# UNIVERSAL ROBOTS

# Kinematic Calibration Manual for e-Series



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# Contents

1	Plat	e Calibration	1
	1.1	Required Equipment	1
	1.2	Accessing Plate Calibration	2
	1.3	Measuring Positions	4
	1.4	Calibration	6
	1.5	Evaluation	7
		1.5.1 Calibration Statistics	8
		1.5.2 Debugging	8
		1.5.3 Applying the Calibration	8
	1.6	Reset Calibration	9
2	Dua	l Robot Calibration	10
	2.1	Required Equipment	11
	2.2	Mounting the Robots to the Calibration Horse	12
	2.3	Safety Settings of the Robots	13
	2.4	Accessing Dual Robot Calibration	13
	2.5	Network Connection Between the Robots	15
		2.5.1 Master/Slave Connection	16
		2.5.2 Manual Mode	16
	2.6	Before Starting	17
	2.7	Mounting the UR Dual Robot Calibration Connector	18
	2.8	Measuring Positions and Calibration Statistics	20
	2.9	Applying the Calibration	21
		2.9.1 Validation	21
		2.9.2 Reset Calibration	23
3	Prog	gram Correction by Key Waypoints	24
Ū	3.1	Introduction	24
	3.2	Accessing Automatic Program Correction	25
	3.3	Redefining Key Waypoints	26
		3.3.1 Corresponding Tool Position	28
		3.3.2 Waypoints from Multiple Programs	29
	3.4	Handling Key Waypoints	30
	3.5	Correcting a Program	31
Ap	pend	lices	33
A	Cali	bration Plate	33
D	<b>D</b>	l Dahat Taala	24
D	Dua	T VODOT 10012	34

# 1 Plate 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 e-Series robots.

This section of the Calibration Manual details the calibration method for the kinematics implemented on the Universal Robots e-Series robot. The following instructions illustrate the proper steps to calibrate the robot.



Figure 1.1: Robot mounted on a plate during Plate Calibration.



# CAUTION:

Calibration must be performed carefully, or the robot risks functioning inaccurately. Verify generated statistics before saving the results of the calibration.

# 1.1 Required Equipment

To perform Plate Calibration, the tool flange must be moved to multiple positions while staying parallel to the plane. The Plate Calibration process is illustrated using a positioning plate. This is a metal plate with built-in holes at regular intervals that can accommodate the tool flange, (see figure 1.1 and Appendix A).

# **1.2** Accessing Plate Calibration

In PolyScope, the Calibration process is only accessible in Expert Mode.

- (1) In the Header, press and hold the Run Tab to access **Expert Mode**, (see Figure 1.2).
- (2) Enter the password and tap **OK**.

Run Program Instalation Move		program <unnamed> installation default</unnamed>	New Open	Save	۰ د د د
		Enter passwoi	rd		
		OK Ca	ncel		
0	Speed	100%		)	13:25:44 July 27, 2018

Figure 1.2: Expert Mode screen

- (3) In the menu on the left, tap **Calibration**.
- (4) Under Kinematics calibration, select Plate Calibration, (see Figure 1.3).

Run Program Instalation Mov		PROGRAM <unnamed> INSTALLATION default*</unnamed>	New Open Save	: : <b>=</b>
File Editor Calibration Joint Zeroing	Joint/Robot replacement Program correction - by key-waypoints	Method for correcting progr 1. Exit Expert mode 2. Select "Program Corre 3. Load program(s) with 4. Select and redefine (e 5. When programs are le 6. Test the corrected pro The accuracy can be li	ams after joint or robot replac action" in Hamburger menu key-waypoints y-waypoints aded they will be corrected agram mproved by adding aditional k	ement ey-waypoints
	Kinematics calibration Dual Robot Calibration Plate Calibration Load plate calibration	Kinematics calibration refines calibration the kinematics, th	s the relation between joint an	gles and XYZ coordinates. By robot can be improved.
0	Speed	100%		11:19:37 June 22, 2018

Figure 1.3: Select Plate Calibration.

