User's manual: KUKA Sunrise Toolbox

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Part I. Introduction

The KUKA Sunrise Toolbox (KST) is a MATLAB toolbox which can be used to control KUKA iiwa R 800 and R 820 manipulators from an external computer using MATLAB. The toolbox is available, under MIT license, from the following Github repository:

`https://github.com/Modi1987/KST-Kuka-Sunrise-Toolbox`

In addition video tutorials about the toolbox are available in the link:

`www.youtube.com/watch?v=_yTK0Gi0p3g&list=PLz558OYgHuZdVzTaB79iM8Y8u6EjFe0d8`

and the link (recommended but still in progress):

`https://www.youtube.com/playlist?list=PLz558OYgHuZd-Gc2-OryITKEXefAmrvae`

The user may consult the videos in tandem with this document.

About

Using the KST, the user can control the KUKA iiwa robot from his/her computer without requiring a knowledge about programming the industrial manipulator, as such any person with a basic knowledge of MATLAB can control the robot remotely from an external PC. The toolbox provides numerous methods that can be divided roughly into the following categories:

- Networking
- Soft real-time control
- Point-to-point motion functions
- Setters
- Getters
- General purpose
- Physical interaction

This documentation provides instructions on the utilization of the KST class, in addition it lists the various methods provided by the Toolbox along with a briefing about their functionality and their way of use. Each method is elaborated in a subsection with the following main entries:

- Syntax: lists the MALAB syntax for calling the method in subject, written in a MATLAB script style.
- Description: a brief description about the the method in subject.
- Arguments: describes the arguments taken by the method in subject.
- Return values: describes the variables returned after the execution of the method in subject.

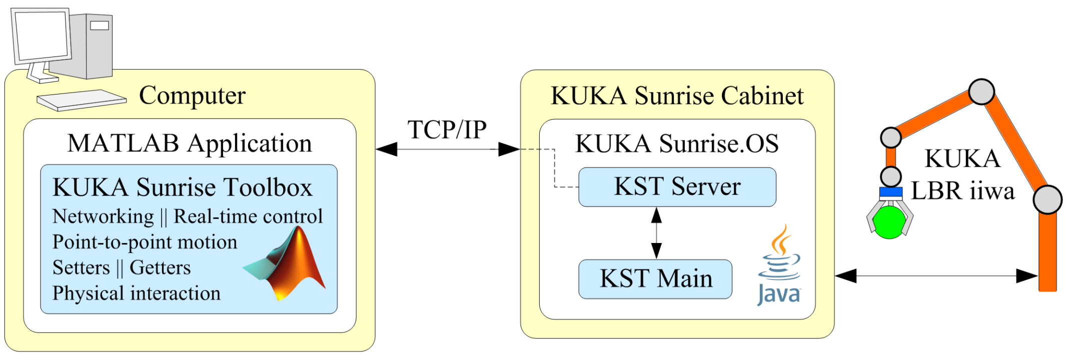


Fig. 0.1: Architecture of the toolbox

Some methods may contain one or both of the following extra entries:

- About: used to give a prerequisite info or an in-depth explanation about the method in subject or about the robot's operation mode, as in the "precise hand-guiding method".
- Tutorial script: this entry refers to the file of the repository where the method in subject is used, the tutorial script is a MATLAB script (m file), the user can open it using MATLAB, it is documented with comments. For a hands on experience the user can run this script to control the robot.

Architecture of KST

The KST has a client server architecture, Figure 0.1, the server is a multi-threaded Java application that runs inside the robot controller. Before starting to utilize the toolbox the user shall synchronize the server application into the robot controller, after being synchronized the user shall run the server, once is running, the toolbox can be used to connect to the robot from Matlab.

On the other hand, the client part is written using Matlab scripting language, the various functions offered by the toolbox are wrapped inside the KST.m class, the user can use this class to control the robot from Matlab.

Part II. Getting started, the requirements

Before starting to use the Toolbox for controlling the robot, the following software/hardware are required:

Hardware requirements

The user is required to have:

1. One of KUKA iiwa manipulators R800 or R820.
2. An up-to-date external PC/laptop with good computational power.
3. Good Ethernet cable, a category five or better.

A network between the robot and the PC shall be established. To establish the network the user shall do the following:

- Using an Ethernet cable, connect the X66 port of the robot to the Ethernet port of your PC.
- From the teach pendant of the manipulator, verify the IP of the robot, (explained in the video tutorials “Tutorial 1”).
- Then on the external PC, the user shall change the IP of the PC into a static IP in the range of robot’s IP.

Software requirements

The following software packages are required:

- MATLAB: the user shall have MATLAB installed on his PC, using MATLAB and KST, the user will be able to control the manipulator from the external PC, in such a case the user may use the operating system of his preference, Windows, Linux or Mac.
- Sunrsie.Workbench: the user will need the Sunrsie.Workbench only once to synchronize the (MatlabToolboxServer) application of the KST to the controller of the robot.

Synchronizing KST server to the controller

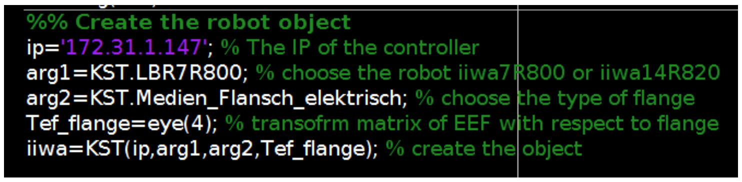
The server application that runs in the robot controller is named (MatlabToolboxServer), it is a Java application written using Kuka’s Sunrsie.Workbench program.

The source code of the server application is given inside the folder ***KUKA Sunrise server source code,*** which is found inside the toolbox repository, several versions of the server are provided the user is advised to read the ***About.txt*** file which is found along with the server source code for more info. This server application shall be synchronized to the robot controller and shall be running before controlling the robot from an external computer using Matlab.

The steps of synchronizing the MatlabToolboxServer application into the robot controller is described in the video tutorial:

`https://youtu.be/fhzCyQRUNiA?list=PLz558OYgHuZd-Gc2-OryITKEXefAmrvae`

The same steps are also described in the file, ***Import KST to Sunrise-Workbench.pdf*** , which is found in the root folder of the toolbox repository.



```
%% Create the robot object
ip='172.31.1.147'; % The IP of the controller
arg1=KST.LBR7R800; % choose the robot iiwa7R800 or iiwa14R820
arg2=KST.Medien_Flansch_elektrisch; % choose the type of flange
Tef_flange=eye(4); % transofrm matrix of EEF with respect to flange
iiwa=KST(ip,arg1,arg2,Tef_flange); % create the object
```

Fig. 0.2: Code snippet from the robot examples where the IP of the controller is defined(variable ip), type of the robot and the flange are defined (variables, arg1 and arg2).

Part III. Practical examples

The toolbox is provided with practical examples (Demos). The user may consult those examples for a quick start up. The examples vary in difficulty, some are simple with straightforward implementation of KST motion functions, others are more complicated and show the user how to utilize the full power of the toolbox by utilizing KST's motion functions along with direct/inverse kinematics, implementing graphical user interfaces and integrating other MALAB toolboxes and/or external hardware to control the manipulator.

How to run the provided examples

To run any of the provided examples on your own iiwa, the user shall follow the steps:

- Using MATLAB, open the example that you want to run.
- Go to the line where the IP of the robot is defined, shown in the code snippet Fig 0.2, change its value into the IP of your own robot.
- Go to the lines where the type of the robot and the type of the flange are defined, Fig 0.2, change them according to the configuration of your own robot/flange combination.
- Go to the line where the tool attached to the flange is defined, change it according to the tool attached to the flange.
- Start the MatlabToolboxServer application from the teach pendant of the robot, shown in Fig 0.3.
- Run The MATLAB script example that you chose.
- Note that by default, the MatlabToolboxServer application turns off automatically if a connection is not established during sixty seconds interval from its initiation. If this happened, you shall turn on the application manually before starting a connection again.

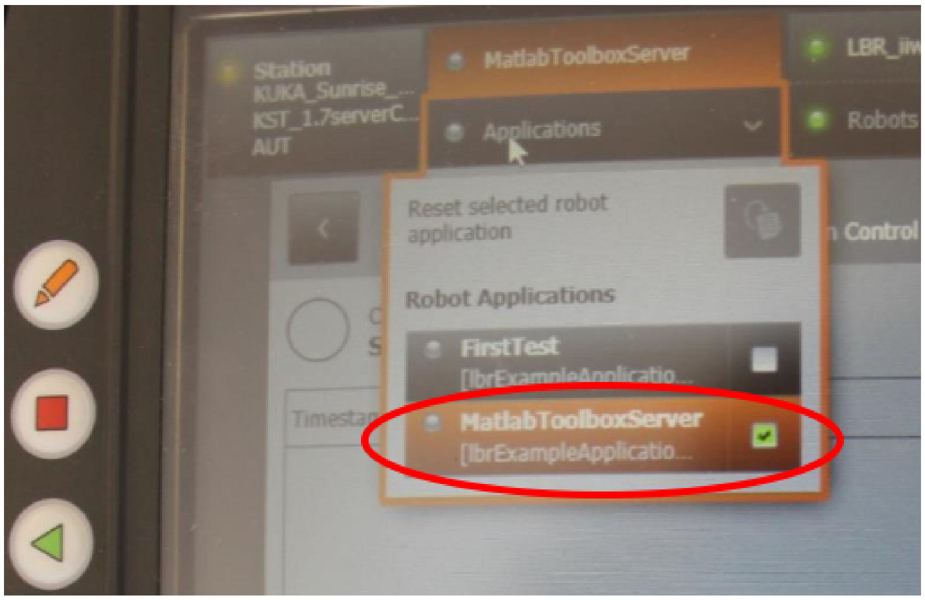


Fig. 0.3: Starting the MatlabToolboxServer application from teach pendant.

