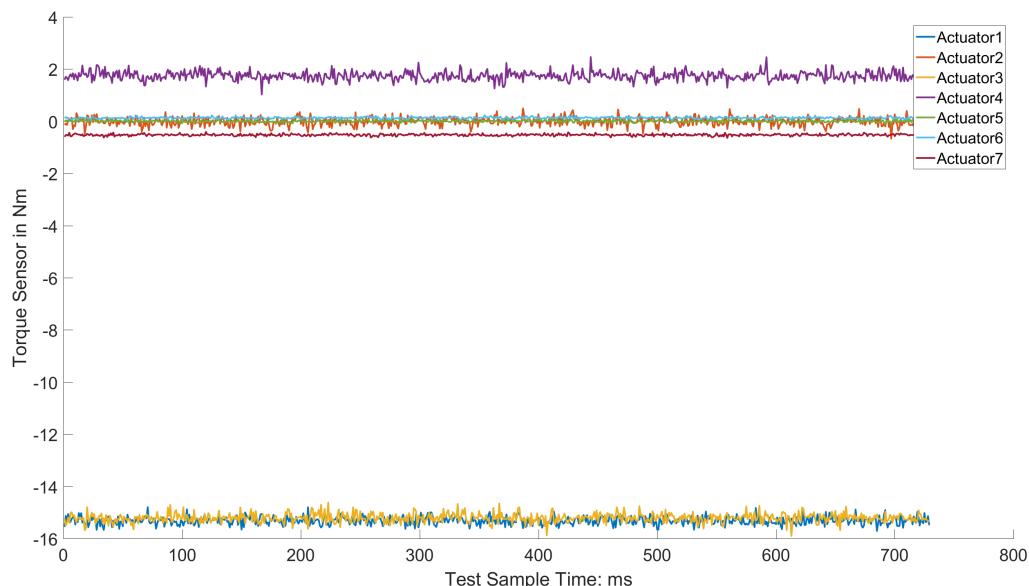


Figure 31: Senso rNoise in Configuration 14

6 Appendix

6.1 Test at robot configuration 1

Robot joint angles are [115.0000236.8500138.2000264.0900 63.0000235.2800155.2800];

Table 3: Joint wrench obtained from PC (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx PC	0.0000	88.3813	40.0077	41.3077	-31.7388	9.3230	-10.1604	2.1196
Fy PC	108.1749	-41.2129	-61.2548	0.9694	-33.4970	-19.3483	-15.6950	12.2486
Fz PC	0.0000	0.0000	-34.1163	48.1370	0.7052	22.6615	-14.7627	10.8864
Tx PC	-26.9294	-6.6482	-6.8397	-0.8133	0.8670	-3.1205	-2.3025	1.1891
Ty PC	0.0000	-14.2571	-2.3645	2.2332	-0.6445	0.6351	0.0795	-0.1716
Tz PC	-10.4385	10.4379	-3.7754	0.6529	8.4087	1.8261	1.5002	-0.0384

Table 4: Joint wrench obtained from Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Robot	0.0000	88.3813	40.0065	41.3069	-31.7388	9.3232	-10.1603	2.1196
Fy Robot	108.1750	-41.2129	-61.2556	0.9694	-33.4971	-19.3482	-15.6951	12.2485
Fz Robot	0.0000	0.0000	-34.1163	48.1376	0.7052	22.6615	-14.7626	10.8865
Tx Robot	-26.9291	-6.6481	-6.8397	-0.8133	0.8670	-3.1205	-2.3024	1.1891
Ty Robot	0.0000	-14.2568	-2.3645	2.2333	-0.6445	0.6351	0.0795	-0.1716
Tz Robot	-10.4385	10.4379	-3.7752	0.6529	8.4087	1.8260	1.5002	-0.0384

Table 5: Joint wrench error between data from PC and Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Error	0.0000	-0.0000	0.0012	0.0008	-0.0000	-0.0002	-0.0001	-0.0000
Fy Error	-0.0001	-0.0000	0.0008	0.0000	0.0001	-0.0001	0.0001	0.0001
Fz Error	0.0000	0.0000	0.0000	-0.0006	0.0000	-0.0000	-0.0001	-0.0001
Tx Error	-0.0003	-0.0001	0.0000	0.0000	-0.0000	-0.0000	-0.0001	-0.0000
Ty Error	0.0000	-0.0003	-0.0000	-0.0001	-0.0000	-0.0000	0.0000	0.0000
Tz Error	0.0000	0.0000	-0.0002	-0.0000	0.0000	0.0001	0.0000	0.0000

Table 6: Joint torque along axis comparison with sensor data (Nm)

	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Tz Sensor	10.0093	-3.4472	1.4829	8.4686	2.5647	1.3346	0.4115
Tz Robot	10.4379	-3.7752	0.6529	8.4087	1.8260	1.5002	-0.0384
Tz PC	10.4379	-3.7754	0.6529	8.4087	1.8261	1.5002	-0.0384

6.2 Test at robot configuration 2

Robot joint angles are [140.0000245.4200 90.9200281.4100353.6200295.0600265.4000];

Table 7: Joint wrench obtained from PC (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx PC	0.0000	62.6833	21.5842	48.8627	-33.4761	23.3919	-21.3574	4.0351
Fy PC	108.1749	-74.7031	-47.1875	16.1795	-29.5078	-5.3970	-9.7163	-14.5373
Fz PC	0.0000	0.0000	-61.8397	37.0822	11.7704	19.9627	-4.1179	6.7394
Tx PC	-28.1356	-12.9746	-13.0452	0.1969	1.3541	-0.3368	-0.6232	-1.0514
Ty PC	0.0000	-10.8870	-1.4418	-1.7831	0.6664	0.6854	0.1599	-0.3263
Tz PC	-14.8875	14.8870	-3.4530	0.5185	5.5219	0.5800	2.8552	-0.0743