(5) On the bottom right of the screen, tap **Add plate**, (see Figure 1.4).



Figure 1.4: Add a plate for the hole positions.

# 1.3 Measuring Positions

Once a plate is added for the Calibration, the holes must also be added as Plate Positions. These positions create a Plate Tree on the screen.

(6) Tap **Add new position** and input Plate Position by tapping the value fields. These are the X, Y and Z coordinates, relative to the positioning plate, (see Figure 1.5).



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

#### (7) Tap Measure robot position

(8) Once the first position is defined, tap Add new point to add a second position, (see Figure 1.6). You can add several plate positions in this manner. A full calibration must include at least 15 positions. Tap Remove this point to remove a position from the Plate Tree, (see Figure 1.6).

Run Program Installation Me		PROGRAM <b><unnamed> []                                   </unnamed></b>	د د د
	Positions	Setup Calibration Parameter overview	
File Editor  Calibration  Joint Zeroing	☐ Plates ♥ ☐ Plate: 1 □ (Pos_1)	Plate Position [mm]: (0.0,0.0,0.0) Joint Configuration: Not defined Tool offset Not defined	)
0	Speed	Remove this point         Add neu           100%         13:35:2	4 (I)

Figure 1.6: The property screen for the selected position.

Tapping **Measure robot position** accesses the Move Tab. Insert the (x, y, z) coordinate, teach the related robot configuration. The screen also has a button to add additional positions.

(9) Once all positions are added to the Plate Tree, tap **Calibration** and select **Make Calibration**, (see Figure 1.6).

Positions used in the calibration must be as distributed as possible on the plate and in the configuration space of the robot. Verify all the combinations of both elbow and wrist up and down solutions are used, as illustrated in Figure 1.7.



Figure 1.7: Configuration need to be used.

# 1.4 Calibration

In this example all desired plate positions are added to the Plate Tree.

- (10) At the top of the Plate Tree, tap **Plates** to select the level of calibration, (see Figure 1.8).
- (11) Select the parameters to calibrate subsequently.
  - (a) Offset angles

This level calibrates the offset angles for the Shoulder, Elbow, Wrist 1 and Wrist 2. This method does not provide enough information to calibrate the Base and Wrist 3.

(b) Partially

This level calibrates more parameters than the Offset angles level using other deviations than offset angles.

(12) Tap Calibration and select Make Calibration to start the calibration.



Figure 1.8: Select the top of the tree item on the left to be able to select the level of calibration, then select the Calibration Tab and press **Make Calibration** to start the calibration.



Figure 1.9: Calibration Tab options

#### 1.5 Evaluation

(13) After the calibration is performed, the results need to be evaluated to ensure the calibration is successful.

Calibration results, as well as the calculated statistics of the achieved precision for the given positions, are the displayed under the **Parameter overview** Tab, (see Figure 1.10). Scroll down to display the complete parameters used to evaluate the success of the calibration.

The calculated statistics are divided into two groups: **Measurement data** which is statistics on positions used in the calibration and **Evaluation data** which is statistics that evaluates the quality of the calibration results.



Figure 1.10: The identified parameters are displayed in the Parameter overview.

#### 1.5.1 Calibration Statistics

An example of the printed statistics:

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

Listing 1.1: Example of printed statistics for a partially calibration

Explanation of line number:

Line **4** to **8**: The statistics for the positions used in the calibration. This calibration example uses over 10 positions.

Line **9** to **13**: The statistics are for the positions reserved for evaluation only. In this case six positions. You must redo the procedure if there is a significant difference between the measurement data and the evaluation data.

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

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

Line 7 and 12: Shows the maximum error in the data. It is formatted like the mean error.

Line **8** and **13**: The range of the robot configuration. The range indicates how well the measurements are distributed.

The printed statistics are saved in the *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).

