UNIVERSAL ROBOTS

Application Guide

High Torque Screwdriving

Original instructions (en)

PolyScope 5

Contents

1. Introduction

Description

This document is intended to assist in integration of a Universal Robot into a high torque screwdriving application, avoiding the common pitfalls and ensuring best possible performance and longest working life for the robot. Topics discussed include maximum achievable torque for the robot, how to best construct the robot program and configure the safety system, plus some options for the screwdriving tool to reduce impact on the robot.

2. Glossary

Description

- Automatic Screwdriver/Nut Runner:
A tool mounted to the robot's tool output flange used for tightening screws or nuts automatically.
- Base Joint:
The first joint of the robot, located at the base.
- Continuous Fastening:
A technique where torque is increased continuously until the target is reached.
- Elbow Joint:
The second joint of the robot, located at the elbow.
- Fast-Steady Mode:
A mode where the robot instantaneously changes into steady mode when torque reaction is detected, allowing higher currents/torques and larger deviations.
- Force Limits:
Restrictions on the forces exerted by the robot at the Tool Center Point (TCP) and elbow joint.
- Joint Deviations:
The difference between the target joint position and the actual joint position, often resulting in protective stop warnings.
- Joint Torque Maximum Values:
The maximum torque values that each joint can withstand.
- Lever Arm:
The perpendicular distance from the axis of rotation to the line of action of a force, used to understand the impact of torque reaction on the robot.
- Payload:
The weight and center of gravity of the load attached to the robot's tool output flange.
- Protective Stop:
A safety mechanism triggered when joint deviations exceed allowed limits.
- Pulse-Driven Tools:
Tools that apply torque in a sequence of increasing pulses, reducing torque reaction compared to continuous fastening.
- Reaction Devices:
Devices mounted on the tool to counteract torque reaction by pushing against the workpiece or fixture.
- Real-Time Data Exchange:
An interface for recording data from the robot, including joint angles, currents, torques, TCP pose, and force.

- Screwdriving Functionality:
  An advanced command and installation setup in PolyScope for setting up screwdriving applications, including fast-steady mode.
- Steady Mode:
  A state where higher currents/torques are permitted for the robot to maintain its position, and larger deviations are allowed before triggering a protective stop.
- Target Torque:
  The desired torque value to be achieved during the screwdriving process.
- TCP (Tool Center Point):
  The position at the tip of the screwdriver or nut runner where it contacts the fastener.
- Torque Arms:
  Devices used to absorb and transfer reaction force from the robot to an external frame or structure.
- Torque Reaction:
  The force transferred to the robot from the tightening process that the robot needs to counteract.
- Wrist Joint:
  The final joint of the robot, located at the wrist.
- Zeroing F/T Sensor:
  The procedure of calibrating the Force and Torque Sensor without any external forces influencing the readings.

3. Maximum Torque

Description

The maximum tightening torque achievable with an automatic screwdriver mounted on a Universal Robot without triggering a protective stop or a force limitation error depends on several factors, including:

- Tool mounting
- Robot programming
- Safety settings
- Robot poses
- Payload
- Others not directly related with the robot, e.g., the tightening setup in the controller of the screwdriver that determines the strategy, torque, speed, angle, etc.

Torque Evaluation

The joint positions and payload determine how much torque from the joints is required to maintain the robot position, and subsequently how much of the torque generation capacity of the joints (its maximum torque values depend on the different joint sizes) is remaining and available to complete the task. Robot tool positions and force limits can also further restrict how much of the remaining joint torque capacity is allowed to be used. The way the tool is mounted to the robot changes the amount of force from the tightening process that the robot is impacted by and must counteract. If the robot is steady (standing still with zero target velocity) the torque restrictions can be less tight and the allowed joint position deviations before triggering a protective stop larger, which would be more favorable to the robot in the process.

Taking all of this into account, the screwdriving torque withstanding capabilities for a UR10/UR10e (the most frequent robot in high torque screwdriving applications) can be categorized as follows:

- < 30 Nm - basic application, not considered high torque
- 30 - 60 Nm - advanced, requires consideration of some of the above factors
- 60 - 100 Nm - expert, requires consideration of all the above factors
- > 100 Nm - not extensively researched, most likely requires innovative technologies or additional hardware

4. Tool Mounting

Description

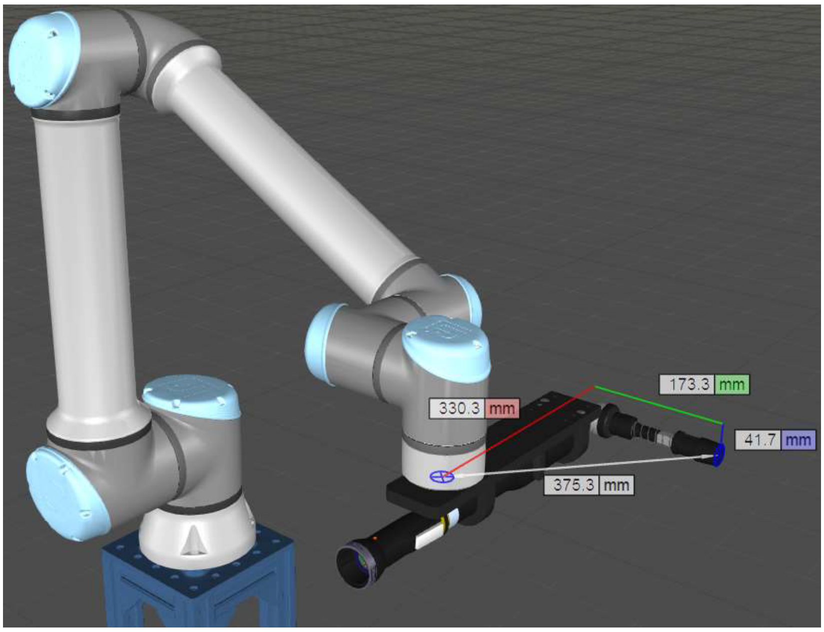
The automatic screwdriver or nut runner should be mounted to the tool output flange of the robot in such way that:

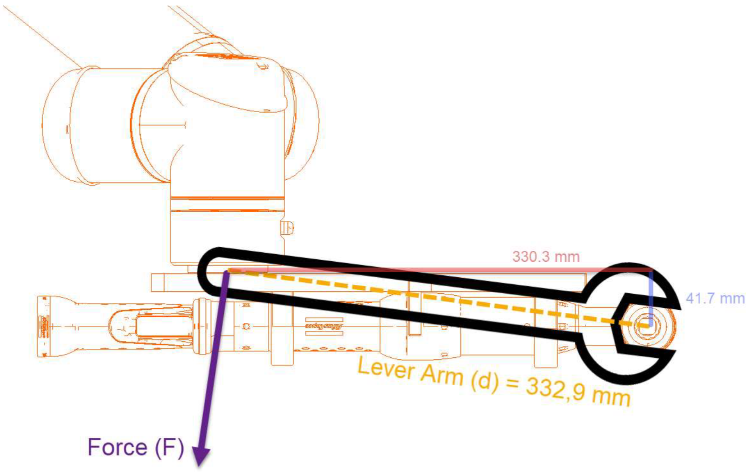
- The lever arm is maximized, thus the force required from the robot is minimized in order to maintain its position during the process
- The possible deviations for a single joint are minimized, avoiding for example that the tightening axis is aligned, parallel or close to parallel with the wrist 3 of the robot.

5. Lever Arm

Description A lever arm is defined as the perpendicular distance from the axis of rotation to the line of action of a force. We can use the concept of the lever arm to understand how the reaction torque from a tightening tool can impact the robot.

Lever Arm Force A force applied to a lever arm has maximum effectiveness in producing (or opposing) torque if it is exerted perpendicular to the wrench. The below drawing is intended to convey the basic principle of a torque arm only, since the robot doesn't need to apply force to produce torque with a wrench; instead the torque is produced by an automatic screwdriver or nut runner, and the robot needs to oppose to the force that is transferred, called torque reaction.





It is important to understand that the lever arm is only measured in the plane perpendicular to the tightening axis. In the example above, the distance of 173.3 mm (shown on the top image in green) in the direction of the tightening axis is not considered for the lever arm calculation.

Torque Calculation

The amount of force required at the tool output flange of the robot, can be calculated with the target torque (moment) and lever arm, using the equation: Moment = Force x Distance or M = (F)(d).
For example:

Target Torque: 30 Nm
Lever Arm: 0.3329 m
Force = Moment / Distance = 30 Nm / 0.3329 m = 90 N

Universal Robots safety system by default limits the force at the tool output flange of the robot at 150 N (125 N considering the tolerance of 25 N), which can be increased up to 250 N. The robot is not always capable of generating or withstanding forces at the tool up to these limit values, but they can restrict the forces that the robot can generate/withstand.

Torque Examples

The below table shows some examples of different combinations of tightening torques and lever arm lengths and the resulting reaction forces (intended to demonstrate the relationship between the parameters only, does not necessarily mean that the robot can handle this torque):

Torque [Nm]	Lever Arm [m]	Force [N]
7.5	0.1	75
15	0.2	75
22.5	0.3	75
30	0.4	75
12.5	0.1	125
25	0.2	125
37.5	0.3	125
50	0.4	125
22.5	0.1	225
45	0.2	225
67.5	0.3	225
90	0.4	225

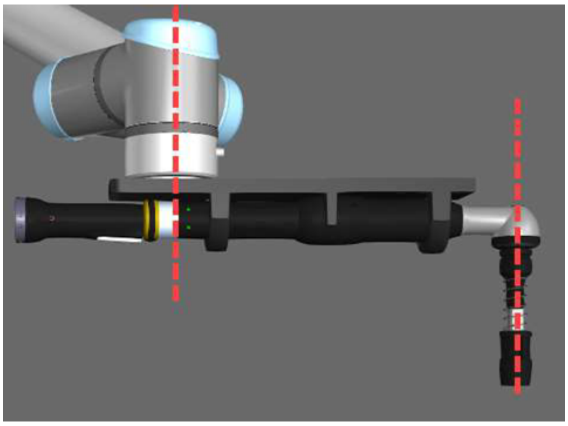
While increasing the lever arm reduces the torque reaction (transferred force to the robot), it should be considered that it will also reduce the capacity of the robot to apply force against the screw. This is because there is also a lever arm operating in the reverse direction, reducing the amount of force that can be generated from the torque of the robot joints.

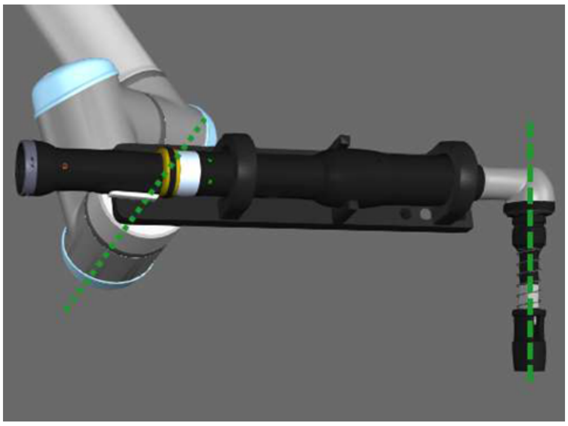
6. Joint Deviations

Description When a joint reaches its maximum allowed torque its position will start to deviate from the joint angle it is trying to maintain. Joint deviations often result in protective stop warnings, which are not an acceptable part of normal operation. Having the robot in a pose which results in a large proportion of the torque reaction force impacting a single joint (with joint axis parallel to screw tightening axis for example) increases the chances of this occurring and should be avoided as much as possible.

While the angles between rotation axes of the first five robot joints and the tool tightening axis will vary depending on the robot pose when tightening the screw, the relationship between the final joint (Wrist 3) and the tightening axis is fixed and defined by the tool mounting bracket. As such, to inimize possible deviations at this joint, it is recommended to maintain at least a 30 degree angle between the rotational axis of Wrist 3 and the tightening axis. Ideally the tool should be mounted in such a way that the tightening axis is not close to parallel with any of the three robot wrist joints when tightening, but this may not be possible at all screw tightening positions.