Table 8: Joint wrench obtained from Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Robot	0.0000	62.6833	21.5833	48.8624	-33.4757	23.3916	-21.3577	4.0357
Fy Robot	108.1750	-74.7031	-47.1879	16.1796	-29.5082	-5.3974	-9.7156	-14.5373
Fz Robot	0.0000	0.0000	-61.8397	37.0826	11.7705	19.9630	-4.1182	6.7390
Tx Robot	-28.1355	-12.9745	-13.0453	0.1970	1.3542	-0.3368	-0.6233	-1.0514
Ty Robot	0.0000	-10.8869	-1.4417	-1.7832	0.6663	0.6855	0.1599	-0.3263
Tz Robot	-14.8877	14.8872	-3.4529	0.5184	5.5217	0.5800	2.8552	-0.0743

Table 9: Joint wrench error between data from PC and Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Error	0.0000	0.0000	0.0009	0.0003	-0.0004	0.0003	0.0003	-0.0006
Fy Error	-0.0001	-0.0000	0.0004	-0.0001	0.0004	0.0004	-0.0007	-0.0000
Fz Error	0.0000	0.0000	-0.0000	-0.0004	-0.0001	-0.0003	0.0003	0.0004
Tx Error	-0.0001	-0.0001	0.0001	-0.0001	-0.0001	0.0000	0.0001	-0.0000
Ty Error	0.0000	-0.0001	-0.0001	0.0001	0.0001	-0.0001	0.0000	0.0000
Tz Error	0.0002	-0.0002	-0.0001	0.0001	0.0002	-0.0000	-0.0000	0.0000

Table 10: Joint torque along axis comparison with sensor data (Nm)

	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Tz Sensor	16.2343	-5.077	1.6388	4.1064	0.48671	1.9726	-0.61055
Tz Robot	14.8872	-3.4529	0.5184	5.5217	0.5800	2.8552	-0.0743
Tz PC	14.8870	-3.4530	0.5185	5.5219	0.5800	2.8552	-0.0743

6.3 Test at robot configuration 3

Robot joint angles are [293.0000137.0500220.5200 87.4000217.9800307.0000103.1300];

6.4 Test at robot configuration 4

Robot joint angles are [10.0000176.7300147.5900 43.3200142.6800275.0000205.1200];

Table 11: Joint wrench obtained from PC (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx PC	0.0000	-89.7658	-54.3901	-16.3872	29.4566	29.8256	-18.0636	5.8455
Fy PC	108.1749	38.1033	-50.6309	46.6132	-10.5962	5.8195	-14.8827	11.5022
Fz PC	0.0000	0.0000	31.5422	39.7883	33.9106	7.1686	4.4402	10.3230
Tx PC	-32.3267	8.2555	7.9955	4.5748	6.0459	0.1017	0.5170	1.1185
Ty PC	0.0000	19.4486	-3.1052	-3.0284	-0.7245	-0.0633	0.1789	-0.4727
Tz PC	-4.2492	4.2486	8.8028	5.4321	-5.4782	-0.3718	2.7028	-0.1067

Table 12: Joint wrench obtained from Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Robot	0.0000	-89.7637	-54.3887	-16.3871	29.4561	29.8257	-18.0637	5.8451
Fy Robot	108.1750	38.1083	-50.6300	46.6138	-10.5959	5.8192	-14.8826	11.5024
Fz Robot	0.0000	0.0000	31.5463	39.7875	33.9111	7.1683	4.4401	10.3230
Tx Robot	-32.3264	8.2564	7.9962	4.5749	6.0460	0.1017	0.5170	1.1185
Ty Robot	0.0000	19.4479	-3.1053	-3.0284	-0.7245	-0.0633	0.1788	-0.4727
Tz Robot	-4.2499	4.2493	8.8023	5.4322	-5.4781	-0.3717	2.7029	-0.1067

Table 13: Joint wrench error between data from PC and Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Error	0.0000	-0.0021	-0.0014	-0.0001	0.0005	-0.0001	0.0001	0.0004
Fy Error	-0.0001	-0.0050	-0.0009	-0.0006	-0.0003	0.0003	-0.0001	-0.0002
Fz Error	0.0000	0.0000	-0.0041	0.0008	-0.0005	0.0003	0.0001	-0.0000
Tx Error	-0.0003	-0.0009	-0.0007	-0.0001	-0.0001	-0.0000	-0.0000	-0.0000
Ty Error	0.0000	0.0007	0.0001	-0.0000	0.0000	0.0000	0.0001	-0.0000
Tz Error	0.0007	-0.0007	0.0005	-0.0001	-0.0001	-0.0001	-0.0001	-0.0000

Table 14: Joint torque along axis comparison with sensor data (Nm)

	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Tz Sensor	3.5107	10.2389	5.2892	-5.333	-1.1707	1.8613	0.16644
Tz Robot	4.2493	8.8023	5.4322	-5.4781	-0.3717	2.7029	-0.1067
Tz PC	4.2486	8.8028	5.4321	-5.4782	-0.3718	2.7028	-0.1067