- (14) If the evaluation was not successful: Examine the correct coordinates were used in the defined calibration points.
- (15) If the configuration is too monotone: Add additional positions.

#### 1.5.3 Applying the Calibration

When a satisfactory calibration is obtained, it is recommended to try the new parameters before they are stored permanently.

(16) Tap **Use Calibration** to try the new calibration without saving the new parameters as the default, (see Figure 1.9).

The current default kinematics can be reloaded by tapping **Restore previous**. This button is not a "load factory default" button. Be aware of the quality of the calibration before applying the new parameters permanently.

- (17) Parameters can be viewed in the **Parameter overview** Tab, (see Figure 1.10).
- (18) Tap Save as default to save the calibration parameters for future use, (see Figure 1.9).
- (19) The robot is now 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 manually removed by replacing all the decimal and hex numbers, in the configuration files, to zeros like in Listing 1.2.

```
1 [mounting]
2 delta_theta = [ 0, 0, 0, 0, 0, 0]
3 delta_a = [ 0, 0, 0, 0, 0, 0]
4 delta_d = [ 0, 0, 0, 0, 0, 0]
5 delta_alpha = [ 0, 0, 0, 0, 0, 0]
6 joint_checksum = [ 0x0, 0x0, 0x0, 0x0, 0x0]
7 calibration_status = 0 # 0 == notInitialized / 1 == notLinearised / 2 == Linearised
8 joint_raw_offset = [ 0x0, 0x0, 0x0, 0x0, 0x0, 0x0]
9 joint_selftest_data_crc = [ 0x0, 0x0, 0x0, 0x0, 0x0]
```

Listing 1.2: calibration.conf file filled with zeros

# 2 Dual Robot Calibration

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 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 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 B.3, Appendix B)
  - One No Go tool used in the validating procedure (Figure B.4, Appendix B)

## 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  $52, 5^{\circ} \pm 5^{\circ}$  and
- (b) The Rotate Robot Base Mounting is 270°.

#### UR5e and UR10e:

- (a) The *Tilt* is approximately  $52, 5^{\circ} \pm 5^{\circ}$  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 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).

arety	Use of Safety Configuration p	arameters different from those of the second sufficiently reduced	defined by the	risk assessment can result in l	hazards that are not
Robot Limits	reasonably carrienced or risks	that are not sufficiently reduced			
Joint Limits	Eastony Brocato				
Planes				•	
Tool Position		Most Restricted		Leas	t Restricted
Tool					
Direction	O Custom				
1/0					
Hardware	Limit	Normai	Reduc	ea	
eatures	Power	300		200 W	
ieldbus	Momentum	25.0		10.0 kg m/s	
	Stopping Time	400		<b>300</b> ms	
	Stopping Distance	500		<b>300</b> mm	
	Tool Speed	1500		<b>750</b> mm/s	
	Tool Force	150.0		120.0 N	
	Elbow Speed	1500		<b>750</b> mm/s	
	Elbow Force	150.0		120.0 N	

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 password and tap OK.

Ref Program Installation Nove UD Log	PROGRAM <b><unnamed></unnamed></b> INSTALLATION <b>default</b>	New Open	Save	сс <b>П</b>
	Enter nasswo	rd		
		ncol		
		incer		
			15	0.25.44
Speed C	100%		) la	y 27, 2018

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

			PROGRAM <b><unnamed></unnamed></b> INSTALLATION <b>default*</b>	New Open Save	
File Editor	Open	Save Save As	Delete	Exit	File Editor
Calibration Joint Zeroing					
	Esc	/ # * 1 2 3	&         @         %         \$           4         5         6         7	· · · · · · · · · · · · · · · · · · ·	≥ ← Backspace
		q w e	r t y	u i o	p _ Enter
		a s c	i f g h	j k I	+ [ ]
	1	Shift z x	c v b	n m ;	: { } ^ . ( ) ·
$\bigcirc$	Speed		100%		11:19:11 June 22, 2018

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

- (12) In the 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).