The torque reaction force will not directly cause a position deviation in a joint if it is parallel to the tightening axis (the lever arm would suggest it will be pushed by the force not rotated), but it will instead be pulled away from its target position if the other robot joints deviate from their positions as a result of the torque reaction (further explanation of this phenomenon is beyond the scope of this document).





7. Robot Programming

Description

It's important to understand how the robot reacts to external forces differently when moving and stationary, and how the Screwdriving functionality in e-Series can help to achieve the best possible performance when programming the robot.

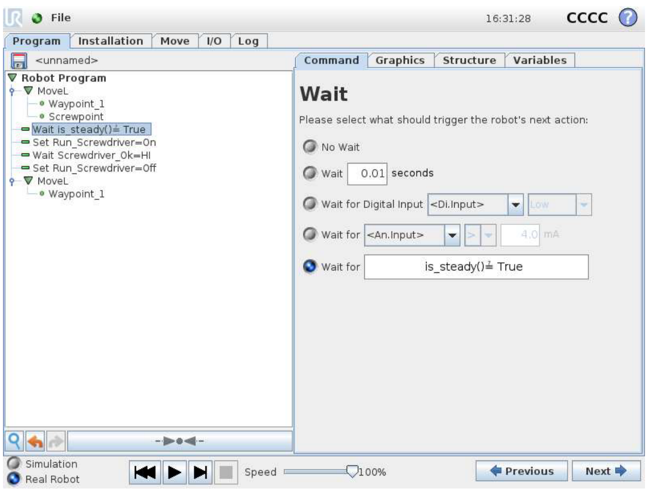
8. Steady Mode

Description If the robot has been standing still with zero target velocity for 500 ms, it will automatically switch into a different state known as steady mode. In this state higher currents/torques are permitted for the robot to maintain its position, and larger deviations are allowed before triggering a protective stop.

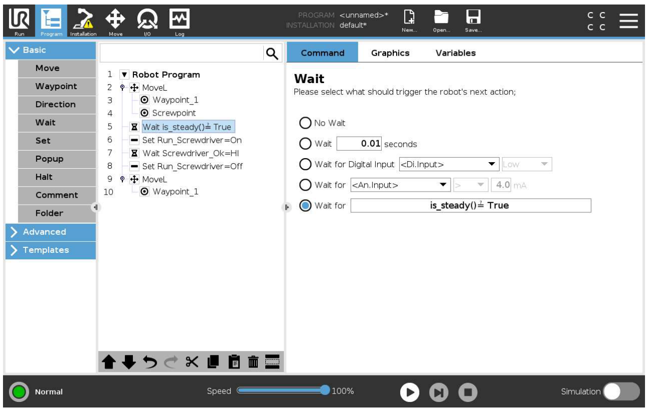
Scripts This behavior was introduced from SW version 3.2.20175 in CB3 and included in all subsequent versions, including all e-Series SW versions. The URScript function *is_steady()* returns *True* when the robot is in steady mode, False otherwise. It is not possible to change the state using this command (the robot will automatically enter it after 500 ms standing still with zero target velocity), it is purely intended to check whether the robot is in the steady state or not before performing the next action.

It is recommended to use the script is_steady() in a Wait command before running the screwdriver, to confirm that the robot is in steady mode before starting the tightening process. The robot should remain in steady mode until the screwdriver completes the tightening task, which means that no motion command should be executed in this time – should this happen, the robot would exit steady mode and execute that command, but it would then be subject to the normal limitations outside of steady mode, which may not be sufficient to counter the torque reaction from the tool at the end of the tightening process.
Since the robot has to be standing still to enter steady mode, it can't be used to push the screw or follow it into the threaded hole. If steady mode is required, a spring or other mechanical compensation should be used to follow the screw, so the robot can be fully at rest during the process.

CB3



E-Series


Robot Program
MoveL
Waypoint_1
Screwpoint
Wait is_steady()≟ True
Set Run_Screwdriver=On
Wait Screwdriver_Ok=HI
Set Run_Screwdriver=Off
MoveL
Waypoint_1
Command
Graphics
Variables
Wait
Please select what should trigger the robot's next action;
No Wait
Wait 0.01 seconds
Wait for Digital Input
Wait for
Wait for is_steady()≟ True
Normal
Speed 100%
Simulation

9. Screwdriving Functionality with Fast-Steady Mode

Description

The Screwdriving functionality is available in all e-Series SW versions from 5.4.0 onwards, but is not available in CB3.

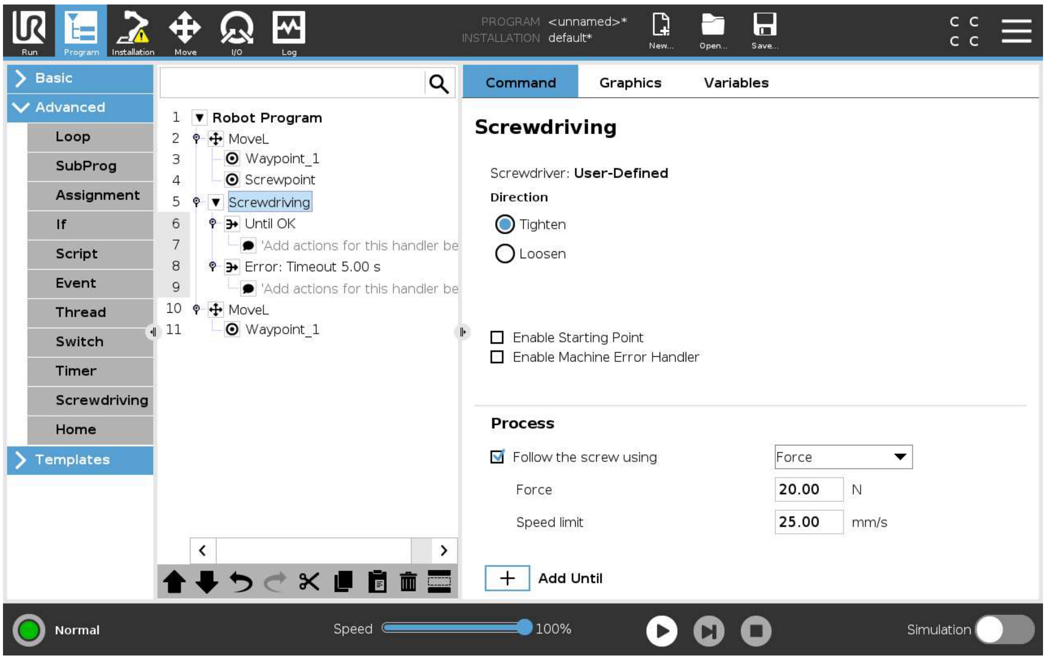
The Screwdriving functionality consists of an advanced command and an installation setup in PolyScope, as well as a URScript function: screw_driving(f, v_limit).

