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A ROS-integrated API for the KUKA LBR iiwa collaborative robot ⋆

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Abstract: The deployment of collaborative robotic systems in industry 4.0 raises the potential for complex human-robot interaction to create highly flexible processes. This brings a need for systems that can facilitate rapid programming and development of safe collaborative processes, without the need for extensive training. In this paper we introduce a novel Application Programming Interface (API) for the KUKA Intelligent Industrial Work Assistant (iiwa) Lightweight Robot (LBR) that enables fast development and integration of devices, using the popular Robot Operating System (ROS), without compromising the inherent safety features of the robot. We describe the API, released as a freely available download, and provide an example application of its use to support a large-scale interactive participant experiment. As flexible manufacturing technologies become ever more connected and complex, it is important to ensure compatibility between networked devices and provide tools to support system integration based on common platforms. Our API is one such tool, and has been designed to support faster and easier system integration and development, providing particular support to scientists in creating experiments for studying human-robot collaboration.

Keywords: Programming, Collaborative Robotics, Industrial Robot, Flexible Manufacturing

1. INTRODUCTION

The manufacturing sector is poised to undergo considerable change over the next decade. Driven by initiatives such as Industry 4.0, the Digital Agenda, and the Internet of Things, the introduction of new technologies and further digitalisation will lead to highly connected, and integrated workplaces. These changes will produce new ways of working, and open up new opportunities for innovation and process flexibility. In particular, developments in robotics will enable humans and robots to work collaboratively, maximising the benefits of manual and automated processes (Pawar et al., 2016).

This shift towards human-robot co-working is enabled by the recent development of collaborative robots, including the KUKA LBR iiwa. Such *cobots* are designed to operate alongside human users in shared environments without safety caging; back-drivable motors and compliant controllers allowing humans to physically interact with the robots without harm. Whilst early adoption focuses on robots working un-caged in human-occupied spaces as assistive tools with little interaction, the full potential of this technology will only be realised through symbiotic human-robot collaborative processes.

A major aim for future manufacturing is greater flexibility to support smaller batch sizes and more customisation. Whereas existing automated processes are highly repetitive, and difficult to reconfigure for new products or tasks, collaborative robots will support much greater variability through task switching. The added complexity of flexible processes and co-working with robots will require the up-skilling of the human workforce, and highly intuitive interfaces to support more variability in worker roles.

To achieve these aims, greater integration of workers, robots, and systems are required. This requires development of robot control interfaces that can safely and flexibly connect to sensors and gather information from external sources; that can be reprogrammed by non-experts; and that can provide intuitive information to users. In this paper, we describe an interface for the KUKA LBR iiwa,

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available online [1], which we have developed to support our experimental research work, and is now supporting development of new industrial processes. The interface enables control and communication via the Robot Operating System (ROS), but with minimal installation requirement, and without compromising the inbuilt safety features.

1.1 The Growing Importance of Co-Working with Robots

Collaboration between humans and robots has been observed in the manufacturing sector since the 1940s. Applications such as sorting, cutting and painting were initially based on simple control and communication methods; on-off switches, analog joysticks and unidirectional communication. Over time, with advances in technology and artificial intelligence methods, co-working with robots has gradually become more robust and safe, offering natural control and communication methods (Sheridan, 1997).

Multiple key requirements have been identified for co-working with robots. Dialogue is a factor needed for effective communication and exchange of information between humans and robots. This communication process, based on multiple modalities, e.g., visual and touch sensing, can be used to ask questions and evaluate the quality of tasks (Fong et al., 2003). To achieve these intelligent co-working platforms, knowing 'what type of information?', 'what medium of communication?' and 'when communication should occur?' is essential to enrich the quality of collaboration (Kaupp et al., 2010).

Safety in human-robot interaction is also a crucial factor, that needs of robust frameworks for collaborative communication, control and monitoring (Thomas et al., 2011). A message-based architecture composed of distributed modules was proposed for teleoperation, which included safety and sensor management modules, wide range of interfaces for communication and supported various degrees of cooperation and autonomy (Fong et al., 2001). A human-robot communication framework, based on integration of data from multiple sensory sources, allowed to exchange information and achieve a task collaboratively (Kaupp et al., 2010). This framework was developed using probabilistic robotics representation to infer when to transmit specific communications between humans and robots. Coordination and control of human and robot actions through dialog was addressed by the design of an operating system for human-robot interaction (Fong et al., 2006). This system used an agent-based paradigm, that supported a variety of user interfaces, task-oriented dialog, resource and interaction management, and integration of robots through an Application Programming Interface (API).