Run Program Installation Mo		PROGRAM INSTALLATION	<unnamed> default*</unnamed>	New Open	Save	د د د د
File Editor • Calibration Joint Zeroing	Conner	ct robots	Connect robot 1. Mount ti 2. Press "C Cautior	:s he robots too Connect robot <b>n: The Robo</b>	I flanges together. s" to connect the to ts will begin to mo	ols. Ve.
	Master Save calibration Correct home position	Slave Save calibration Correct home position				
	Measurement status Number saved State status Main state	0 of 0 Idle				
	This Robot Second Robot	Idle				
					Back	Home Exit
0	Speed C	100%	C			11:24:39 June 22, 2018

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

File Editor Calibration Joint Zeroing	Conne Auto step	ct robots	Connect robo 1. Mount 1 2. Press <sup>n</sup> Cautio	ts the robots too Connect robot n: The Robo	I flanges together. Is to connect the tools. Is will begin to move.	
	Master Save calbration Correct home position	Slave Save calibration Correct home position				
	Measurement status Number saved	0 of 0				
	Main state	Idle				
	This Robot Second Robot	Idle Idle				
					Back Home	e Exit

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

		i <unnamed> 📮 🛅 🔓 i default* New, Open, Sa</unnamed>	<b>⊒</b> :: ≡
File Editor • Calibration Joint Zeroing	Connect robots  Auto step  Master Slave Slave Calbration  Source toom position  Correct home position  Correct home position	Cannect robots 1. Mount the robots tool file 2. Press "Connect robots" to Caution: The Robots w	nges together. o cornect the tools. <b>All begin to move</b> .
	Meancram Kindler on State state Mann state This Robot Second Robot Encode National Second Robot Second Robot Executing	nne are mounted to the calibration ort Calibration	
		[	Back Home Exit
0		000	11:25:36 June 22, 2018

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).

			PROGRAM INSTALLATION	<unnamed> default*</unnamed>	New Oper	x Søve		сс сс	≡
•	Correct by	ome position		The rebet b	ave been disc	opported			
File Editor	Correct In	onie posicion		Press 'Exit' t	o finish or 'C	orrect Home Posit	ion' correct the h	nome pos	ition.
Calibration	🗹 Auto step			lt is not reco	ommended ar	nd only optional to	o 'Correct joints z	ero angle	e - 1
loint Zeroing				since this ca	in introduces	errors to existing	programs if the	robot wa	IS
				The calibrate		place.			
	Master	Slave	ration						
	Correct home position	Correct ho	ome position						
	Calibration Results			ı					
	Mean deviation	0.877 mrad	0.284 mm						
	Standard deviation	0.420 mrad	0.161 mm						
	Max deviation	2.540 mrad	0.907 mm						
	Control Results			1					
	Mean deviation	0.916 mrad	0.267 mm						
	Standard deviation	0.421 mrad	0.126 mm						
	Max deviation	2.435 mrad	0.613 mm						
	Scale Result			1					
	Error		0.145 mm						
	Limit		0.300 mm						
				J		Back	Home	Exit	
•	Speed		100%			0	11:52: June 2:	45 2, 2018	Ċ

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 will be 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%

# 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  $2.5 \text{ mm} \pm 1 \text{ mm}$  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 B.3, Appendix B)
  - (b) Verify the 3.5 mm *No Go* tool **can not** pass between the two robots tool flanges (Figure B.4, Appendix B)
- (29) If the verification is successful in Step 28, *Proceed* to the next validation step... see Figure 2.28.



