

# **Gravity Model Report**

**DRAFT**

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**By**

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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.

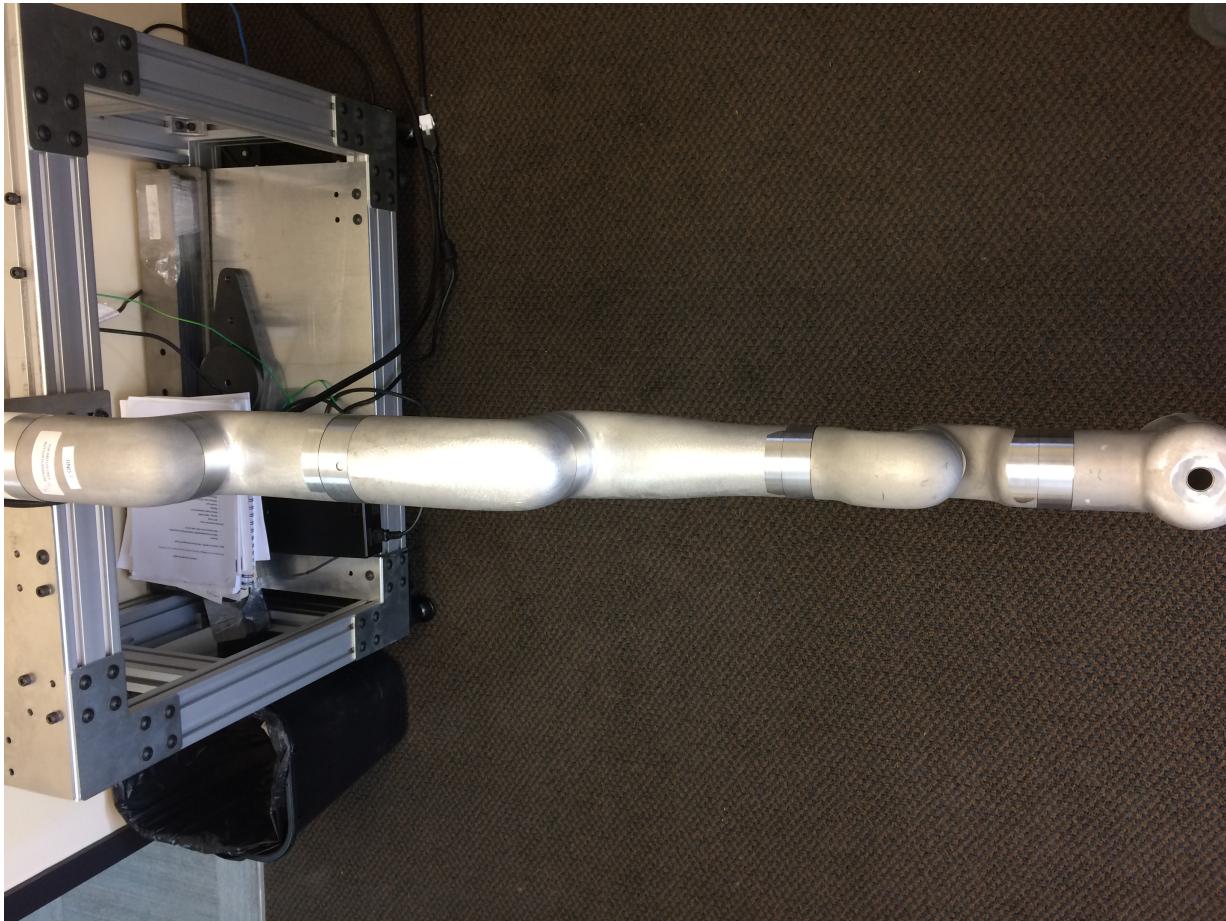


Figure 1: Test setup

## 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)

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