Over time, as robots stop being passive tools for humans to use and become more sophisticated and automated co-working partners, the relationship between humans and robots will change to start resembling the interaction between two individuals (Ososky et al., 2013). In addition, the current shift in industry for manufacturing tasks to incorporate human-robot co-working increases the need for improved interfaces to make this interaction more efficient. The level of autonomy, complexity and safety measures will continue to increase, yet to enable true collaboration robots will also need to gain the confidence of human operators (Cameron et al., 2015). These issues will be exacerbated by the introduction, and up-skilling, of workers without robotics experience.

[1] `https://github.com/jonaitken/KUKA-IIWA-API`

2. KUKA IIWA LBR

The KUKA iiwa is a lightweight industrial robotic arm with seven axes. Each of its joints is equipped with torque sensors as well as a position sensor. Sensory data enables the use of impedance control in addition to position control, thus making it possible to implement compliant behaviors. Highly accurate measurements, with down to millisecond update intervals, enables the robot to react very quickly to process forces and makes it particularly suitable for interaction with humans. The KUKA iiwa can be programmed for a variety of tasks trough "KUKA Sunrise control technology". This comprises "KUKA Sunrise OS" control software which can execute programs in JAVA as the programming language on "KUKA Sunrise Cabinet" control hardware. Although Java is a flexible and common language, an in depth knowledge about the Sunrise system is required for programming the robot and utilising its functionality.

Out-of-the-box, the robot can only be controlled through a Java-based program and all the sensory data or information related to the ongoing task is only available locally on the robot control system or the KUKA Smartpad. Even though control of the robot and access to the task information by other systems in a network can be made possible by opening a network socket in the controlling program, the desire for compatibility with ancillary systems and languages has lead us to develop our own interface.

2.1 ROS

ROS (Quigley et al., 2009) provides a unified platform independent of languages and platforms for publishing and subscribing to data streams. It also comprises a large collection of commonly used functionality and applications for robot software development such as hardware drivers, robot models, simulation tools, data-types, planning, perception and other algorithms. It provides a useful architecture for developing and deploying robot systems, which can be easily modeled using graph-based techniques (Aitken et al., 2014).

2.2 Alternative APIs

There are several existing alternative APIs available for the KUKA LBR iiwa. Each has been built with a slightly different focus and consequently is customised to its own domain. In this section we provide a brief summary of the most prominent.

ROS Industrial is a working group developing interfaces aimed at wide-scale industrial usage, typically the framework focuses on the larger capacity arms that are part of the KUKA range (Edwards and Lewis, 2012). At present this is only an experimental package so is subject to regular alterations, however, the main focus of the API is not on co-working, but capturing more general industrial use.

Khansari-Zadeh and Khatib (2015) and Virga et al. (2016) focus on the interaction between operators and the robot. Khansari-Zadeh and Khatib (2015) focuses on learning actions from human demonstration, displaying different impedance to motions for critical parts of the exercise. Virga et al. (2016) investigates force-compliant motion within the medical domain. Both of the APIs produced require specific components installing upon the KUKA iiwa, which require modification of the operational parameters on board the KUKA Sunrise controller; these either change the modes of operation or require custom installation of third-party libraries.

The API developed within this paper is a simple, standalone application, which can be placed on the KUKA Sunrise controller, and provides functionality without necessitating any modification of the control unit. It allows direct integration with ROS, without requiring any configuration. This enables full compatibility with the Robot Systems Toolbox in Matlab and Simulink [2] , which widens the choice of development platforms for API users and allows the inclusion of model-based design as a choice for verifying potential applications (McAree et al., 2016).

3. BUILDING THE API

The API developed within this paper is designed to be simple, and interface to ROS to provide an easy platform for development.