Table 15: Joint wrench obtained from PC (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx PC	0.0000	16.9338	13.9951	-24.1999	12.4947	-10.7742	-5.6655	-2.7496
Fy PC	108.1749	96.0365	0.7996	58.6379	-12.4110	28.0756	8.7477	-15.1215
Fz PC	0.0000	0.0000	79.4996	-0.6284	42.6585	8.3963	21.4215	-6.0676
Tx PC	-37.5746	25.9755	15.1159	2.9538	10.4943	2.3780	3.1230	-1.3331
Ty PC	0.0000	-4.5802	-8.8592	1.3075	2.6242	1.8363	-0.0277	0.2224
Tz PC	-10.3631	10.3626	-2.5719	8.2603	-2.3103	-3.0890	0.8373	0.0499

Table 16: Joint wrench obtained from Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Robot	0.0000	16.9338	13.9951	-24.1998	12.4944	-10.7745	-5.6656	-2.7491
Fy Robot	108.1750	96.0365	0.7998	58.6379	-12.4113	28.0754	8.7480	-15.1215
Fz Robot	0.0000	0.0000	79.4996	-0.6285	42.6585	8.3965	21.4214	-6.0678
Tx Robot	-37.5747	25.9755	15.1161	2.9539	10.4943	2.3779	3.1230	-1.3331
Ty Robot	0.0000	-4.5802	-8.8593	1.3076	2.6242	1.8364	-0.0277	0.2223
Tz Robot	-10.3634	10.3628	-2.5719	8.2604	-2.3102	-3.0890	0.8373	0.0499

Table 17: Joint wrench error between data from PC and Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Error	0.0000	-0.0000	-0.0000	-0.0001	0.0003	0.0003	0.0001	-0.0005
Fy Error	-0.0001	-0.0000	-0.0002	-0.0000	0.0003	0.0002	-0.0003	-0.0000
Fz Error	0.0000	0.0000	-0.0000	0.0001	-0.0000	-0.0002	0.0001	0.0002
Tx Error	0.0001	-0.0000	-0.0002	-0.0001	-0.0000	0.0001	-0.0000	-0.0000
Ty Error	0.0000	-0.0000	0.0001	-0.0001	-0.0000	-0.0001	0.0000	0.0001
Tz Error	0.0003	-0.0002	0.0000	-0.0001	-0.0001	-0.0000	-0.0000	0.0000

Table 18: Joint torque along axis comparison with sensor data (Nm)

	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Tz Sensor	9.8927	0.3421	8.0436	-0.39419	-3.3573	-0.19854	-0.57235
Tz Robot	10.3628	-2.5719	8.2604	-2.3102	-3.0890	0.8373	0.0499
Tz PC	10.3626	-2.5719	8.2603	-2.3103	-3.0890	0.8373	0.0499

6.5 Test at robot configuration 5

Robot joint angles are [85.0000255.9300141.2900236.0900 65.8400228.2600130.5000];

Table 19: Joint wrench obtained from PC (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx PC	0.0000	97.1469	19.5504	8.5309	-33.5485	3.0373	-10.0236	-4.9469
Fy PC	108.1749	8.4993	-78.0062	13.9225	-30.0302	-23.5128	-12.0491	13.3684
Fz PC	0.0000	0.0000	7.0357	61.3011	10.1285	20.3161	-17.9401	8.3576
Tx PC	-21.0004	0.8543	4.6632	2.4953	3.4746	-3.8614	-2.6493	1.2333
Ty PC	0.0000	-9.7647	1.3271	7.9974	-0.7541	1.2320	-0.0504	0.3995
Tz PC	1.0877	-1.0882	1.7565	-2.1636	9.2729	2.0032	1.5141	0.0910

6.6 Test at robot configuration 6

Robot joint angles are [140.0000205.5100 96.1200275.1600313.2000260.6200229.5700];

Table 20: Joint wrench obtained from Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Robot	0.0000	97.1469	19.5510	8.5311	-33.5489	3.0371	-10.0239	-4.9471
Fy Robot	108.1750	8.4992	-78.0061	13.9228	-30.0297	-23.5131	-12.0485	13.3686
Fz Robot	0.0000	0.0000	7.0357	61.3010	10.1287	20.3157	-17.9404	8.3572
Tx Robot	-21.0006	0.8543	4.6633	2.4954	3.4747	-3.8613	-2.6493	1.2333
Ty Robot	0.0000	-9.7648	1.3272	7.9974	-0.7542	1.2321	-0.0504	0.3995
Tz Robot	1.0878	-1.0883	1.7564	-2.1637	9.2729	2.0032	1.5141	0.0910

Table 21: Joint wrench error between data from PC and Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Error	0.0000	0.0000	-0.0006	-0.0002	0.0004	0.0002	0.0003	0.0002
Fy Error	-0.0001	0.0001	-0.0001	-0.0003	-0.0005	0.0003	-0.0006	-0.0002
Fz Error	0.0000	0.0000	-0.0000	0.0001	-0.0002	0.0004	0.0003	0.0004
Tx Error	0.0002	-0.0000	-0.0001	-0.0001	-0.0001	-0.0001	-0.0000	-0.0000
Ty Error	0.0000	0.0001	-0.0001	0.0000	0.0001	-0.0001	0.0000	-0.0000
Tz Error	-0.0001	0.0001	0.0001	0.0001	-0.0000	-0.0000	-0.0000	0.0000

Table 22: Joint torque along axis comparison with sensor data (Nm)