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

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

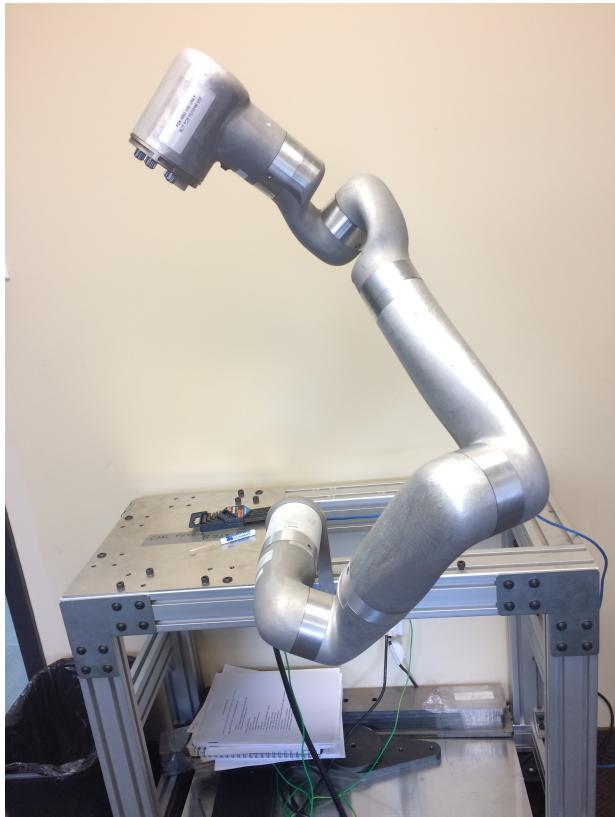


Figure 2: Pose1



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

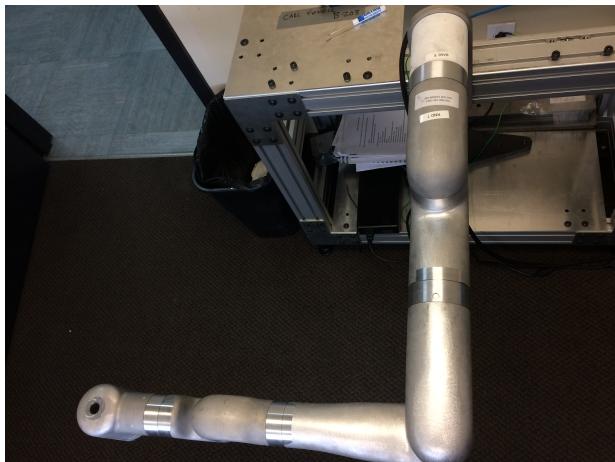


Figure 14: Pose14



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