While the Screwdriving functionality makes it easier to set up a screwdriving application in general by enabling TCP selection, I/O exchange, direction selection, starting point, several strategies to follow the screw, and multiple success and errors conditions to end the process; one of the key benefits to using it is the ability to instantaneously change into steady mode when the torque reaction is detected (aka “fast-steady mode”).

When executing a Screwdriving command that uses controlled force and speed to push and follow the screw into the threaded hole, at the instant the torque reaction from the automatic screwdriver is detected, the robot automatically goes into fast-steady mode, in which the joints are allowed to generate more torque and accept larger deviations.

Screwdriving Command

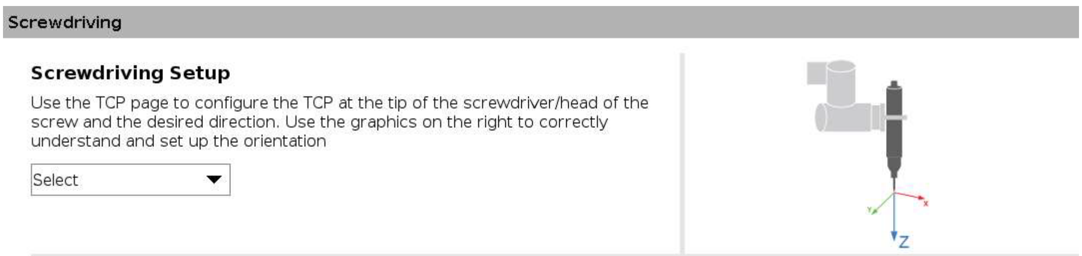
The Screwdriving command with the fast-steady mode behavior enables the robot to move during the tightening process, pushing and following the screw going into the threaded hole, while also ensuring that when the torque reaction is detected, this motion will be immediately stopped and the robot will be standing still with the maximum allowed current to maintain its position, and ready to accept larger joint deviations, should they occur, before triggering a protective stop.



The fast-steady mode behavior is only enabled when the checkbox "Follow the screw using" is selected with the "Force" option from its dropdown, in the process section of the Screwdriving command; or by using directly the URScript function screw_driving(f, v_limit).

Tool Center Position

The Tool Center Position should be defined as instructed in the Screwdriving installation setup in order to successfully detect the torque reaction that triggers fast-steady mode through Force and Torque Sensor readings and internal calculations. It should be observed that the positive Z direction of the TCP Orientation must be pointing directly into the hole into which the screw will be tightened.



Screwdriving Function

Since the torque reaction coming from the screwdriver is detected using the Force and Torque Sensor in the robot, its zeroing should be carefully considered. The F/T Sensor zero procedure must be carried out without the screwdriver pushing against the screw, or under the influence of any other external forces.

When using the Screwdriving command from PolyScope, the F/T Sensor is automatically zeroed at the start of each execution. Just before running a Screwdriving command, the screwdriver must be in the right position to start the tightening process, without any contact with the screw, workpiece, or anything else that could bias the F/T Sensor readings.

On the other hand, if using the URScript function screw_driving(f, v_limit) directly, the zero_ftsensor() function should be called before it manually, under the same conditions as described above.

screw_driving(*f*, *v_limit*)

Enter screw driving mode. The robot will exert a force in the TCP Z-axis direction at limited speed. This allows the robot to follow the screw during tightening/loosening operations.

Parameters

`f`: The amount of force the robot will exert along the TCP Z-axis (Newtons).

`v_limit`: Maximum TCP velocity along the Z axis (m/s).

Notes:

- Zero the F/T sensor without the screw driver pushing against the screw.
- Call `end_screw_driving` when the screw driving operation has completed.

```
>>> def testScrewDriver():
>>>     # Zero F/T sensor
>>>     sleep(0.02)
>>>     zero_ftsensor()
>>>
>>>     # Move the robot to the tightening position
>>>     # (i.e. just before contact with the screw)
>>>     ...
>>>
>>>     # Start following the screw while tightening
>>>     screw_driving(5.0, 0.1)
>>>
>>>     # Wait until screw driver reports OK or NOK
>>>     ...
>>>
>>>     # Exit screw driving mode
>>>     end_screw_driving()
>>> end
```

10. Safety Settings

Description	The safety system limits the current/torque of each joint according to the force limit, tool positions settings and several other parameters. The tool position should be defined at the tip of the screwdriver or nut runner, where it contacts the fastener. Having the TCP/tool positions configured properly and defining the least restricted tool force limit value that the risk assessment permits, enables the robot arm to handle higher tightening torques from an automatic screwdriver or nut runner.

