Kinematic Calibration Manual for CB3

Version 1.0.0

Contents

1 Plate Calibration

This user manual goes through the calibration method for the kinematics, implemented on the Universal Robots controller from software version 1.4 to 1.8 and from 3.3 and onwards. The manual is organised as a step by step tutorial.

Figure 1.1: Robot mounted on a plate with holes to align the robot tool flange.

CAUTION:

It is important to point out that not all calibrations are good calibrations. Please pay attention to the generated statistics before saving the result of the calibration. If a calibration is not performed with care, the robot may become inaccurate.

1.1 Required Equipment

The method is based on the assumption that it is possible to fixate the tool in multiple positions with the tool flange parallel to the plane. In this tutorial we use a stiff plate with holes at known positions. The holes fits the tool flange as displayed in Figure 1.1 (see details in Appendix A).

1.2 Accessing the Functionality

The starting point for the steps of the tutorial is a screen that looks like Figure 1.2.
The steps are as follows:

(1) The functionality can enabled in the *Expert Mode* on the controller screen by pressing the "Kinematics Calibration" button as illustrated in Figure 1.2.

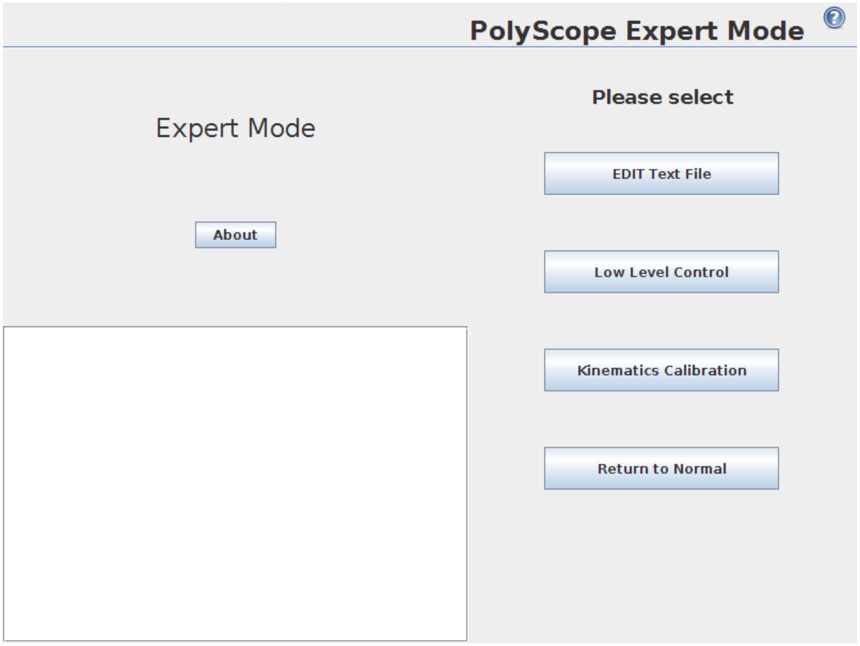

Figure 1.2: Select "Kinematics Calibration" in "Expert Mode" to enable the calibration functionality.

(2) This takes you to the Calibration screen. It also enables a new button called "Calibrate robot" on the "Welcome" screen, should you need to return to the Calibration screen at a later time. Clicking the "Kinematics Calibration" button again removes the new button from the "Welcome" screen.

(3) The first tab on the next screen is called "Calibration". In this tab three cases can be chosen, see Figure 1.3:

(a) Program correction:
A method for adjusting programs after joint or robot replacement.

(b) Dual Robot Calibration:
Calibrate the robot with two robots of the same type.

(c) Plate Calibration:
Calibrate the robot by known positions on plates. Press this button to begin the calibration procedure.

(d) Load an existing calibration:
Makes it possible to load a previously saved calibration.

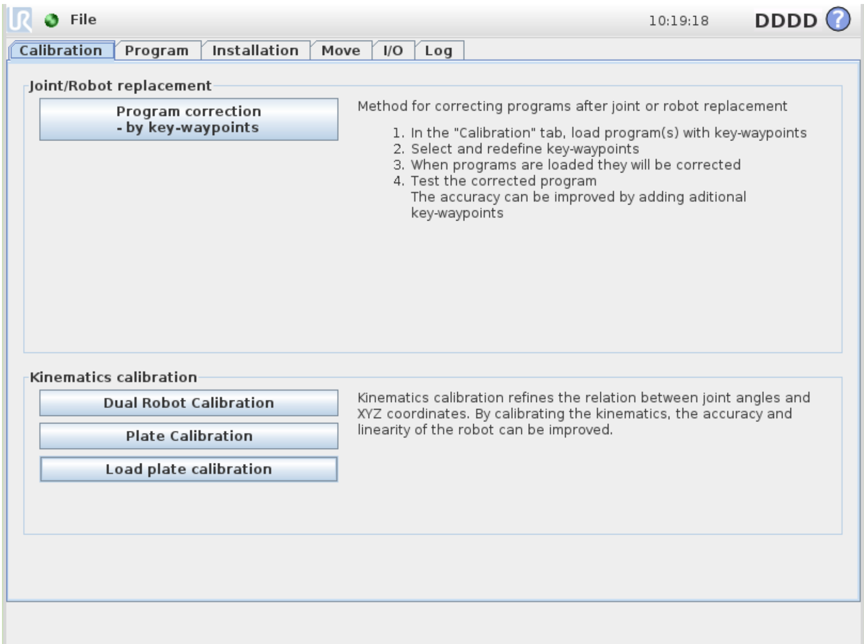

Figure 1.3: Select "Plate Calibration" to select this method.

1.3 Measuring Positions

Multiple metal plates with a number of holes can be used. Add a plate to start adding positions.

(4) Add the first plate for the positions.

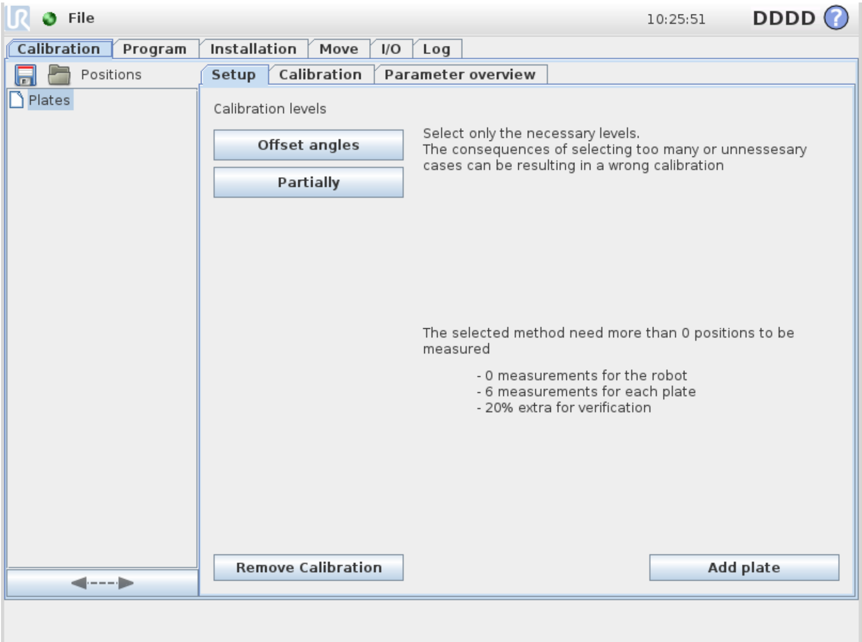

Figure 1.4: Add a plate for the hole positions.

(5) Add the first position to the selected plate by pressing "Add new position".

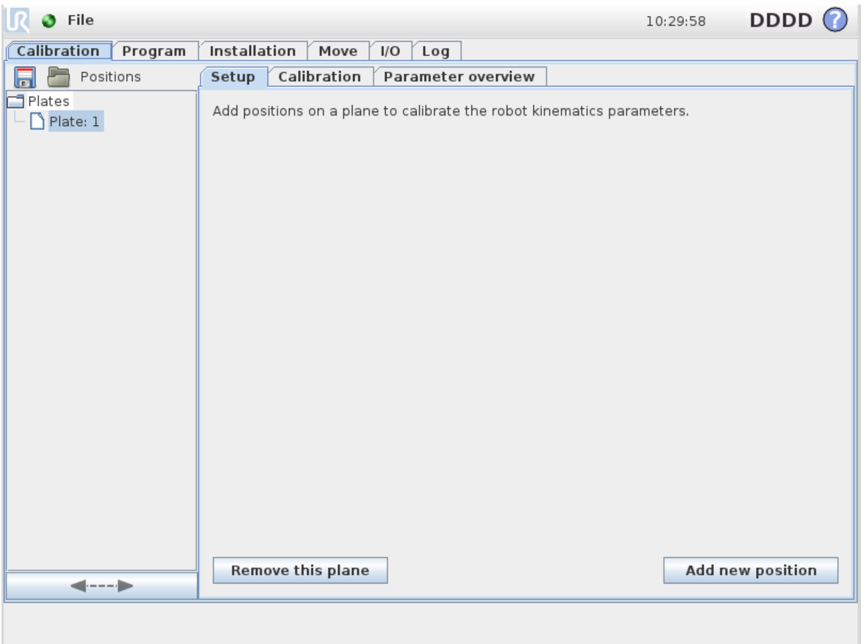

Figure 1.5: Select "Add new positions" to add a position to the selected plate.

(6) Insert the (x, y, z) coordinate relative to the plate for the position at the top of the screen shown in Figure 1.6.

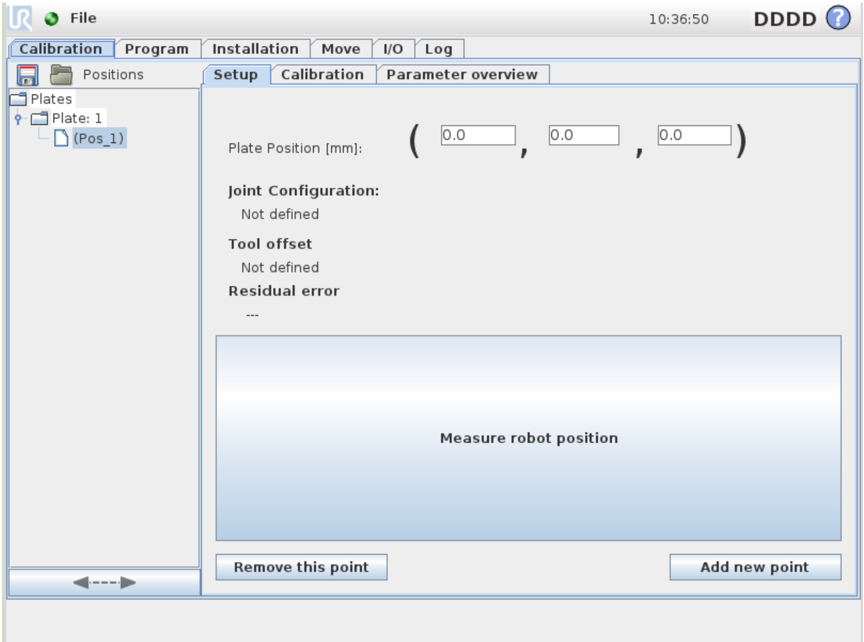

Figure 1.6: The property screen for the selected position. Insert the (x, y, z) coordinate, teach the related robot configuration. The screen has also a button to add additional positions.

(7) Move the related robot configuration by pressing "Measure robot position" (see Figure 1.6).

(8) In the "Move" tab teach the robot the corresponding position and press "OK" to complete the measurement.

(9) To continue adding multiple positions press "Add new point" in the screen on Figure 1.6.

(10) Step no.: 6 to 9 is repeated until enough positions are added.

(11) Before starting on the calibration part it is recommenced to save the collected data. This is done by pressing on the disk in the top left corner. Please note that the save function in the file menu save robot programs and not calibrations and therefore can not be used, see Figure 1.6.

The configuration used in the calibration needs to be as distributed as possible on the plate but also in the configuration space of the robot. Ensure that all the combinations of both elbow and wrist up and down solutions are used, see Figure 1.7.

It is recommended that a full calibration at least includes 30 positions on each plate. To add an additional plate select the top of the tree item "Positions" on the left and repeat the steps from 4.