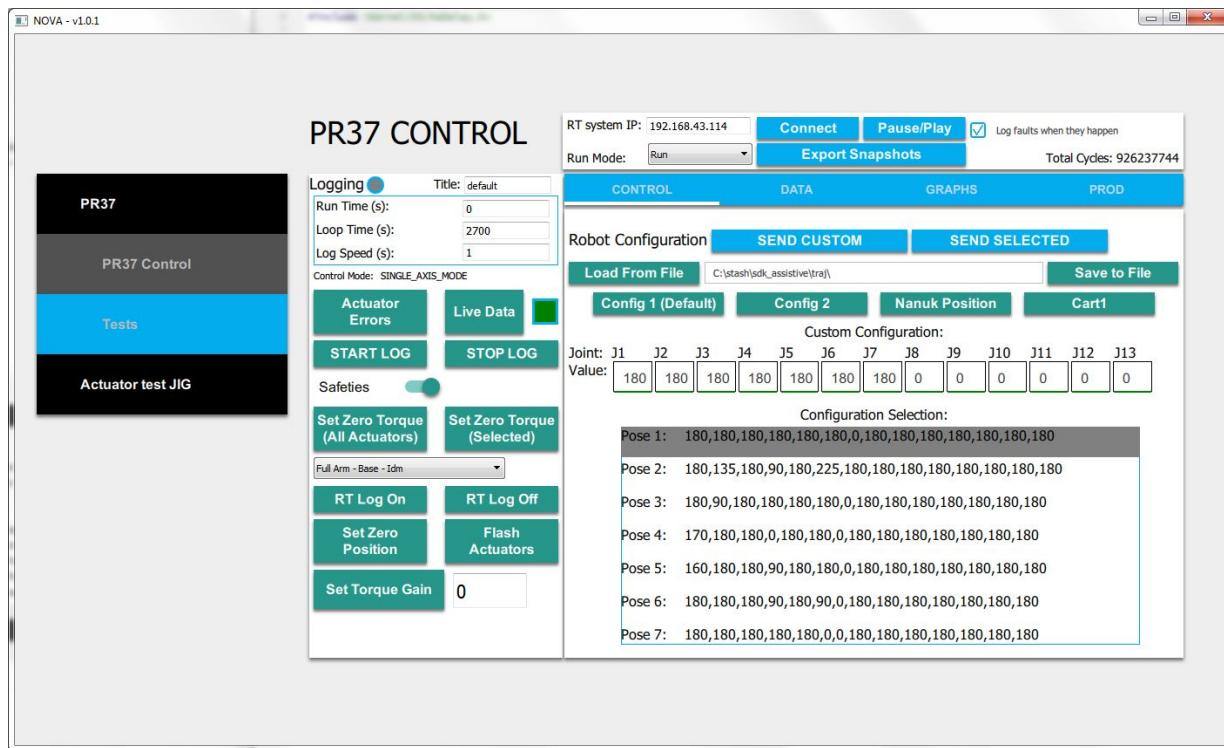


Figure 16: NOVA interface

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

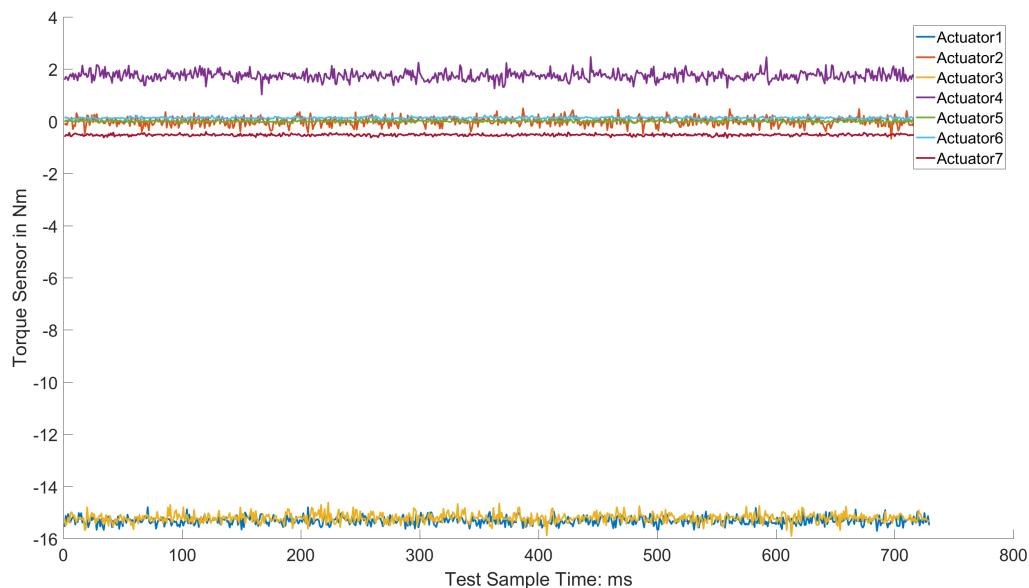


Figure 31: Senso rNoise in Configuration 14

## 6 Appendix

### 6.1 Test at robot configuration 1

Robot joint angles are [ 115 236.85 138.2 264.09 63 235.28 155.28];

