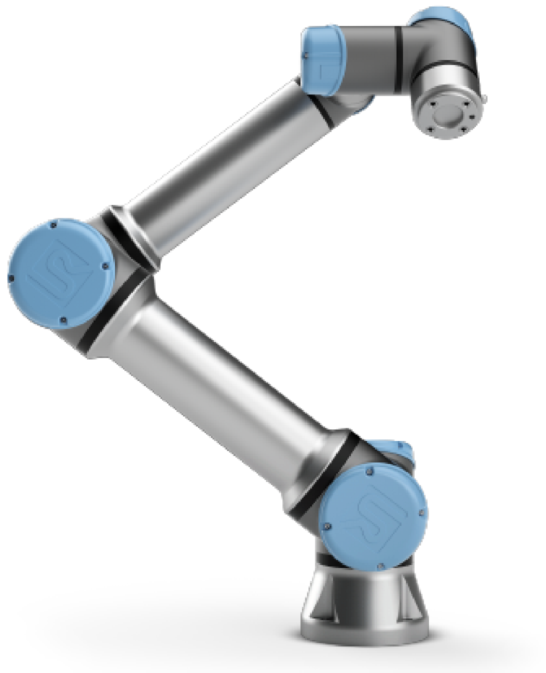
UNIVERSAL ROBOTS

Kinematic Calibration Manual for e-Series



Version 5.8

Contents

1 Plate Calibration

NOTE:

Plate Calibration will not be available in versions of the Calibration Manual after and including Version 5.5

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 implemented on the Universal Robots e-Series robot.

The Dual Robot Calibration method is patent 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 applying the Dual Robot Calibration method.

CAUTION:

Pay attention to the generated statistics of the dual calibration before saving the results. If a calibration is not performed with care, the robot may become inaccurate.

2.1 Required Equipment

The Dual Robot Calibration method requires a Dual Robot Calibration Kit from Universal Robots (purchase number: 185500) and a pair of UR3e, UR5e, or UR10e robots, respectively, with an e-Series 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 are connected, they 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 lengths of the Robot Arm and the robots' link rotations (i.e. the Denavit-Hartenberg parameters).
Note the UR3e and UR10e are mounted differently on the Calibration Horse and their cables point toward each other, as illustrated in Figure 2.2.

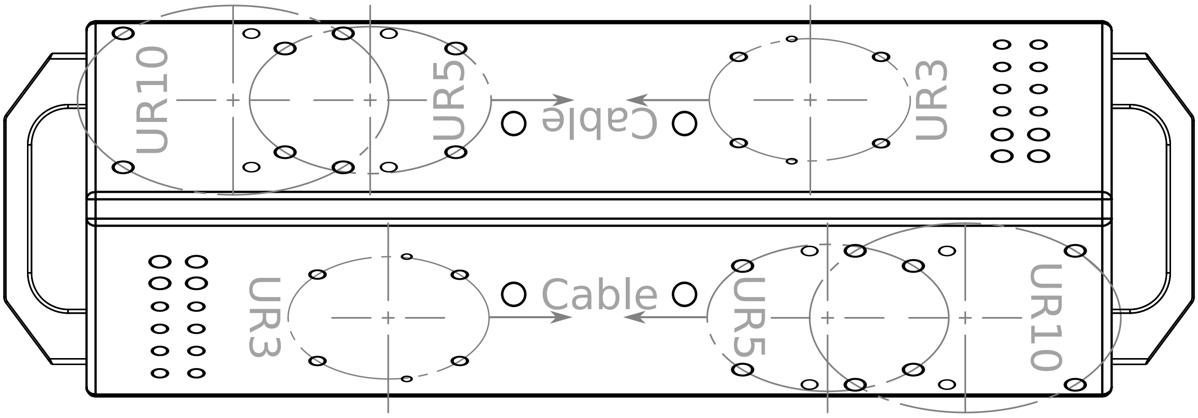


Figure 2.2: The Dual Robot Calibration Horse displaying where the UR3e, UR5e, or UR10e robot can be mounted.

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 UR3e, UR5e, or UR10e 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, which includes:
  - The UR Dual Robot Calibration Horse with alignment pins (Figure A.1, Appendix A)
  - The UR Dual Robot Calibration Tool Connector with alignment pins (Figure A.2, Appendix A)
  - 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 UR5e and UR10e 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 UR3e robots to the Calibration Horse
  - One *Go* tool used in the validating procedure, (Figure A.3, Appendix A)
  - One *No Go* tool used in the validating procedure (Figure A.4, Appendix A)

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) In the PolyScope Header, tap the **Installation Tab**.

(4) Also in the PolyScope Header, tap New and select Installation.

(5) Under General set the mounting and angle to 90 degrees for each robot and tap Exit (see Figure 2.4):

UR3e:

(a) The *Tilt* is approximately $52,5° \pm 5°$ and

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

UR5e and UR10e:

(a) The *Tilt* is approximately $52,5° \pm 5°$ and

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

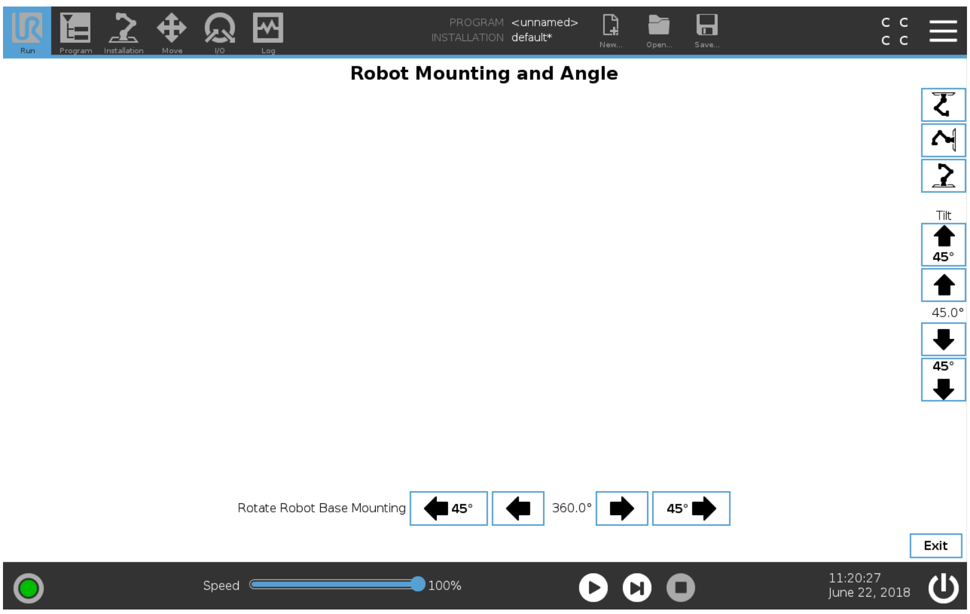


Figure 2.4: Mounting the robot

2.3 Safety Settings of the Robots

(6) In the Side Menu on the left, tap **Safety** and select **Robot Limits**.

(7) Enter your safety password to unlock Safety Configuration.

(8) Set Factory Presets to **Least Restricted** and tap **Apply** (see Figure 2.5).

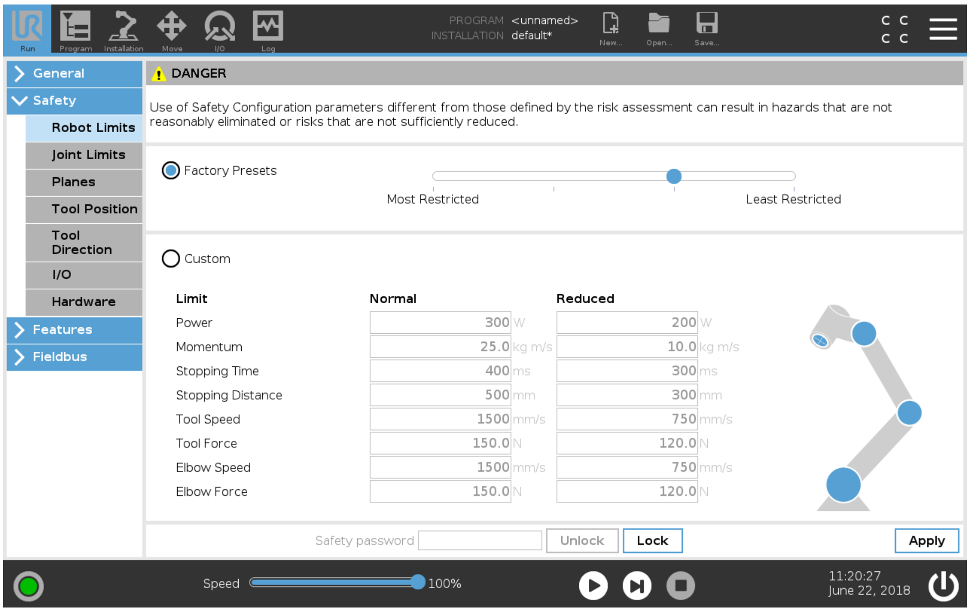
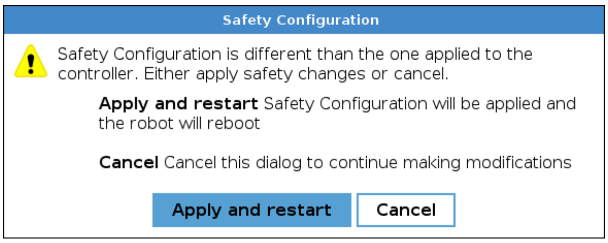


Figure 2.5: Safety settings

(9) When the Safety Configuration dialog box appears, select **Apply and restart**.