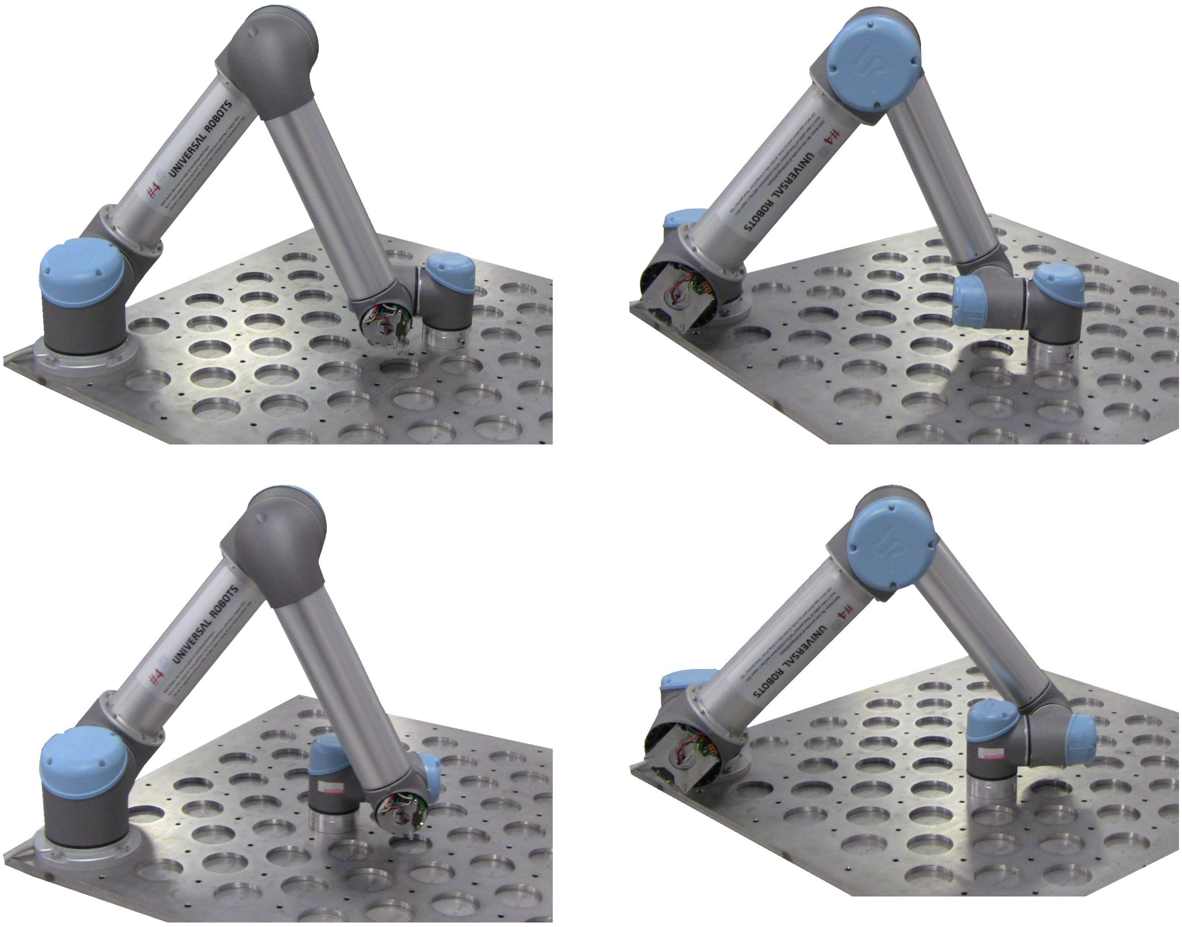

Figure 1.7: Configuration need to be used.

1.4 Calibration

Now all the needed positions for the calibration are added to the tree. In this example 26 Positions on one plate are used.

(12) Select the top of the tree item "Plates" on the left to be able to select the level of calibration, see Figure 1.8.

(a) Offset angles
This level calibrates the offset angles for the shoulder, elbow, wrist 1 and wrist 2. The method does not provide enough information to calibrate the base and wrist 3.

(b) Partially
This level calibrates more parameters than 12a using other deviations than offset angles. It is not a full calibration, but as full as the nature of the method allow it to be.

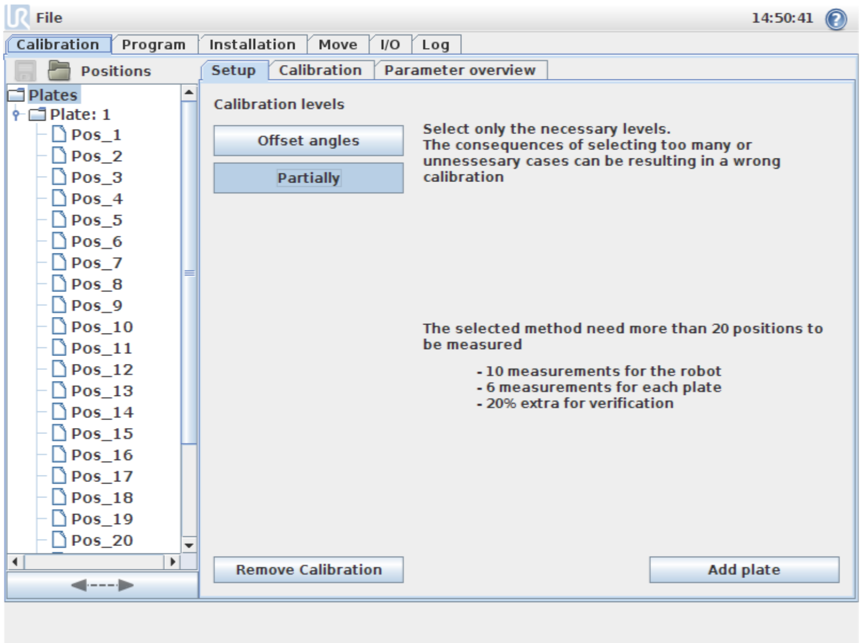

Figure 1.8: Select the top of the tree item on the left to be able to select the level of calibration.

(13) The calibration is started from the "Calibration" tab.

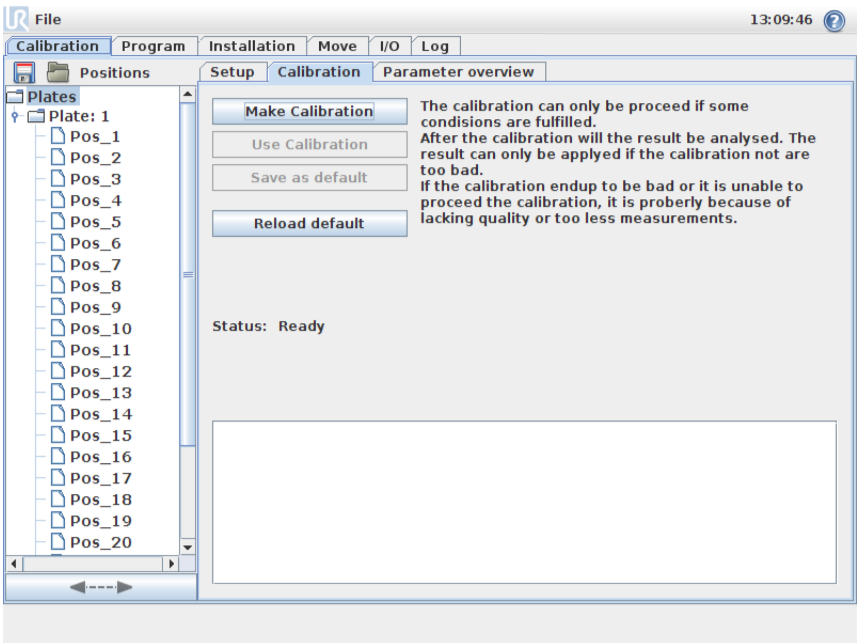

Figure 1.9: Select the calibration tab and press "Make Calibration" to start the calibration.

(14) Start the calibration by pressing "Make Calibration".

1.5 Evaluation

(15) After the calibration has been performed the results needs to be evaluated to ensure that the calibration is successfully.

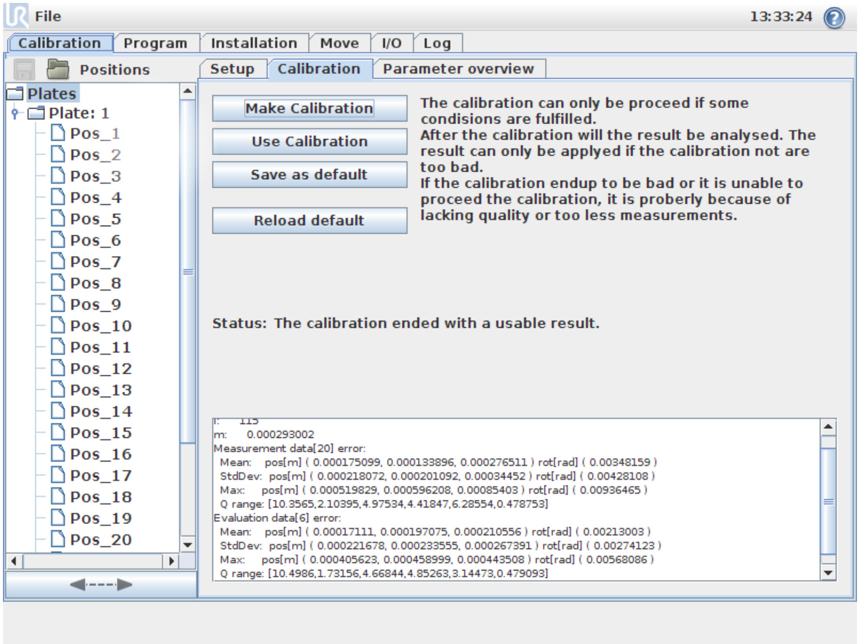

Figure 1.10: The calibration is done and the result needs to be evaluated. Afterwards it is possible to try the new parameters and apply them to the robot.

The results from the calibration are the parameters displayed in the "Parameter overview" tab and the calculated statistics of the archived precision for the given positions. The last part is displayed lower part of Figure 1.10 and is used to evaluate the calibration.

The calculated statistics is divided into two groups: a) "Measurement data" which is statistics on positions used in the calibration and b) "Evaluation data" which is statistics that evaluates the quality of the calibration result.

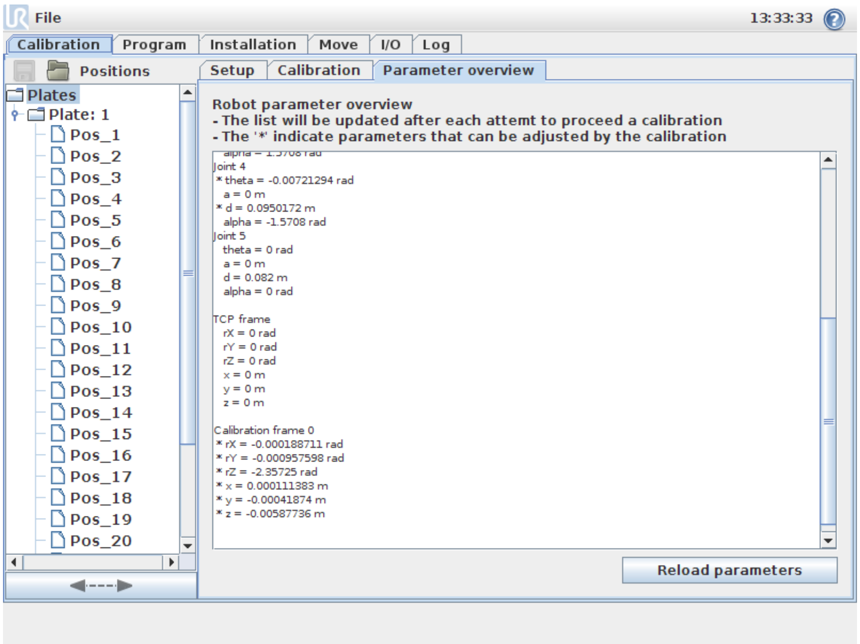

Figure 1.11: The identified parameters are displayed in the "Parameter overview".

1.5.1 Calibration Statistics

An example of the printed statistics:

```
1  ##############
2  I:      118
3  m:      0.000292995
4  Measurement data[20] error:
5    Mean:   pos[m] ( 0.000175164, 0.000134324, 0.00027655 ) rot[rad] ( 0.00348157 )
6    StdDev: pos[m] ( 0.000218127, 0.000201774, 0.000344546 ) rot[rad] ( 0.00428109 )
7    Max:    pos[m] ( 0.000518104, 0.000596791, 0.000853992 ) rot[rad] ( 0.00936474 )
8    Q range: [ 10.3565, 2.10395, 4.97534, 4.41847, 6.28554, 0.478753 ]
9  Evaluation data[6] error:
10   Mean:   pos[m] ( 0.000171146, 0.00019818, 0.000210623 ) rot[rad] ( 0.00212999 )
11   StdDev: pos[m] ( 0.000221324, 0.00023433, 0.000267463 ) rot[rad] ( 0.00274118 )
12   Max:    pos[m] ( 0.000405676, 0.000459457, 0.000443527 ) rot[rad] ( 0.00568077 )
13   Q range: [ 10.4986, 1.73156, 4.66844, 4.85263, 3.14473, 0.479093 ]
```

Listing 1.1: Example of printed statistics for a partially calibration

Explanation of line number:

1: This line is used to indicate that the calibration is running. *Not important.*

2: The number of used iterations finding the solution. *Not important.*

3: The sum of the calibrations residual error. *Not important for the normal user.*

4 to **8**: The statistics for the positions used in the calibration. In this case the calibration is based on 20 positions.