11. Force Limits

Description

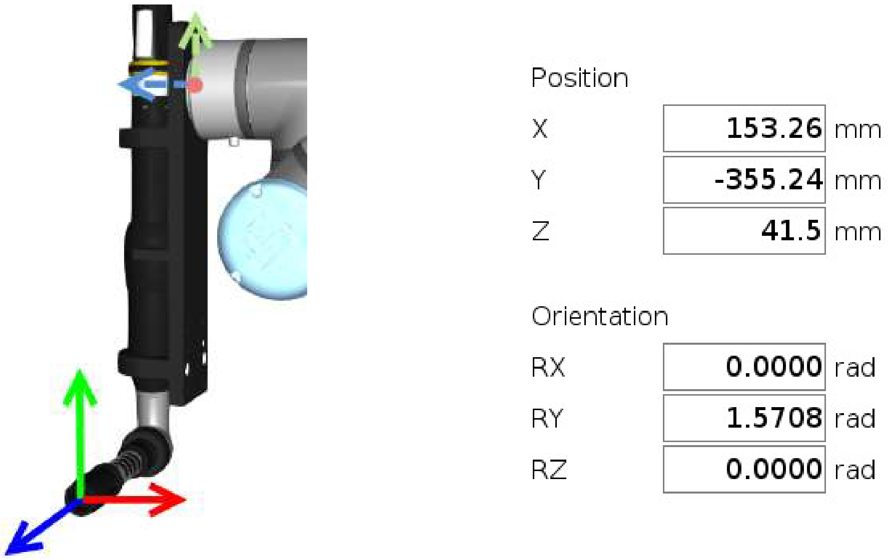
The force limits restrict the forces exerted by the robot at the TCP/tool positions (Tool Force) and elbow joint (Elbow Force, on e-Series only). The UR safety system continuously calculates the torque allowed for each joint, so that the TCP/tool positions and elbow joint stay within the force limits.

The least restricted force limits that the risk assessment permits should be implemented, to allow the joints to use more current/torque if needed.

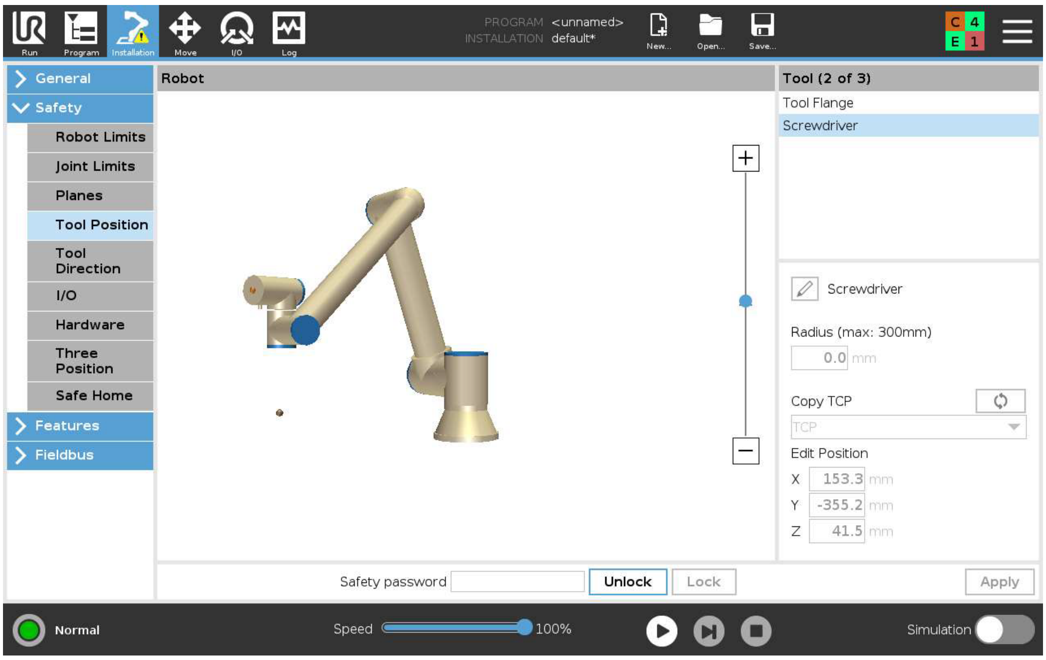
12. Tool Positions

Description

Define the Tool Center Point Position at the tip of the screwdriver or nut runner, and the Orientation with the positive Z direction pointing along the tightening axis towards the threaded hole into which the screw will be tightened.



In e-Series the TCP should be copied as a Tool Position in the Safety settings.



13. Robot Poses

Description

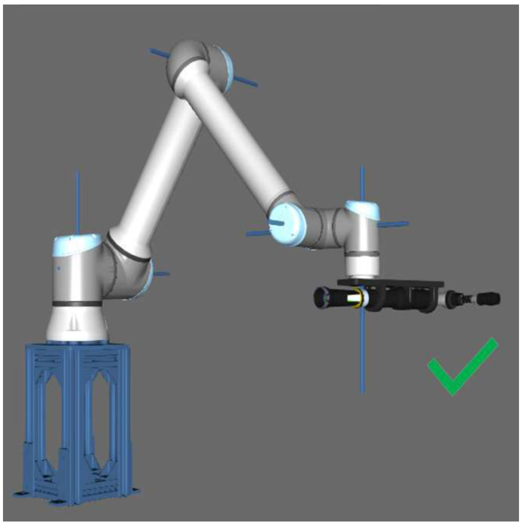
The robot poses for automatic screwdriving should be such that the screwdriving points are as far as possible from the robot joint axes, as long as none of the joints is loaded close to its maximum torque.

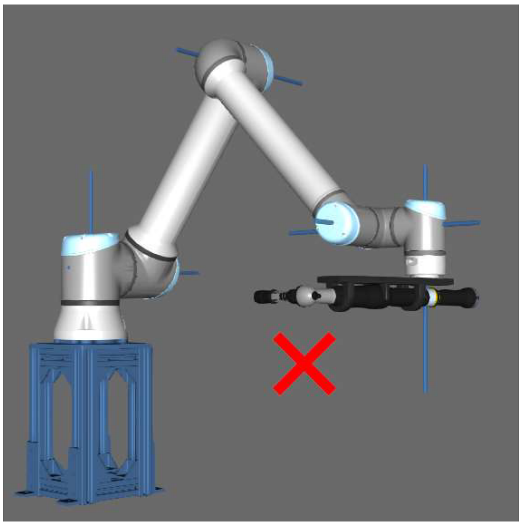
14. Screwdriving Points

Description

With the TCP/tool position properly defined, at each of the screwdriving points the tool force limit restricts the amount of torque allowed to be generated by each of the joints. Further to this, the lever arm concept tells us that a shorter lever arm results in generation of a larger force from the same torque. So if the robot is in a pose where the TCP is very close to any of the joints, the torque generated by that joint will be more restricted by the safety system to prevent high forces.