2.4 Accessing Dual Robot Calibration

(10) In the Header, hold down the Run Tab to access **Expert Mode**. See Figure 2.5.

(11) Enter **lightbot** and tap **OK**.

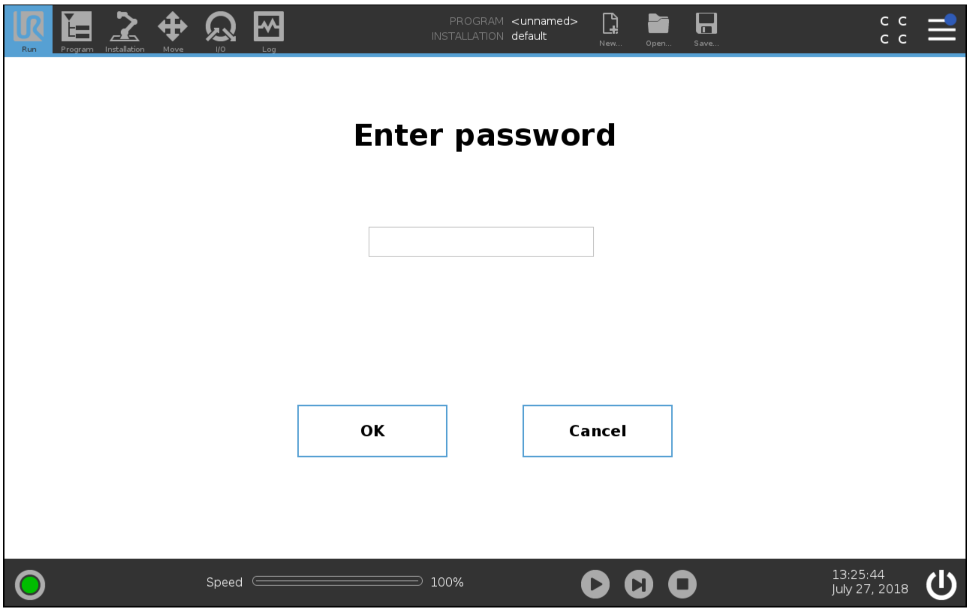


Figure 2.6: Entering **Expert Mode** requires a password

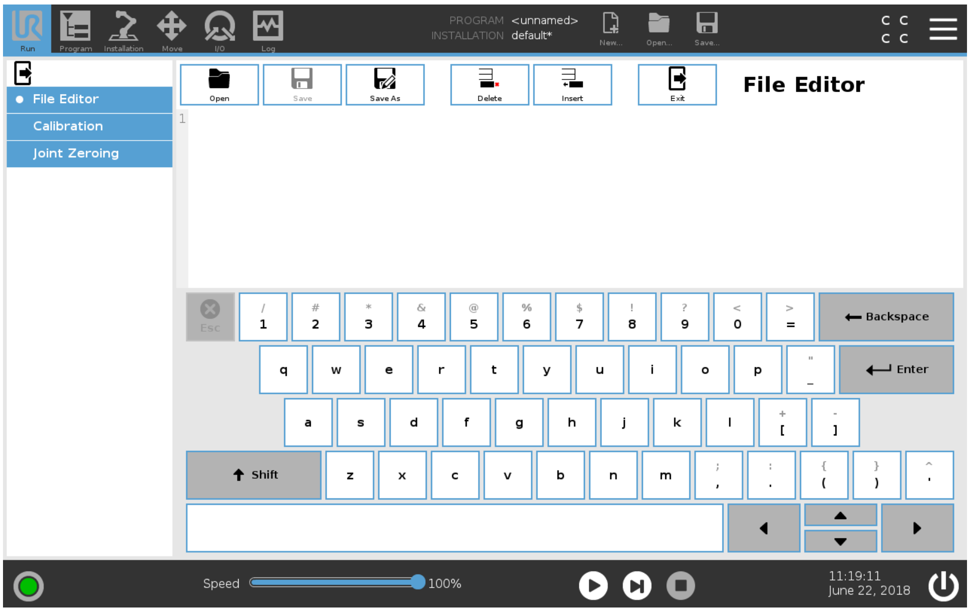


Figure 2.7: Select **Calibration** in **Expert Mode**.

(12) In the Side Menu on the left, tap **Calibration**. See Figure 2.7.

(13) Under **Kinematics Calibration**, select **Dual Calibration**. See Figure 2.8.

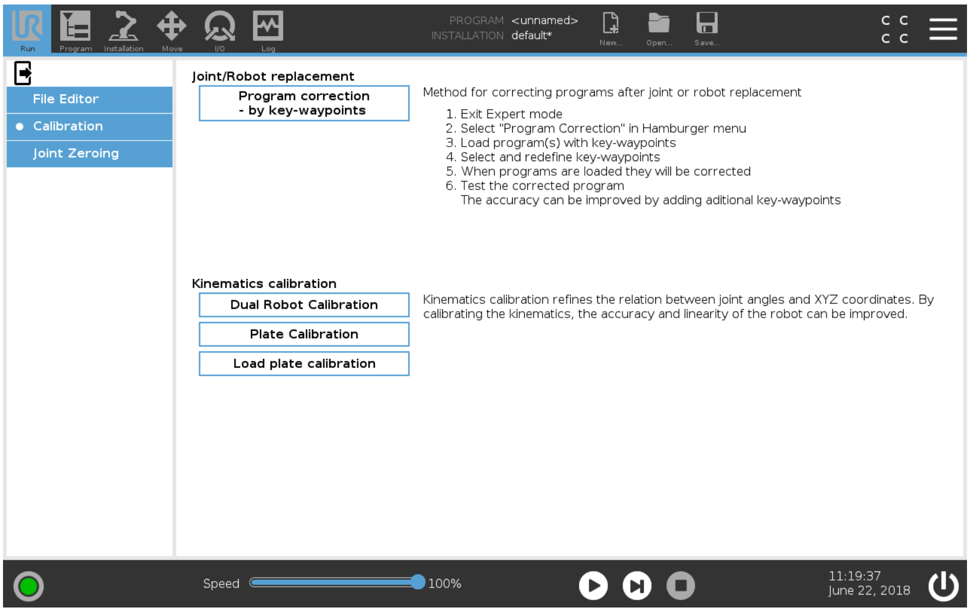


Figure 2.8: Select **Dual Robot Calibration** as the method.

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 main robot in the calibration process. Make sure the other robot is selected as Slave and the two robots are connected with a network cable or switch.
- Slave - The subordinate robot in the calibration process. Make sure the other robot is selected as Master and 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 a user supplied IP-address (see description below).

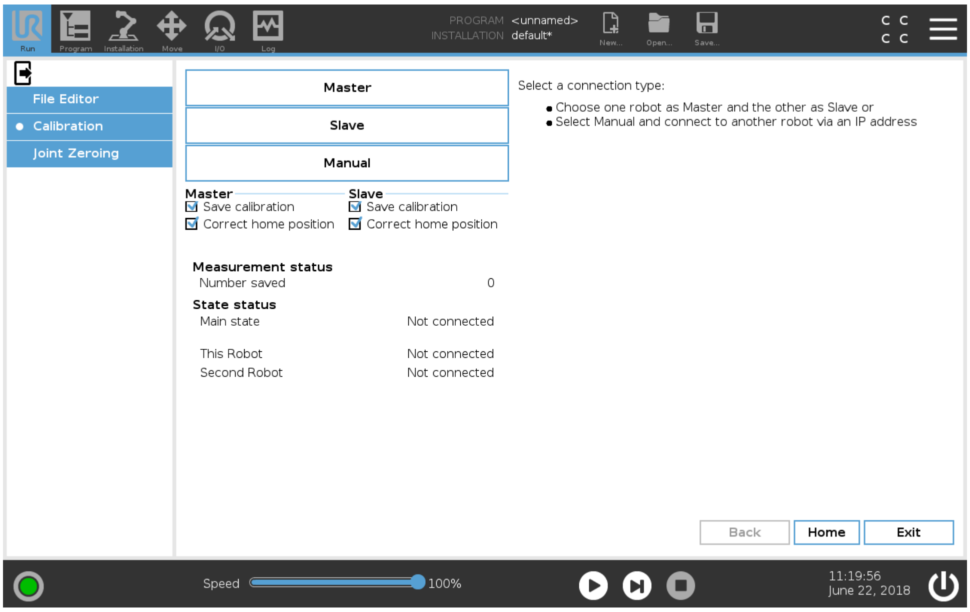


Figure 2.9: Network options in Dual Robot Calibration.

Use the Master/Slave connection or the Manual connection method to establish network connection between the two robots controllers. Robot 1 is the master robot and Robot 2 is the slave.

2.5.1 Master/Slave Connection

(14) Connect two robots via a network cable or using a network switch.

(15) Define one robot as Master and the other as Slave. Selecting one of these cases sets up the IP address automatically.

CAUTION:

The IP-addresses `10.17.17.18` and `10.17.17.19` is used for Master/Slave connections. Connecting the robots to a local area network may interfere with other devices sharing these IP addresses.