Total list of examples

Example	Description
KSTclass_Tutorial_getters	Demonstrates how to utilize the getters functions supported by KST, which are used to read the various parameters of the robot.
KSTclass_Tutorial_generalPorpuse	Demonstrates how to utilize the general purpose functions of the KST for calculating: Jacobian matrix, mass matrix, centrifugal matrix, Coriolis matrix. In addition it demonstrates how to use KST for calculating direct/inverse kinematics, direct/inverse dynamics, etc.
KSTclass_Tutorial_move_ptp	Demonstrates how to utilize the point to point motion functions supported by KST.
KSTclass_Tutorial_circles	Demonstrates how to utilize the various circle motion functions supported by KST.
KSTclass_Tutorial_ptpConditional Torques	Demonstrates how to utilize the conditional point to point motion functions supported by the KST. In those functions the motion can be interrupted during physical interaction with the robot, such is the case if one of the joint's torques exceeds a predefined limit.
KSTclass_Tutorial_nonBlocking PTPLinesJoints	Demonstrates how to utilize the non blocking functions provided by KST toolbox.
KSTclass_Tutorial_ptpPickPlace	A pick and place application. When

Example	Description
KSTclass_Tutorial_directServo Cartesian	Demonstrates how to utilize KST's soft-real-time motion functionalities based on KUKA's DirectServo interface. In this example the robot is in joints position control mode, the motion of the first joint of the robot is controlled by streaming joints destination angles to the robot. In this example the motion of the first joint is specified by a sinusoidal function, while the other joints angles are kept fixed.
KSTclass_Tutorial_softRealTime JointsVelControl	Demonstrates how to utilize KST's soft-real-time motion functionalities based on KUKA's DirectServo interface. In this example the robot is in joints velocity control mode, the motion of the first joint of the robot is controlled by streaming the joints angular velocities to the robot. The motion of the first joint is specified by a sinusoidal function.
KSTclass_Tutorial_realTime ImpedencePlotTorqueFeedBack	Demonstrates how to utilize KST's soft-real-time impedance motion functionalities based on KUKA's SmartServo interface. In this example the robot is in impedance control mode, the motion of the various joints of the robot is controlled by streaming angular positions to the robot. The motion of the joints are specified by a sinusoidal function. At the same time Matlab plots a graph of joints torques as acquired from the robot.

Tab. 2: Practical examples provided with the KST repository (2)

Example	Description
KSTclass_Tutorial_tele Operation	In this example the user can control the EEF of the robot using a 3Dconnexion SpaceMouse. To run this example the user shall first install the appropriate 3Dconnexion drivers, then he/she shall connect the SpaceMouse to the PC. In general, this example demonstrates how to use external hardware to control the robot, in addition it demonstrates how to use the direct/inverse kinematics functions provided by KST.
KSTclass_Tutorial_iiwa_vrep	Example of controlling KUKA iiwa from 3D simulation by using KST as a middle-ware. The simulator used is V-rep. This software is a powerful robotic simulation environment that offers users the option to control their 3D simulations from MATLAB. In such a case, by using KST the user can control KUKA iiwa manipulator directly from his/her 3D simulation developed using V-rep & MATLAB. This example is provided with V-rep simulation scene: iiwaFromVrep.ttt
KSTclass_Tutorial_gampade_EEF PosControl	In this example the user is able to use a game pad for controlling the position and orientation of the EEF of KUKA iiwa robot. This example demonstrates how to integrate external hardware to control the robot, at the same time it demonstrates how to utilize direct/inverse kinematics functions of KST toolbox.
KSTclass_Tutorial_gampade_joints PosControl	In this example the user is able to use a game pad for controlling joints positions of KUKA iiwa robot. This example demonstrates how to integrate external hardware to control the robot, at the same time it demonstrates how to integrate a graphical user interface into the application.

Tab. 3: Practical examples provided with the KST repository (3)

Part IV. KST class

Starting from version KST_1.7, object oriented programming is implemented, as such the various functionalities of the toolbox is encapsulated inside the KST.m class, this class contains various properties and methods, using which the user can control the robot. To get an access to those methods, the user shall instantiate an object from the KST class first, as in the following:

```
>> iiwa = KST(ip,robot_Type,flange_Type,Tef_flange);
```

Where:

- `iiwa`: is an instance of the KST class.
- `ip`: a string variable which contains the IP of the robot, e.g. “172.31.1.147”. In order to figure out the IP of your robot, first go to the teach pendant of the robot and click on the button “Station” that is found at the top side of the teach pendant’s screen, then click on the button “Information”, finally you can find the IP of the robot listed under the title “Station Server IP”.
- `robot_Type`: is a constant referring to robot type 7R800 or 14R820, please refer to section V **Properties of KST class** for more info.
- `flange_Type`: is a constant referring to flange’s type, please refer to section V **Properties of KST class** for more info.
- `Tef_flange`: is 4x4 matrix, representing the transformation matrix of EEF with respect to the frame of the flange. `Tef_flange` is an optional argument if omitted the KST uses the identity matrix by default.

Example:

In this example an instance of the KST class associated with LBR7R800 robot is created.

```
>> ip='172.31.1.147';
>> robot_Type=KST.LBR7R800;
>> flange_Type=KST.Medien_Flansch_elektrisch;
>> Tef_flange=eye(4);
>> iiwa = KST(ip,robot_Type,flange_Type,Tef_flange)
```

Property	Description
m	1x7 array of links masses
pcii	3x7 array, each column specifies the position vector of Center Of Mass (COM) of each link described in its local frame
I	4x4x7 each 4x4 matrix specifies the inertial tensor of a link
Fs	1x7 array of joints Coulomb friction
Fv	1x7 array of joints viscous friction coefficients

Tab. 4: Different fields of the property from an instance of KST class.

Property	Description
LBR7R800	For specifying 7 R 800 robot
LBR14R820	For specifying 14 R 820 robot

Tab. 5: Robot's type enumeration‘

Part V. Properties of KST class

KST class implements several properties, some are read only while others can be modified. The different properties are:

1. ip: a string variable specifying the IP of the robot, this variable is assigned when the constructor of the KST class is called.

2. I_data: a structure with several fields, Table 4, used to specify the inertial/dynamic constants of the robot, this structure is loaded automatically when the constructor of the KST class is called. The appropriate data of the LBR7R800 or the LBR14R820 is loaded according to the type of robot specified when the constructor of the KST class is called. The inertial data identified in [1] are used for the LBR14R820, while the inertial data identified [2] in are used for LBR7R800

3. dh_data: a structure with DH parameters of the robot, the appropriate DH parameters, of the LBR7R800 or the LBR14R820, are loaded automatically according the the type of robot specified when the constructor of the KST class is called.

4. Teftool: is the transformation matrix from the frame of EEF to the frame of the flange.

Also the toolbox provides the following two groups of enumerations, one is used to specify the robot's type, Table 5, while the other is used to specify the flange's type, Table 6.

Property	Description
Medien_Flansch_elektrisch	For an electric median flange
Medien_Flansch_pneumatisch	For a pneumatic flange
Medien_Flansch_IO_pneumatisch	For a pneumatic flange with IOs
Medien_Flansch_Touch_pneumatisch	For a touch pneumatic flange

Tab. 6: Flange type enumeration

Part VI. Methods of KST class

In this part of the documentation a list of the supported methods by KST is presented along with a brief description about its utilization in a MATLAB script. In the following the variable `iiwa` is used as an instance of the KST class.

1 Networking

Networking functions are used to administer the network communication between the external PC and the controller. This section lists those functions along with a brief description:

1.1 `net_establishConnection`

- `Syntax:`

  `>> iiwa.net_establishConnection()`

- Description:

  This function is used to establish a connection with the MatlabToolboxServer application on the controller.

- Arguments:

  - `None`.

- Return values:

  - `None`.

- Tutorial script

  - `KSTclass_Tutorial_networking.m`

1.2 `net_turnOffServer`

- `Syntax:`

  `>> iiwa.net_turnOffServer()`

- Description:

  This function is used to turn off the server on the robot.

- Arguments:

  - None.

- Return values:
  - None.