Therefore, where possible it's best to avoid poses where the TCP is closer to any of the joints.

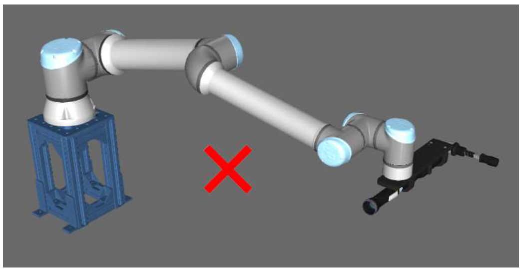


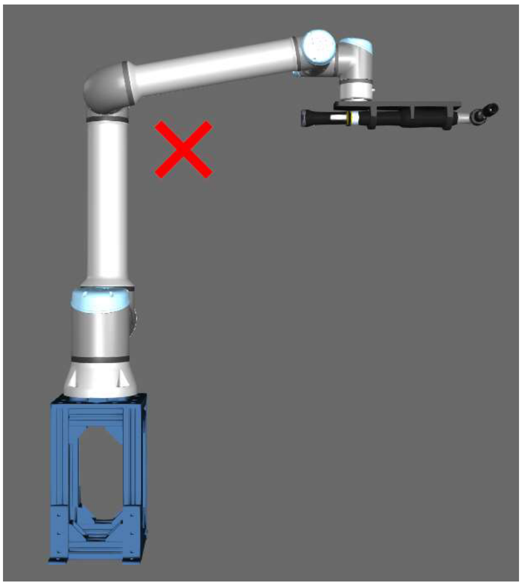


15. Maximum Joint Torque Values

Description

Robot poses with the arm fully extended (tool flange close to the outer workspace limit), or with one or more joints close to their maximum torque values should be avoided. Ideally the robot can use as much of the available torque in every joint as possible in counteracting the screwdriving torque, rather than maintaining the robot position.

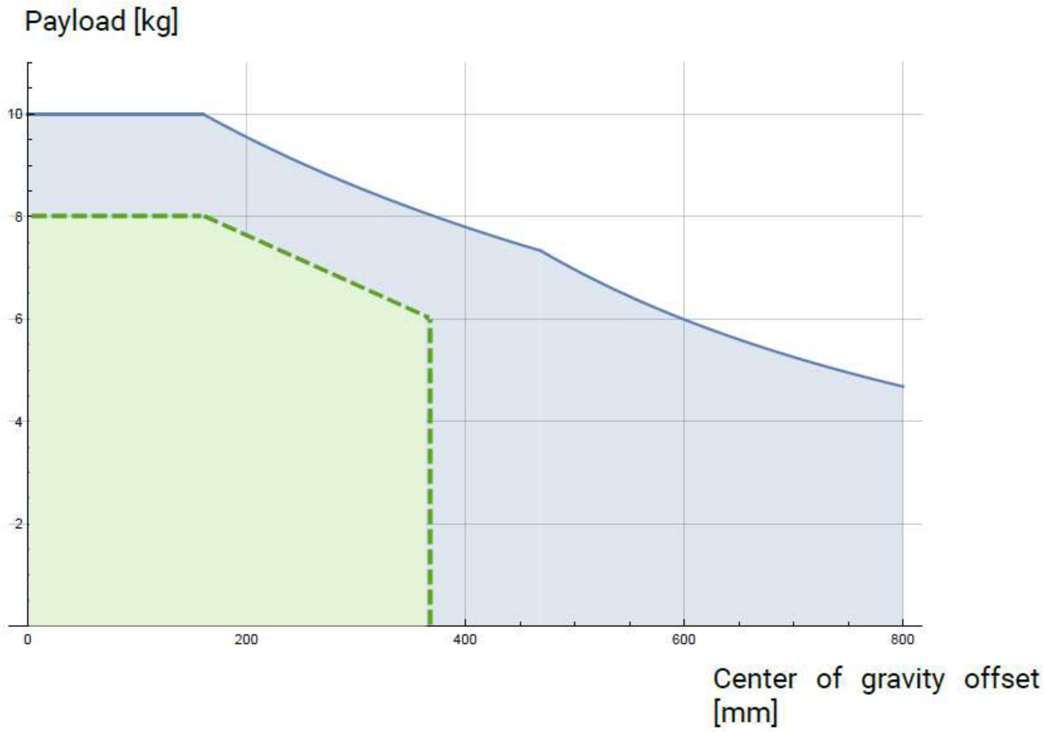




16. Payload

Description

The weight and center of gravity of the payload attached to the tool output flange of the robot should be defined accurately. In high torque screwdriving applications, the tool mounting should be as lightweight as possible, and its center of gravity offset should not be too close to the maximum payload vs center of gravity offset curve shown in the user manual. The below example shows the curve for UR10; the offset vs payload should lie within the green area for this type of application.