(16) When the Slave robot is ready and displays the screen in Figure 2.10, tap **Connect network** on the Master to establish the network connection. See Figure 2.11. The screens that follow are described in Section 2.7.

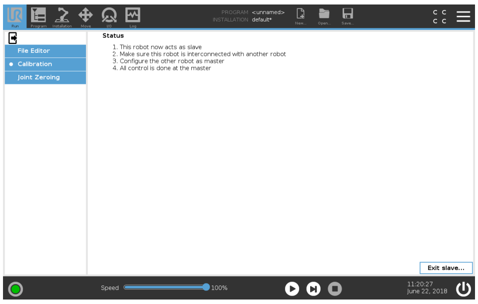


Figure 2.10: Slave Mode

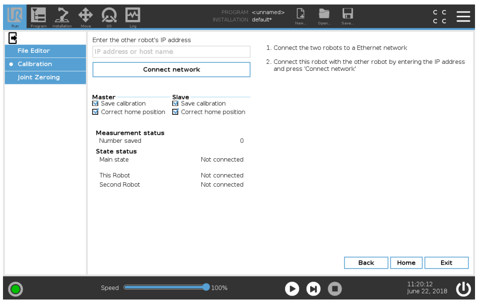


Figure 2.11: Master Mode

NOTE:

Network communication between the Master robot and the Slave robot can break down, causing the calibration screen to change as displayed in Figure 2.12.

Figure 2.12: Network Communication break during calibration

2.5.2 Manual Mode

As a alternate to the Master/Slave method. You can use the Manual Mode method.

(17) In Expert Mode, once Calibration is selected, tap **Manual** to access the screen displayed in Figure 2.13.

(18) Tap the **IP address or host name** text box and enter the IP number or host name of the Slave robot.

(19) Tap **Connect network** to connect.

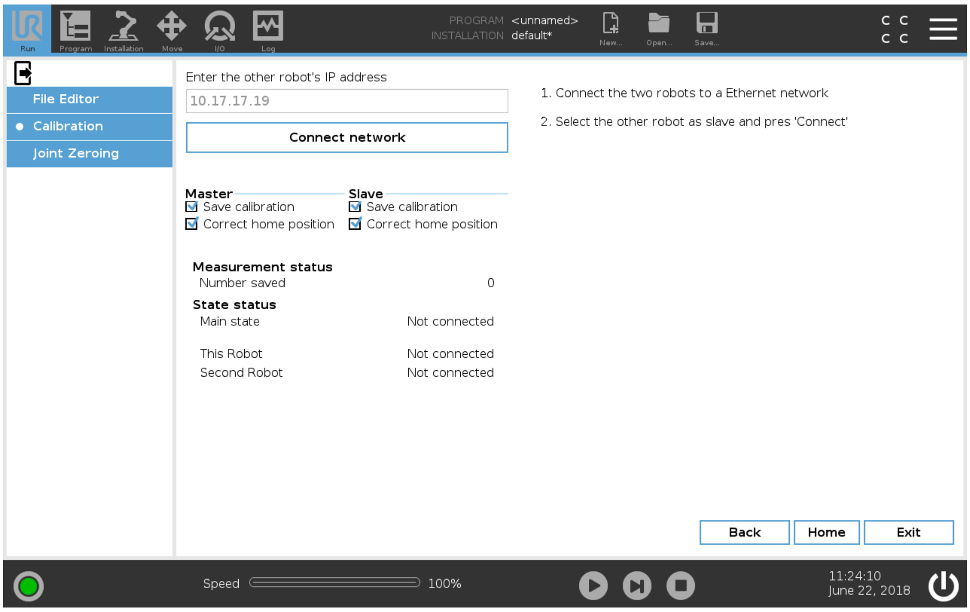


Figure 2.13: Manual enter IP address

2.6 Before Starting

The calibration is performed automatically. If operator intervention is required, disable the **Auto step** check box,(see Figure 2.14).

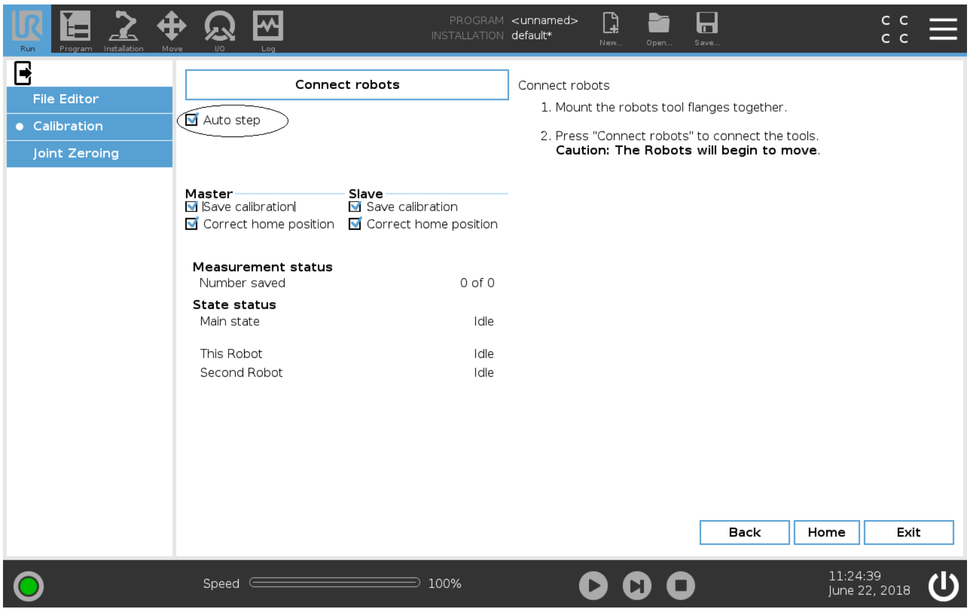


Figure 2.14: Calibration options

You can save and correct the Home Position of each robot which is relevant if one of the robots must be calibrated.

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

Correct home position - 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 2.15).

(20) Ensure the robots are in the Home Position.

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

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

(23) Tap **Connect Robots** (see 2.16). If the robots are not in home position, a pop-up asks to move the robot to Home Position before trying again.

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

Figure 2.15: Robots moved to the Home Position

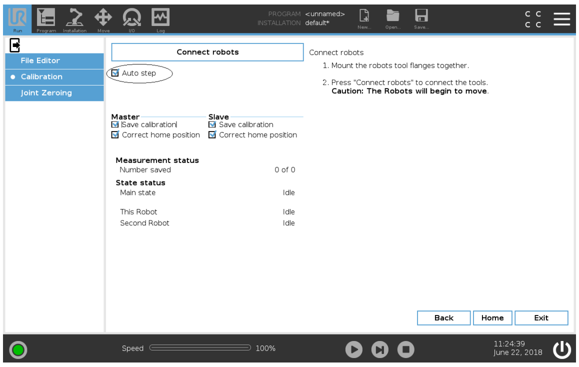


Figure 2.16: Tap **Connect robots** to connect the robots

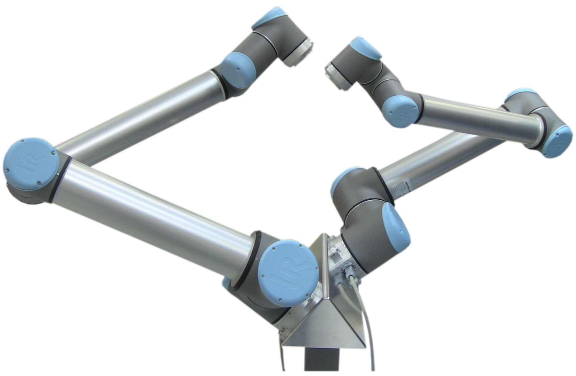


Figure 2.17: Robots are ready to be connected

(24) The Slave robot (Robot 2) enters Free Drive Mode. Move the Slave toward the connector and attach the screws with washers. See Figure 2.20.

(25) after the Slave robot (Robot 2) is also mounted on the tool, tap **Proceed** in the pop-up Figure 2.21. This starts the robot measuring each other by moving around.

Figure 2.18: Device connected to the Master robot (Robot 1)

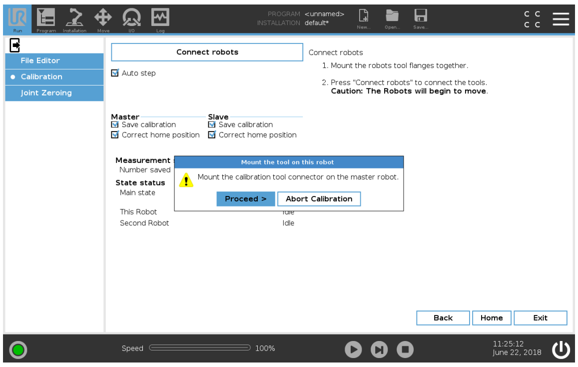


Figure 2.19: *Proceed* when the tool is mounted on the Master robot (Robot 1)

Figure 2.20: Robots are fully connected

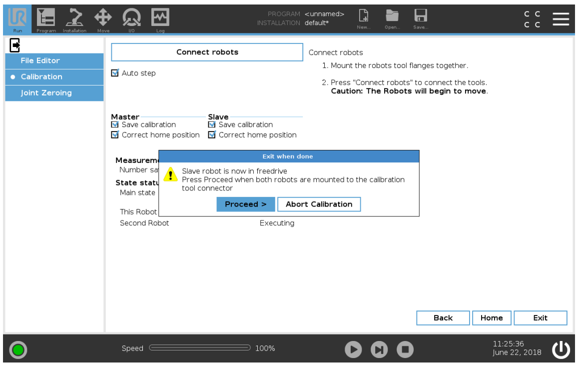


Figure 2.21: *Proceed* when the robots are connected

2.8 Measuring Positions and Calibration Statistics

After step 25, the robot begins to measure and identify the calibration. First, a number of initial measurements are collected. A preliminary calibration is calculated. Second, the final set of measurements is done and the final calibration is calculated, (see Figure 2.22 and 2.23).