- Tutorial script
  - `KSTclass_Tutorial_networking.m`

1.3 `net_updateDelay`

- **Syntax:**

  `>> [time_stamps,time_delay] = iiwa.net_updateDelay()`

- Description:

  This function is used to establish a plot of the communication delay between the computer and the controller, i. e., it tests the timing connection characteristics between KUKA iiwa and the computer.

- Arguments:
  - None.

- Return values:
  - `time_stamps`: is the time stamp of each socket.
  - `time_delay`: is the delay for each socket.

- Tutorial script
  - `KSTclass_Tutorial_plotNetHealth.m`

1.4 `net_pingIIWA`

- **Syntax:**

  `>> iiwa.net_pingIIWA()`

- Description:

  This function is used to ping the robot controller, afterwards it prints on MATLAB's command window the timing characteristics of the ping operation.

- Arguments:
  - None.
- Return values:
  - None.
- Tutorial script
  - `KSTclass_Tutorial_networking.m`

2 Soft real-time control

In this group of functions the user can move the robot on-the-fly by streaming the positions to the controller, this is important for dynamic paths where the path is changing according to changes in the surrounding environment, for example according to the position of dynamic obstacles moving in the environment. Below, it is listed the soft real-time control functions along with utilization instructions.

2.1 `realTime_moveOnPathInJointSpace`

- `Syntax:`

  `>> iiwa.realTime_moveOnPathInJointSpace(trajectory, delayTime)`

- Description:

  This function is used to move the robot continuously in joint space.

- Arguments:

  - `trajectory:` is a 7xn array, this array is a concatenation of the joints angles describing the configurations taken by the robot during the motion.
  - `delayTime`: is the time delay between two

- Return values:

  - None.

- Tutorial script

  - `KSTclass_Tutorial_do_some_stuff.m`

2.2 `realTime_startDirectServoJoints`

- `Syntax:`

  `>> iiwa.realTime_startDirectServoJoints()`

- Description:

  This method is used to turn on the DirectServo function on the robot for initiating the soft real-time control in a joint space. After starting DirectServo function, the user have to stream the joints' target positions to the robot using the function `(sendJointsPositions)`.

- Arguments:

  - None.

- Return values:
  - None.

- Related functions:
  - `sendJointsPositions`
  - `realTime_stopDirectServoJoints`

- Tutorial script
  - `KSTclass_Tutorial_directServo.m`

2.3 `realTime_stopDirectServoJoints`

- **Syntax:**

  ```
  >> iiwa.realTime_stopDirectServoJoints()
  ```

- Description:

  This function is used to turn off the DirectServo function on the robot ending the soft real-time control.

- Arguments:
  - None.

- Return values:
  - None.

- Related functions:
  - `sendJointsPositions`
  - `realTime_startDirectServoJoints`

- Tutorial script
  - `KSTclass_Tutorial_directServo.m`

2.4 `realTime_startImpedanceJoints`

- `Syntax:`

  `>> iiwa.realTime_startImpedanceJoints(tw, cOMx, cOMy, cOMz, cS, rS, nS)`

- Description:

  This function is used for starting the soft real-time control at the joints level in the impedance mode.

- Arguments:

  - `tw`: is the weight of the tool attached to the flange (kg).
  - `cOMx`: is the X position of the tool's center of the mass in the flange referenced frame.
  - `cOMy`: is the Y position of the tool's center of the mass in the flange referenced frame.
  - `cOMz`: is the Z position of the tool's center of the mass in the flange referenced frame.
  - `cS`: is the Cartesian linear stiffness in the range of [0 to 4000].
  - `rS`: is the cartesian angular stifness in the range of [0 to 300].
  - `nS`: is the null space stiffness.

- Return values:

  - None.

- Related functions:

  - `sendJointsPositions`
  - `realTime_stopImpedanceJoints`

- Tutorial script

  - `KSTclass_Tutorial_realTimeImpedencePlotTorqueFeedBack.m`

2.5 `realTime_stopImpedanceJoints`

- **Syntax:**

  `>> iiwa.realTime_stopImpedanceJoints()`

- Description:

  This function is used to stop the soft real-time control at the joints level in the impedance mode.

- Arguments:
  - None.

- Return values:
  - None.

- Related functions:
  - `sendJointsPositions`
  - `realTime_startImpedanceJoints`

- Tutorial script
  - `KSTclass_Tutorial_realTimeImpedencePlotTorqueFeedBack.m`

2.6 `sendJointsPositions`

- **Syntax:**

  `>> [ret]=iiwa.sendJointsPositions(jPos)`

- Description:

  This function is used to send target joints' position to the robot for the soft real-time control at the joints level, it can be used in both modes, the DirectServo mode and the impedance mode. This function is blocking, it awaits for an acknowledgment from the server before returning back to execution.

- Arguments:
  - `jPos`: is a 7x1 cell array representing the target joints' positions, units in radians.

- Return values:

  - `ret`: the return value is true if the joints' position message has been received and processed successfully by the server, or false otherwise.

- Tutorial script
  - `KSTclass_Tutorial_directServo.m`

2.7 `sendJointsPositionsf`

- **Syntax:**

  `>> iiwa.sendJointsPositionsf(jPos)`

- Description:

  This function is used to send target joints' position to the robot for the soft real-time control at the joints level, it can be used in both modes, the DirectServo mode and the impedance mode. This function is non-blocking, it is one way and does not awaits for an acknowledgment from the server. This function is computationally light-weight, and it is designed for implementation in computationally expensive algorithms. When utilized in low-computational-cost algorithms, this function can execute very fast, as a result sending command packets to the robot at high rates (4K hz), this might cause execution issues, to solve this problem the user may need to perform some timing as to guarantee a transmission rate of around 275 packets/second, for an example about the best practice for using this function please refer to script (`Tutorial_directServoFast.m`) in github repo.

- Arguments:
  - `jPos`: is a 7x1 cell array representing the target joints' positions, units in radians.

- Return values:
  - None.

- Tutorial script
  - `KSTclass_Tutorial_directServoFast.m`

2.8 `sendJointsPositionsExTorque`

- `Syntax:`

  `>> [torques] = iiwa.sendJointsPositionsExTorque(jPos)`

- Description:

  This function is used to send target joints' position to the robot for the soft real-time control at the joints level while simultaneously it returns a feed back about the external torques in the joints due to external forces acting on the structure of the robot, this function can be used in both modes, the DirectServo mode and the impedance mode. This function is blocking, it awaits for the torques message from the server before returning back to execution.

- Arguments:

  - `jPos`: is a 7x1 cell array representing the target joints' positions, units in radians.

- Return values:

  - `torques`: a 7x1 cell array with joints' torques due to the external forces acting on the robot structure.

2.9 `sendJointsPositionsMTorque`

- `Syntax:`

  `>> [torques] = iiwa.sendJointsPositionsMTorque(jPos)`

- Description:

  This function is used to send target joints' position to the robot for the soft real-time control at the joints level while simultaneously it returns a feed back about the torques in the joints as measured by the integrated sensors, this function can be used in both modes, the DirectServo mode and the impedance mode. This function is blocking, it awaits for the torques message from the server before returning back to execution.

- Arguments:

  - `jPos`: is a 7x1 cell array representing the target joints' positions, units in radians.

- Return values:

  - `torques`: a 7x1 cell array with joints' torques as measured by the integrated torque sensors.

- Tutorial script

  - `KSTclass_Tutorial_realTimeImpedencePlotTorqueFeedBack.m`

2.10 `sendJointsPositionsGetActualJpos`

- **Syntax:**

  `>> [actual_JPOS] = iiwa.sendJointsPositionsGetActualJpos(target_jPos)`

- Description:

  This function is used to send target joints' position to the robot for the soft real-time control at the joints level while simultaneously it returns a feed back about the actual joints positions as measured by the encoders integrated in the robot. This function can be used in both modes, the DirectServo mode and the impedance mode. This function is blocking, it awaits for the position message from the server before returning back to execution.

- Arguments:

  - `target_jPosos`: is a 7x1 cell array representing the target joints' positions, units in radians.

- Return values:

  - `actual_JPOS`: a 7x1 cell array with joints' actual positions as measured by the integrated sensors in the robot.

2.11 `sendJointsPositionsGetActualEEFpos`

- **Syntax:**

  `>> [EEF_POS] = iiwa.sendJointsPositionsGetActualEEFpos(jPos)`

- Description:

  This function is used to send target joints' position to the robot for the soft real-time control at the joints level while simultaneously it returns a feed back about the actual EEF positions as measured by the sensors integrated in the robot. This function can be used in both modes, the

DirectServo mode and the impedance mode. This function is blocking, it awaits for the position message from the server before returning back to execution.

- Arguments:
  - `jPos`: is a 7x1 cell array representing the target joints' positions, units in radians.
- Return values:
  - `EEF_POS`: a 6x1 cell array with EEF actual positions as measured by the integrated sensors in the robot.