	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Tz Sensor	0.021227	2.1926	-1.5405	9.573	2.6239	0.65048	0.40946
Tz Robot	-1.0883	1.7564	-2.1637	9.2729	2.0032	1.5141	0.0910
Tz PC	-1.0882	1.7565	-2.1636	9.2729	2.0032	1.5141	0.0910

Table 23: Joint wrench obtained from PC (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx PC	0.0000	62.6833	46.8310	52.2432	-16.1423	18.7452	-16.3613	8.4161
Fy PC	108.1749	-74.7031	-22.3472	31.4114	-36.7034	-2.6220	-17.1991	-7.7387
Fz PC	0.0000	0.0000	-61.8397	17.5616	22.8515	24.8307	-2.0006	11.9297
Tx PC	-40.1542	-22.1814	-15.1976	3.6196	2.9506	-0.4845	-0.4897	-0.4069
Ty PC	0.0000	-18.6124	-0.9151	-5.4116	0.1957	0.3763	0.2198	-0.6805
Tz PC	-9.7958	9.7952	-11.1784	-1.0884	2.3987	0.4055	2.1152	-0.1543

Table 24: Joint wrench obtained from Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Robot	0.0000	62.6833	46.8305	52.2433	-16.1421	18.7449	-16.3619	8.4165
Fy Robot	108.1750	-74.7031	-22.3482	31.4108	-36.7037	-2.6220	-17.1985	-7.7388
Fz Robot	0.0000	0.0000	-61.8397	17.5623	22.8511	24.8309	-2.0006	11.9293
Tx Robot	-40.1541	-22.1813	-15.1978	3.6196	2.9505	-0.4845	-0.4897	-0.4069
Ty Robot	0.0000	-18.6123	-0.9152	-5.4118	0.1957	0.3764	0.2199	-0.6805
Tz Robot	-9.7962	9.7957	-11.1784	-1.0882	2.3985	0.4055	2.1153	-0.1543

Table 25: Joint wrench error between data from PC and Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Error	0.0000	-0.0000	0.0005	-0.0001	-0.0002	0.0003	0.0006	-0.0004
Fy Error	-0.0001	-0.0000	0.0010	0.0006	0.0003	0.0000	-0.0006	0.0001
Fz Error	0.0000	0.0000	0.0000	-0.0007	0.0004	-0.0002	-0.0000	0.0004
Tx Error	-0.0001	-0.0001	0.0002	0.0000	0.0001	-0.0000	0.0000	0.0000
Ty Error	0.0000	-0.0001	0.0001	0.0002	0.0000	-0.0001	-0.0001	-0.0000
Tz Error	0.0004	-0.0005	-0.0000	-0.0002	0.0002	0.0000	-0.0001	0.0000

Table 26: Joint torque along axis comparison with sensor data (Nm)

	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Tz Sensor	11.2995	-12.9665	0.0023581	0.81721	0.33965	1.2177	-0.6378
Tz Robot	9.7957	-11.1784	-1.0882	2.3985	0.4055	2.1153	-0.1543
Tz PC	9.7952	-11.1784	-1.0884	2.3987	0.4055	2.1152	-0.1543

6.7 Test at robot configuration 7

Robot joint angles are [120.0000240.3100140.2000239.8800 66.7400239.2400115.3800];

Table 27: Joint wrench obtained from PC (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx PC	0.0000	84.4530	34.6273	41.2102	-14.9883	7.1472	-16.4419	1.0798
Fy PC	108.1749	-48.7590	-60.7327	-6.9508	-43.3553	-7.9648	-16.1318	12.1105
Fz PC	0.0000	0.0000	-40.3630	47.7267	-5.0566	29.3308	-6.0771	11.1894
Tx PC	-29.3426	-9.0721	-12.5834	-2.7018	-0.3930	-1.2577	-0.9995	1.1835
Ty PC	0.0000	-15.7133	-3.3880	-2.9276	-0.2412	1.8144	0.0853	-0.0876
Tz PC	-15.8765	15.8760	-5.6975	1.9066	3.2334	0.7992	2.4778	-0.0194

Table 28: Joint wrench obtained from Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Robot	0.0000	84.4530	34.6274	41.2101	-14.9889	7.1479	-16.4410	1.0797
Fy Robot	108.1750	-48.7590	-60.7327	-6.9516	-43.3550	-7.9649	-16.1327	12.1100
Fz Robot	0.0000	0.0000	-40.3630	47.7267	-5.0573	29.3307	-6.0771	11.1900
Tx Robot	-29.3424	-9.0720	-12.5835	-2.7021	-0.3933	-1.2578	-0.9996	1.1835
Ty Robot	0.0000	-15.7131	-3.3882	-2.9274	-0.2412	1.8142	0.0853	-0.0876
Tz Robot	-15.8767	15.8761	-5.6974	1.9068	3.2335	0.7992	2.4777	-0.0194

6.8 Test at robot configuration 8

Robot joint angles are [285.0000113.2500129.7300289.6700 7.8900195.5400 83.4400];

Table 29: Joint wrench error between data from PC and Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Error	0.0000	-0.0000	-0.0001	0.0001	0.0006	-0.0007	-0.0009	0.0001
Fy Error	-0.0001	-0.0000	0.0000	0.0008	-0.0003	0.0001	0.0009	0.0005
Fz Error	0.0000	0.0000	0.0000	0.0000	0.0007	0.0001	0.0000	-0.0006
Tx Error	-0.0002	-0.0001	0.0001	0.0003	0.0003	0.0001	0.0001	0.0000
Ty Error	0.0000	-0.0002	0.0002	-0.0002	0.0000	0.0002	-0.0000	-0.0000
Tz Error	0.0002	-0.0001	-0.0001	-0.0002	-0.0001	0.0000	0.0001	0.0000