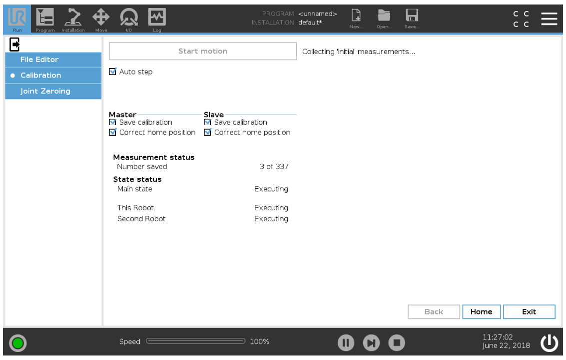


Figure 2.22: Collecting measurements

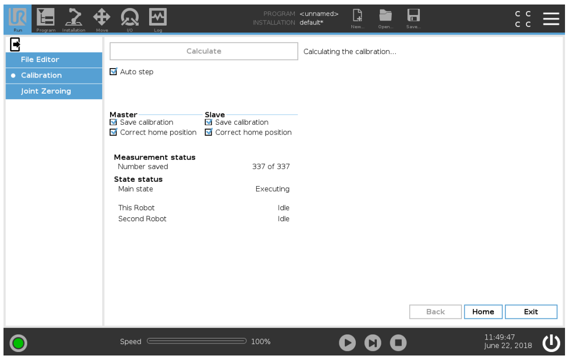


Figure 2.23: Calculating the calibration

Afterward, a statistic is given that describes whether the found calibration is usable (shown in green, in Figure 2.24). If the found calibration is problematic, the Calibration Results appear red.

If the results were successful, and the **Auto step** box is checked, the process automatically continues to Step 26.

If the results were unsuccessful, the calibration procedure will continue. A calibration may fail for various different reasons. Use one or more of the troubleshooting methods listed below and start a new calibration by going back to Step 1:

- Check security settings are set to least restricted, (see Chapter 2.3, Step 8).
- Remove 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, check that they are mounted correctly. For example, check the screw washers are on the correct side of the output flange.
- If one or more joints have been replaced, adjust the joint's zero position (see the Service Manual).

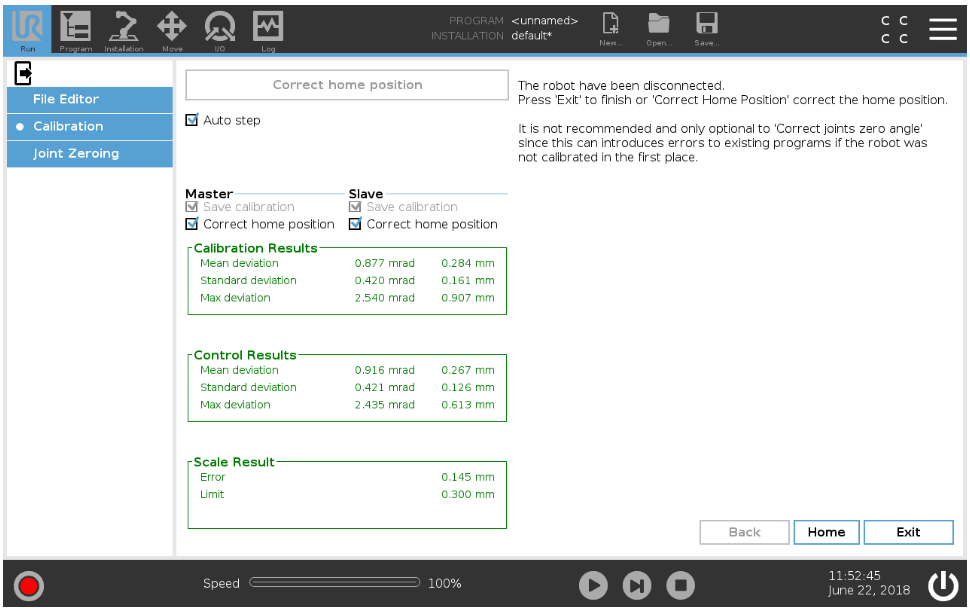


Figure 2.24: Successful calibration

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

The statistics are provided in two units millimeters (mm) and milliradians (mrad) which refers to the RMS deviation in Cartesian Space. The statistics contains the following 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 the basis of the above

Max deviation: The maximal measured deviation

Expected Results

The calibration is successful if:

- The mean deviation is less than 1 mm and 2 mrad
- The standard deviation is less than 0.5 mm and 1 mrad
- The difference between the Calibration and Control results is no more than 50%
- The Error value is less than the Limit value, in the Scale Result.

2.9 Applying the Calibration

After Step 25 the calibration is applied to the controller software. The calibration is permanently saved after succesful validation. Then the robots are ready to be disconnected.

(26) When the **Remove screws** dialog box appears, dismount the screws from the tool connector and tap *Proceed.*. If the *Auto step* box is checked, the robots will continue correcting the Home Position.

NOTE:

If you tap *Proceed* without removing all of the screws from the tool connector on the slave robot, each robot can make a protective stop. To resolve the problem, verify all screws are removed and clear the Protective Stop/s. Once this is done, press *Proceed* again.

CAUTION:

If either robot enters a Protective Stop while disconnecting, you must remove the Tool Connector and jog the robots to separate them manually. Once the robots are separate and the Protective Stop is cleared, the disconnection dialog box reappears on PolyScope and you can retry the step.

2.9.1 Validation

To validate the calibration, both robot tool flanges need to be completely free from e.g. screws and alignment pins.

(27) Remove the Calibration Tool Connector and alignment pins Etc. and *Proceed* with the validation, (see Figure 2.26). The robots TCP will now approach one another.

(28) Verify that the distance in-between the robot tools is within a distance of 2.5 mm ±1 mm using the *Go* and *No Go* tools, see Figure 2.27.

(a) Verify the 1.5 mm *Go* tool **can** pass between the robots tool flanges (Figure A.3, Appendix A)

(b) Verify the 3.5 mm *No Go* tool **can not** pass between the two robots tool flanges (Figure A.4, Appendix A)

(29) If the verification is successful in Step 28, *Proceed* to the next validation step... see Figure 2.28.

Figure 2.25: Robots are ready for the validation proceedure

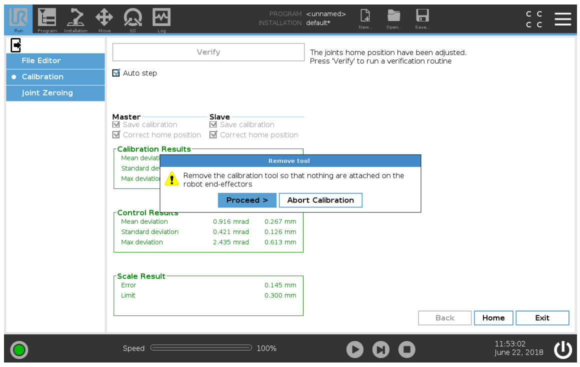


Figure 2.26: *Proceed* to the Verification procedure when the Calibration Tool Connector, screws, and alignment pins are removed from the robots tool flange

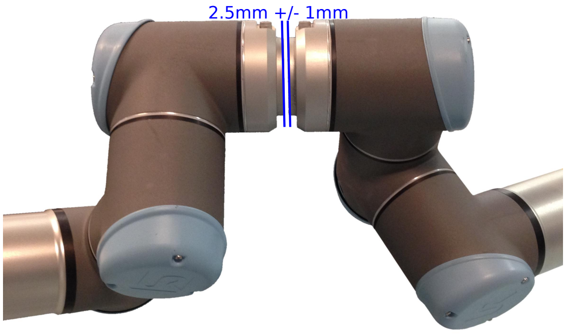


Figure 2.27: Verification by alignment of tools

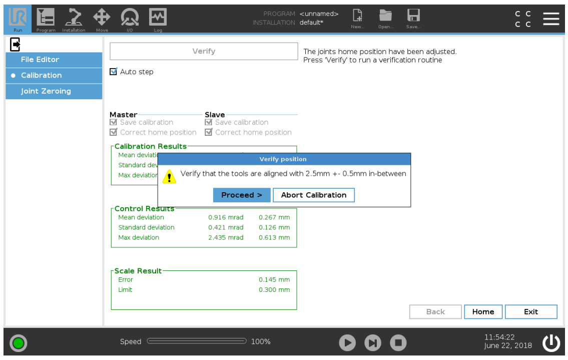


Figure 2.28: *Proceed* if the verification in step 28 is successful

Secondly the robots move to their new calibrated Home Position. It is important that the robots are fully stretched out and the tools are pointing in the right direction, like in Figure 2.29. After Step 31 the Dual Robot Calibration procedure is complete, (see Figure 2.31).