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

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

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

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

	<b>Joint1</b>	<b>Joint2</b>	<b>Joint3</b>	<b>Joint4</b>	<b>Joint5</b>	<b>Joint6</b>	<b>Joint7</b>
<b>Tz Sensor</b>	10.0093	-3.4472	1.4829	8.4686	2.5647	1.3346	0.4115
<b>Tz Robot</b>	10.4379	-3.7752	0.6529	8.4087	1.8260	1.5002	-0.0384
<b>Tz PC</b>	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 [ 140 245.42 90.92 281.41 353.62 295.06 265.4];

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

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

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

	<b>Base</b>	<b>Joint1</b>	<b>Joint2</b>	<b>Joint3</b>	<b>Joint4</b>	<b>Joint5</b>	<b>Joint6</b>	<b>Joint7</b>
<b>Fx Error</b>	0.0000	0.0000	0.0009	0.0003	-0.0004	0.0003	0.0003	-0.0006
<b>Fy Error</b>	-0.0001	-0.0000	0.0004	-0.0001	0.0004	0.0004	-0.0007	-0.0000
<b>Fz Error</b>	0.0000	0.0000	-0.0000	-0.0004	-0.0001	-0.0003	0.0003	0.0004
<b>Tx Error</b>	-0.0001	-0.0001	0.0001	-0.0001	-0.0001	0.0000	0.0001	-0.0000
<b>Ty Error</b>	0.0000	-0.0001	-0.0001	0.0001	0.0001	-0.0001	0.0000	0.0000
<b>Tz Error</b>	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)

	<b>Joint1</b>	<b>Joint2</b>	<b>Joint3</b>	<b>Joint4</b>	<b>Joint5</b>	<b>Joint6</b>	<b>Joint7</b>
<b>Tz Sensor</b>	16.2343	-5.077	1.6388	4.1064	0.48671	1.9726	-0.61055
<b>Tz Robot</b>	14.8872	-3.4529	0.5184	5.5217	0.5800	2.8552	-0.0743
<b>Tz PC</b>	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 [ 293 137.05 220.52 87.4 217.98 307 103.13];

### 6.4 Test at robot configuration 4

Robot joint angles are [ 10 176.73 147.59 43.32 142.68 275 205.12];

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

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

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

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

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

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

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

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

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

	<b>Joint1</b>	<b>Joint2</b>	<b>Joint3</b>	<b>Joint4</b>	<b>Joint5</b>	<b>Joint6</b>	<b>Joint7</b>
<b>Tz Sensor</b>	9.8927	0.3421	8.0436	-0.39419	-3.3573	-0.19854	-0.57235
<b>Tz Robot</b>	10.3628	-2.5719	8.2604	-2.3102	-3.0890	0.8373	0.0499
<b>Tz PC</b>	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 [ 85 255.93 141.29 236.09 65.84 228.26 130.5];

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

	<b>Base</b>	<b>Joint1</b>	<b>Joint2</b>	<b>Joint3</b>	<b>Joint4</b>	<b>Joint5</b>	<b>Joint6</b>	<b>Joint7</b>
<b>Fx PC</b>	0.0000	97.1469	19.5504	8.5309	-33.5485	3.0373	-10.0236	-4.9469
<b>Fy PC</b>	108.1749	8.4993	-78.0062	13.9225	-30.0302	-23.5128	-12.0491	13.3684
<b>Fz PC</b>	0.0000	0.0000	7.0357	61.3011	10.1285	20.3161	-17.9401	8.3576
<b>Tx PC</b>	-21.0004	0.8543	4.6632	2.4953	3.4746	-3.8614	-2.6493	1.2333
<b>Ty PC</b>	0.0000	-9.7647	1.3271	7.9974	-0.7541	1.2320	-0.0504	0.3995
<b>Tz PC</b>	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 [ 140 205.51 96.12 275.16 313.2 260.62 229.57];