2.12 `realTime_startDirectServoCartesian`

- `Syntax:`

  `>> iiwa.realTime_startDirectServoCartesian()`
- Description:

  This function starts the DirectServo for controlling the robot in Cartesian space at the robot's EEF level.
- Arguments:
  - None.
- Return values:
  - None.
- Related functions:
  - `sendEEfPosition`
  - `realTime_stopDirectServoCartesian`
- Tutorial script
  - `KSTclass_Tutorial_directServoCartesian.m`

2.13 `realTime_stopDirectServoCartesian`

- `Syntax:`
  `>> iiwa.realTime_stopDirectServoCartesian()`
- Description:
  This function stop the DirectServo for controlling the robot in Cartesian space at the robot's EEF level.
- Arguments:
  - None.
- Return values:
  - None.
- Related functions:
  - `sendEEfPosition`
  - `realTime_startDirectServoCartesian`
- Tutorial script
  - `KSTclass_Tutorial_directServoCartesian.m`

2.14 `sendEEfPosition`

- `Syntax:`
  `>> [ret] = iiwa.sendEEfPosition(EEEFpos)`
- Description:
  This function is used to set the target position of the End-Effector, this function is blocking, it awaits for an acknowledgment from the server before returning the execution.
- Arguments:
  - `EEEFpos:` is a 6x1 cell array where the first three elements represent (X, Y, Z) target positions of EEF (mm) and the last three elements represent the fixed rotation angles of EEF (radians).
- Return values:
  - `ret`: the return value is true if the position message has been received and processed successfully by the server, or false otherwise.

- Related functions:
  - `realTime_startDirectServoCartesian`
  - `realTime_stopDirectServoCartesian`
- Tutorial script
  - `KSTclass_Tutorial_directServoCartesian1.m`

2.15 `sendEEfPositionf`

- **Syntax:**

  `>> iiwa.sendEEfPositionf(EEEFpos)`

- Description:

  This function is used to set the target position of the End-Effector, this function is not blocking, and does not wait for an acknowledgment from the server before returning the execution. As a result, this function is computationally light-weight, and it is designed for implementation in computationally expensive algorithms. When utilized in low-computational-cost algorithms, this function can execute very fast, as a result sending command packets to the robot at high rates (4K hz), this might cause execution issues, to solve this problem the user may need to perform some timing as to guarantee a transmission rate of around 275 packets/second.

- Arguments:
  - `EEEFpos:` is a 6x1 cell array where the first three elements represent (X, Y, Z) target positions of EEF (mm) and the last three elements represent the fixed rotation angles of EEF (radians).
- Return values:
  - None
- Related functions:
  - `realTime_startDirectServoCartesian`
  - `realTime_stopDirectServoCartesian`
- Tutorial script
  - `KSTclass_Tutorial_directServoCartesian.m`

2.16 sendEEfPositionExTorque

- Syntax:
  `>> [ExTorque] = iiwa.sendEEfPositionExTorque(EEEFpos)`
- Description:
  This function is used to send target position of EEF to the robot for the soft real-time control at the EEF level while simultaneously it returns a feed back about the external torques due to external forces acting on the robot. This function is blocking, it awaits for the torques message from the server before returning back to execution.
- Arguments:
  - `EEEFpos:` is a 6x1 cell array where the first three elements represent (X, Y, Z) target positions of EEF (mm) and the last three elements represent the fixed rotation angles of EEF (radians).
- Return values:
  - `ExTorque`: 7x1 cell array of the joint torques due to external forces acting on robot structure.
- Related functions:
  - `realTime_startDirectServoCartesian`
  - `realTime_stopDirectServoCartesian`

2.17 sendEEfPositionMTorque

- Syntax:
  `>> [MT] = iiwa.sendEEfPositionMTorque(EEEFpos)`
- Description:
  This function is used to send target position of EEF to the robot for the soft real-time control at the EEF level while simultaneously it returns a feed back about the measured torques due to external forces acting on the robot. This function is blocking, it awaits for the torques message from the server before returning back to execution.
- Arguments:
  - `EEEFpos:` is a 6x1 cell array where the first three elements represent (X, Y, Z) target positions of EEF (mm) and the last three elements represent the fixed rotation angles of EEF (radians).

- Return values:
  - `MT`: 7x1 cell array of the joint torques as measured by the sensors.
- Related functions:
  - `realTime_startDirectServoCartesian`
  - `realTime_stopDirectServoCartesian`

2.18 `sendEEfPositionGetActualJpos`

- `Syntax:`

  `>> [JPOS] = iiwa.sendEEfPositionGetActualJpos(EEEFpos)`
- Description:

  This function is used to send target position of EEF to the robot for the soft real-time control at the EEF level while simultaneously it returns a feed back about the actual joints positions as measured by the integrated encoders. This function is blocking, it awaits for the position message from the server before returning back to execution.
- Arguments:
  - `EEEFpos:` is a 6x1 cell array where the first three elements represent (X, Y, Z) target positions of EEF (mm) and the last three elements represent the fixed rotation angles of EEF (radians).
- Return values:
  - `JPOS`: 7x1 cell array of the joint positions as measured by the encoders.
- Related functions:
  - `realTime_startDirectServoCartesian`
  - `realTime_stopDirectServoCartesian`

2.19 `sendEEfPositionGetActualEEFpos`

- `Syntax:`

  `>> [actual_EEFpos] = iiwa.sendEEfPositionGetActualEEFpos(target_EEFpos)`

- Description:

  This function is used to send target position of EEF to the robot for the soft real-time control at the EEF level while simultaneously it returns a feed back about the actual EEF position by measurements using the integrated encoders. This function is blocking, it awaits for the position message from the server before returning back to execution.

- Arguments:

  - `target_EEFpos:` is a 6x1 cell array where the first three elements represent (X, Y, Z) target positions of EEF (mm) and the last three elements represent the fixed rotation angles of EEF (radians).

- Return values:

  - `actual_EEFpos`: 6x1 cell array of EEF position.

- Related functions:

  - `realTime_startDirectServoCartesian`
  - `realTime_stopDirectServoCartesian`

2.20 `realTime_startVelControlJoints`

- `Syntax:`

  `>> [ret] = iiwa.realTime_startVelControlJoints()`

- Description:

  This function is used to start the soft real-time control at joints velocities level.

- Arguments:

  - None.

- Return values:

  - `ret`: a boolean value, true if the function is executed successfully, false otherwise.

- Related functions:
  - `sendJointsVel`
  - `realTime_stopVelControlJoints`
- Tutorial script
  - `KSTclass_Tutorial_softRealTimeJointsVelControl.m`

2.21 `realTime_stopVelControlJoints`

- `Syntax:`

  `>> iiwa.realTime_stopVelControlJoints()`
- Description:

  This function is used to stop the soft real-time control at joints velocities level.
- Arguments:
  - None.
- Return values:
  - None.
- Related functions:
  - `sendJointsVel`
  - `realTime_startVelControlJoints`
- Tutorial script
  - `KSTclass_Tutorial_softRealTimeJointsVelControl.m`

2.22 `sendJointsVelocities`

- `Syntax:`

  `>> [ret] = iiwa.sendJointsVelocities(jvel)`

- Description:

  This function is used to set reference joints' velocities for soft real-time control at joints level.

- Arguments:
  - `jvel`: is a 7x1 cell array representing the target angular velocity for each joint, in rad/sec.

- Return values:
  - `ret`: a boolean value, true if the function is executed successfully, false otherwise.

- Related functions:
  - `realTime_startVelControlJoints`
  - `realTime_stopVelControlJoints`

- Tutorial script
  - `KSTclass_Tutorial_softRealTimeJointsVelControl.m`

2.23 `sendJointsVelocitiesExTorques`

- `Syntax:`

  `>> [ExT] = iiwa.sendJointsVelocitiesExTorques(jvel)`

- Description:

  This function is used to set reference joints' velocities for the soft real-time control at joints velocities level, simultaneously, this function returns a feed back about the external torques due to external forces acting on the robot. This function is blocking, it awaits for the torques message from the server before returning back to execution.

- Arguments:
  - `jvel`: is a 7x1 cell array representing the target angular velocity for each joint, in rad/sec.

- Return values:
  - ExT: 7x1 cell array of external torques.
- Related functions:
  - realTime_startVelControlJoints
  - realTime_stopVelControlJoints

2.24 sendJointsVelocitiesMTorques

- Syntax:

  ```
  >> [MT] = iiwa.sendJointsVelocitiesMTorques(jvel)
  ```

- Description:

  This function is used to set reference joints' velocities for the soft real-time control at joints velocities level, simultaneously, this function returns a feed back about the measured torques from integrated sensors in the robot joints. This function is blocking, it awaits for the torques message from the server before returning back to execution.

- Arguments:
  - jvel: is a 7x1 cell array representing the target angular velocity for each joint, in rad/sec.
- Return values:
  - MT: 7x1 cell array of measured torques.
- Related functions:
  - realTime_startVelControlJoints
  - realTime_stopVelControlJoints

2.25 sendJointsVelocitiesGetActualJpos

- Syntax:

  `>> [JPoS] = iiwa.sendJointsVelocitiesGetActualJpos(jvel)`

- Description:

  This function is used to set reference joints' velocities for the soft real-time control at joints velocities level, simultaneously, this function returns a feed back about the actual joints positions from integrated sensors in the robot. This function is blocking, it awaits for the position message from the server before returning back to execution.