(30) Verify the robots' Home Positions, see 2.29.

(31) If Step 30, tap **Proceed**, (see Figure 2.30).

(32) Save the calibration.

(33) Once the calibration is done,tap **Exit**, (see Figure 2.31).

Figure 2.29: Verify the robots' new Home Position

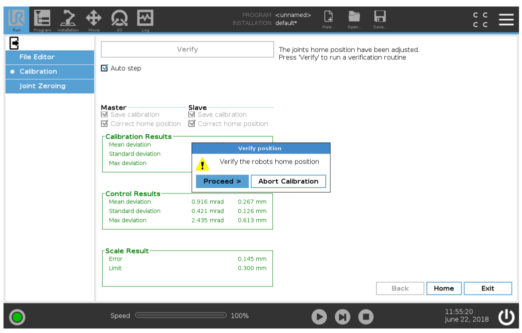


Figure 2.30: Tap **Proceed** if the verification in Step 30 is successful

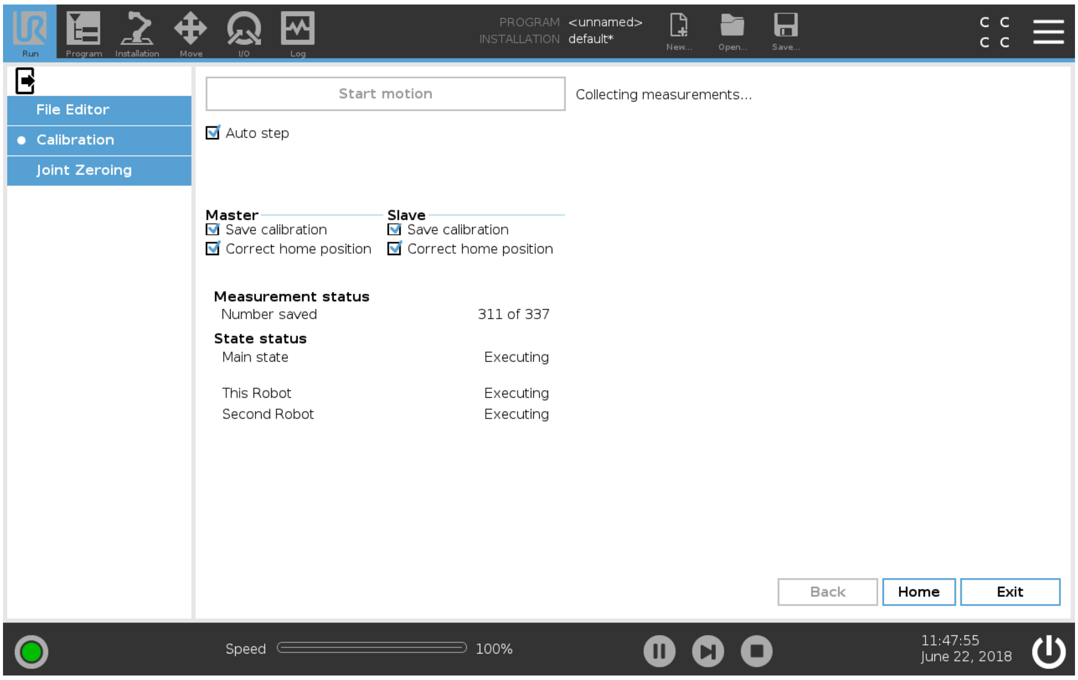


Figure 2.31: Kinematic Calibration is done

(34) Above the Side Menu on the left, tap the arrow to exit **Expert Mode**.

2.9.2 Reset Calibration

```
[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 = [ 0xb86d04a5, 0x8d29526e, 0x21a274b7, 0x5134a655, 0xc44d7e89,
    0x1be4dbeb]
calibration_status = 2 # 0 == notInitialized / 1 == notLinearised / 2 == Linearised
joint_raw_offset = [ 0.1, -.81973522672052201e-05, 3.81973522672052201e-05,
    .81973522672052201e-04, 0, 1.3]
joint_selftest_data_crc = [ 0xfd8c0ed6, 0x9c3bef33, 0xfcca0113, 0x3ddc1b38, 0xad3f2781,
    0x848b8665]
file_save_count = 2
```

Listing 2.1: calibration.conf file filled with zeros

The calibration can manually be adjusted or reset by editing the `/root/.urcontrol/calibration.conf` file placed with the other configurations. Before editing, backup your original calibration file by saving it under a different name.

To reset the calibration, set all numbers in delta arrays to zero and increase `file_save_count` by one. See example in 2.1. Reboot the robot to apply changes.

3 Program Correction by Key Waypoints

This tutorial describes how to perform Automatic Program Correction using key waypoints, so a program works when moved from one uncalibrated robot to another. This technique can also be used after robot joint replacements.

3.1 Introduction

Before starting Automatic Program Correction, backup your original program and save it under a new name. Once a program is corrected and subsequently saved, it cannot be corrected again.

Once properly selected and redefined, key waypoints allow you to make a model describing the difference between the old and the new robot. After the model is 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, the accuracy with which they are defined and distance between key waypoints.

NOTE:

Automatic Program Correction does not currently support the following:

- Other types of waypoints with the exception fixed waypoints
- Move node with Use Joint Angles selected

The unsupported program nodes above may need to be corrected manually after the Automatic Program Correction process is complete.

3.2 Accessing Automatic Program Correction

This tutorial shows how to access and perform Automatic Program Correction.

(1) In the Header, press and hold the Run Tab to access **Expert Mode**.

(2) Enter your password and tap **OK**.

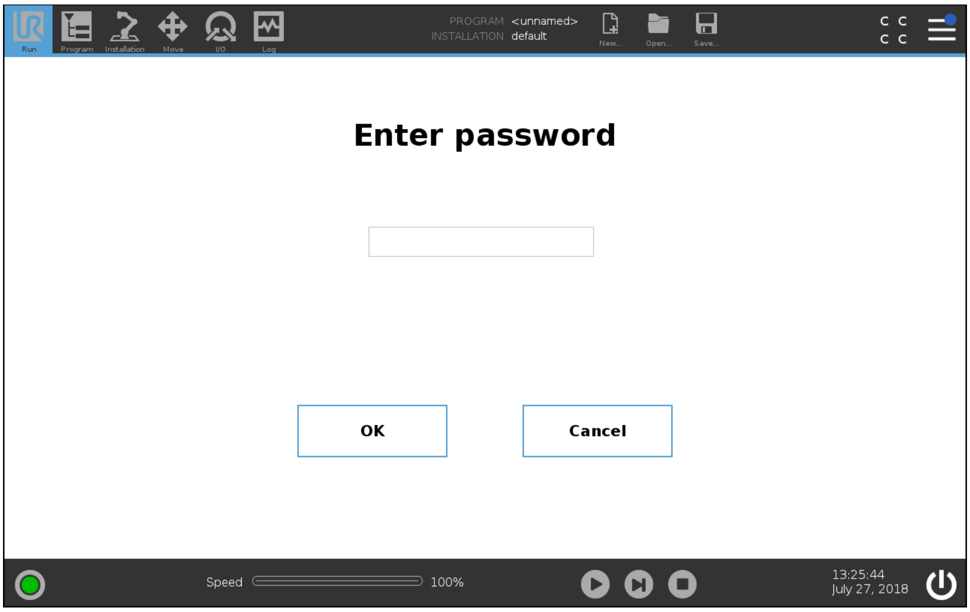


Figure 3.1: Expert Mode screen

(3) In the Side Menu on the left, select **Calibration** and tap **Program correction by key-waypoints**.

(4) Tap the exit button to exit Expert Mode, (see Figure 3.2)

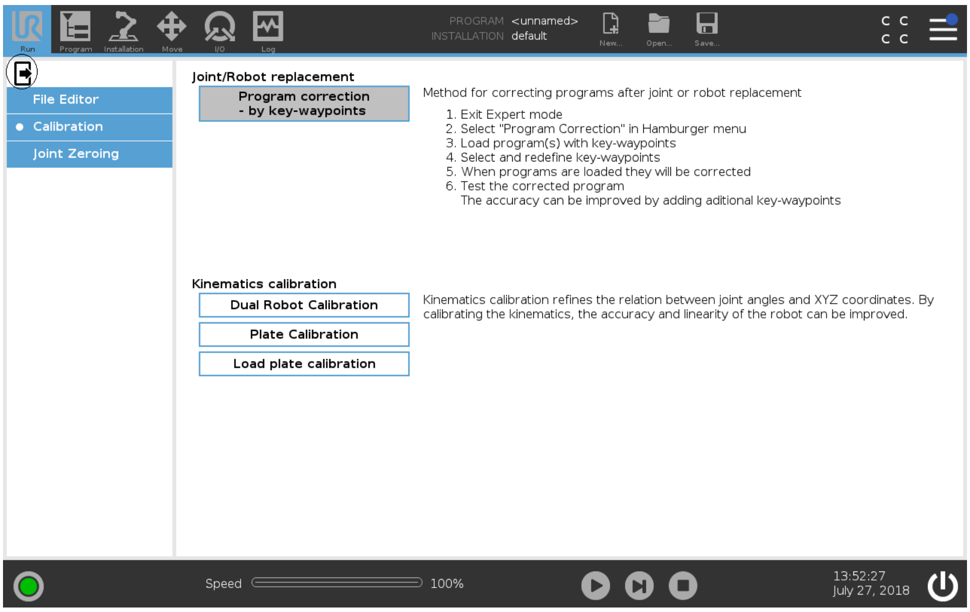


Figure 3.2: Exit button is under the Run Tab

(5) In the Header, tap the Hamburger Menu and select **Program Correction**.