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

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

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

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

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

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

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

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

	<b>Joint1</b>	<b>Joint2</b>	<b>Joint3</b>	<b>Joint4</b>	<b>Joint5</b>	<b>Joint6</b>	<b>Joint7</b>
<b>Tz Sensor</b>	11.2995	-12.9665	0.0023581	0.81721	0.33965	1.2177	-0.6378
<b>Tz Robot</b>	9.7957	-11.1784	-1.0882	2.3985	0.4055	2.1153	-0.1543
<b>Tz PC</b>	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 [ 120 240.31 140.2 239.88 66.74 239.24 115.38];

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

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

	<b>Base</b>	<b>Joint1</b>	<b>Joint2</b>	<b>Joint3</b>	<b>Joint4</b>	<b>Joint5</b>	<b>Joint6</b>	<b>Joint7</b>
<b>Fx Robot</b>	0.0000	84.4530	34.6274	41.2101	-14.9889	7.1479	-16.4410	1.0797
<b>Fy Robot</b>	108.1750	-48.7590	-60.7327	-6.9516	-43.3550	-7.9649	-16.1327	12.1100
<b>Fz Robot</b>	0.0000	0.0000	-40.3630	47.7267	-5.0573	29.3307	-6.0771	11.1900
<b>Tx Robot</b>	-29.3424	-9.0720	-12.5835	-2.7021	-0.3933	-1.2578	-0.9996	1.1835
<b>Ty Robot</b>	0.0000	-15.7131	-3.3882	-2.9274	-0.2412	1.8142	0.0853	-0.0876
<b>Tz Robot</b>	-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 [ 285 113.25 129.73 289.67 7.89001 195.54 83.44];

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

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

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

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

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

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

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

	<b>Joint1</b>	<b>Joint2</b>	<b>Joint3</b>	<b>Joint4</b>	<b>Joint5</b>	<b>Joint6</b>	<b>Joint7</b>
<b>Tz Sensor</b>	3.3341	18.5119	1.1798	9.2112	0.98877	-4.0431	0.3875
<b>Tz Robot</b>	4.1928	17.3806	0.1311	10.8744	-0.0447	-3.0209	-0.0400
<b>Tz PC</b>	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 [ 285 121.22 234.46 131.94 356.65 77.01 227.27];

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

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

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

	<b>Base</b>	<b>Joint1</b>	<b>Joint2</b>	<b>Joint3</b>	<b>Joint4</b>	<b>Joint5</b>	<b>Joint6</b>	<b>Joint7</b>
<b>Fx Error</b>	0.0000	-0.0000	0.0010	0.0006	0.0011	-0.0012	0.0001	-0.0003
<b>Fy Error</b>	-0.0001	0.0000	-0.0006	-0.0006	0.0007	0.0007	-0.0005	-0.0002
<b>Fz Error</b>	0.0000	0.0000	-0.0000	0.0005	-0.0004	-0.0004	0.0005	0.0004
<b>Tx Error</b>	0.0007	-0.0001	0.0001	-0.0003	-0.0002	0.0001	0.0001	-0.0000
<b>Ty Error</b>	0.0000	-0.0007	-0.0001	-0.0003	-0.0001	0.0001	0.0000	-0.0000
<b>Tz Error</b>	-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 [ 340 141.74 22.27 67.95 16.12 61.73 153.11];

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

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

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

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

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

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

	<b>Joint1</b>	<b>Joint2</b>	<b>Joint3</b>	<b>Joint4</b>	<b>Joint5</b>	<b>Joint6</b>	<b>Joint7</b>
<b>Tz Sensor</b>	-1.4312	10.9292	-11.2448	-0.8095	3.1447	0.87527	0.20194
<b>Tz Robot</b>	1.1710	7.9144	-10.6054	-2.3179	3.0005	0.0011	-0.1377
<b>Tz PC</b>	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 [ 180 180 180 180 180 180 180];