9 to **13**: The statistics for the positions reserved for evaluation only. In this case 6 positions. If there is a large difference between the results of the evaluation and the measurement data, the calibration was not successful and the positions needs to be verified.

5 and **10**: The mean error. First with position error as a vector(x,y,z) followed by the rotation error.

6 and **11**: The standard deviation of the error. It is formatted like the mean error.

7 and **12**: shows the maximum error in the data. It is formatted like the mean error.

8 and **13**: is the range of the used robot configuration. The range gives an indication of how well the measurements are distributed.

The printed statistics is also saved in *calibration.log* file.

1.5.2 Debugging

To pinpoint the source for the maximum error, each position's contribution to the residual error is displayed in the position property screens, see Figure 1.6.

(16) If the evaluation was not successful: Examine that the correct coordinates were used in the defined calibration points.

(17) If the configuration is too monotone: Add additional positions.

1.5.3 Applying the Calibration

When a satisfied calibration has been obtained it is recommended to try the new parameters before they are stored permanently.

(18) Try the new calibration without saving them as the default by press "Use Calibration", see Figure 1.10.

The current default kinematics can be reloaded with the "Reload default". This button is not a "load factory default" button. So please be aware of the quality of the calibration before applying them as permanently.

(19) The found parameters can be viewed in the "Parameter overview" tab, see Figure 1.11.

(20) Save the calibration for future use by pressing "Save as default", see Figure 1.10.

(21) The Robot is know calibrated.

1.6 Reset Calibration

The kinematic calibration can be removed by deleting the */root/.urcontrol/calibration.conf* file, placed together with the other configurations. It can also be removed by manually replace all the decimal and hex numbers, in the configuration files, to zeros like in Listing 1.2.

```
[mounting]
delta_theta = [ 0, 0, 0, 0, 0, 0]
delta_a = [ 0, 0, 0, 0, 0, 0]
delta_d = [ 0, 0, 0, 0, 0, 0]
delta_alpha = [ 0, 0, 0, 0, 0, 0]
joint_checksum = [ 0x0, 0x0, 0x0, 0x0, 0x0, 0x0]
calibration_status = 0 # 0 == notInitialized / 1 == notLinearised / 2 == Linearised
joint_raw_offset = [ 0x0, 0x0, 0x0, 0x0, 0x0, 0x0]
joint_selftest_data_crc = [ 0x0, 0x0, 0x0, 0x0, 0x0, 0x0]
```

Listing 1.2: calibration.conf file filled with zeros

2 Dual Robot Calibration

This manual is a step-by-step tutorial for integrators that describes how to perform Dual Robot Calibration of the kinematics. The method can be used on Universal Robots—with Software version 3.0.16000 up to version 3.3 and later.

The method is patented pending under the patent*Calibration and Programming of Robots*, Søe-Knudsen, Rune (inventor); Petersen, Henrik Gordon (inventor); Østergård, Esben Hallundbæk (inventor), IPC: B25J9/16, Patent number: EP2012/068337, September 18, 2012. International Publication number WO 2013/045314 A1.

Figure 2.1: The Dual Robot Calibration method.

CAUTION:

Stay clear of the robot when using Dual Robot Calibration.

CAUTION:

Not all calibrations are good calibrations. Please pay attention to the generated statistics before saving the result of the calibration. If a calibration is not performed with care, the robot may become inaccurate.

The method requires a Dual Robot Calibration kit from Universal Robots (purchase number: 185500) and one pair of UR3, UR5 or UR10 robots, respectively, with a CB3 control box. The robot bases are connected with the Calibration Horse and the robot tools are connected by the Tool Connector, see Figure 2.1. This creates a closed chain where the distance between the bases and the tools are fixed to known distances. When the robots has been connected it can perform a number of measurements from coordinated movements to different positions. This creates a set of data which creates a mathematical foundation for determining the robot arm lengths and link rotations of the robots, i.e. the Denavit-Hartenberg parameters.

2.1 Required Equipment

The method requires a Dual Robot Calibration Kit from Universal Robots (purchase number: 185500) and one pair of UR3, UR5 or UR10 robots with control box CB3. The robot bases are connected with a device and the robot tools are connected by a device (Appendix B). This creates a closed chain where the distance between the bases and the tools are fixed to known distances. In addition, the calibration horse, (Figure 2.2), have holes with threads at the bottom for temponary and long term storage of screws.

Please note that the UR3, UR5 and UR10 are mounted differently on the Calibration Horse and that their cables are pointing toward each other, as illustrated in Figure 2.2.

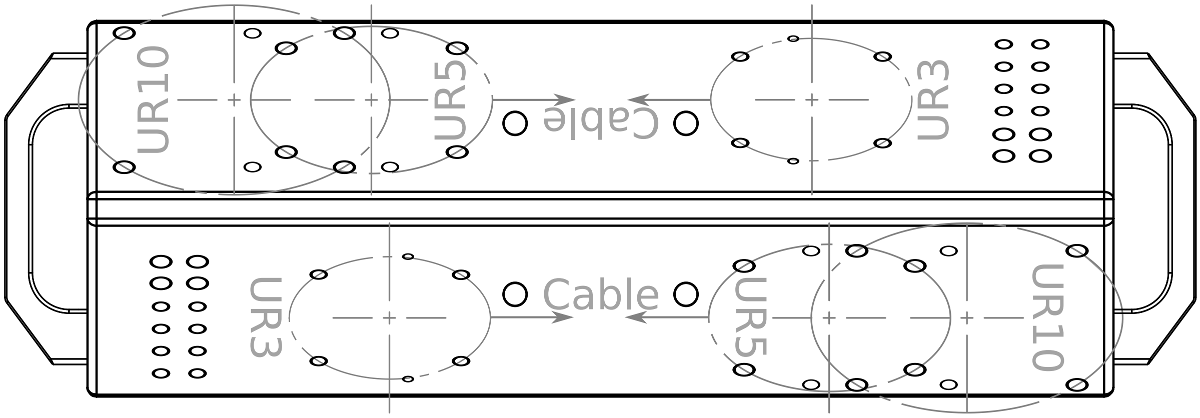

Figure 2.2: A sketch of the Dual Robot Calibration Horse and where the UR3, UR5 or UR10 robot can be mounted

To complete the assembly, mount the two handles at each end of the Calibration Horse with two M8-1.25x25, each. The handles and screws are included in the Dual Robot Calibration Kit.

Required equipment:

- A pair of UR3, UR5 or UR10 robots, respectively, to be calibrated
- A stand with a height of at least 0.5 m for the Calibration Horse
- Dual Robot Calibration Kit from Universal Robots with purchase number: 185500, including:
  - The UR Dual Robot Calibration Horse with alignment pins (Figure B.1, Appendix B)
  - The UR Dual Robot Calibration Tool Connector with alignment pins (Figure B.2, Appendix B)
  - Four M8-1.25x70 to mount the Calibration Horse to the stand (may differ depending on the robot stand)
  - Eight M8-1.25x25 screws with washers to mount UR5 and UR10 robots to the Calibration Horse
  - Eight M6-1.0x25 screws with washers to mount the robot tools to the Calibration Tool Connector
  - Eight M6-1.0x25 screws to mount UR3 robots to the Calibration Horse
  - One *Go* tool used in the validating procedure, (Figure B.3, Appendix B)
  - One *No Go* tool used in the validating procedure (Figure B.4, Appendix B)

Exception:

- The alignment pin for the tool connector, should not be used when calibrating UR5s produced prior to end of 2014. This is due to the calibration requiring an improved version of the tool flange in UR5.

2.2 Mounting the Robots to the Calibration Horse

(1) Mount the Calibration Horse to a stand of a height of at least 0.5 m and mount the robots to the Calibration Horse, as in Figure 2.3.

(2) Mount two robots of the *same type and version* on the Calibration Horse, see Figure 2.3.

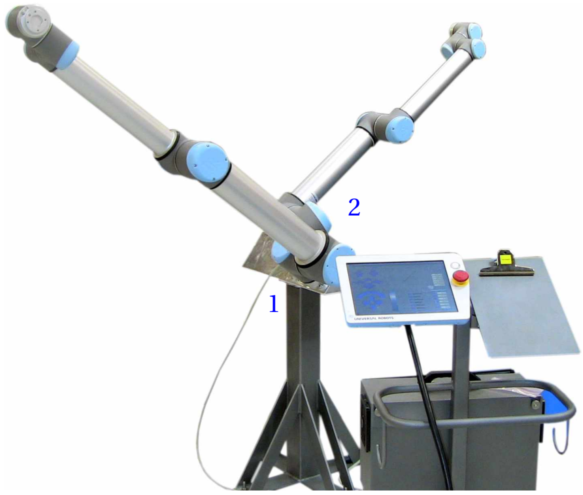

Figure 2.3: Mount the robots on the Calibration Horse, connecting the robot bases

(3) From the Initialization screen set the robot mounting and angle (click the "Configure Mounting" button), see Figure 2.4:

UR3:

(a) The *Tilt* is approximately 52,5° ±5° and

(b) The *Rotate Robot Base Mounting* is 270°.

UR5 and UR10:

(a) The *Tilt* is approximately 52,5° ±5° and

(b) The *Rotate Robot Base Mounting* is 90°.

(4) From the Initialization screen set the payload to 0 kg for both robot types, see Figure 2.5.

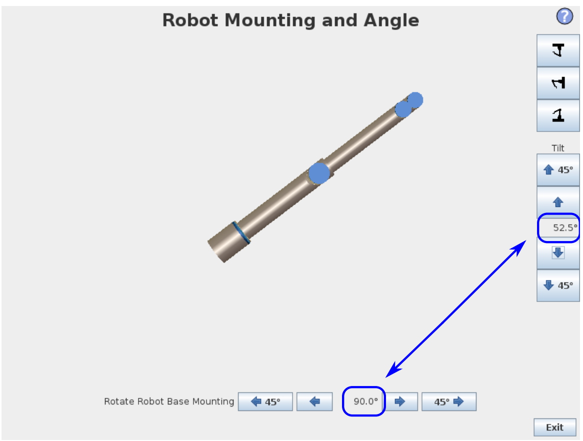

Figure 2.4: Mounting of the robot

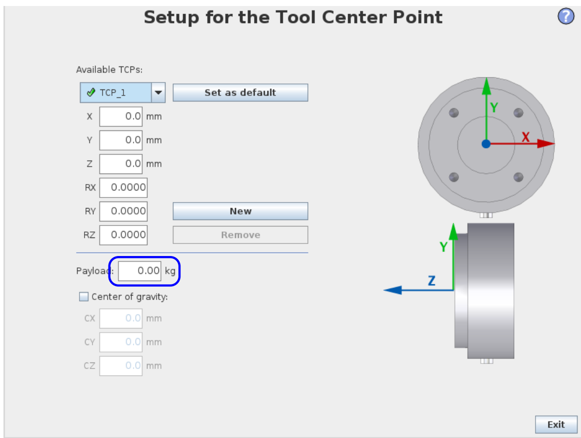

Figure 2.5: TCP settings

2.3 Accessing the Functionality

The starting point for the method is to enable *Kinematics Calibration* in *Expert Mode*.

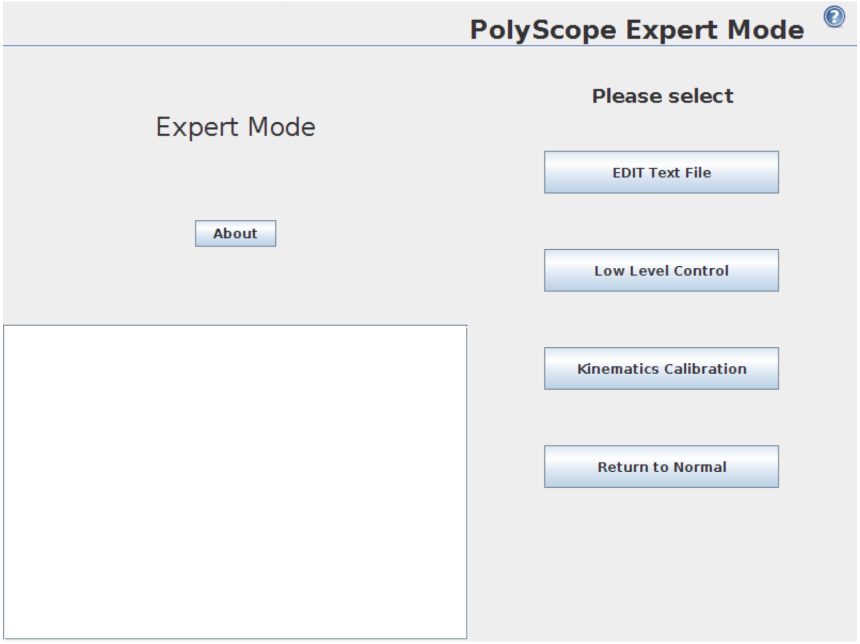

Figure 2.6: Select *Kinematics Calibration* in *Expert Mode*.