ceedure

File Editor		Verify		Press 'Verify'	me position l to run a ver	have been adjus fication routine	sted.	
Calibration	🖬 Auto step							
Joint Zeroing								
	Master Save calbration Correct home position	Slave Save calib on Sove calib	ration ome position					
	Calibration Results Mean deviat Standard de		Remove to	50l	tached on th			
	Max deviation 1 Rer	nove the caloraci	311 CO 31 313 CI 16	c nothing are a	cucines or i ci	~		
	Max deviation	Procee	d > Abc	rt Calibration				
	Control Resurce Mean deviation	0.916 mrad	d > Abc	rt Calibration				
	Max deviation	0.916 mrad 0.421 mrad	d > Abc 0.267 mm 0.126 mm	rt Calibration				
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	Max deviation Control Resurs Mean deviation Standard deviation Max deviation Scale Result Error	0.916 mrad 0.916 mrad 0.421 mrad 2.435 mrad	d > Abc 0.267 mm 0.126 mm 0.613 mm	rt Calibration		70		
	Max deviation Max deviation Max deviation Max deviation Max deviation Scale Result Error Limit	0.916 mrad 0.916 mrad 0.421 mrad 2.435 mrad	d > Abc 0.267 mm 0.126 mm 0.613 mm 0.145 mm 0.300 mm	rt Calibration				

Figure 2.25: Robots are ready for the validation pro- Figure 2.26: Proceed to the Verification procedure when the Calibration Tool Connector, screws, and alignment pins are removed from the robots tool flange

2.5m	*/- 1mm

:: ≡ Back Home Exit 000 11:54:22 June 22, 2018

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

3		Verify		The joints hor	ne position	have been adjusted.	
Calibration	Auto step			<ul> <li>Press verify</li> </ul>	to run a ve	incación rocióne	
	Manhan	<b>F</b> 10.00					
	Master M Save calibration	M Save call:	ration				
	Correct home positio	n 🗹 Correct h	ome position				
	Calibration Results-			1	_		
	Standard deviation		Verity posit	lion			
	Max deviation	1 Ve	rify the robots	home position			
		_			- 1		
		Procee	a > Abo	rt Calibration			
	Control Results	0.016 mmd	0.367.000		_		
	President deviation	0.010 mmd	0.125 mm				
	Max deviation	2.435 mrad	0.613 mm				
				]			
	Scale Result						
	Droor		0.145 mm				
	100		0.300 mm				

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



Figure 2.31: Kinematic Calibration is done

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

#### 2.9.2 Reset Calibration

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

# **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**.

	PROGRAM <b><unnamed></unnamed></b> INSTALLATION <b>default</b>	New Open	Save	сс <b>П</b>
	Enter passwo	rd		
[				
		ancel		
O Speed	100%		<b>)</b>	13:25:44 July 27, 2018

Figure 3.1: Expert Mode screen

- (3) In the 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)

Run Program Installation Mov		PROGRAM <b><unnamed></unnamed></b> INSTALLATION <b>default</b>	New Open Save	د د د د
File Editor • Calibration Joint Zeroing	Joint/Robot replacement Program correction - by key-waypoints	Method for correcting prog 1. Exit Expert mode 2. Select "Program Corr 3. Load program(5) with 4. Select and redefine k 5. When programs are 6. Test the corrected p The accuracy can be	rams after joint or robot replac rection" in Hamburger menu h key-waypoints ey-waypoints loaded they will be corrected rogram improved by adding aditional k	ement ey-waypoints
	Kinematics calibration Dual Robot Calibration Plate Calibration Load plate calibration	Kinematics calibration refin calibrating the kinematics, t	as the relation between joint an he accuracy and linearity of the	gles and XYZ coordinates. By robot can be improved.
0	Speed C	∋ 100%	000	13:52:27 July 27, 2018

Figure 3.2: Exit button is under the Run Tab

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

	program <b>«unnamed» 🏠 🛅 🗔</b> Installation <b>default new.</b> open. save.	c c X
Program	Variables	<b>?</b> Help
		About
<unnamed></unnamed>		Settings
Load Program		Program Correction
status Stopped	No Variables	
Robot Age		
Days Hours Minutes Seconds 0 00 36 21		
	Show Waypoints	
Speed		13:58:25 July 27, 2018

Figure 3.3: Program Correction in Hamburger Menu

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

Run Program Installation Move		PROGRAM <unnamed> [ INSTALLATION default <sub>Ne</sub></unnamed>	Cpen Save	د د <b>ال</b>
	Ent	er password	1	
Esc / 1	# * & @ 2 3 4 5	% \$ ! ? 6 7 8 9	< > 0 =	← Backspace
c	, wert	y u i	o p _	Submit
<b>↑</b> shift	a s d f	g h j k	, ; , ;	1 ( ) . ( ) .