- Arguments:
  - `jvel`: is a 7x1 cell array representing the target angular velocity for each joint, in rad/sec.

- Return values:
  - `JPoS`: 7x1 cell array of the actual positions of the joints.

- Related functions:
  - `realTime_startVelControlJoints`
  - `realTime_stopVelControlJoints`

2.26 sendJointsVelocitiesGetActualEEfPos

- Syntax:

  `>> [EEfPos] = iiwa.sendJointsVelocitiesGetActualEEfPos (jvel)`

- Description:

  This function is used to set reference joints' velocities for the soft real-time control at joints velocities level, simultaneously, this function returns a feed back about the actual position of EEF of the robot. This function is blocking, it awaits for the position message from the server before returning back to execution.

- Arguments:
  - `jvel`: is a 7x1 cell array representing the target angular velocity for each joint, in rad/sec.

- Return values:

- EEfPos: 6x1 cell array of the actual EEF position.

- Related functions:
  - realTime_startVelControlJoints
  - realTime_stopVelControlJoints

3 Point-to-point motion

This group of functions is used to move the robot towards a destination point, according to the function used the destination point can be specified in Cartesian space or in joints space. KST implements several point to point motion functions that allow the user to move the robot from one configuration to another in joint space, or to move the EEF of the robot on a linear, circular or elliptical trajectory in Cartesian space. By using the point to point motion functions the path towards the destination point is planned by the software, so the user is not required to perform the path planning him-self. In this section the point to point motion functions are described.

3.1 `movePTPJointSpace`

- `Syntax:`

  `>> [ret] = iiwa.movePTPJointSpace(jPos, relVel)`

- Description:

  This function is used to move the robot from the current configuration to a new configuration in joint space.

- Arguments:

  - `jPos`: is a 7x1 cell array representing the target angular positions, in rad/sec.
  - `relVel`: is a double, from zero to one, specifying the override relative velocity.

- Return values:

  - `ret`: the return value is true if the command message has been received and processed successfully by the server, or false otherwise.

- Tutorial script

  - `KSTclass_Tutorial_move_ptp.m`

3.2 `movePTPLineEEF`

- `Syntax:`

  `>> [ret] = iiwa.movePTPLineEEF(Pos, vel)`

- Description:

  This function is used to move the end-effector in a straight line from the current position to a destination position. When called, the function causes the end-effector to move on a line. The robot can keep the orientation of the end-effector fixed or it can change the orientation while moving on a line.

- Arguments:
  - `Pos`: is a 6x1 cell array representing the destination position of EEF, the first three elements are the XYZ coordinates in (mm), the remaining three elements are the fixed rotation angles, in radians.
  - `vel`: linear velocity of the motion (mm/sec).

- Return values:
  - `ret`: the return value is true if the command message has been received and processed successfully by the server, or false otherwise.

- Tutorial script
  - `KSTclass_Tutorial_move_ptp.m`

3.3 `movePTPHomeJointSpace`

- `Syntax:`

  `>> [ret]= iiwa.movePTPHomeJointSpace(relVel)`

- Description:

  This function is used to move the robot to home configuration.

- Arguments:
  - `relVel`: is a double, from zero to one, specifying the override relative velocity.

- Return values:
  - `ret`: the return value is true if the command message has been received and processed successfully by the server, or false otherwise.

3.4 movePTPTransportPositionJointSpace

- `Syntax:`

  `>> [ret] = iiwa.movePTPTransportPositionJointSpace(relVel)`

- Description:

  This function moves the robot to the transport configuration.

- Arguments:

  - `relVel`: is a double, from zero to one, specifying the override relative velocity.

- Return values:

  - `ret`: the return value is true if the command message has been received and processed successfully by the server, or false otherwise.

3.5 movePTPLineEefRelBase

- `Syntax:`

  `>> [ret] = iiwa.movePTPLineEefRelBase(Pos, vel)`

- Description:

  This function moves the end-effector in a straight-line path using relative motion, in such a case, the motion is defined using displacements along the axes of the robot base.

- Arguments:

  - `Pos`: is a 3x1 cell array representing the XYZ displacements along the base axes by which the EEF has to move, unit is (mm).
  - `vel`: linear velocity of the motion (mm/sec).

- Return values:

  - `ret`: the return value is true if the command message has been received and processed successfully by the server, or false otherwise.

- Tutorial script

  - `KSTclass_Tutorial_move_lin_relative.m`

3.6 `movePTPLineEefRelEef`

- `Syntax:`
  `>> [ret] = iiwa.movePTPLineEefRelEef(Pos, vel)`
- Description:
  This function moves the end-effector in a straight-line path using relative motion, in such a case, the motion is defined using displacements along the axes of EEF.
- Arguments:
  - `Pos`: is a 3x1 cell array representing the XYZ displacements along the axes of EEF by which the EEF has to move, unit is (mm).
  - `vel`: linear velocity of the motion (mm/sec).
- Return values:
  - `ret`: the return value is true if the command message has been received and processed successfully by the server, or false otherwise.
- Tutorial script
  - `KSTclass_Tutorial_move_lin_relative.m`

3.7 `movePTPCirc1OrintationInter`

- `Syntax:`
  `>> [ret] = iiwa.movePTPCirc1OrintationInter(f1, f2, vel)`
- Description:
  This function moves the end-effector in arc specified by two frames.
- Arguments:
  - `f1`: is 6x1 cell array, specifying the intermediate frame of the arc.
  - `f2`: is 6x1 cell array, specifying the final frame of the arc. In both frames, the first three elements are the X, Y and Z coordinates in (mm), the remaining elements are the fixed rotation angles (radians).
  - `vel`: linear velocity of the motion (mm/sec).
- Return values:
  - `ret`: the return value is true if the command message has been received and processed successfully by the server, or false otherwise.

- Tutorial script
  - `KSTclass_Tutorial_circles.m`

3.8 `movePTPArc_AC`

- **Syntax:**

  `>> [ret] = iiwa.movePTPArc_AC(theta, c, k, vel)`

- Description:

  This function moves the end-effector in arc specified by the arc's: center, starting point, angle and a normal to its plane.

- Arguments:
  - `theta`: is the arc'a angle in radians.
  - `c`: is a 3x1 vector representing the x, y and z coordinates of the arc's center.
  - `k`: is a 3x1 vector representing the normal vector on the plane of the arc.
  - `vel`: linear velocity of the motion (mm/sec).

- Return values:
  - `ret`: the return value is true if the command message has been received and processed successfully by the server, or false otherwise.

- Tutorial script
  - `KSTclass_Tutorial_circles.m`

3.9 `movePTPArcXY_AC`

- **Syntax:**

  `>> [ret] = iiwa.movePTPArcXY_AC(theta, c, vel)`

- Description:

  This function moves the end-effector in an arc parallel to the XY plane of the base of the robot, the arc is specified by its: center, starting point, and angle.

- Arguments:
  - `theta`: is the arc'a angle in radians.
  - `c`: is a 2x1 vector representing the x and y coordinates of the arc's center.
  - `vel`: linear velocity of the motion (mm/sec).
- Return values:
  - `ret`: the return value is true if the command message has been received and processed successfully by the server, or false otherwise.
- Similar functions:
  - `movePTPArcXZ_AC`
  - `movePTPArcYZ_AC`
- Tutorial script
  - `KSTclass_Tutorial_circles.m`

4 Setters

Those functions are used to set the outputs of the pneumatic flange of the KUKA iiwa robot, in case the user is using a manipulator with another flange, then the functions can still be called but they will have no effect on the robot.

4.1 `setBlueOff`

- `Syntax:`

  `>> [ret]= iiwa.setBlueOff()`

- Description:

  This function is used to turn off the blue light of the pneumatic flange.

- Arguments:
  - None.

- Return values:
  - `ret`: the return value is true if the command message has been received and processed successfully by the server, or false otherwise.

4.2 `setBlueOn`

- `Syntax:`

  `>> [ret]= iiwa.setBlueOn()`

- Description:

  This function is used to turn on the blue light of the pneumatic flange.

- Arguments:
  - None.

- Return values:
  - `ret`: the return value is true if the command message has been received and processed successfully by the server, or false otherwise.

4.3 `setPin1Off`

- `Syntax:`
  `>> [ret]= iiwa.setPin1Off()`
- Description:
  This function is used to set off the output (Pin 1) of the output connector of the pneumatic media flange.
- Arguments:
  - None.
- Return values:
  - `ret`: the return value is true if the command message has been received and processed successfully by the server, or false otherwise.
- Similar functions:
  `setPin11Off,setPin12Off,setPin2Off` used to set pins 11, 12 and 2 off.