This takes you to the Calibration screen. It also enables a new button called "Calibrate robot" on the "Welcome screen", should you need to return to the Calibration screen at a later time. Clicking the "Kinematics Calibration" button again removes the new button from the "Welcome" screen.

Select *Dual Robot Calibration* in the "Calibration" tab, see Figure 2.7.

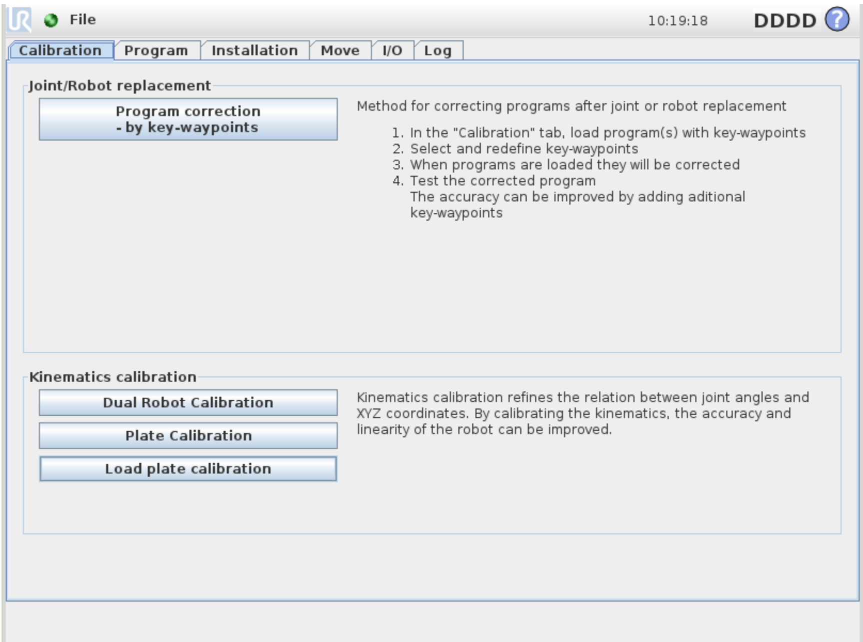

Figure 2.7: Select *Dual Robot Calibration* to select the method.

2.4 Safety Settings of the Robots

(5) Go to the Installation tab and click on Safety. Unlock the Safety tab and in the General Limits select and apply the *Least restricted* safety preset limits before performing the dual robot calibration (see Figure 2.8).

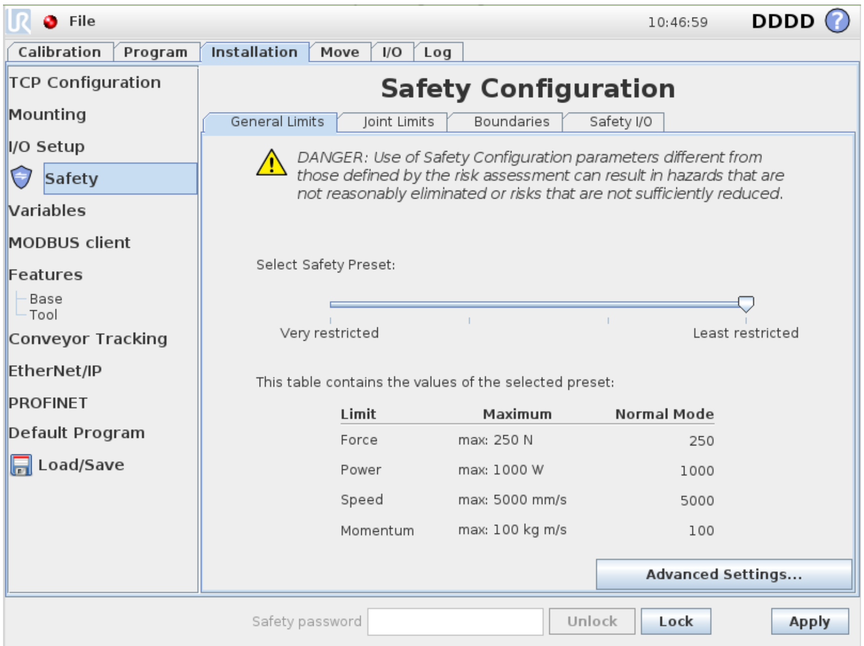

Figure 2.8: Safety settings

2.5 Network Connection Between the Robots

The Dual Robot Calibration screen appears as shown in Figure 2.9. There are a number of options to choose from within connection types which are described below:

- Master - the robot acts as master of the calibration process. Make sure that the other robot is selected as Slave and that the two robots are connected with a network cable or switch.
- Slave - the robot acts as a slave in the calibration process. Make sure that the other robot is selected as Master and that the two robots are connected with a network cable or switch.
- Manual - the robot acts as a master, but the slave robot is selected by an user supplied IP-address (see description below).

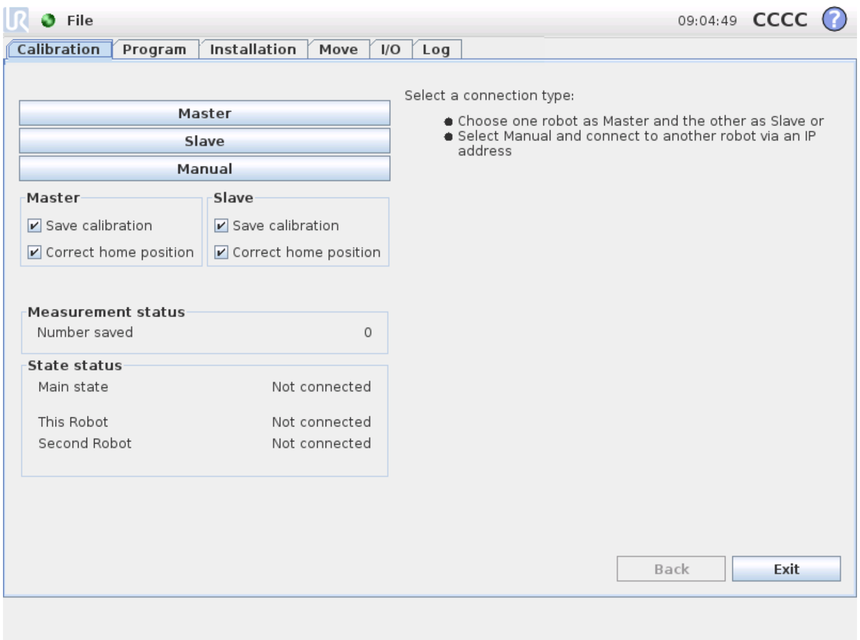

Figure 2.9: Network options in Dual Robot Calibration.

The different connection types Master/Slave or Manual are described below.

(6) Connect the robot controllers with a network cable or through a network switch.

(7) Use ether the master/slave or manual connection method to establishment network connection between the two robots controllers.

Note: Robot 1 is the master robot and Robot 2 is the slave.

2.5.1 Master/Slave Connection

A Master/Slave connection works by connecting two robots via a network cable or over a network switch. One robot have to be selected as master and the other as slave. Selecting one of these cases sets up the IP address automatically.

CAUTION:

Notice that the IP-addresses `10.17.17.17.18` and `10.17.17.17.19` will be used for master/slave connections. Connecting the robots to a local area network may interfere with other devices having the same IP.

(8) When the slave (Robot 2) is ready and have entered the screen in Figure 2.10, press *Connect network* on the master to establish the network connection, see Figure 2.11. The screens that follow are described in Section 2.7.

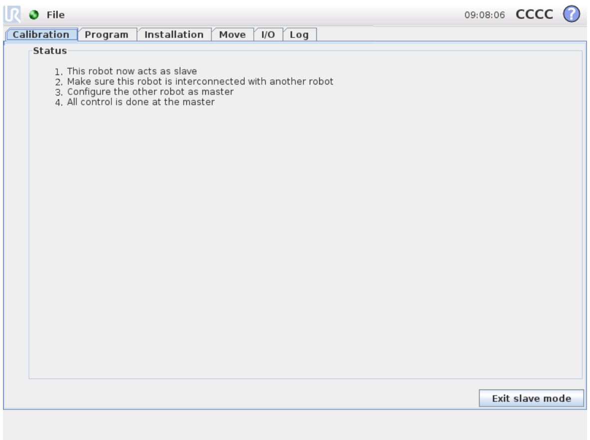

Figure 2.10: Slave mode

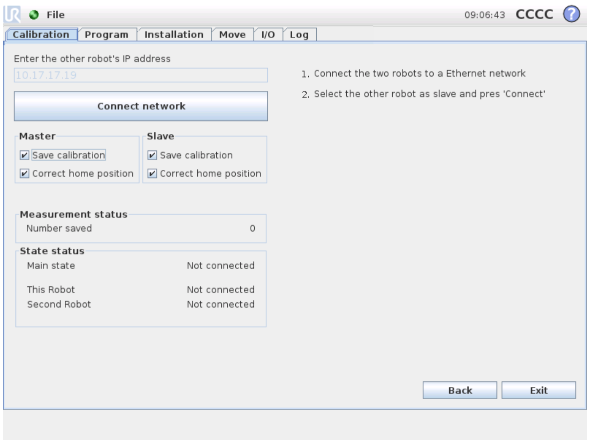

Figure 2.11: Master mode

2.5.2 Manual mode

Selecting *Manual* leads to the screen in Figure 2.12.

(9) In Figure 2.12, Enter the IP number or host name of the *Slave* by clicking the text field with the text "IP address or host name".

(10) Connect by press *Connect network*, see Figure 2.12.

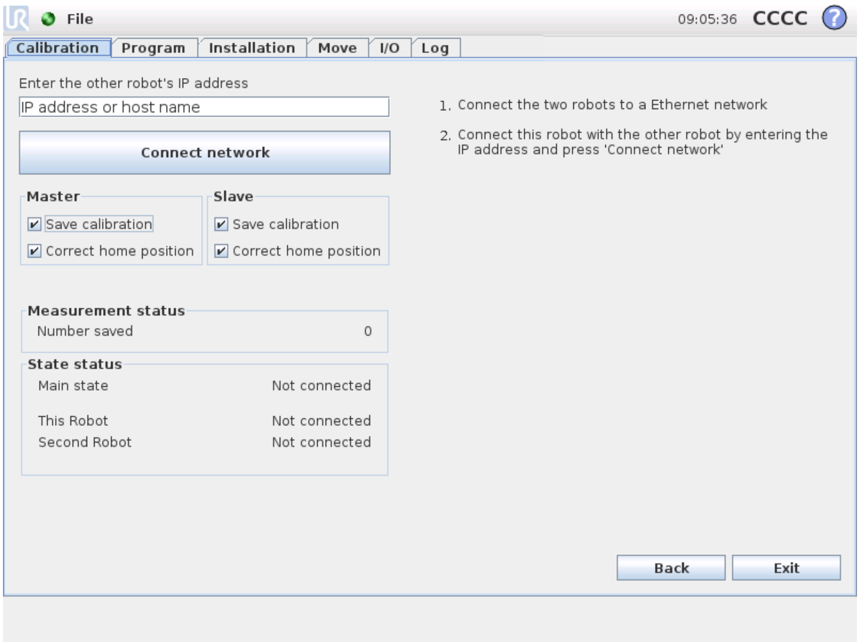

Figure 2.12: Manual enter IP address

2.6 Before starting

The steps through the calibration are by default done automatically, unless it needs help from an operator. This can be disabled by the *Auto step* checkbox, see Figure 2.13.