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.

IR



Figure 3.5: Load Program Tab

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

ن Program C	Program		<b>4</b>	÷ (		Log	PROGF INSTALLAT	RAM <unnamed> TON default</unnamed>	New	Open	Save		с с с с	=
							Load P	rogram						
	Ŧ	×		E	Ŵ									3
	New	Cut	Сору	Paste	Delete	Rename							Back	ap
	ft 👘													
	Filename:							Filter:						
								Universal Robo	ts Progra	m files				<u>·</u>
												Ope	n Cancel	
0				s	peed		∋ 100%		0 (	<b>)</b> (	)		14:04:12 July 27, 2018	

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.

Frogram C Program Installation Move NO Log		PROGRAM <unnamed> INSTALLATION default</unnamed>	New Open	Save	сс <b>—</b>
▼         Correction model           ▼         P.PPIddPlace           ●         + Movel           □         0	+ Load Program Overview of saved key-v	vaypoints			This Robot information: Serial Number: 20155512345 Checksum: 0x5769ffa0
Speed C	•	100%		)	Delete 13:47:29 July 27, 2018

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**.

Program C. Program Instalation Nove NO Lo	PROGRAM <unnamed> INSTALLATION default</unnamed>	New Oper		=
▼ correction model         ♥ ▼ P:PickPlace         ♥ ↓ Movel         └ 0 To_Pick         ♥ ➡ Movel         □ 0 Eck         - = Set DO[0]=On         - ♡ Wat: 0.1         ♥ ➡ Movel         └ 0 To_Pick         ♥ ➡ Movel         └ 0 To_Pick         ♥ ➡ Movel         └ 0 Piace         ■ Set DO[0]=Off         ♡ Wat: 0.1         ♥ ➡ Movel         └ 0 To_Piace         ■ Movel         └ 0 Wat: 0.1         ♥ ₩ Movel         └ 0 To_Piace	Waypoint: pick		Move to old position Old joint angles [-88.84 -105.16 -143.28 -22.96 91.46 1.09]* Change this waypoint	
			Reset	
Speed 🥌	100%		13:47:29 July 27, 2018	Ċ

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.

Program C Program Instalation Move NO Log	PROGRAM <unnamed> INSTALLATION default</unnamed>	Nam. Open., Save.	¢ € <b>=</b>
▼ Correction model         ▼ Movel         ↓ @ To_Pick         ♥ + Movel         ↓ [@] pick         ■ Set D0(0)=On         • ⊕ Movel         ↓ @ To_Pick         ♥ + Movel         ↓ @ To_Pick         ♥ + Movel         ↓ @ To_Pice         ♥ + Movel         ↓ @ To_Piace         ■ Set D0(0)=Off         • ⊕ Movel         ↓ @ To_Piace	Waypoint: pick	Move to Old joint an [-88.84-105. Change Move New joint an [-89.05-111. Change [-0.0,0.0,0.0]	> oid position gles 16 - 143.28 - 22.96 91.46 1.09] * this waypoint robot here ngles 28 - 132.07 - 28.05 91.46 0.89] * inge CTP ling Tool Position: Imm
Speed 🥌	100%		13:47:29 July 27, 2018

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.