Table 30: Joint torque along axis comparison with sensor data (Nm)

	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Tz Sensor	17.3061	-6.9872	2.9837	1.7733	0.77568	1.6021	0.27495
Tz Robot	15.8761	-5.6974	1.9068	3.2335	0.7992	2.4777	-0.0194
Tz PC	15.8760	-5.6975	1.9066	3.2334	0.7992	2.4778	-0.0194

Table 31: Joint wrench obtained from PC (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx PC	0.0000	-94.1951	-30.7803	-28.0880	-31.6901	21.7839	20.5809	2.1618
Fy PC	108.1749	25.2395	-71.6430	-8.1081	33.0280	1.0097	11.9723	-14.1209
Fz PC	0.0000	0.0000	20.8934	56.3006	-5.8985	-22.3442	0.7704	-8.3043
Tx PC	-40.7575	7.6504	9.0381	-4.0882	-0.7479	0.1878	0.1377	-1.2932
Ty PC	0.0000	28.5518	1.1857	15.0731	1.2244	-5.0407	-0.0424	-0.1744
Tz PC	-4.1932	4.1927	17.3807	0.1311	10.8741	-0.0447	-3.0209	-0.0400

Table 32: Joint wrench obtained from Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Robot	0.0000	-94.1951	-30.7796	-28.0877	-31.6909	21.7844	20.5809	2.1611
Fy Robot	108.1750	25.2395	-71.6433	-8.1077	33.0272	1.0089	11.9723	-14.1210
Fz Robot	0.0000	0.0000	20.8934	56.3008	-5.8983	-22.3437	0.7698	-8.3043
Tx Robot	-40.7574	7.6504	9.0382	-4.0882	-0.7479	0.1876	0.1376	-1.2932
Ty Robot	0.0000	28.5518	1.1857	15.0732	1.2244	-5.0407	-0.0424	-0.1744
Tz Robot	-4.1934	4.1928	17.3806	0.1311	10.8744	-0.0447	-3.0209	-0.0400

Table 33: Joint wrench error between data from PC and Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Error	0.0000	-0.0000	-0.0007	-0.0003	0.0008	-0.0005	-0.0000	0.0007
Fy Error	-0.0001	0.0000	0.0003	-0.0004	0.0008	0.0008	-0.0000	0.0001
Fz Error	0.0000	0.0000	-0.0000	-0.0002	-0.0002	-0.0005	0.0006	-0.0000
Tx Error	-0.0001	-0.0000	-0.0001	0.0000	0.0000	0.0002	0.0001	-0.0000
Ty Error	0.0000	0.0000	-0.0000	-0.0001	0.0000	0.0000	-0.0000	-0.0000
Tz Error	0.0002	-0.0001	0.0001	-0.0000	-0.0003	-0.0000	-0.0000	-0.0000

Table 34: Joint torque along axis comparison with sensor data (Nm)

	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Tz Sensor	3.3341	18.5119	1.1798	9.2112	0.98877	-4.0431	0.3875
Tz Robot	4.1928	17.3806	0.1311	10.8744	-0.0447	-3.0209	-0.0400
Tz PC	4.1927	17.3807	0.1311	10.8741	-0.0447	-3.0209	-0.0400

6.9 Test at robot configuration 9

Robot joint angles are [285.0000121.2200234.4600131.9400356.6500 77.0100227.2700];

Table 35: Joint wrench obtained from PC (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx PC	0.0000	-94.1951	-40.4166	-5.1016	25.8768	-16.4586	17.0267	-0.8567
Fy PC	108.1749	25.2395	-66.6832	35.3885	-28.2400	-18.4101	-8.9598	15.2865
Fz PC	0.0000	0.0000	20.8934	52.4029	25.7448	19.1050	-14.0468	6.2148
Tx PC	-33.5108	5.7749	7.3088	7.6205	5.0807	-1.2807	-2.0721	1.3491
Ty PC	0.0000	21.5521	-1.1772	-3.2051	1.0385	-0.9321	-0.0839	0.0690
Tz PC	-3.2177	3.2171	10.3810	2.9064	-3.9677	-2.0016	-2.4582	0.0161

Table 36: Joint wrench obtained from Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Robot	0.0000	-94.1951	-40.4176	-5.1022	25.8757	-16.4574	17.0266	-0.8564
Fy Robot	108.1750	25.2395	-66.6826	35.3891	-28.2407	-18.4108	-8.9593	15.2867
Fz Robot	0.0000	0.0000	20.8934	52.4024	25.7452	19.1054	-14.0473	6.2144
Tx Robot	-33.5115	5.7750	7.3087	7.6208	5.0809	-1.2808	-2.0722	1.3491
Ty Robot	0.0000	21.5528	-1.1771	-3.2048	1.0386	-0.9322	-0.0839	0.0690
Tz Robot	-3.2176	3.2170	10.3816	2.9063	-3.9674	-2.0016	-2.4581	0.0161