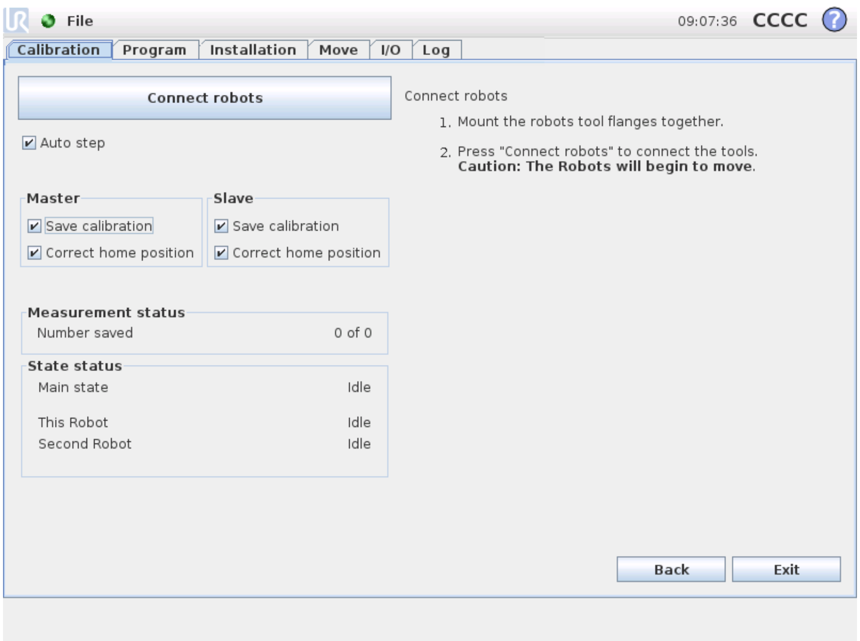

Figure 2.13: Calibration options

Furthermore, It is optional to save and correct the home position of each robot, which can be relevant if only one of the robots need to be calibrated. However it is by default enabled.

Save calibration - means that the calculated kinematic calibration is applied and saved on the robot

Correct home position - means that it estimates and sets the home position using the calibration (define new joint offset angles).

2.7 Mounting the UR Dual Robot Calibration Connector

The robots are now ready to be physically connected if the robots are in their home position, see Figure 2.14.

(11) Ensure that the robots are in the Home position.

(12) Continue the procedure by pressing *Connect Robots*, see 2.15. If the robots are not in home position, a pop-up will ask to move the robot to home (see Figure 2.16), before trying again.

Afterwards the robots will move into position as shown in Figure 2.17, ready to be connected.

Figure 2.14: Robots moved to the home position

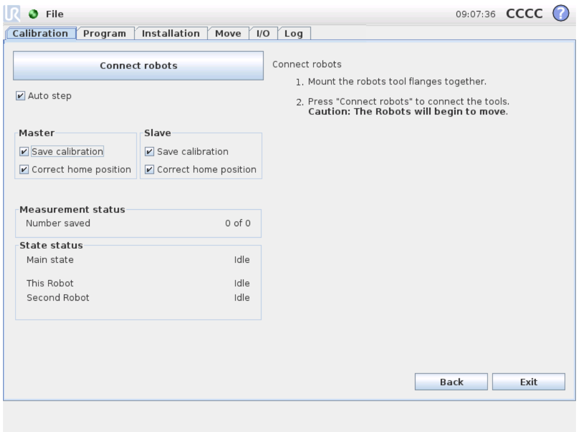

Figure 2.15: Press *Connect robots* to begin connection the robots together, physically

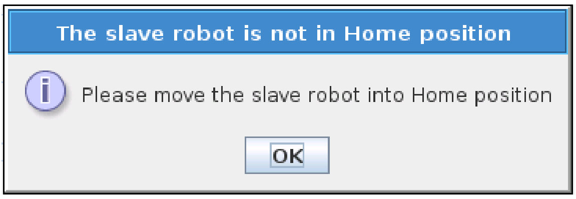

Figure 2.16: Message telling that step no.: 11 was not performed. Press *OK* and move the robot to Home

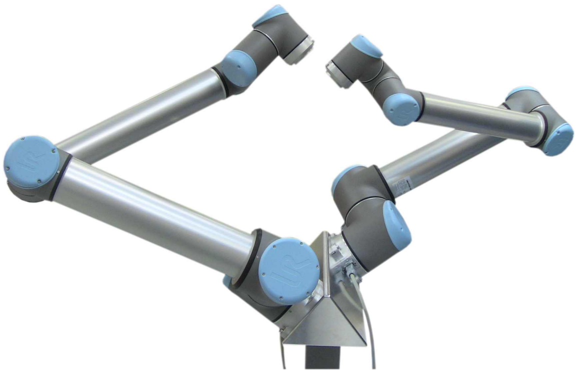

Figure 2.17: Robots ready to be connected

(13) Attach the tool connector to the master robot (Robot 1) as in Figure 2.18.

(14) When the tool is mounted on the master robot (Robot 1), Press *Proceed* in the pop-up Figure 2.19.

(15) The slave robot (Robot 2) now enters free drive mode. Move the slave towards the connector and attach the screws with washers. When done it looks like the fully connected robots shown in Figure 2.20.

(16) When the slave robot (Robot 2) is also mounted on the tool, Press *Proceed* in the pop-up Figure 2.21. This step also starts the robot measuring each other by moving around.

Figure 2.18: Device connected to the master robot

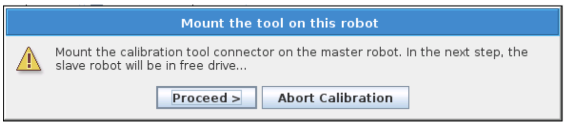

Figure 2.19: *Proceed* when the tool is mounted on the master robot (Robot 1)

Figure 2.20: Robots fully connected

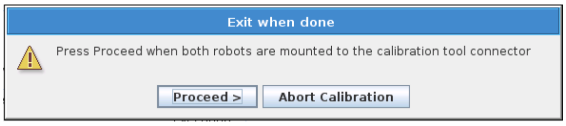

Figure 2.21: *Proceed* when the robots are connected

2.8 Measuring Positions and Calibration Statistics

After step no.: 16, the robot will begin measure and identify the calibration. First a number of initial measurements are collected. A preliminary calibration is calculated from those. Second, the final set of measurements will be done and the final calibration will be calculated, see Figure 2.22 and 2.23.

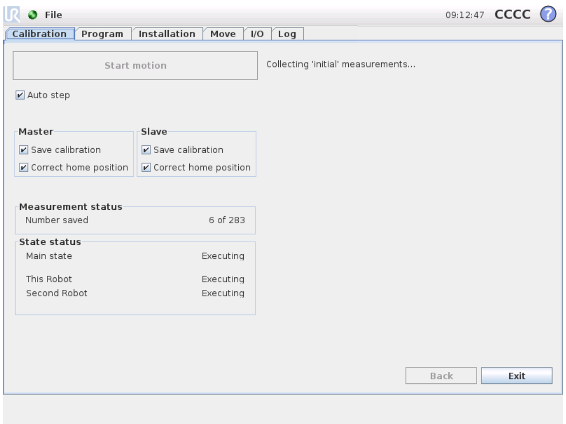

Figure 2.22: Collecting measurements

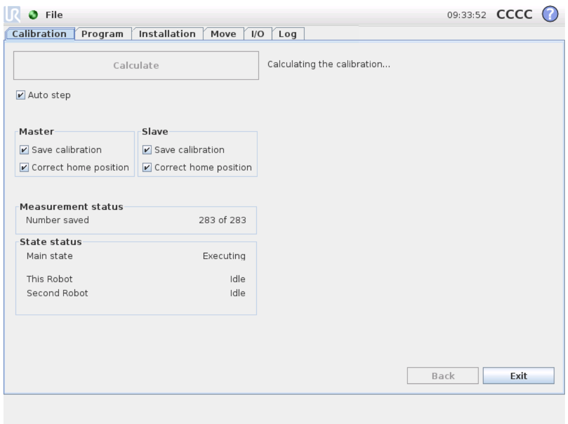

Figure 2.23: Calculating the calibration

Afterwards, a statistic is given that describes whether the found calibration is usable (shown in green, see Figure 2.24) or problematic (shown with red, see Figure 2.25).

If the result was successful as expected and the *Auto step* box is checked, it will automatically continue to step no: 17.

If the result was unsuccessful, the calibration procedure will not be able to continue. Calibration may fail for various different reasons. Please use one or more of the troubleshooting hints listed below and start a new calibration by going back to step 1:

- Check that security settings are set to least restricted (see step 5).
- Remote the tool connector and unmount the robots from the calibration horse. Clean all surfaces on the robots, the calibration horse and the tool connector. Remount the robots while making sure that nothing is stuck between the parts.
- If one or more joints have been replaced, then check that they are mounted correctly. For example, check that the screw washers are on the correct side of the output flange.
- If one or more joints have been replaced, then adjust the joint's zero position (see Service Manual).

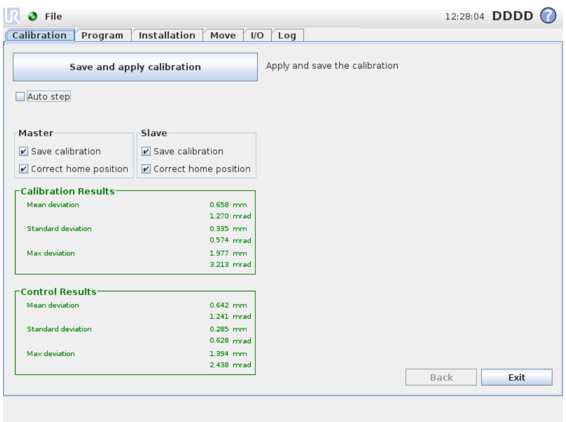

Figure 2.24: Successful calibration

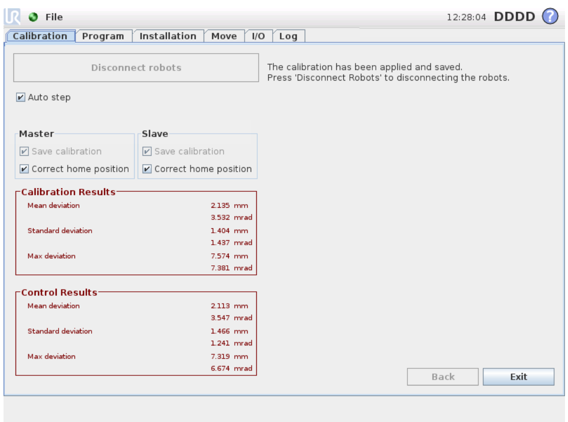

Figure 2.25: Problematic calibration

The section *Calibration Results* contains the statistics for the accuracy of the found calibration. The *Control Results* are statistics for a number of control measurements done throughout the calibration process which only are used to validate the calibration.

The statistics are given in two units a) millimeters (mm) and milliradians (mrad) which refers to the RMS deviation in Cartesian space. The statistics contains the fields:

Mean deviation: The average deviation in millimeters and in milliradians between the positions measured by the first and second robot

Standard deviation: The standard deviation calculated on basis of the above

Max deviation: The maximal measured deviation

Expected results

The calibration is passed successfully if:

- Mean deviation will be less than 1 mm and 2 mrad
- Standard deviation is less than 0.5 mm and 1 mrad
- The different between the Calibration and Control results is not more than 50% different

2.9 Applying the Calibration

After step no: 16 the calibration is applied to the controller and saved to be used in the future. The robots are now ready to be disconnected.

(17) A pop-up appears as shown in Figure 2.26. Dismount the screws from the connector and press *Proceed*. If the *Auto step* box is checked, the robots will continue with correcting the robots' *home position*.

Figure 2.26: Remove screws

2.9.1 Validation

Next follows a validation procedure. Here both robot tool flanges need to be completely free from e.g. screws and alignment pins.

(18) Remove the Calibration Tool Connector and alignment pins etc. and *Proceed* with the validation, see Figure 2.28. The robots TCP will now approach one another.

(19) Verify that the distance in-between the robot tools is within a distance of 2.5 mm ±0.5 mm using the *Go* and *No Go* tools, see Figure 2.29.

 (a) Verify that the 2 mm *Go* tool **can** pass in-between the two robot's tool flanges (Figure B.3, Appendix B)

 (b) Verify that the 3 mm *No Go* tool **can not** pass in-beween the two robot's tool flanges (Figure B.4, Appendix B)

(20) If the verification is successful in step no. 19, *Proceed* to the next validation step, see Figure 2.30.

Figure 2.27: Robots ready for the validation procedure

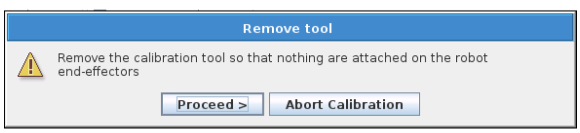

Figure 2.28: *Proceed* to the Verification procedure when the Calibration Tool Connector, screws, and alignment pins are removed from the robots tool flange

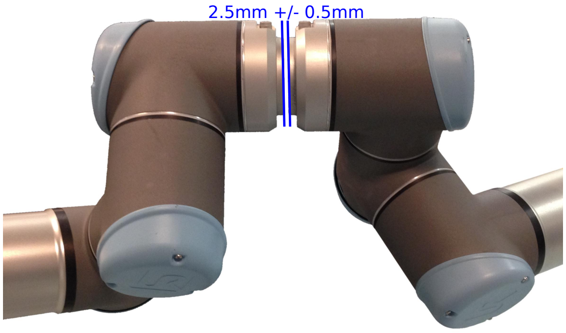

Figure 2.29: Verification by alignment of tools

Figure 2.30: *Proceed* if the verification in step no. 19 is successful

Secondly the robots will move to their new calibrated home position. Here it is important that the robots are fully stretch out and that the tools are pointing in the right direction, like in Figure 2.31. After completion of step no. 22 the Dual Robot Calibration procedure has been completed, see Figure 2.33

(21) Verity the robot home positions, see 2.31.