17. Alternative Solutions

Description

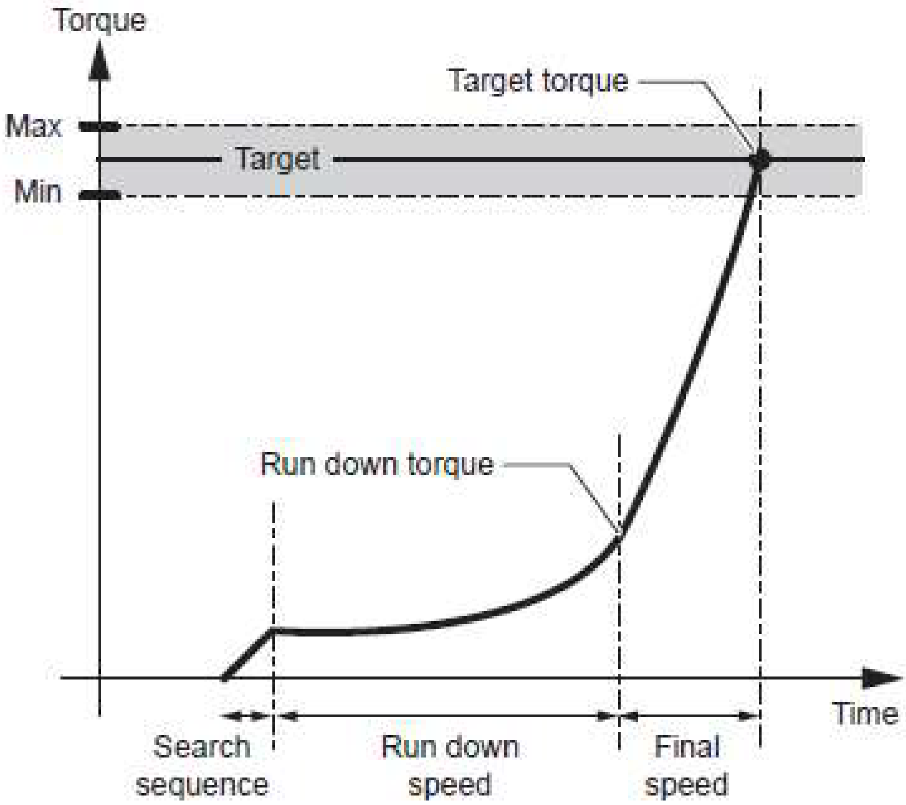
See the following topics about different solutions and methods for configuring a screwdriving installation:

18 Pulse-Driven Tools on the next page
19 Advanced Tightening Strategies on page 32
20 Torque Arms on page 33
21 Reaction Devices on page 34

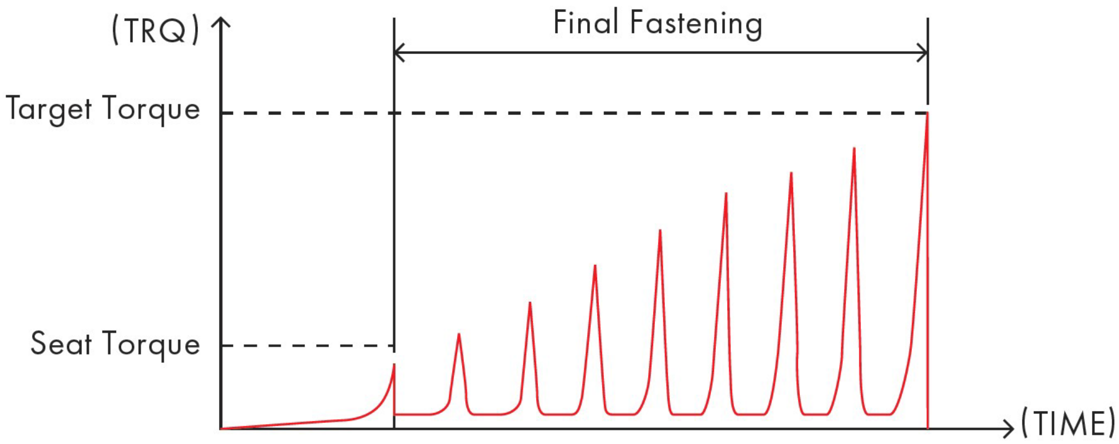
18. Pulse-Driven Tools

Description

Most automatic screwdrivers and nut runners use continuous fastening techniques, in which the torque is increased continuously until the target is reached:



A smaller group of tools use pulse-driven fastening techniques, in which the torque reaction is smaller than in continuous fastening (some manufacturers claim reductions of up to 70-80 % with pulse-driven tools) by applying the torque in a sequence of increasing torque pulses as shown below:



Some pulse-driven tools can reach tightening torques up to 150 Nm – 180 Nm, but accuracy of this torque may not be as high as a continuous tool, so they might not be suitable for some processes.

There have been successful trials using pulse-driven tools mounted to UR10/UR10e robots tightening up to 140 Nm, but while reducing the torque reaction with a pulse-driven tool could be better for the robot, the vibrations associated with this technique should always be carefully observed.

For reference, the following list includes pulse driven models from multiple manufacturers:

- ESTIC
  - Handy 2000 Lite plus (some models, e.g., EH2-R2120-A)
  - Handy 2000 Touch (some models)
  - Handy 2000 Cordless (some models)
- ATLAS COPCO
  - Pistol Cordless Pulse Tool TBP

19. Advanced Tightening Strategies

Description

Some manufacturers reduce the torque reaction of their tools by using advanced tightening strategies. The tightening strategy is one of the factors that impacts the maximum torque withstanding capabilities of the robot. These strategies control the speed, acceleration, torque progression and other parameters of the screw tightening process, all of which are significant to the maximum tightening torque that the robot can handle.

One example of this is Atlas Copco and their TurboTight strategy, in which the screwdriver controller reads joint stiffness feedback from the tool and based on this, regulates the speed of the tool such that it slows down at the exact time when the target torque is reached, almost completely eliminating the reaction force in the tool.

20. Torque Arms

Description

Torque arms can be used to absorb and transfer reaction force generated at the screwdriver during fastening from the robot to an external frame or structure. With a torque arm the robot only needs to move to the screwdriving point, the torque reaction is received by the torque arm. Some can balance the weight of the tool; however, they may also have a significant effect on freedom of movement, reducing the flexibility and reach of the robot.

One example is the SMC Carbon Arm from Atlas Copco, which has a lightweight telescopic design to maximize flexibility, and allow for smooth movements.

There are several options available with different mechanical configurations and payloads, however they do make the installation and programming of the robot more complex.

21. Reaction Devices

Description

This method involves mounting a reaction bar or plate onto the front of the tool and ensuring it has something solid to react against, which could be the workpiece itself if allowed. The torque reaction is then counteracted by the reaction device pushing against the workpiece or fixture.