4.4 `setPin1On`

- `Syntax:`
  `>> [ret]= iiwa.setPin1On()`
- Description:
  This function is used to set on the output (Pin 1) of the pneumatic media flange.
- Arguments:
  - None.
- Return values:
  - `ret`: the return value is true if the command message has been received and processed successfully by the server, or false otherwise.
- Similar functions:
  `setPin11On,setPin12On,setPin2On` used to set pins 11, 12 and 2 on.

5 Getters

Those functions are used to get a feedback about the various parameters and sensory-measurements from the robot.

5.1 `getEEF_Force`

- **`Syntax:`**

  `>> [f] = iiwa.getEEF_Force()`

- Description:

  This function is used to acquire the force at the flange reference frame. The components of the force are described in the base reference frame of the robot.

- Arguments:
  - None.

- Return values:
  - `f`: is a 1x3 cell array representing the X, Y and Z components of the force (Newton).

- Tutorial script
  - `KSTclass_Tutorial_getters.m`

5.2 `getEEF_Moment`

- **`Syntax:`**

  `>> [m] = iiwa.getEEF_Moment()`

- Description:

  This function returns the measured moment at the flange reference frame. The components of the moment are described in the base frame of the robot.

- Arguments:
  - None.

- Return values:

  - `m`: is a 1x3 cell array representing the X, Y and Z components of the force (Newton).

- Tutorial script
  - `KSTclass_Tutorial_getters.m`

5.3 `getEEFCartesianOrientation`

- **Syntax:**
  `>> [ori] = iiwa.getEEFCartesianOrientation()`
- Description:
  This function returns the orientation (Z, Y and X fixed rotations angles) in radians.
- Arguments:
  - None.
- Return values:
  - `ori`: is a 1x3 cell array representing the ZYX fixed rotation angles of EEF.
- Tutorial script
  - `KSTclass_Tutorial_getters.m`

5.4 `getEEFCartesianPosition`

- **Syntax:**
  `>> [Pos] = iiwa.getEEFCartesianPosition()`
- Description:
  This function returns the Cartesian position of the end-effector relative to robot base reference frame.
- Arguments:
  - None.

- Return values:
  - `Pos`: is a 1x3 cell array representing the XYZ coordinates of EEF in base frame of robot (mm).
- Tutorial script
  - `KSTclass_Tutorial_getters.m`

5.5 `getEEFPos`

- **`Syntax:`**
  `>> [Pos] = iiwa.getEEFPos()`
- Description:
  This function returns the position and orientation of the end-effector relative to robot base reference frame.
- Arguments:
  - None.
- Return values:
  - `Pos`: is a 1x6 cell array, first three elements represent the XYZ coordinates of EEF (mm), remaining three elements represent the ZYX fixed rotation angles of EEF (radians).
- Tutorial script
  - `KSTclass_Tutorial_getters.m`

5.6 `getJointsExternalTorques`

- **`Syntax:`**
  `>> [torques] = iiwa.getJointsExternalTorques()`
- Description:
  This function returns the robot joints' torques due to external forces.
- Arguments:

  - None.

- Return values:
  - `torques`: is a 1x7 cell array of joints torques, in Newton.Meter.

- Tutorial script
  - `KSTclass_Tutorial_getters.m`

5.7 `getJointsMeasuredTorques`

- `Syntax:`
  `>> [torques] = iiwa.getJointsMeasuredTorques()`

- Description:
  This function returns the robot joints' torques as measured by the integrated torque sensors.

- Arguments:
  - None.

- Return values:
  - `torques`: is a 1x7 cell array of joints torques, in Newton.Meter.

- Tutorial script
  - `KSTclass_Tutorial_getters.m`

5.8 `getJointsPos`

- `Syntax:`
  `>> [jPos] = iiwa.getJointsPos()`

- Description:
  This function returns the robot joints' angles.

- Arguments:
  - None.

- Return values:
  - `jPos`: is a 1x7 cell array of actual joints positions as measured by the encoders, in radians.

5.9 `getMeasuredTorqueAtJoint`

- **Syntax:**

  `>> [torque] = iiwa.getMeasuredTorqueAtJoint(k)`
- Description:

  This function returns the measured torque in a specific joint.
- Arguments:
  - None.
  - `k`: is the joint index, from 1 to 7.
- Return values:
  - `torque`: is the measured torque at joint k, torque unit is Newton.Meter.
- Tutorial script
  - `KSTclass_Tutorial_getters.m`

5.10 `getExternalTorqueAtJoint`

- **Syntax:**

  `>> [torque] = iiwa.getExternalTorqueAtJoint(k)`
- Description:

  This function returns the external torque in a specific joint.
- Arguments:
  - `k`: is the joint index, from 1 to 7.
- Return values:
  - `torque`: is the external torque at joint k, torque unit is Newton.Meter.

- Tutorial script
  - `KSTclass_Tutorial_getters.m`

5.11 `getEEFOrientationR`

- `Syntax:`

  `>> [rMat] = iiwa.getEEFOrientationR()`
- Description:

  This function returns the rotation matrix representing the orientation of the EEF relative to the base frame of the robot.
- Arguments:
  - None.
- Return values:
  - `rMat`: 3x3 rotation matrix representing the orientation of the EEF relative to the base frame of the robot.
- Tutorial script
  - `KSTclass_Tutorial_getters.m`

5.12 `getEEFOrientationQuat`

- `Syntax:`

  `>> [quaternion] = iiwa.getEEFOrientationQuat()`
- Description:

  This function returns the quaternion representing the orientation of the EEF relative to the base frame of the robot.
- Arguments:
  - None.
- Return values:
  - `quaternion`: 1x4 quaternion vector representing the orientation of the EEF relative to the base frame of the robot.

- Tutorial script
  - `KSTclass_Tutorial_getters.m`

6 General purpose

Those functions are used for calculating the direct/inverse kinematics, the direct/inverse dynamics, and the various physical quantities of the LBR7R800 and the LBR14R820 manipulator. It is worthy to mention that in the calculations of the general purpose functions the base of the robot is considered to be mounted horizontally where the Z axes is facing upwards. In those functions the dynamic parameters used for LBR14R820 are as reported in article [1], and the dynamic parameters used for LBR7R800 are as reported in the article [2]. While the Denavit-Hartenberg data used for of LBR7R800 and LBR14R820 are as reported in the drawings and the dimensions of manual [3].

As described in part IV **KST class**, when the iiwa object is instantiated by calling the constructor of the KST class, The user has to pass arrangements specifying the type of the robot and the mounting flange. In such a case, the constructor automatically loads the appropriate Kinematics/Inertial data of the robot.

Kinematics Methods

The KST toolbox offers several methods that allows the user to calculate the various kinematic quantities required to implement the control algorithms, including:

- Forward kinematics, this function is used to calculate the direction/orientation of the EEF at certain joints angles of the robot, KST utilizes the mathematics of the transformation matrices for calculating the forward kinematics, the Denavit-Hartenberg (DH) parameters are loaded automatically when the constructor of KST class is called. According to the arguments passed to the constructor specifying the type of the robot and the type of the flange, the right DH parameters are calculated and loaded implicitly by the toolbox into a read only property, as such the user does not have to load the DH parameters by himself. If a tool is attached to the flange of the robot, then the user shall specify the transformation matrix of the Tool Center Point (TCP) with respect to the flange of the robot and pass it as an argument to the constructor .

- The Jacobian of the manipulator, which is a 6xn matrix, where n is the number of joints of the manipulator, this matrix gives a relationship between the velocity of the EEF linear/angular and the angular velocities of the joints of the robot.

- Inverse kinematics, this function is used to calculate the joint angles of the robot for a given position/orientation (pose) of the EEF, for redundant manipulators there are infinite solutions that gives the same pose of the EEF, KST utilizes the damped least squares for calculating a solution of the joint angles that correspond to a specific pose of the EEF.

6.1 `gen_DirectKinematics`

- **`Syntax:`**
  `>> [eef_transform, J] = iiwa.gen_DirectKinematics(q)`
- Description:
  This function calculates the forward kinematics/Jacobian of the manipulator, the Jacobian returned by this function is the geometric Jacobian.
- Arguments:
  - `q`: the angles of the robot joints.
- Return values:
  - `eef_transform`: is the transformation matrix from end-effector to the base frame of the robot.
  - `J`: is the Jacobian at the tool center point of the EEF.
- Tutorial script
  - `KSTclass_Tutorial_generalPorpuse.m`

6.2 `gen_partialJacobean`

- **`Syntax:`**
  `>> [Jp] = iiwa.gen_partialJacobean(q, linkNum ,Pos)`
- Description:
  This function calculates the partial Jacobian.
- Arguments:
  - `q`: is a 7x1 vector with joints angle.
  - `linkNum`: is the number of the link at which the partial Jacobian is associated, it shall be an integer in the range [1,7].
  - `Pos`: is a 3x1 vector that represents the position vector of the point where the partial Jacobian is going to be calculated
- Return values:
  - `Jp`: is the partial Jacobian.
- Tutorial script
  - `KSTclass_Tutorial_generalPorpuse.m`

6.3 `gen_InverseKinematics`

- **Syntax:**

  `>> [qs] = iiwa.gen_InverseKinematics(qin, Tt, n, lambda)`

- Description:

  This function calculates the inverse kinematics of the robot at a given position/orientation of its EEF. The joints' angles are calculated numerically, where the damped least squares (DLS) method is utilized for performing the calculations, given this fact the user shall keep in mind that the achieved solution is approximate, and that the precision of the answer depends on the values of parameters passed to the function as described below.