(22) If the verification is successful in step no. 21, *Proceed* to the next validation step, see Figure 2.32.

(23) Calibration done, press *Exit*, see Figure 2.33.

Figure 2.31: Verify the robots new home position

Figure 2.32: *Proceed* if the verification in step no. 21 succeed

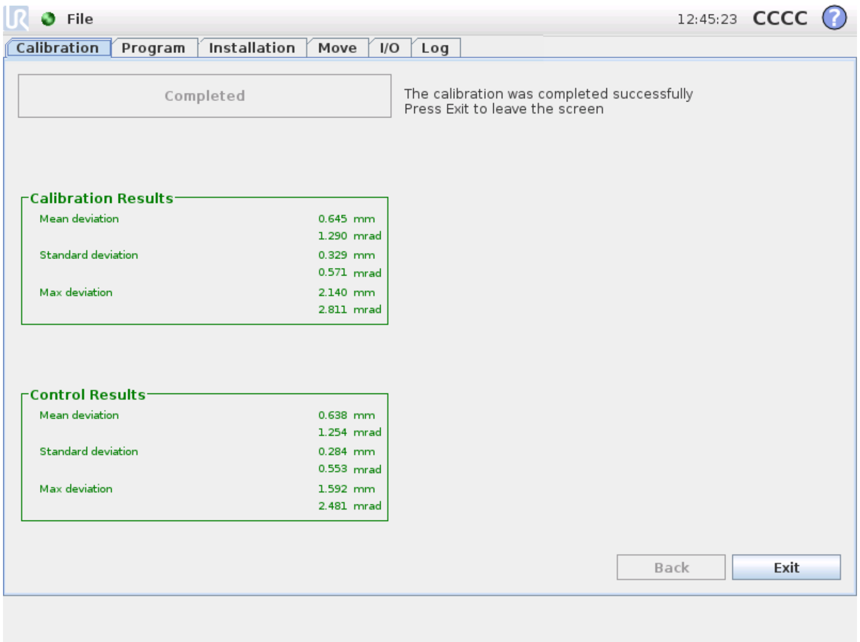

Figure 2.33: Kinematic Calibration is done

2.9.2 Reset Calibration

The calibration can manually be adjusted or reset by editing the */root/.urcontrol/calibration.conf* file placed together with the other configurations. To reset the calibration all decimal and hex numbers is reset to zero like in Listing 1.2 in page 10.

3 Program Correction by Key-waypoints

This tutorial describes how to perform an automatic program correction of key-waypoints, so that a program can be moved from an uncalibrated robot to another and still work. The technique can also be used to make programs work after e.g. replacements of joints in a robot.

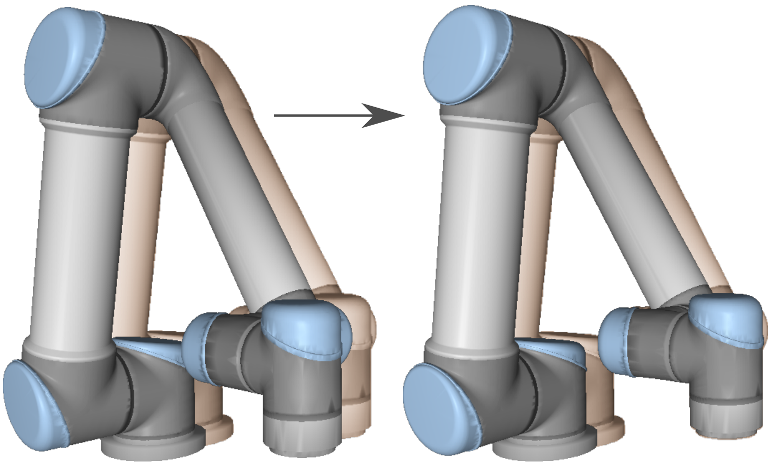

Figure 3.1: Illustration of the correction

The functionality is available on Universal Robot controllers with software version 1.7, 1.8, 3.3 and onwards.

3.1 Introduction

NOTE:

Before starting with program correction, backup your original program e.g. by saving it under a new name. Once a program has been corrected and subsequently saved again, it cannot be corrected again.

With properly selected and redefined key-waypoints, it is possible to make a model which describes the difference between the old and the new robot. After the model has been built, the programs are corrected when loaded. The model can be extended/improved at any time by defining more key-waypoints. The model is specific for each installation file on the robot.

The quality of the model is determined by the number of key-waypoints and the accuracy with which they are defined. If further correction is desired, the model can be improved by adding more key-waypoints at a later time.

The accuracy of a corrected waypoint correlates with the quality of the model, and the distance to the nearest key-waypoint.

Note that currently the program correction functionality does not support the following:

- Other types of waypoints besides fixed waypoints
- Waypoints contained in the "BeforeStart" program node
- A "Move" node which has a selected feature for the motion (different from the "Base" feature)
- A "Move" node which sets a selected TCP for the motion.

The unsupported program nodes mentioned above might need to be corrected manually after the automatic correction process has completed.

3.2 Accessing the Functionality

The starting point for the tutorial steps are as follows:

(1) From *Expert Mode* on the controller screen enable calibration by toggling the "Kinematics Calibration" button.

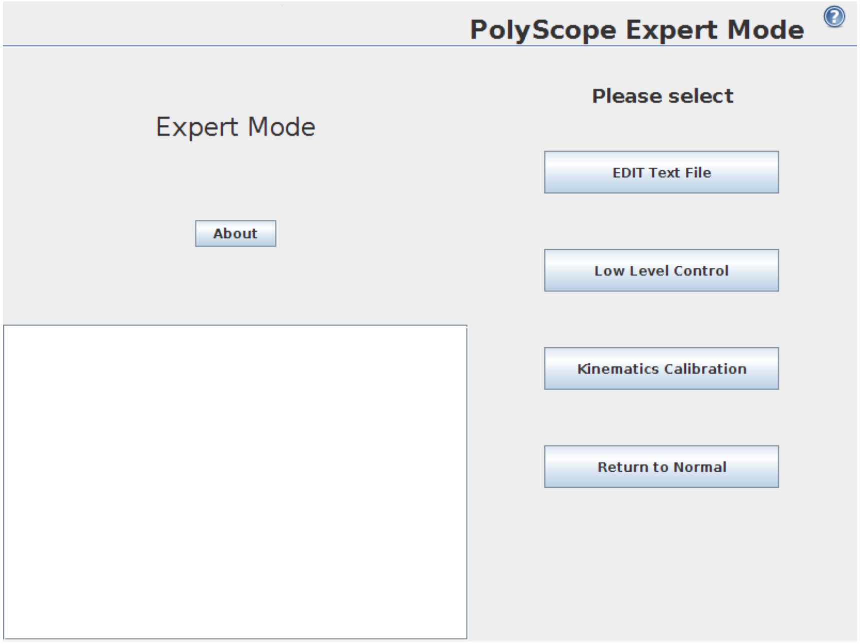

Figure 3.2: Select "Kinematics Calibration" in "Expert Mode" to enable the calibration functionality.

(2) This takes you to the Calibration screen. It also enables a new button called "Calibrate robot" on the "Welcome screen", should you need to return to the Calibration screen at a later time. Clicking the "Kinematics Calibration" button again removes the new button from the "Welcome" screen.

(3) The next screen contains a new tab called "Calibration". This tab offers three options. Chose "Program correction - by key-waypoints".

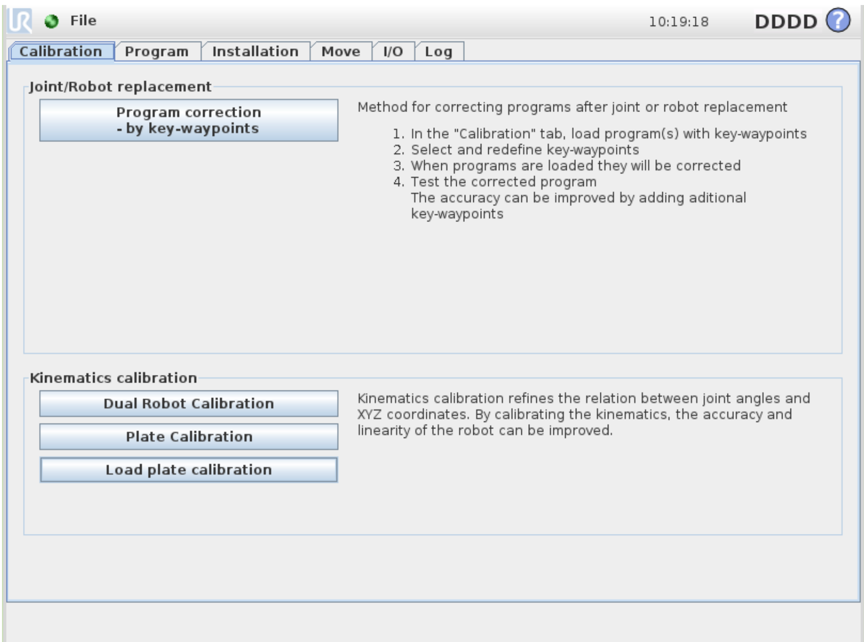

Figure 3.3: Select "Program correction–by key-waypoints".

3.3 Redefine Key-waypoints

The program used in this tutorial is a simple pick and place program with two key-waypoints, the waypoint for the pick and place positions.

(4) The chosen program can now be loaded by pressing "Load Program":

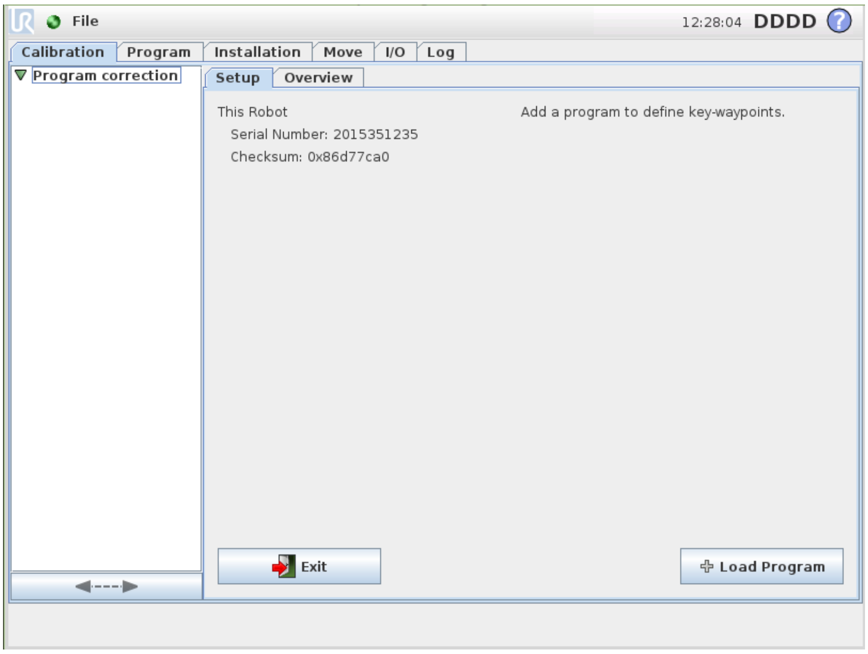

Figure 3.4: Select "Load Program" to import a program.