22. Real-Time Data Analysis

Description

The software from Universal Robots makes it possible to log real-time data about your robot installation and how it is operating on a daily basis.
Please see the following topics to see some options for data collection and analysis.

23. Data Collection

Description

When recording data from the robot, the preferred interface is the Real-Time Data Exchange (port number 30004), and the most valuable fields to capture are:

- Joint angles/deviations
  - Target joint positions *(target_q)*
  - Actual joint positions *(actual_q)*
- Joint currents/torques
  - Target joint currents *(target_current)*
  - Actual joint currents *(actual_current)*
  - Joint current windows *(current_window)*
  - Target joint moments *(target_moment)*
- TCP pose
  - Target Cartesian coordinates of the tool *(target_TCP_pose)*
  - Actual Cartesian coordinates of the tool *(actual_TCP_pose)*
- TCP force
  - Generalized forces in the TCP *(actual_TCP_force)*
  - Raw force and torque measurement *(ft_raw_wrench)* - e-Series only, SW > 5.9.0
- Robot status
  - Safety mode *(safety_mode)*
  - Program state *(runtime_state)*

24. Data Interpretation

Description

When analyzing these data fields from a high torque screwdriving application with the payload properly defined, we should see that the actual currents start to deviate from target currents (in the main joints counteracting the tightening torque) during run down of the screw, with the largest deviation at the conclusion of the tightening as the torque reaction occurs.

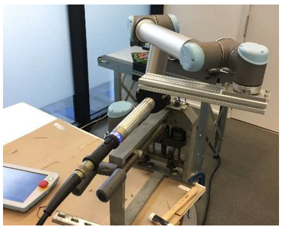
If any of the actual current values deviating from its target flattens out to horizontal as if they have hit a limit, this could be due to joint torque maximum values or safety system limitations (restricting allowed joint torques). These safety limit values change significantly depending on whether the robot is steady or not. When the joint current does hit a limit, position deviation is expected to occur, i.e., actual joint position deviates from target position since the joint does not have any more torque available to maintain its position. Once the joint angles start to deviate, a protective stop will be triggered if any joint exceeds its allowed position deviation. This permitted deviation is also larger when the robot is in steady mode.

While a gap between the actual and target currents during the screw or nut tightening process is acceptable, hitting any of the joint torque limits should be avoided. Any visible deviation of joint positions is not acceptable, even if not triggering a protective stop. Similarly, protective stops and any other types of errors or warnings (even if occurrence is isolated and random) should never be accepted as part of a well-deployed application.

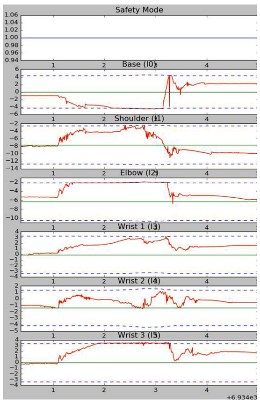
25. Example

UR10 CB3.0

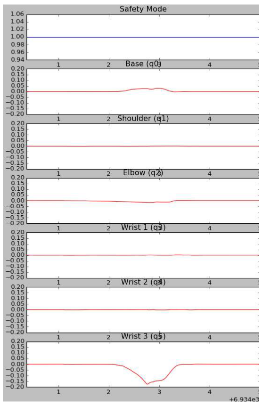
Robot	UR10 CB3.0
Software	3.4.5-100
Safety settings	Default (CCCC)
Steady mode	Yes
Fastening technique	Continuous
Target torque	120 Nm
Tool type	Right-angle nut runner



Joint Graphs



Joint currents [A]
----target ----actual



Joint deviations [rad]

Description

According to the above data plots, although the robot is in steady mode and no protective stop has occurred, this is not an acceptable scenario for a high torque screwdriving application.

The Base, Elbow and Wrist 3 currents are deviating from their targets as expected, but they are then hitting a limit, shown by the plots flattening to horizontal. This means that these joints cannot apply any more torque to oppose to the force that is transferred from the screwdriver, and position deviation protective stops are likely to occur.

In the right plots, angle deviations can be observed in all three joints that hit the limit in the left plots, with the biggest deviation in Wrist 3. Mounting a right-angle nut runner with Wrist 3 aligned with the tightening axis is likely to produce a large deviation in that joint when torque limits are reached. Wrist 3 deviation reaches roughly 10 degrees, at which point it would also be clearly visible to the naked eye.

The robot pose has the tip of the screwdriver (TCP) beneath the lower arm very close to the elbow joint axis of the robot. This condition together with the default safety settings force limit restricts the allowed torque of this joint, and it is subsequently the first one to hit its limit.

A number of the recommendations presented in this document to increase the torque withstanding capabilities of the robot have been applied in this example, but due to the 120 Nm target torque (that we earlier classified in the most difficult category - not extensively researched, most likely requires innovative technologies or additional hardware), careful consideration of all recommendations and an exhaustive analysis of data is required. Even then, alternative solutions such as pulse-driven tools or torque arms may be necessary to successfully deploy this application.

26. Change Log

Description

Date	Version	Description	Author
31. December 2020	1.0	Document creation in final version.	Germán Baños
4. January 2021	1.1	Added real-time data analysis information. Added more information to screwdriving functionality with fast-steady mode.	Germán Baños
20. January 2021	1.2	Content/copy editing	Andrew Pether
29. January 2021	2.0	Internal release	Germán Baños

27. Glossary

A

Automatic Screwdriver/Nut Runner

A tool mounted to the robot's tool output flange used for tightening screws or nuts automatically.

C

Coordinated Motion

Coordinated Motion is part of the MotionPlus software add-on package that synchronizes time, position, and speed between the robot’s six motorized axes and one or more external axes. This synchronization allows for the motion of the TCP relative to a moving frame attached to an external axis, streamlining complex tasks across various applications.

CSI

Custom Systems Integrator

E

e-Series

M

MyTerm

T

TCP

The robot's tool center point

740-949-00