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

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

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

	<b>Base</b>	<b>Joint1</b>	<b>Joint2</b>	<b>Joint3</b>	<b>Joint4</b>	<b>Joint5</b>	<b>Joint6</b>	<b>Joint7</b>
<b>Fx Error</b>	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0000	0.0000
<b>Fy Error</b>	-0.0001	-0.0000	0.0000	-0.0000	0.0000	-0.0000	-0.0000	-0.0000
<b>Fz Error</b>	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0000	0.0000
<b>Tx Error</b>	0.0000	-0.0000	0.0000	-0.0000	-0.0000	0.0000	-0.0001	0.0000
<b>Ty Error</b>	0.0000	0.0000	0.0000	0.0000	-0.0000	0.0000	0.0000	-0.0000
<b>Tz Error</b>	-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)

	<b>Joint1</b>	<b>Joint2</b>	<b>Joint3</b>	<b>Joint4</b>	<b>Joint5</b>	<b>Joint6</b>	<b>Joint7</b>
<b>Tz Sensor</b>	-0.0084548	0.004673	0.020459	0.024678	0.012828	0.012407	-0.53406
<b>Tz Robot</b>	-0.0011	0.0000	-0.0004	0.0000	-0.0007	-0.0000	0.0005
<b>Tz PC</b>	-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 [ 270 180 180 180 180 180 180];

## 6.13 Test at robot configuration 13

Robot joint angles are [ 180 180 180 180 180 90 180];

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

	<b>Base</b>	<b>Joint1</b>	<b>Joint2</b>	<b>Joint3</b>	<b>Joint4</b>	<b>Joint5</b>	<b>Joint6</b>	<b>Joint7</b>
<b>Fx PC</b>	0.0000	-97.5180	-80.7260	-63.4384	-46.1509	-31.2221	-23.8223	16.5238
<b>Fy PC</b>	108.1749	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
<b>Fz PC</b>	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
<b>Tx PC</b>	-59.1388	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
<b>Ty PC</b>	0.0000	47.9403	7.7253	24.3045	2.0463	6.2177	0.3979	-1.3353
<b>Tz PC</b>	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)

	<b>Base</b>	<b>Joint1</b>	<b>Joint2</b>	<b>Joint3</b>	<b>Joint4</b>	<b>Joint5</b>	<b>Joint6</b>	<b>Joint7</b>
<b>Fx Robot</b>	0.0000	-97.5180	-80.7260	-63.4384	-46.1509	-31.2221	-23.8223	16.5238
<b>Fy Robot</b>	108.1750	-0.0000	-0.0000	-0.0000	-0.0000	-0.0000	-0.0000	0.0000
<b>Fz Robot</b>	0.0000	0.0000	-0.0000	0.0000	-0.0000	0.0000	-0.0000	0.0000
<b>Tx Robot</b>	-59.1388	-0.0000	-0.0000	-0.0000	-0.0000	-0.0000	-0.0000	0.0000
<b>Ty Robot</b>	0.0000	47.9403	7.7253	24.3045	2.0463	6.2177	0.3979	-1.3353
<b>Tz Robot</b>	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)

	<b>Base</b>	<b>Joint1</b>	<b>Joint2</b>	<b>Joint3</b>	<b>Joint4</b>	<b>Joint5</b>	<b>Joint6</b>	<b>Joint7</b>
<b>Fx Error</b>	0.0000	-0.0000	0.0000	-0.0000	0.0000	0.0000	-0.0000	-0.0000
<b>Fy Error</b>	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0000
<b>Fz Error</b>	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
<b>Tx Error</b>	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0000
<b>Ty Error</b>	0.0000	0.0000	0.0000	-0.0000	0.0000	-0.0000	0.0000	-0.0000
<b>Tz Error</b>	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)