(5) Select one of the decided key-waypoints in the program. The waypoint called "pick" is selected:

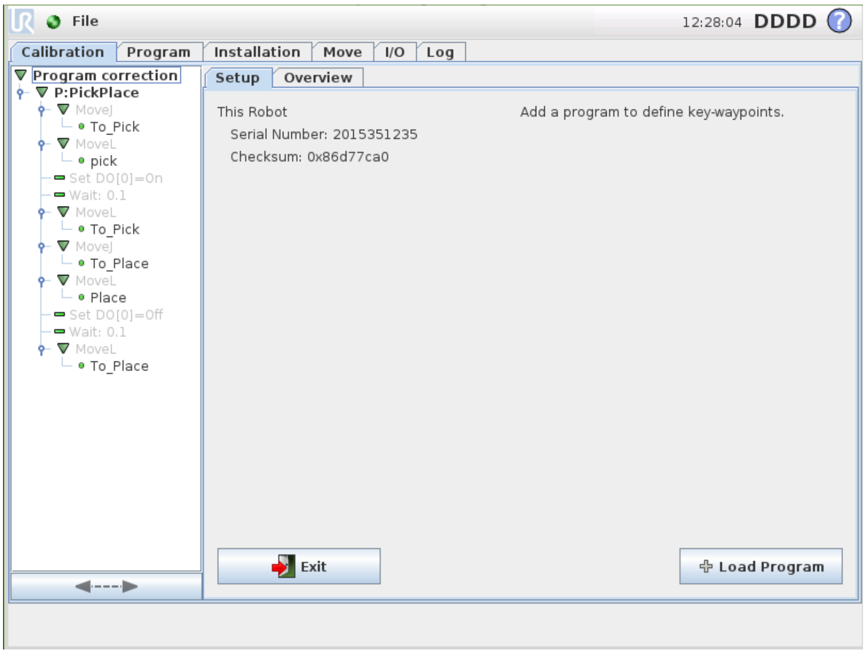

Figure 3.5: Select one of the key-waypoints. In this case waypoint named "pick"

(6) Press "New configuration" to redefine the configuration for the selected waypoint:

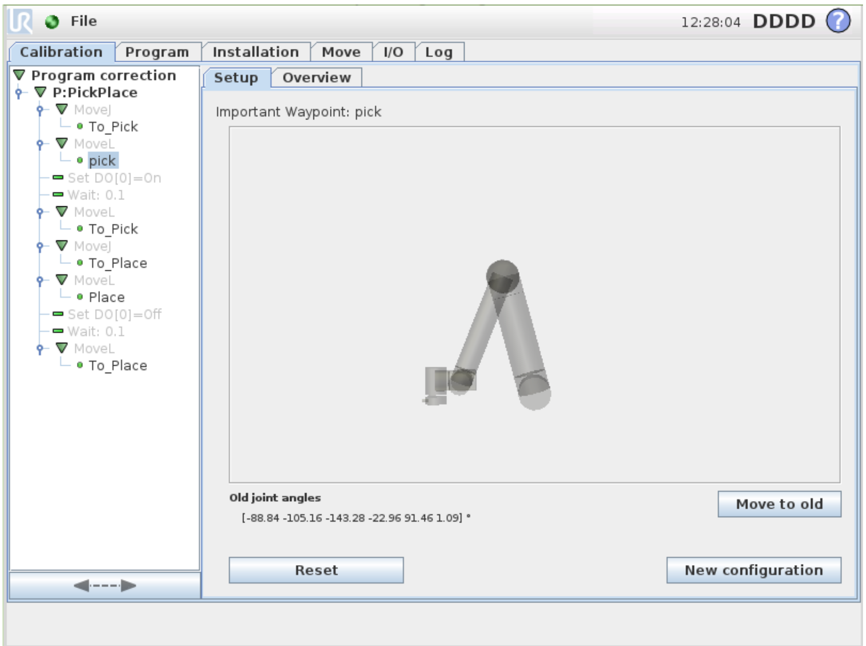

Figure 3.6: Select "New configuration" to redefine the configuration for this waypoint.

(7) This leads to the "Move" tab. Move the robot to the new position and press "OK".

3.3.1 Corresponding Tool Position

To help the method, it is important to adjust the Corresponding Tool Position (CTP) which is the offset from the endpoint of the robot with or without e.g. picked objects. Examples of typical CTP locations:

- The tool center point where the robot is going to pick an object.
- The end location of the object where the object is going to be placed.

This value is used in the process that redefines the waypoint. The CTP can be defined individually for each key-waypoint which improves the accuracy of the correction. The selected Tool Center Point (TCP) from the program installation is used as default.

(8) Specify the Corresponding Tool Position by pressing "Change CTP":

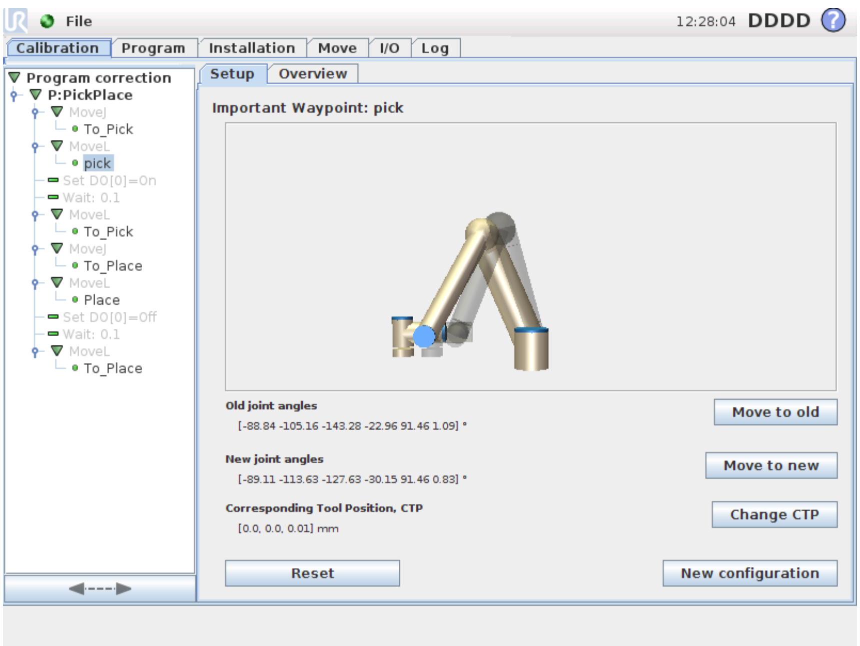

Figure 3.7: Press "Change CTP" and change the Corresponding Tool Position.

(9) Change the CTP coordinates and press OK:

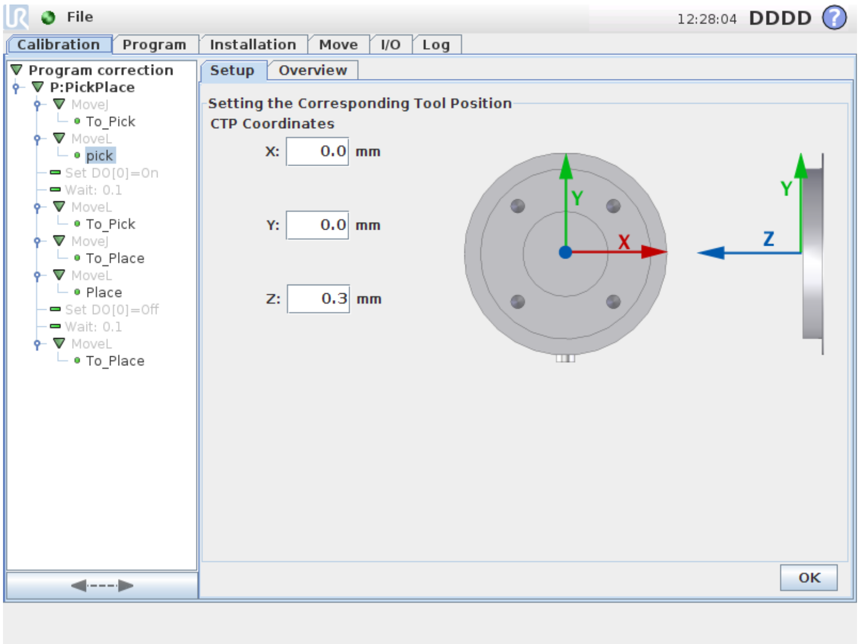

Figure 3.8: Change the CTP coordinates and press OK

(10) This completes redefining the "pick" key-waypoints. Continue by repeating step 5 to 9 until all key-waypoints are redefined.

3.3.2 Waypoints from Multiple Programs

It is possible to add key-waypoints from multiple programs. This is done by adding additional programs and afterwards select and redefine as previously described in step 4 to 10.

(11) If the key-waypoints are distributed over multiple programs, select the root node of the program tree and press "Load Program" and repeat from step 4:

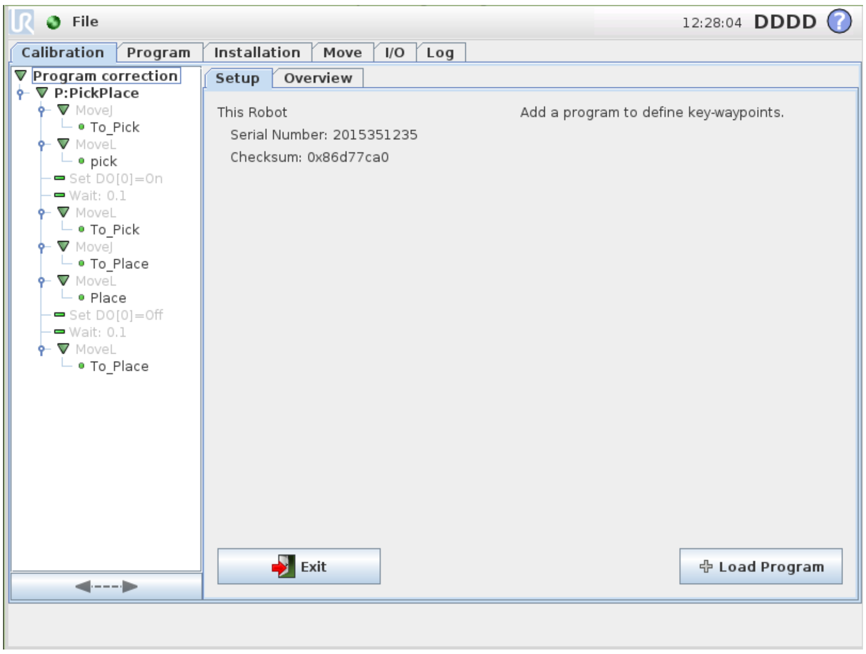

Figure 3.9: Add an additional program by pressing "Load Program" and repeat from step 4.

3.4 Handling Key-waypoints

An overview of the redefined key-waypoints is showed in the "Overview" tab, see Figure 3.10. The key-waypoints are grouped by the source robot's relationship to this robot and installation. Each key-waypoint is marked with its name and the program it is coming from as shown in Figure 3.10 and 3.11. It is possible to delete key-waypoints from the model by selecting a waypoint or a group of waypoints and press "Delete".

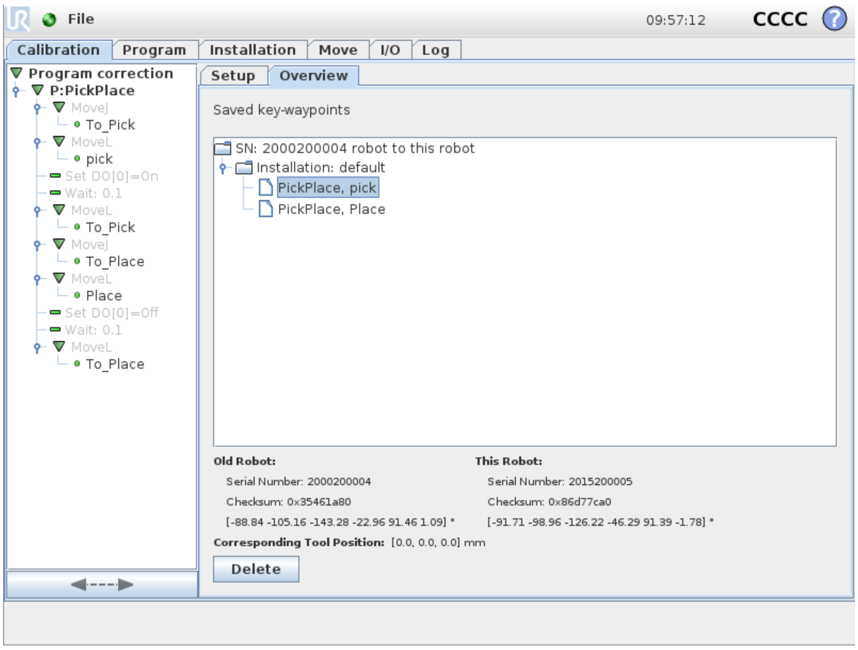

Figure 3.10: The overview tab

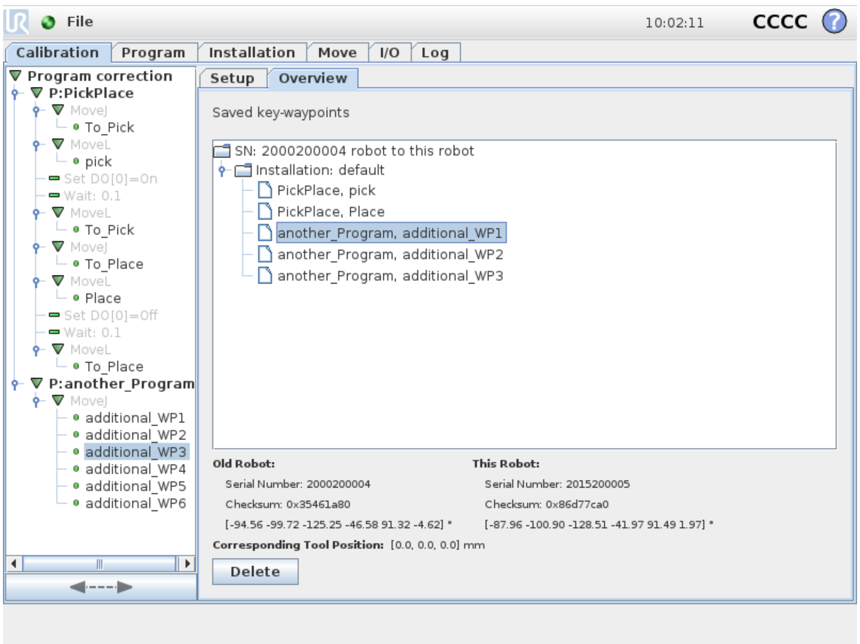

Figure 3.11: Waypoints from multiple programs can be added and displayed in the "Overview" tab

3.5 Correcting a Program

After the key-waypoints are redefined, the programs can be corrected during a normal program loading.