Table 37: Joint wrench error between data from PC and Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Error	0.0000	-0.0000	0.0010	0.0006	0.0011	-0.0012	0.0001	-0.0003
Fy Error	-0.0001	0.0000	-0.0006	-0.0006	0.0007	0.0007	-0.0005	-0.0002
Fz Error	0.0000	0.0000	-0.0000	0.0005	-0.0004	-0.0004	0.0005	0.0004
Tx Error	0.0007	-0.0001	0.0001	-0.0003	-0.0002	0.0001	0.0001	-0.0000
Ty Error	0.0000	-0.0007	-0.0001	-0.0003	-0.0001	0.0001	0.0000	-0.0000
Tz Error	-0.0001	0.0001	-0.0006	0.0001	-0.0003	0.0000	-0.0001	-0.0000

6.10 Test at robot configuration 10

Robot joint angles are [340.0000141.7400 22.2700 67.9500 16.1200 61.7300153.1100];

Table 38: Joint torque along axis comparison with sensor data (Nm)

	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Tz Sensor	0.64883	13.8044	2.6118	-3.6479	-2.1038	-2.521	-0.45804
Tz Robot	3.2170	10.3816	2.9063	-3.9674	-2.0016	-2.4581	0.0161
Tz PC	3.2171	10.3810	2.9064	-3.9677	-2.0016	-2.4582	0.0161

Table 39: Joint wrench obtained from PC (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx PC	0.0000	-33.3531	-21.6796	-6.8255	10.9234	1.3213	-0.0534	7.4982
Fy PC	108.1749	91.6369	-17.0969	-61.6225	-0.9329	31.1877	1.1159	-14.7042
Fz PC	0.0000	0.0000	75.8576	13.4356	-44.8298	0.6311	23.7961	-0.7740
Tx PC	-45.9037	32.6122	18.5977	-9.1616	-9.8036	1.4349	3.3356	-1.2024
Ty PC	0.0000	11.8699	11.5327	-1.2975	-3.4075	-0.1215	0.1374	-0.6059
Tz PC	-1.1715	1.1710	7.9143	-10.6054	-2.3179	3.0004	0.0010	-0.1377

Table 40: Joint wrench obtained from Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Robot	0.0000	-33.3531	-21.6795	-6.8250	10.9233	1.3217	-0.0536	7.4981
Fy Robot	108.1750	91.6369	-17.0969	-61.6225	-0.9326	31.1877	1.1162	-14.7042
Fz Robot	0.0000	0.0000	75.8576	13.4356	-44.8298	0.6309	23.7961	-0.7742
Tx Robot	-45.9037	32.6123	18.5977	-9.1616	-9.8037	1.4350	3.3356	-1.2024
Ty Robot	0.0000	11.8699	11.5328	-1.2976	-3.4076	-0.1215	0.1374	-0.6059
Tz Robot	-1.1716	1.1710	7.9144	-10.6054	-2.3179	3.0005	0.0011	-0.1377

Table 41: Joint wrench error between data from PC and Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Error	0.0000	0.0000	-0.0001	-0.0005	0.0001	-0.0004	0.0002	0.0001
Fy Error	-0.0001	0.0000	-0.0000	-0.0000	-0.0003	0.0000	-0.0003	0.0000
Fz Error	0.0000	0.0000	-0.0000	0.0000	-0.0000	0.0002	0.0000	0.0002
Tx Error	-0.0000	-0.0001	-0.0000	0.0000	0.0001	-0.0001	-0.0000	0.0000
Ty Error	0.0000	0.0000	-0.0001	0.0001	0.0001	0.0000	0.0000	0.0000
Tz Error	0.0001	-0.0000	-0.0001	0.0000	0.0000	-0.0001	-0.0001	0.0000

Table 42: Joint torque along axis comparison with sensor data (Nm)

	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Tz Sensor	-1.4312	10.9292	-11.2448	-0.8095	3.1447	0.87527	0.20194
Tz Robot	1.1710	7.9144	-10.6054	-2.3179	3.0005	0.0011	-0.1377
Tz PC	1.1710	7.9143	-10.6054	-2.3179	3.0004	0.0010	-0.1377

6.11 Test at robot configuration 11

Robot joint angles are [180.0000180.0000180.0000180.0000180.0000180.0000180.0000];

Table 43: Joint wrench obtained from PC (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx PC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Fy PC	108.1749	-97.5180	0.0000	-63.4384	0.0000	-31.2221	0.0000	16.5238
Fz PC	0.0000	0.0000	-80.7260	0.0000	-46.1509	0.0000	-23.8223	0.0000
Tx PC	-59.1388	-47.9403	-36.3751	-24.3045	-14.8206	-6.2177	-3.3222	1.3353
Ty PC	0.0000	0.0000	0.0006	0.0000	0.0002	0.0000	0.0001	0.0000
Tz PC	0.0005	-0.0011	0.0000	-0.0004	0.0000	-0.0007	0.0000	0.0005

Table 44: Joint wrench obtained from Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Robot	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0000
Fy Robot	108.1750	-97.5180	0.0000	-63.4384	0.0000	-31.2221	0.0000	16.5238
Fz Robot	0.0000	0.0000	-80.7260	0.0000	-46.1509	0.0000	-23.8223	0.0000
Tx Robot	-59.1388	-47.9403	-36.3751	-24.3045	-14.8206	-6.2177	-3.3221	1.3353
Ty Robot	0.0000	0.0000	0.0006	0.0000	0.0002	0.0000	0.0001	0.0000
Tz Robot	0.0005	-0.0011	0.0000	-0.0004	0.0000	-0.0007	-0.0000	0.0005