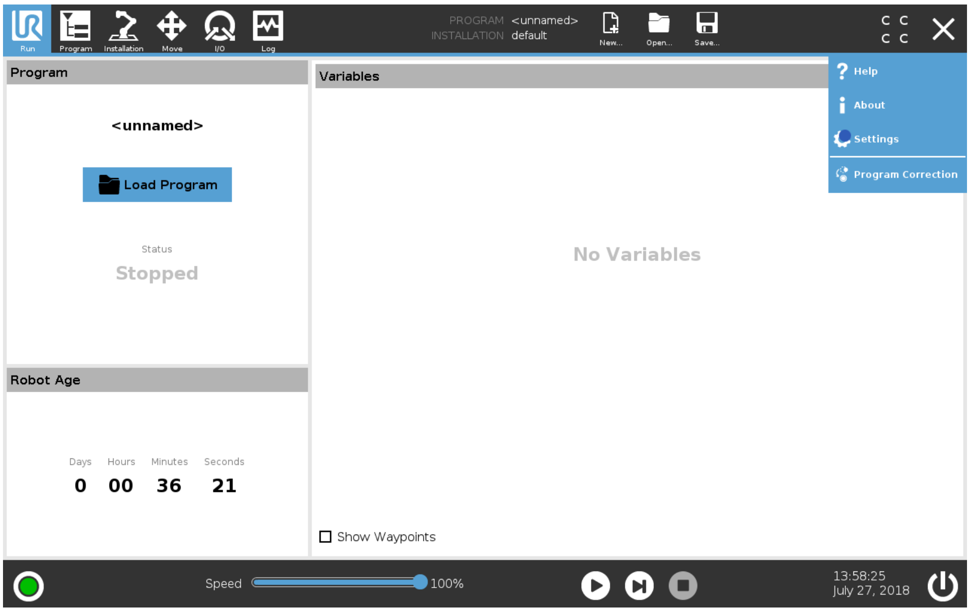


Figure 3.3: Program Correction in Hamburger Menu

(6) Enter your password to access **Correction model**.

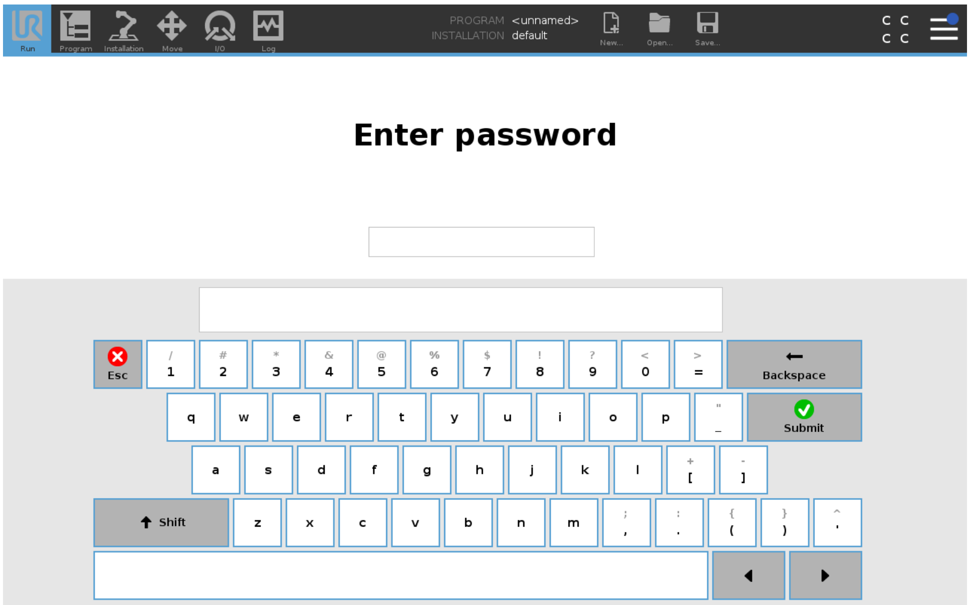


Figure 3.4: Program Correction in Hamburger Menu

3.3 Redefining Key Waypoints

This example uses a simple pick and place program with two key waypoints.

(7) Tap **Load Program** to load a desired program as the Correction Model.

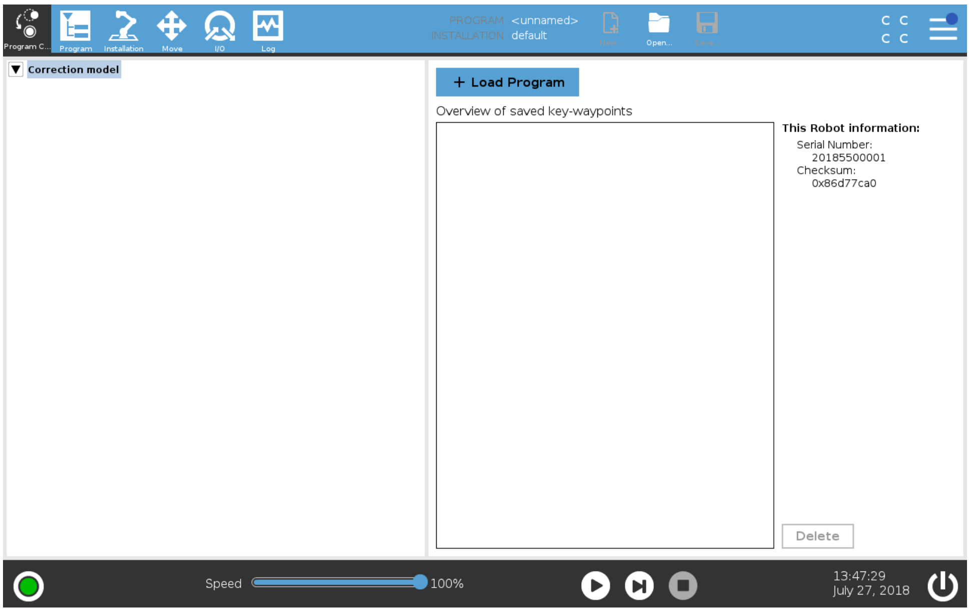


Figure 3.5: Load Program Tab

(8) In the program, select one of the key waypoints.

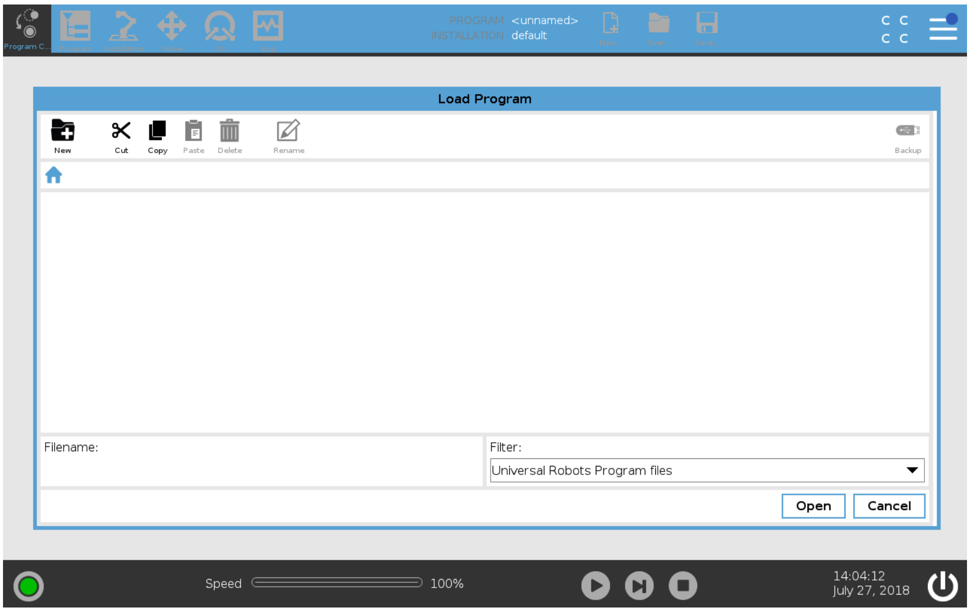


Figure 3.6: Load Program Tab

In the Program Tree, waypoints that are not re-taught are displayed in *italics* with the undefined waypoint icon.