(12) Load the program to be corrected from the "Program" tab or the top "File" menu.

(13) The robot controller realizes that the program comes from a different robot and asks whether you want to correct the program. To correct the program press "yes" (see Figure 13).

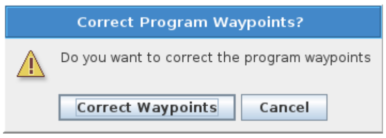

Figure 3.12: Load the program which are going to be corrected

(14) Another popup tells when the correction is done. As the correction can take some time, please be patient. If the correction failed, please verify your key-waypoints and improve their accuracy.

(15) After the program is corrected **and before saving**, it is recommended that:

- it is tested by letting the robot move through its waypoints, by playing the program or by selecting waypoints individually and using the "Move robot here" functionality.
- you save it under a new name. **Note, that once a program that is corrected has been saved, it is overwritten and cannot be corrected again.**

If a better accuracy is needed, add additional key-waypoints to the model and repeat from step 12.

(16) Save the program when the program is tested and it works as intended.

(17) Correct other programs by repeating from step 12.

A Calibration Plate

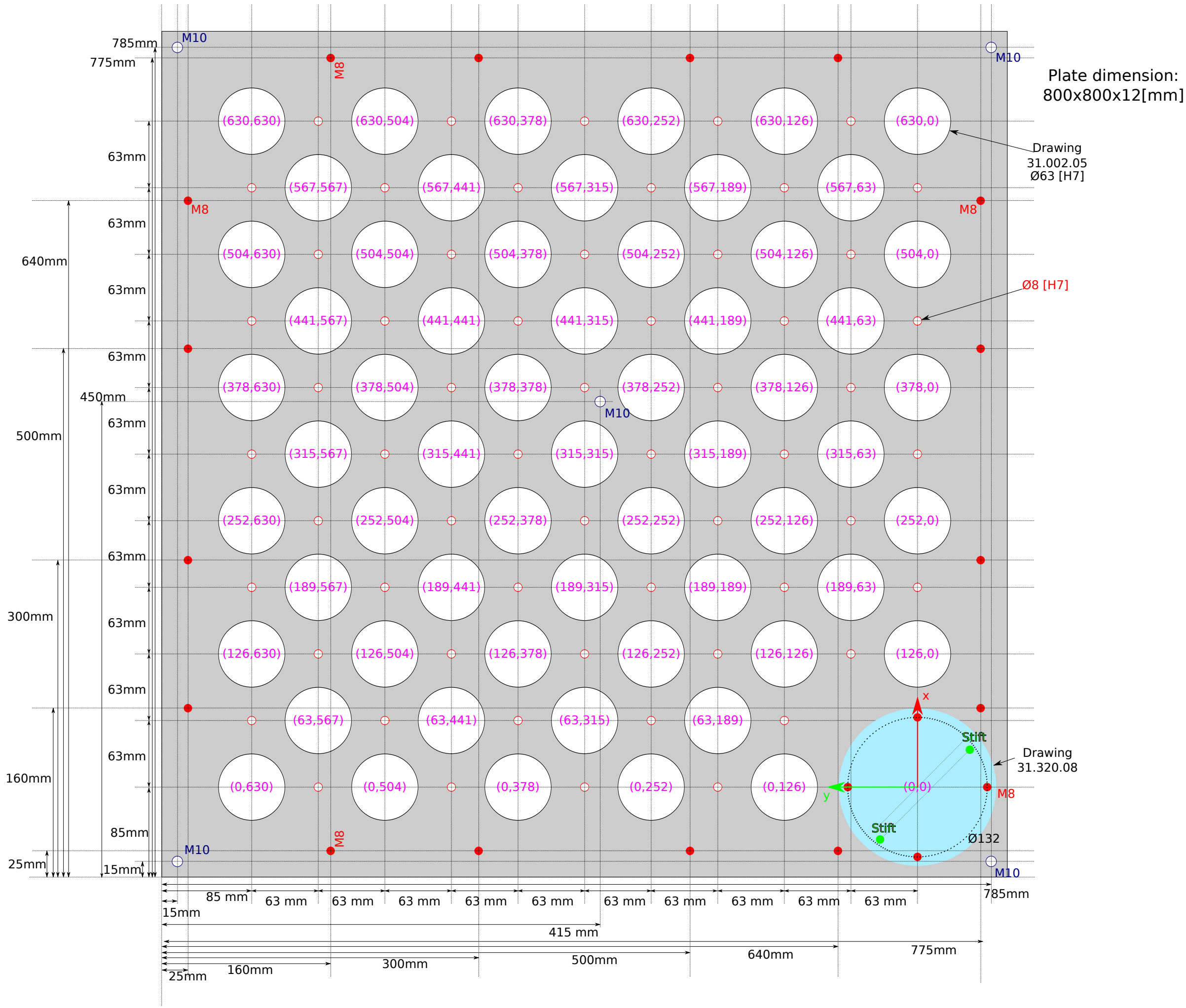

Figure A.1: Drawing of the calibration plate.

B Dual Robot Tools

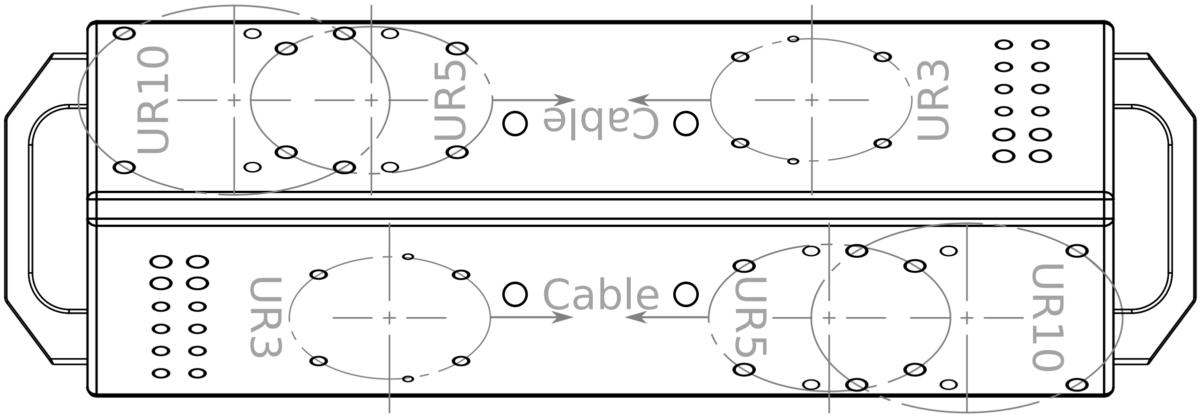

Figure B.1: A sketch of the Dual Robot Calibration Horse

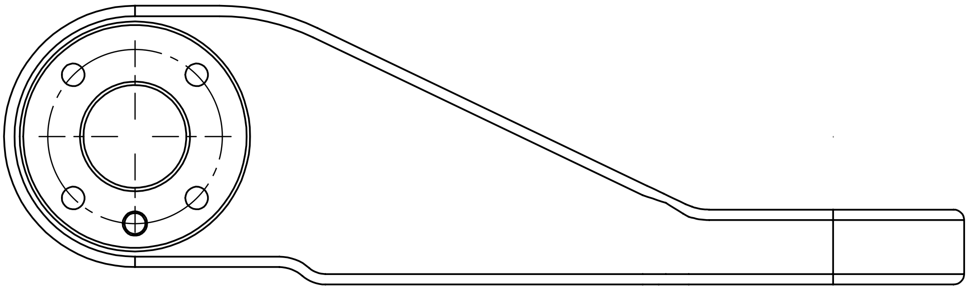

Figure B.2: A sketch of the Dual Robot Calibration Tool Connector

Figure B.3: *Go* tool used in the validating procedure (2 mm thickness)

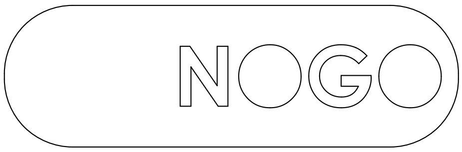

Figure B.4: *No Go* tool used in the validating procedure (3 mm thickness)

C Robot DH Parameter

The robots kinematic transformations for each link are given by Denavite-Hartenberg(DH) parameters.

C.1 UR3

	$\boldsymbol{\theta}\,[rad]$	$\boldsymbol{a}\,[m]$	$\boldsymbol{d}\,[m]$	$\boldsymbol{\alpha}\,[rad]$
Joint 1:	0	0	0.118	$\frac{\pi}{2}$
Joint 2:	0	−0.2437	0	0
Joint 3:	0	−0.2133	0	0
Joint 4:	0	0	0.1124	$\frac{\pi}{2}$
Joint 5:	0	0	0.0854	$\frac{-\pi}{2}$
Joint 6:	0	0	0.0819	0

Table C.1: Denavit-Hartenberg parameters for the UR3 robot

C.2 UR5

	$\boldsymbol{\theta}\,[rad]$	$\boldsymbol{a}\,[m]$	$\boldsymbol{d}\,[m]$	$\boldsymbol{\alpha}\,[rad]$
Joint 1:	0	0	0.08920	$\frac{\pi}{2}$
Joint 2:	0	−0.42500	0	0
Joint 3:	0	−0.39243	0	0
Joint 4:	0	0	0.10900	$\frac{\pi}{2}$
Joint 5:	0	0	0.09300	$\frac{-\pi}{2}$
Joint 6:	0	0	0.08200	0

Table C.2: Denavit-Hartenberg parameters for the UR5 **serie 1**

	$\boldsymbol{\theta}\,[rad]$	$\boldsymbol{a}\,[m]$	$\boldsymbol{d}\,[m]$	$\boldsymbol{\alpha}\,[rad]$
Joint 1:	0	0	0.08920	$\frac{\pi}{2}$
Joint 2:	0	−0.42500	0	0
Joint 3:	0	−0.39225	0	0
Joint 4:	0	0	0.11000	$\frac{\pi}{2}$
Joint 5:	0	0	0.09475	$\frac{-\pi}{2}$
Joint 6:	0	0	0.08250	0

Table C.3: Denavit-Hartenberg parameters for the UR5 **serie 2**

	$\boldsymbol{\theta}\,[rad]$	$\boldsymbol{a}\,[m]$	$\boldsymbol{d}\,[m]$	$\boldsymbol{\alpha}\,[rad]$
Joint 1:	0	0	0.089159	$\frac{\pi}{2}$
Joint 2:	0	−0.42500	0	0
Joint 3:	0	−0.39225	0	0
Joint 4:	0	0	0.10915	$\frac{\pi}{2}$
Joint 5:	0	0	0.09465	$\frac{-\pi}{2}$
Joint 6:	0	0	0.08230	0

Table C.4: Denavit-Hartenberg parameters for the UR5 **serie 3**.

C.3 UR10

	$\boldsymbol{\theta}\,[rad]$	$\boldsymbol{a}\,[m]$	$\boldsymbol{d}\,[m]$	$\boldsymbol{\alpha}\,[rad]$
Joint 1:	0	0	0.118	$\frac{\pi}{2}$
Joint 2:	0	−0.6127	0	0
Joint 3:	0	−0.5716	0	0
Joint 4:	0	0	0.1639	$\frac{\pi}{2}$
Joint 5:	0	0	0.1157	$\frac{-\pi}{2}$
Joint 6:	0	0	0.0922	0

Table C.5: Denavit-Hartenberg parameters for the UR10 robot