Table 45: Joint wrench error between data from PC and Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Error	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0000	0.0000
Fy Error	-0.0001	-0.0000	0.0000	-0.0000	0.0000	-0.0000	-0.0000	-0.0000
Fz Error	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0000	0.0000
Tx Error	0.0000	-0.0000	0.0000	-0.0000	-0.0000	0.0000	-0.0001	0.0000
Ty Error	0.0000	0.0000	0.0000	0.0000	-0.0000	0.0000	0.0000	-0.0000
Tz Error	-0.0000	-0.0000	0.0000	0.0000	0.0000	-0.0000	0.0000	0.0000

Table 46: Joint torque along axis comparison with sensor data (Nm)

	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Tz Sensor	-0.0084548	0.004673	0.020459	0.024678	0.012828	0.012407	-0.53406
Tz Robot	-0.0011	0.0000	-0.0004	0.0000	-0.0007	-0.0000	0.0005
Tz PC	-0.0011	0.0000	-0.0004	0.0000	-0.0007	0.0000	0.0005

6.12 Test at robot configuration 12

Robot joint angles are [270.0000180.0000180.0000180.0000180.0000180.0000180.0000];

6.13 Test at robot configuration 13

Robot joint angles are [180.0000180.0000180.0000180.0000180.0000 90.0000180.0000];

Table 47: Joint wrench obtained from PC (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx PC	0.0000	-97.5180	-80.7260	-63.4384	-46.1509	-31.2221	-23.8223	16.5238
Fy PC	108.1749	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Fz PC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Tx PC	-59.1388	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ty PC	0.0000	47.9403	7.7253	24.3045	2.0463	6.2177	0.3979	-1.3353
Tz PC	11.4968	-11.4973	36.3751	-4.2715	14.8206	-0.3282	3.3222	-0.3026

Table 48: Joint wrench obtained from Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Robot	0.0000	-97.5180	-80.7260	-63.4384	-46.1509	-31.2221	-23.8223	16.5238
Fy Robot	108.1750	-0.0000	-0.0000	-0.0000	-0.0000	-0.0000	-0.0000	0.0000
Fz Robot	0.0000	0.0000	-0.0000	0.0000	-0.0000	0.0000	-0.0000	0.0000
Tx Robot	-59.1388	-0.0000	-0.0000	-0.0000	-0.0000	-0.0000	-0.0000	0.0000
Ty Robot	0.0000	47.9403	7.7253	24.3045	2.0463	6.2177	0.3979	-1.3353
Tz Robot	11.4968	-11.4973	36.3751	-4.2715	14.8206	-0.3282	3.3221	-0.3025

Table 49: Joint wrench error between data from PC and Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Error	0.0000	-0.0000	0.0000	-0.0000	0.0000	0.0000	-0.0000	-0.0000
Fy Error	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0000
Fz Error	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Tx Error	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0000
Ty Error	0.0000	0.0000	0.0000	-0.0000	0.0000	-0.0000	0.0000	-0.0000
Tz Error	0.0000	-0.0000	-0.0000	0.0000	0.0000	-0.0000	0.0001	-0.0001

Table 50: Joint torque along axis comparison with sensor data (Nm)

	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Tz Sensor	-14.223	37.1155	-4.5126	15.042	-0.40186	3.4402	-0.78022
Tz Robot	-11.4973	36.3751	-4.2715	14.8206	-0.3282	3.3221	-0.3025
Tz PC	-11.4973	36.3751	-4.2715	14.8206	-0.3282	3.3222	-0.3026

Table 51: Joint wrench obtained from PC (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx PC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Fy PC	108.1749	-97.5180	0.0000	-63.4384	0.0000	-31.2221	0.0000	16.5238
Fz PC	0.0000	0.0000	-80.7260	0.0000	-46.1509	0.0000	-23.8223	0.0000
Tx PC	-55.8165	-44.6181	-33.0529	-20.9822	-11.4984	-2.8955	-3.3222	1.3353
Ty PC	0.0000	0.0000	3.3226	0.0000	3.3223	0.0000	0.0001	0.0000
Tz PC	3.3226	-3.3231	0.0000	-3.3225	0.0000	-3.3227	0.0000	0.0005

Table 52: Joint wrench obtained from Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Robot	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0000	0.0000
Fy Robot	108.1750	-97.5180	0.0000	-63.4384	0.0000	-31.2221	0.0000	16.5238
Fz Robot	0.0000	0.0000	-80.7260	0.0000	-46.1509	0.0000	-23.8223	0.0000
Tx Robot	-55.8165	-44.6181	-33.0529	-20.9822	-11.4984	-2.8955	-3.3221	1.3353
Ty Robot	0.0000	0.0000	3.3226	0.0000	3.3223	0.0000	0.0001	0.0000
Tz Robot	3.3226	-3.3232	0.0000	-3.3225	0.0000	-3.3228	0.0000	0.0005

Table 53: Joint wrench error between data from PC and Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Error	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Fy Error	-0.0001	-0.0000	0.0000	-0.0000	0.0000	0.0000	-0.0000	-0.0000
Fz Error	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0000	0.0000
Tx Error	0.0000	-0.0000	-0.0000	0.0000	0.0000	-0.0000	-0.0001	0.0000
Ty Error	0.0000	0.0000	-0.0000	0.0000	-0.0000	0.0000	0.0000	0.0000
Tz Error	-0.0000	0.0001	0.0000	-0.0000	0.0000	0.0001	-0.0000	0.0000

Table 54: Joint torque along axis comparison with sensor data (Nm)

	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Tz Sensor	-3.4566	0.023453	-3.3845	0.023353	-3.4193	1.182	-0.52291
Tz Robot	-3.3232	0.0000	-3.3225	0.0000	-3.3228	0.0000	0.0005
Tz PC	-3.3231	0.0000	-3.3225	0.0000	-3.3227	0.0000	0.0005