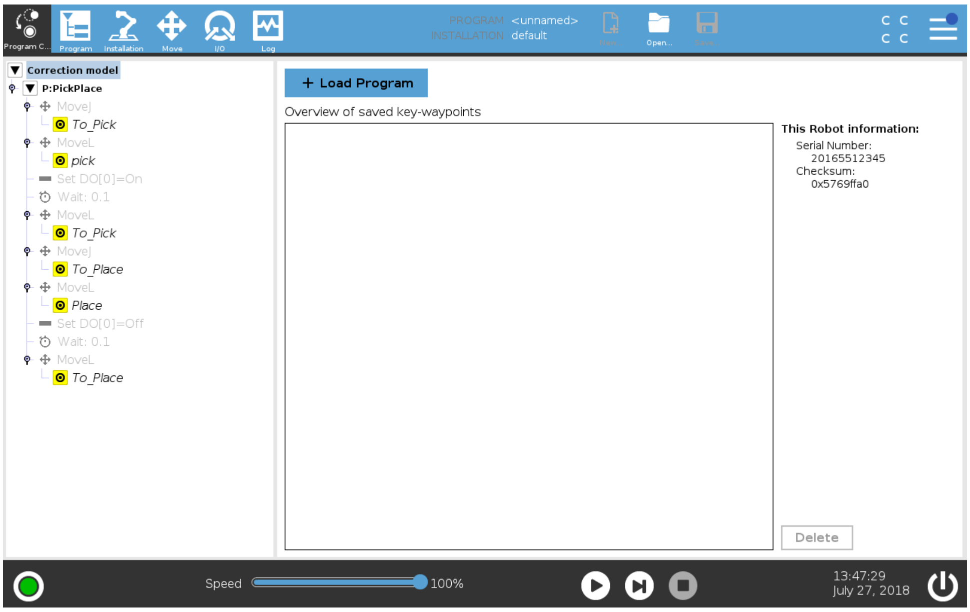


Figure 3.7: In this case, the waypoint **pick** is selected

(9) On the right of the screen, tap **Change this waypoint** to redefine the configuration for the selected waypoint.

(10) When the Move Tab is activated, move the robot to a new position and tap **OK**.

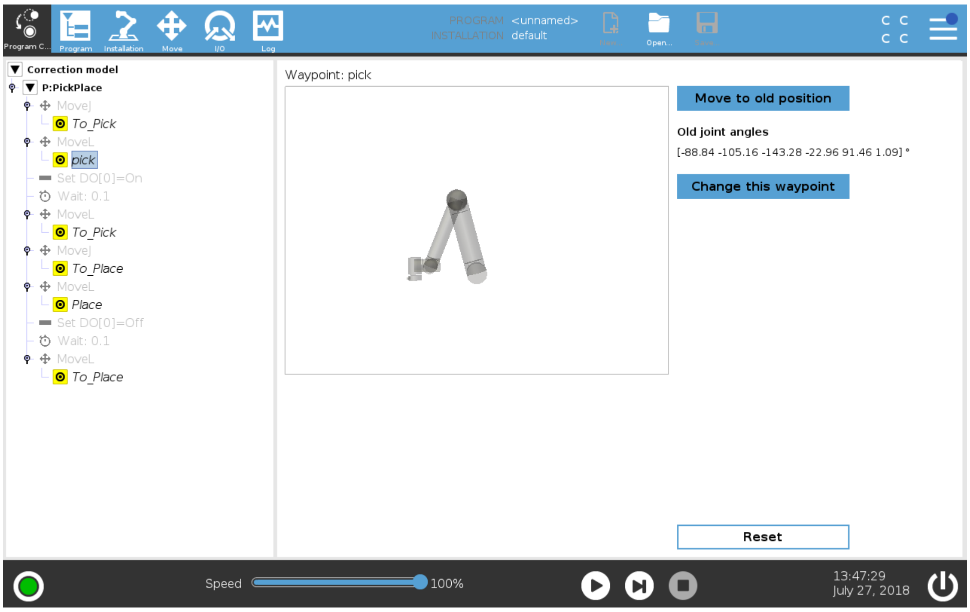


Figure 3.8: "Waypoint:pick" is displayed on screen

3.3.1 Corresponding Tool Position

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

- The TCP where the robot is picks an object.
- The end location where the object is placed.

The CTP value redefines the waypoint. The CTP is defined individually for each key waypoint which improves the accuracy of the correction. The TCP selected from the program installation is used as default.

(11) Tap **Change CTP** to specify the CTP.

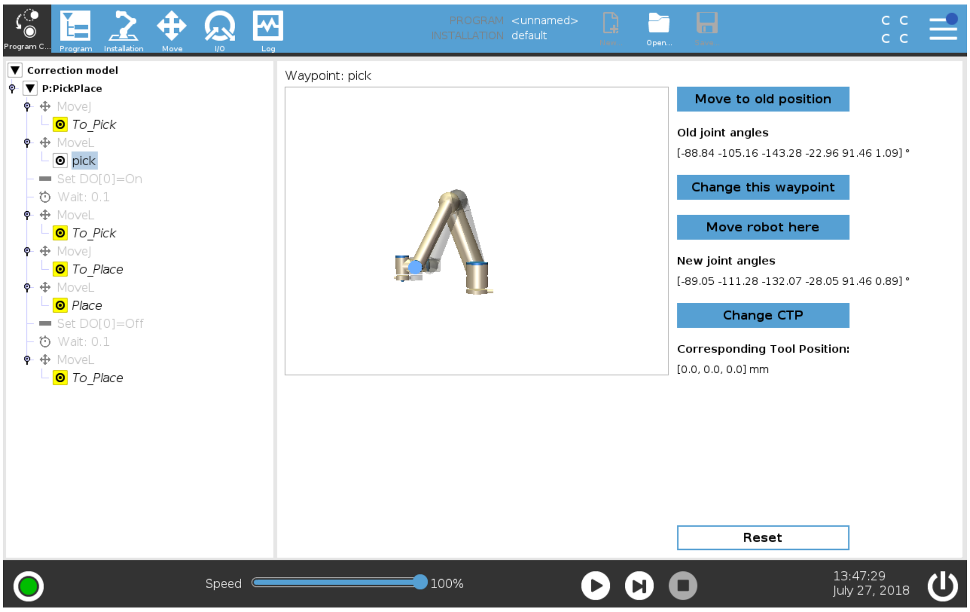


Figure 3.9: Tap **Change CTP** and change the CTP.

(12) Change the CTP coordinates and tap **OK**. This completes redefining the "pick" key waypoints. In the Program Tree, the re-taught waypoint is no longer displayed in italics and the icon is the one for a defined waypoint. Continue by repeating steps 8 - 12 until all key waypoints are redefined.

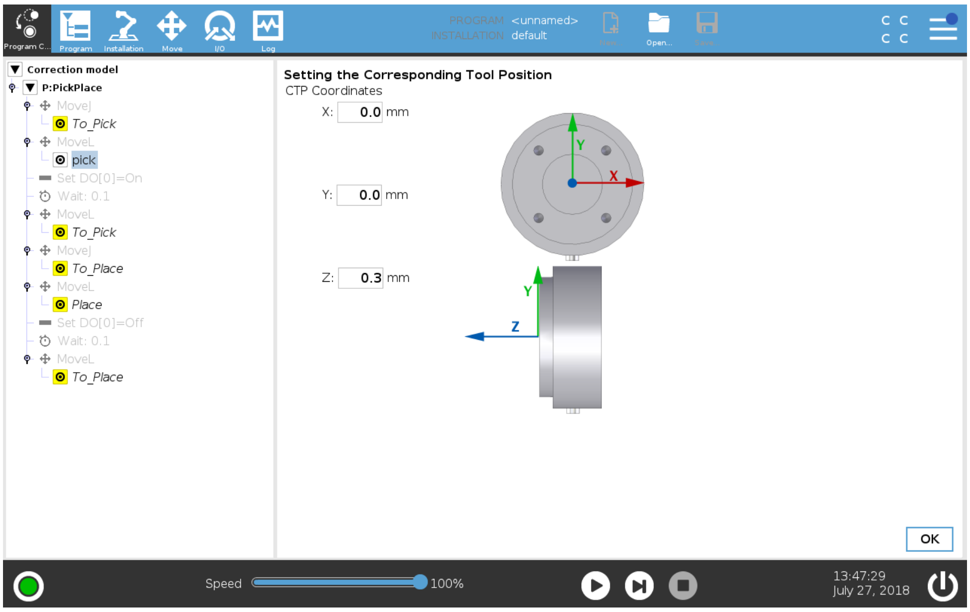


Figure 3.10: Change the CTP coordinates and tap OK

3.3.2 Waypoints from Multiple Programs

You can add key waypoints from multiple programs by adding programs, then selecting and redefining them as previously described in steps 7 - 12.

(13) If the key waypoints are distributed over multiple programs, select the root node of the Program Tree and tap **Load Program** and repeat steps from 7 onward:

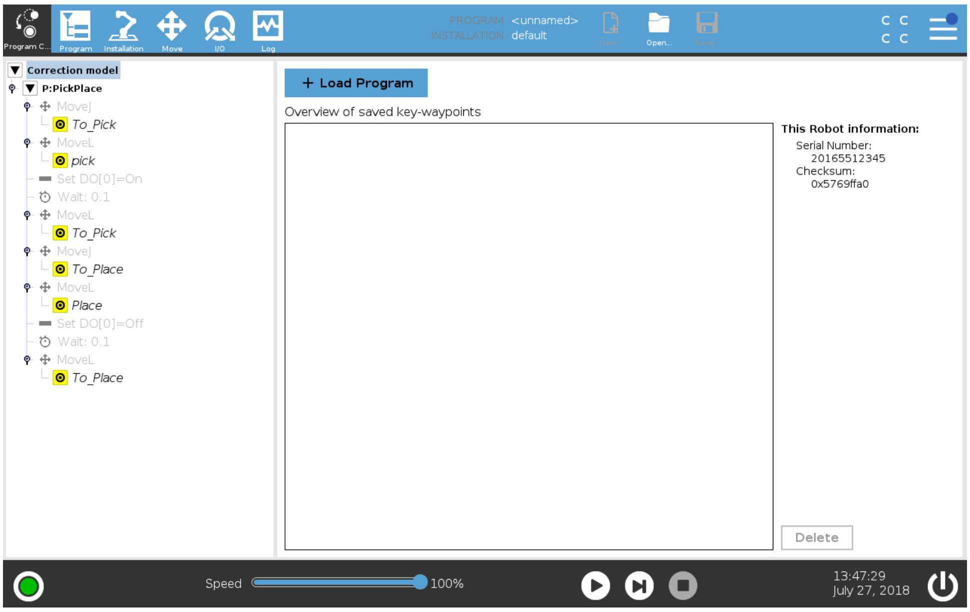


Figure 3.11: Add an a program by tapping **Load Program** and repeat from step 7.