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

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

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

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

	<b>Base</b>	<b>Joint1</b>	<b>Joint2</b>	<b>Joint3</b>	<b>Joint4</b>	<b>Joint5</b>	<b>Joint6</b>	<b>Joint7</b>
<b>Fx Error</b>	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
<b>Fy Error</b>	-0.0001	-0.0000	0.0000	-0.0000	0.0000	0.0000	-0.0000	-0.0000
<b>Fz Error</b>	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0000	0.0000
<b>Tx Error</b>	0.0000	-0.0000	-0.0000	0.0000	0.0000	-0.0000	-0.0001	0.0000
<b>Ty Error</b>	0.0000	0.0000	-0.0000	0.0000	-0.0000	0.0000	0.0000	0.0000
<b>Tz Error</b>	-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)

	<b>Joint1</b>	<b>Joint2</b>	<b>Joint3</b>	<b>Joint4</b>	<b>Joint5</b>	<b>Joint6</b>	<b>Joint7</b>
<b>Tz Sensor</b>	-3.4566	0.023453	-3.3845	0.023353	-3.4193	1.182	-0.52291
<b>Tz Robot</b>	-3.3232	0.0000	-3.3225	0.0000	-3.3228	0.0000	0.0005
<b>Tz PC</b>	-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 [ 180 180 180 90 180 180 180];

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

	<b>Base</b>	<b>Joint1</b>	<b>Joint2</b>	<b>Joint3</b>	<b>Joint4</b>	<b>Joint5</b>	<b>Joint6</b>	<b>Joint7</b>
<b>Fx PC</b>	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
<b>Fy PC</b>	108.1749	-97.5180	0.0000	-63.4384	0.0000	-31.2221	0.0000	16.5238
<b>Fz PC</b>	0.0000	0.0000	-80.7260	0.0000	-46.1509	0.0000	-23.8223	0.0000
<b>Tx PC</b>	-44.3179	-33.1195	-21.5543	-9.4837	-14.8206	-6.2177	-3.3222	1.3353
<b>Ty PC</b>	0.0000	0.0000	14.8209	0.0000	0.0002	0.0000	0.0001	0.0000
<b>Tz PC</b>	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 90 180 180 180 180 180];

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

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

	<b>Base</b>	<b>Joint1</b>	<b>Joint2</b>	<b>Joint3</b>	<b>Joint4</b>	<b>Joint5</b>	<b>Joint6</b>	<b>Joint7</b>
<b>Fx Error</b>	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0000	0.0000
<b>Fy Error</b>	-0.0001	-0.0000	0.0000	-0.0000	-0.0000	0.0000	-0.0000	-0.0000
<b>Fz Error</b>	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0000	0.0000
<b>Tx Error</b>	-0.0000	0.0000	-0.0000	-0.0000	-0.0000	0.0000	-0.0001	0.0000
<b>Ty Error</b>	0.0000	0.0000	-0.0000	0.0000	-0.0000	0.0000	0.0000	0.0000
<b>Tz Error</b>	-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)

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

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

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

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

	<b>Base</b>	<b>Joint1</b>	<b>Joint2</b>	<b>Joint3</b>	<b>Joint4</b>	<b>Joint5</b>	<b>Joint6</b>	<b>Joint7</b>
<b>Fx Error</b>	0.0000	0.0000	0.0000	0.0000	-0.0000	0.0000	-0.0000	0.0000
<b>Fy Error</b>	-0.0001	-0.0000	-0.0000	-0.0000	-0.0000	0.0000	-0.0000	-0.0000
<b>Fz Error</b>	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-0.0000	0.0000
<b>Tx Error</b>	0.0000	-0.0000	0.0000	0.0000	-0.0000	0.0000	-0.0001	0.0000
<b>Ty Error</b>	0.0000	0.0000	0.0000	0.0000	-0.0000	0.0000	0.0000	0.0000
<b>Tz Error</b>	-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)

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