6.14 Test at robot configuration 14

Robot joint angles are [180.0000180.0000180.0000 90.0000180.0000180.0000180.0000];

Table 55: Joint wrench obtained from PC (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx PC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Fy PC	108.1749	-97.5180	0.0000	-63.4384	0.0000	-31.2221	0.0000	16.5238
Fz PC	0.0000	0.0000	-80.7260	0.0000	-46.1509	0.0000	-23.8223	0.0000
Tx PC	-44.3179	-33.1195	-21.5543	-9.4837	-14.8206	-6.2177	-3.3222	1.3353
Ty PC	0.0000	0.0000	14.8209	0.0000	0.0002	0.0000	0.0001	0.0000
Tz PC	14.8209	-14.8214	0.0000	-14.8208	0.0000	-0.0007	0.0000	0.0005

6.15 Test at robot configuration 15

Robot joint angles are [180.0000 90.0000180.0000180.0000180.0000180.0000];

Table 56: Joint wrench obtained from Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Robot	0.0000	0.0000	0.0000	0.0000	-0.0000	0.0000	0.0000	0.0000
Fy Robot	108.1750	-97.5180	0.0000	-63.4384	0.0000	-31.2221	0.0000	16.5238
Fz Robot	0.0000	0.0000	-80.7260	0.0000	-46.1509	0.0000	-23.8223	0.0000
Tx Robot	-44.3179	-33.1195	-21.5543	-9.4837	-14.8206	-6.2177	-3.3221	1.3353
Ty Robot	0.0000	0.0000	14.8209	0.0000	0.0002	0.0000	0.0001	0.0000
Tz Robot	14.8209	-14.8214	0.0000	-14.8208	0.0000	-0.0007	-0.0000	0.0005

Table 57: Joint wrench error between data from PC and Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Error	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0000	0.0000
Fy Error	-0.0001	-0.0000	0.0000	-0.0000	-0.0000	0.0000	-0.0000	-0.0000
Fz Error	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0000	0.0000
Tx Error	-0.0000	0.0000	-0.0000	-0.0000	-0.0000	0.0000	-0.0001	0.0000
Ty Error	0.0000	0.0000	-0.0000	0.0000	-0.0000	0.0000	0.0000	0.0000
Tz Error	-0.0000	0.0000	0.0000	0.0000	-0.0000	-0.0000	0.0000	0.0000

Table 58: Joint torque along axis comparison with sensor data (Nm)

	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Tz Sensor	-15.3095	-0.0042463	-15.2085	1.7405	0.00066198	0.12946	-0.52346
Tz Robot	-14.8214	0.0000	-14.8208	0.0000	-0.0007	-0.0000	0.0005
Tz PC	-14.8214	0.0000	-14.8208	0.0000	-0.0007	0.0000	0.0005

Table 59: Joint wrench obtained from PC (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx PC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Fy PC	108.1749	-97.5180	0.0000	-63.4384	0.0000	-31.2221	0.0000	16.5238
Fz PC	0.0000	0.0000	-80.7260	0.0000	-46.1509	0.0000	-23.8223	0.0000
Tx PC	-22.7631	-11.5646	-36.3751	-24.3045	-14.8206	-6.2177	-3.3222	1.3353
Ty PC	0.0000	0.0000	0.0006	0.0000	0.0002	0.0000	0.0001	0.0000
Tz PC	36.3751	-36.3756	0.0000	-0.0004	0.0000	-0.0007	0.0000	0.0005

Table 60: Joint wrench obtained from Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Robot	0.0000	0.0000	-0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Fy Robot	108.1750	-97.5180	0.0000	-63.4384	0.0000	-31.2221	0.0000	16.5238
Fz Robot	0.0000	0.0000	-80.7260	0.0000	-46.1509	0.0000	-23.8223	0.0000
Tx Robot	-22.7631	-11.5646	-36.3751	-24.3045	-14.8206	-6.2177	-3.3221	1.3353
Ty Robot	0.0000	0.0000	0.0006	0.0000	0.0002	0.0000	0.0001	0.0000
Tz Robot	36.3751	-36.3756	0.0000	-0.0004	0.0000	-0.0007	-0.0000	0.0005

Table 61: Joint wrench error between data from PC and Robot (N/Nm)

	Base	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Fx Error	0.0000	0.0000	0.0000	0.0000	-0.0000	0.0000	-0.0000	0.0000
Fy Error	-0.0001	-0.0000	-0.0000	-0.0000	-0.0000	0.0000	-0.0000	-0.0000
Fz Error	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0000	0.0000
Tx Error	0.0000	-0.0000	0.0000	0.0000	-0.0000	0.0000	-0.0001	0.0000
Ty Error	0.0000	0.0000	0.0000	0.0000	-0.0000	0.0000	0.0000	0.0000
Tz Error	-0.0000	-0.0000	-0.0000	0.0000	0.0000	-0.0000	0.0000	0.0000

Table 62: Joint torque along axis comparison with sensor data (Nm)

	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6	Joint7
Tz Sensor	-37.5028	2.146	-0.057257	0.30268	-0.003178	0.052608	-0.52433
Tz Robot	-36.3756	0.0000	-0.0004	-0.0000	-0.0007	-0.0000	0.0005
Tz PC	-36.3756	0.0000	-0.0004	0.0000	-0.0007	0.0000	0.0005