3.4 Handling Key Waypoints

The key waypoints are grouped by the source robot's relationship to the new robot and its installation. Each key waypoint is named and refers to the source program, (see Figure 3.12 and 3.13).

- You can expand the Correction Model node for an overview of the redefined key waypoints, (see Figure 3.12).
- You can select a waypoint, or a group of waypoints, and tap **Delete** to remove key waypoints from Correction Model.

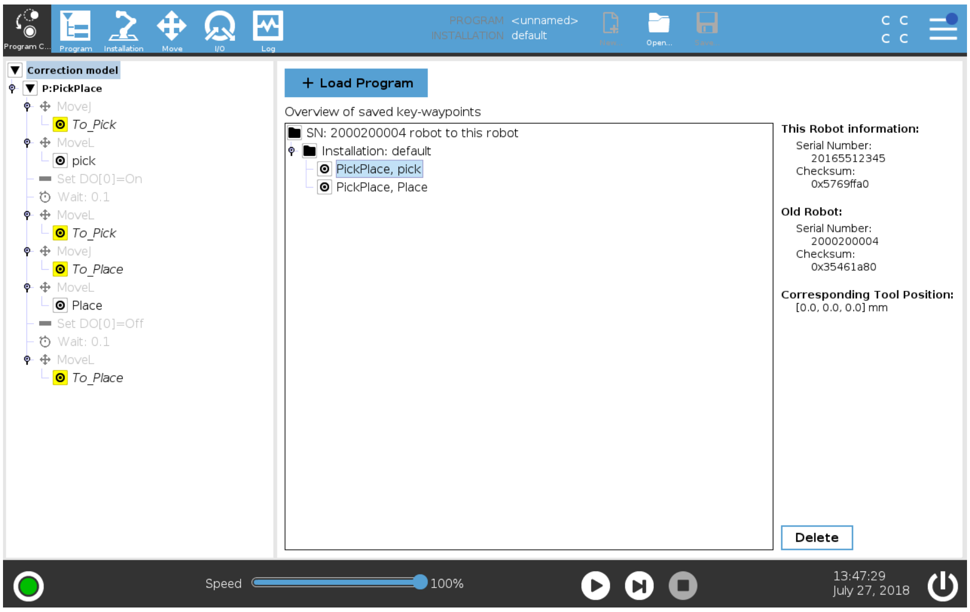


Figure 3.12: Correction Model overview

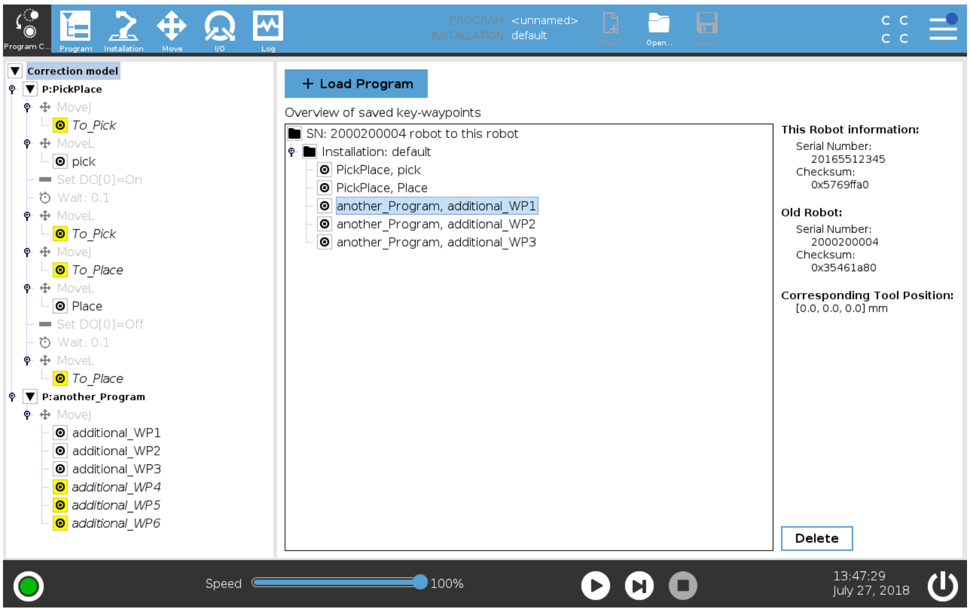


Figure 3.13: Waypoints from multiple programs can be added and displayed in the Correction Model overview

3.5 Correcting a Program

Once key waypoints are redefined, PolyScope attempts to correct the program while in Program Correction Mode.

(14) Tap **Load Program** and, in the **Load Program** screen, select the program to be corrected.

Robot controller software detects if a correction is applicable.

(15) Once the Correct Program Waypoint pop-up appears, select **Correct Waypoints** to correct the program.

(16) Another pop-up indicates when the correction is done.

(17) If the correction failed, verify your key waypoints and improve their accuracy.

WARNING:

Do not save an untested program, as it overwrites any previous program. Test and correct the unsaved program before saving it.

(18) After the program is corrected, you must:

- Test by letting the robot move through its waypoints. You can play the program or select waypoints individually and use the Move Robot Here functionality.
- Save the program under a new name. Once a corrected program is saved, the previous program is overwritten and cannot be corrected again.

If a better accuracy is needed, add additional key waypoints to the model and repeat from step 14.

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

(20) Correct other programs by repeating from step 14.

A Dual Robot Tools

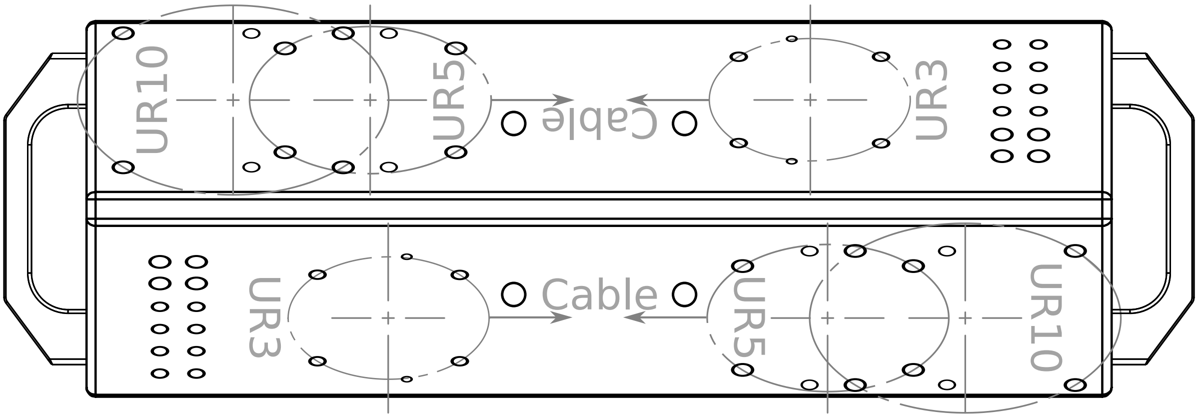


Figure A.1: The Dual Robot Calibration Horse

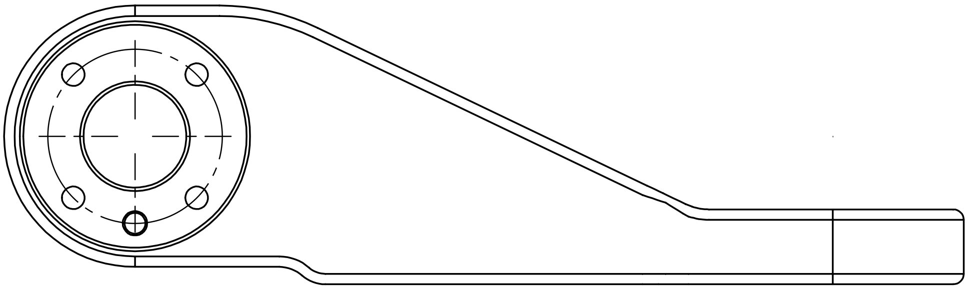


Figure A.2: The Dual Robot Calibration Tool Connector

Figure A.3: *Go* tool used in the validating procedure (1.5 mm thickness)

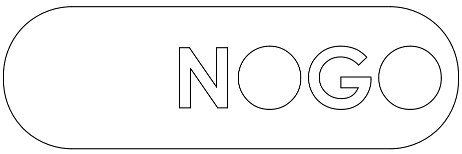


Figure A.4: *No Go* tool used in the validating procedure (3.5 mm thickness)