- Arguments:

  - `qin`: is the initial guess used by the solver, in general case this vector can be chosen to be zero. On the other hand for soft real-time control applications, where the requirement is to control the joints angles as to perform certain motion of the EEF, the user shall consider to use the current joints' angles of the robot as an initial guess (radians), an example code is shown in the file KST-class_Tutorial_moveRealtimeEllipse.m.
  - `Tt`: is the target transformation matrix position/orientation of the robot.
  - `n`: is the number of iterations used by the solver, given that the DLS method is a numerical algorithm, the solution is achieved by performing several iterations, in general higher number of iterations gives a more precise answer, this is at the expense of an increasing computational cost.
  - `lambda`: is the damping constant, this factor gives the algorithm more numerical stability near singular configurations, yet a high value damping value results in less precise answer.

- Return values:

  - `qs`: is the solution joints' angles of the robot.

- Tutorial script

  - `KSTclass_Tutorial_generalPorpuse.m`

6.4 gen_NullSpaceMatrix

- Syntax:
  `>> [N] = iiwa.gen_NullSpaceMatrix(q)`
- Description:
  This function calculates the null space matrix of the robot.
- Arguments:
  - q: is a 1x7 vector with angles of the manipulator.
- Return values:
  - N: is 7x7 matrix – a null space projection matrix for the KUKA iiwa 7 R 800.
- Tutorial script
  - KSTclass_Tutorial_generalPorpuse.m

Dynamics Methods

KST integrates several functions for calculating the different dynamics quantities of KUKA iiwa robot, including:

- Mass matrix of the robot: it is a positive definite matrix, of dimension of 7x7, this matrix gives a relationship between the angular accelerations of the joints and the resulting torques due to acceleration only.
- Coriolis matrix: this matrix gives is 7x7 matrix, it gives a relationship between the angular velocities of the joints and the torques due to Coriolis and centrifugal forces.
- Centrifugal matrix: this matrix gives is 7x7 matrix, it gives a relationship between the square of the angular velocities of the joints and the torques due to centrifugal forces only.
- Inverse dynamics: this function calculates the joints' torques required to generate certain motion of the robot.
- Direct dynamics: this function calculates the joints' accelerations in some state due to joint torques.
- Gravity vector: this function calculates the torques acting on the joints of the robot due to gravitational pull, in this function the robot is considered to be mounted in the upright position, with its base is in the horizontal position.

6.5 `gen_MassMatrix`

- `Syntax:`
  `>> [M] = iiwa.gen_MassMatrix(q)`
- Description:
  This function is used to calculate the mass matrix of the robot, in the configuration specified by the angular positions `q`.
- Arguments:
  - `q`: is a 1x7 vector with angles of the manipulator,
- Return values:
  - `M`, is a 7x7 matrix – the mass matrix of the manipulator.
- Tutorial script
  - `KSTclass_Tutorial_generalPorpuse.m`

6.6 `gen_CoriolisMatrix`

- `Syntax:`
  `>> [B] = iiwa.gen_CoriolisMatrix(q, dq)`
- Description:
  This function calculates Coriolis matrix of the manipulator at configuration `q` with angular velocities `dq`.
- Arguments:
  - `q`: is a 1x7 vector with angles of the manipulator,
  - `dq`: is a 1x7 vector with the joints' angular velocity.
- Return values:
  - `B`, is a 7x7 matrix – the Coriolis matrix of the robot.
- Tutorial script
  - `KSTclass_Tutorial_generalPorpuse.m`

6.7 gen_CentrifugalMatrix

- **Syntax:**
  `>> [C] = iiwa.gen_CentrifugalMatrix(q, dq)`
- Description:
  This function calculates Coriolis matrix of the manipulator at configuration `q` with angular velocities `dq`.
- Arguments:
  - `q`: is a 1x7 vector with angles of the manipulator,
  - `dq`: is a 1x7 cell array with the joints' angular velocity.
- Return values:
  - `C`: is a 7x7 matrix – the centrifugal matrix of the manipulator.
- Tutorial script
  - `KSTclass_Tutorial_generalPorpuse.m`

6.8 gen_GravityVector

- **Syntax:**
  `>> [G] = iiwa.gen_GravityVector(q)`
- Description:
  This function calculates joints torques due to gravity at configuration `q`.
- Arguments:
  - `q`: is a 1x7 vector with angles of the manipulator,S
- Return values:
  - `G`: is a 7x1 vector – the gravity vector of the manipulator.
- Tutorial script
  - `KSTclass_Tutorial_generalPorpuse.m`

6.9 `gen_DirectDynamics`

- `Syntax:`
  `>> [d2q] = iiwa.gen_DirectDynamics(q, dq, taw)`
- Description:
  This function calculates the direct dynamics of the manipulator.
- Arguments:
  - `q`: is a 1x7 vector with angles of the manipulator,
  - `dq`: is a 1x7 vector with the joints' angular velocity.
  - `taw`: is the torques at the joints.
- Return values:
  - `d2q`: is a 7x1 vector representing the angular accelerations of the joints.
- Tutorial script
  - `KSTclass_Tutorial_generalPorpuse.m`

6.10 `gen_InverseDynamics`

- `Syntax:`
  `>> [taw] = iiwa.gen_InverseDynamics(q, dq, d2q)`
- Description:
  This function calculates the inverse dynamics of the manipulator.
- Arguments:
  - `q`: is a 1x7 vector with angles of the manipulator.
  - `dq`: is a 1x7 vector with the joints' angular velocity.
  - `d2q`: is a 1x7 vector representing the angular accelerations of the joints.
- Return values:
  - `taw`: is the torques at the joints
- Tutorial script
  - `KSTclass_Tutorial_generalPorpuse.m`

7 Physical Interaction

This category contains functions that are used for physical human robot interaction.

7.1 `startHandGuiding`

- `Syntax:`

  `>> iiwa.startHandGuiding()`

- Description:

  This function is used to start KUKA's off-the-shelf the hand guiding for a manipulator with a pneumatic flange. Once called, the hand-guiding is initiated, afterwards to perform the hand-guiding the user has to press the flange's white button to deactivate the brakes and move the robot around. To terminate this functionality, the user has to press the green button continuously for more than 1,5 seconds, in such a case, after 1,5 seconds the blue LED light starts to flicker, when the green button is released the function is terminated.

- Arguments:

  – `iiwa`: is the TCP/IP communication object.

- Return values:

  – None.

- Tutorial script

  – `KSTclass_Tutorial_HandTeaching.m`

7.2 `startPreciseHandGuiding`

- About:

Why the precision hand-guiding?
During our work in the Collaborative Robotics Lab at the university of Coimbra, we had a requirement to use KUKA manipulator as a third hand, where KUKA will assist the worker in performing assembly tasks of satellite components using the hand-guiding functionality, in such a case KUKA will carry most of the weight of the equipment, offer precision, and will hold the component in place, some times in hard-to-access tight locations, while the worker fixes the component in place.

The first idea that came to mind is to utilize KUKA hand-guiding, we started to test this mode using a dummy satellite, unfortunately KUKA hand-guiding did not match the precision criteria required. The experiments carried out are demonstrated in the following video:

`https://youtu.be/p459YeagBXM`

As a conclusion, several draw backs has been experienced while testing KUKA hand-guiding:

1. From the video you can see the author is struggling to adjust the position/orientation of the dummy, attached to the robot, into its place in the structure. Even after several trials the author was not able to insert the dummy into its place. The test was repeated with other people performing the same operation, the result was always the same: the dummy instrument was always overshooting right and left, up and down, while trying to adjust its position in place inside the structure.

2. The test was performed on a dummy that weighs around 1 Kg, though the requirement is to use the hand-guiding for installing sensitive instruments that have a weight range of several kilograms, overshooting could cause the instrument to hit the structure of the satellite, which might damage sensitive and expensive equipment, unacceptable situation.

3. Using KUKA hand-guiding the user can not adjust the orientation of the dummy while keeping its position fixed.

4. Using KUKA hand-guiding the user can not adjust the position of the dummy while keeping its orientation fixed.

5. KUK hand-guiding works at the joints level, as such it can not offer precision in Cartesian space. At best case scenario, it can be as precise as the operator can be.

When we faced this problem, a top-of-the-head solution that first came into mind was to utilize the teach-pendant, while it offers precision it did not match the requirements due to the following:

1. Unlike the hand-guiding, when using the teach-pendant the user does not have a feel of the force applied between the instrument and its surrounding in case of contact. Accidents could happen and the user might over press the sensitive instrument against the surrounding without noticing.