Program C		PROGRAM <unnamed> INSTALLATION default</unnamed>	New. Open Sa		
▼ Correction model         ▼ PrickHace         ◆ Movel         □ O To_Pick         ◆ Movel         □ O Dick         - => Set DO(0)=001         - ③ Vat: 0.1         ◆ Movel         □ O To_Pick         ◆ Movel         □ O To_Pick         ◆ Movel         □ Ø Pace         ● Movel.         □ Ø Pace         - => Set DO(0)=0ff         - ⑤ Wat: 0.1         ◆ Movel.         □ Ø Pace         - ⑤ Wat: 0.1         ◆ Movel.         □ Ø To_Piace	Setting the Corresp. CTP Coordinates X: 0.0 mm Y: 0.0 mm Z: 0.3 mm	onding Tool Position	×		
		100%		13:47:	ок
Speed		100%		July 27	, 2018 U

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:

Program C	<b>₩</b>	PROGRAM <unnamed> INSTALLATION default</unnamed>	New Open	Save	сс <b>—</b>
▼         Correction model           ▼         P.PPIckPlace           ●         + Movel           □         0           □         0           □         0           0         0           0         0           0         0           ●         Movel           □         0	+ Load Program Overview of saved key	waypoints			This Robot Information: Serial Number: 20155512345 Checksum: 0x5769ffa0
Speed (		100%		)	13:47:29 July 27, 2018

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.

Program C. Program Installation Move NO	PROGRAM <unnamed></unnamed>	сс <b>=</b>
▼ Correction model         ▼ Movel         □ To_Pick         ♥ Hovel         □ □ pick         ■ Set D0(0)=0n         ♥ Wait: 0.1         ♥ Hovel         □ 0 To_Pick         ♥ Hovel         □ 0 To_Pick         ♥ Hovel         □ 0 To_Pick         ♥ Hovel         □ 0 To_Piace         ♥ Hovel         □ 0 To_Piace         □ 0 To_Piace         ■ Set D0(0)=0ff         □ 0 Wait: 0.1         ♥ Hovel         □ 0 To_Piace	+ Load Program         Overview of saved key-waypoints         ■ SN: 200020004 robot to this robot         ● Installation: default         ● PickPlace, pick         ● PickPlace, Place	This Robot information: Serial Number: 20165512345 Checksum: 0x5769ffa0 Old Robot: Serial Number: 2000200004 Checksum: 0x35461a80 Corresponding Tool Position: [0.0, 0.0, 0.0] mm
Speed C	<b>1</b> 00% <b>D</b>	13:47:29 July 27, 2018

Figure 3.12: Correction Model overview

Program C		PROGRAM <unnamed></unnamed>	Oper Save.	сс сс
▼         Correction model           ▼         P:PickPlace           ◆         Movel           □         To_Pick           ◆         Movel           □         Set DO(0)=On           •         Wate 0.1           ◆         Movel           □         To_Pick           ◆         Movel           □         O To_Pick           ◆         Movel           □         O To_Picce           ◆         Movel           □         O To_Piace           ●         Vate 0.1           ◆         Movel           □         O To_Piace           ●         Movel           □         O To_Piace           ●         To_Piace           ●         To_Piace           ●         Additional_WP1           □         O additional_WP2           □         O additional_WP3           □         O additional_WP5           ■         O additional_WP5           ●         additional_WP5	H Load Program Overview of saved key-wayn     SN: 2000200004 robot t     ⊡ Installation: default     ⊡ PickPlace, Picce     ⊡ another_Program,     ⊡ another_Program,     ⊡ another_Program,     ⊡ another_Program,     ⊡	o this robot additional_WP1 additional_WP2 additional_WP3		This Robot information: Serial Number: 2015512345 Checksum: 0x5769ffa0 Old Robot: Serial Number: 200020004 Checksum: 0x35461a80 Corresponding Tool Position: [0.0, 0.0, 0.0]mm
Spe	ed	» <b>(</b>	0	13:47:29 July 27, 2018

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 Calibration Plate



Figure A.1: The calibration plate.

# **B** Dual Robot Tools



Figure B.1: The Dual Robot Calibration Horse



Figure B.2: The Dual Robot Calibration Tool Connector



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



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