2. When using the teach-pendant to position the EEF in Cartesian space, the user has to keep a track of the orientation of the robot base, this could become confusing even for the experienced worker, not to mention that in our study case, KUKA iiwa manipulator is mounted on a mobile platform, as such the robot is always moving around the structure of the satellite.

3. The teach pendant convention in describing the orientation is the XYZ, fixed rotation angles. This was for describing orientation is not intuitive for

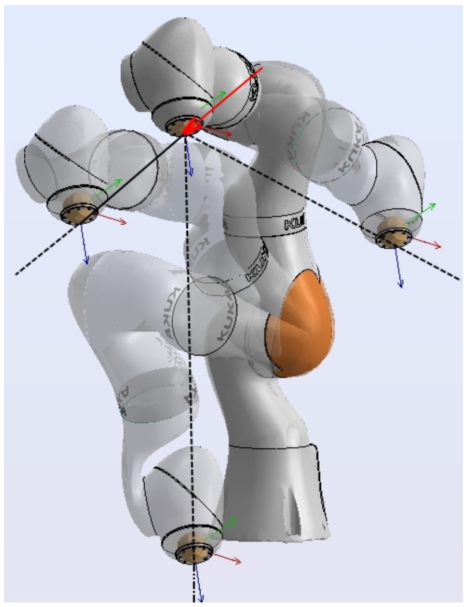


Fig. 7.1: Precise hand-guiding first motion group

humans. Even the experienced roboticest agrees that in the general case it is hard to imagine an orientation of an object based on three numbers.

4. The override control to change the velocity of the robot while performing the positioning operation is not that convenient.

As such the author proposed the precision hand-guiding that addresses the precision requirements in precise positioning operations. The precision hand-guiding convention for defining EEF orientation is build upon a well known action that we always do when we try to insert a key inside a keyhole. From users feedback, the proposed orientation convention is more intuitive for use than the teach pendant convention which utilizes fixed rotation angles convention.

To show case the advantages of the precision hand-guiding, a comparison between the precision hand-guiding and KUKA hand-guiding is presented in the following videos. A qualitative assessment proves that the precision hand-guiding offers superior precision, convenience and smoother operation when it comes to performing precise positioning operations.

In the following video KUKA hand-guiding is utilized, you can notice precision criteria was not satisfied, and the author is struggling to maintain the orientation of the tool in the required direction:

`https://youtu.be/xKlyHxptIEE`

And in the following video precise hand-guiding offered a reasonable solution:

`https://youtu.be/SM_2TSsq8kQ`

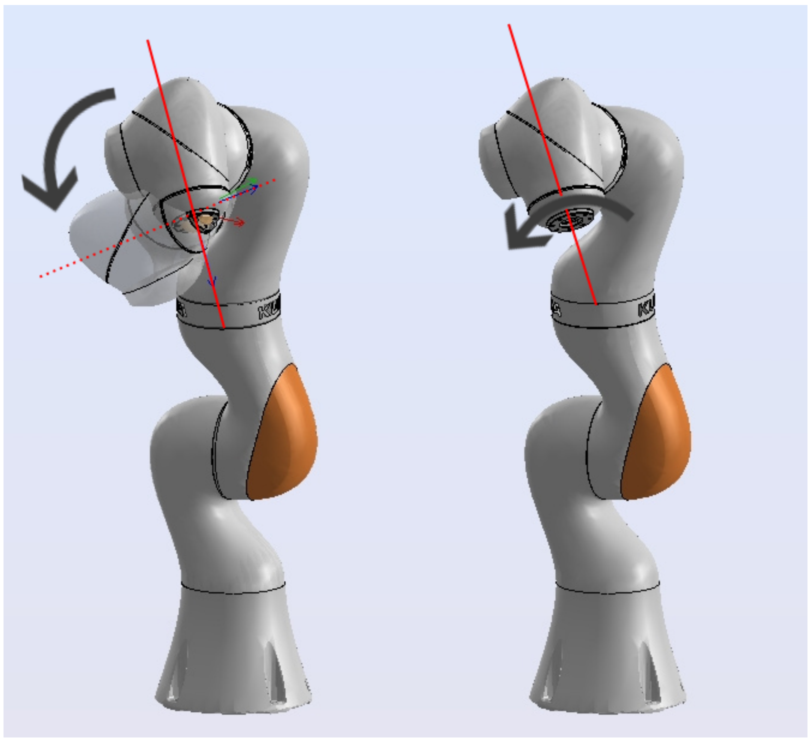


Fig. 7.2: Precise hand-guiding, second motion group to the left, third motion group to the right

To address the precision requirements, each motion allowed by the precision hand-guiding is constrained in specific way, so the allowed motions can be divided into three main motion groups:

1. First motion group, Fig. 7.1: in this case the operator can move the EEF on a line along the axes of the robot base frame, once at a time. In such a case, the orientation of the EEF is kept unchanged while performing the motion.

2. Second motion group, left of Fig. 7.2, in this case the operator can orient the axis of EEF by applying a moment. In such a case the position of the EEF is kept fixed.

3. Third motion group, right of Fig. 7.2, in this case the user can rotate the EEF of the robot round its axis. In such a case the position of the EEF is fixed, and the orientation of the EEF's axis is also fixed.

The first motion group is demonstrated in Fig. 7.1. To explain this motion group, consider the case where the operator is applying a force on the EEF of the robot, the force applied is approximately aligned with the positive X-axis of the robot-base and exceeds a predefined threshold value, as such the robot starts moving from its initial position, opaque, on a line parallel to X axes. When the applied force drops below the predefined threshold or seizes to exist the robot stops in its final position, transparent robot. During the motion the magnitude of EEF velocity is proportional to the magnitude of the applied force, and the orientation of the EEF stays the same.

This allows the user to move the robot precisely on a line in the directions of base axes one at a time, while keeping the orientation of the EEF of the robot fixed. Similar to the way the teach-pendant works but more intuitively and with an ability to control the velocity of the motion through the magnitude of the applied force.

The second motion group is demonstrated in left of Fig. 7.2, in this mode the user can rotate the axis of the EEF by applying a moment, when the EEF is rotated its position stays fixed. The third motion group is demonstrated in right of Fig. 7.2, in this motion group the user can rotate the EEF around its axis by applying a torque around EEF's axis.

- `Syntax:`

  `>> iiwa.startPreciseHandGuiding(wot, com)`

- Description:

  This function is used to initialize a precise hand-guiding functionality.

- Arguments:
  - `wot`: is the weight of the tool (Newton).
  - `com`: is 1x3 vector, representing the coordinates of the center of mass of the tool described in the reference frame of the flange (mm).

- Return values:
  - None.

- Tutorial script
  - `KSTclass_Tutorial_preciseHandGuidingExample.m`

7.3 `performEventFunctionAtDoubleHit`

- `Syntax:`

  `>> iiwa.performEventFunctionAtDoubleHit()`

- Description:

  This function is used to detect the double touch in Z direction of the end-effector.

- Arguments:
  - None.
- Return values:
  - None.

7.4 `EventFunctionAtDoubleHit`

- **Syntax:**
  `>> iiwa.EventFunctionAtDoubleHit()`
- Description:
  This function is called when a double touch in the Z direction of the robot's end-effector is detected.
- Arguments:
  - None.
- Return values:
  - None.

7.5 `moveWaitForDTWhenInterrupted`

- **Syntax:**
  `>> iiwa.moveWaitForDTWhenInterrupted (Pos, VEL, joints_indexes, max_torque, min_torque, w)`
- Description:
  This function is used to perform an interruptible point-to-pint motion of the end-effector on a line. If the value of torque on any of the specified joints `joints_indexes` exceeds the predefined torque limits, `max_torque/ min_torque`, the motion is interrupted. Afterwards, the robot waits for a double tap on the end-effector along the Z axis, upon which the robot returns to motion execution again.
- Arguments:
  - `Pos`: is 1x6 cell array of EEF position.

  - `VEL`: is the linear velocity of the motion (mm/sec).
  - `joints_indexes`: indexes of the joints where torques limits are to be specified.
  - `max_torque`: the maximum torques limits of the joints specified by `joints_indexes`.
  - `min_torque`: the maximum torques limits of the joints specified by `joints_indexes`.
  - `w`: is the weight of the tool (Newton).

- Return values:
  - None.

- Tutorial script
  - `KSTclass_Tutorial_ptpPickPlacePhysicalInteraction.m`

Part VII. References

[1] Stürz, Y. R., Affolter, L. M., & Smith, R. S. (2017). Parameter Identification of the KUKA LBR iiwa Robot Including Constraints on Physical Feasibility. IFAC-PapersOnLine, 50(1), 6863-6868.

[2] Hayat, A. A., Abhishek, V., & Saha, S. K. Dynamic identification of manipulator: Comparison between cad and actual parameters. iNaCoMM, 15, 1-6.

[3] KUKA Roboter GmbH. Medien-Flansch Für Produktfamilie LBR iiwa Montage- und Betriebsanleitung. Stand: 20.01.2015. Version: Option Media Flange V3