3.1 API Architecture

The API architecture focuses on breaking out the functionality that would normally be available within the KUKA Sunrise controller run on the Smartpad.

The architecture can be viewed as extending the capability of the KUKA LBR iiwa, using the generic structure shown in Figure 1. The API exposes an interface to operation on a network of machines. This allows different sensing methods and extra computing resources to be easily deployed and exploited in operations of the KUKA LBR iiwa.

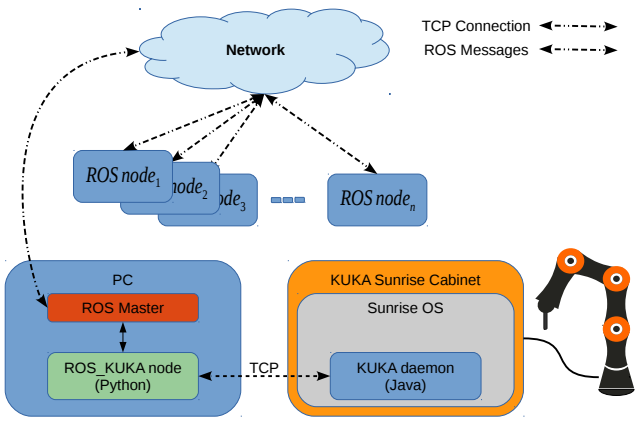

Fig. 1. *Components of the KUKA ROS interface architecture.*

The KUKA server also handles some low-level, but generic and critical controlling tasks, such as collision detection. Handling such tasks locally on the Sunrise system leverages the inherent safety protocols to enable compliance with existing regulation and standards, and ensures the underlying operation of the robot is still safe. The API presented in this paper forms a wrapper which utilizes these underlying safety-critical protocols.

A ROS-KUKA node is also implemented in the Python scripting language, which is a ROS node and plays an intermediate interface between the KUKA server and ROS master. It *subscribes* to the commands coming from other controlling ROS nodes and passes them to the KUKA server. Similarly it receives sensory and status information from the KUKA server and *publishes* them under their specific *Topics*. Running this ROS-KUKA node externally on a separate computer, rather than on the KUKA Sunrise OS, means that no modification is required of the KUKA Sunrise Cabinet. Therefore the inherent safety protocols are preserved, and functionality is added rather than altered. Instead of installing third party software such as ROS on the Sunrise system, the KUKA iiwa ROS interface can be set up with a standard Sunrise-based application. The topics available for use within ROS available through the API are shown in Table 1.

The kuka_command topic is used to send instructions through the API to the KUKA LBR iiwa. A list of commands and descriptions is shown in Table 2.

3.2 Safety within API

It is important that the native safety of the KUKA iiwa Lightweight Robotic Arm is preserved. The arm has been developed as a robot for co-working, especially with the available compliance modes that provide the ability to work without a safety cage (Shepherd and Buchstab, 2014; Kirchner et al., 2015). This provides exceptional capability as a user is able to physically move the robot arm, whilst exposed to a level of risk deemed safe.

The API developed uses the standard safety settings on the KUKA LBR iiwa, acting as part of a subsumption architecture (Brooks, 1986). Ultimately the safety settings on the KUKA Sunrise Cabinet always interpret the control provided from ROS, whilst checking any command to ensure the arm remains within the valid operating parameters and spatial areas. If this region is not specified, or an inaccessible position is demanded, the KUKA controller will not permit movement of the arm.

By relying on the inbuilt safety functionality within a subsumption architecture our KUKA iiwa API maintains safety whilst extending the capability of the system. The safety functionality within the KUKA Sunrise Controller is separated from the ROS interface, ensuring the high-integrity safety elements operate as intended by the manufacturer without being compromised. This enables a standard risk-assessment to be conducted for experimental work, which leverages the inbuilt safety and compliance supplied with the KUKA iiwa.

With these features in place a participant is able to co-work in very close proximity to the robot without needing special instructions, training or a safety cage, as the API and KUKA Sunrise Controller enables “safe-by design” application development.

[2] `https://www.mathworks.com/products/robotics/`

Table 1. Topics available through KUKA iiwa ROS interface. Update on a frequency of 10Hz

Topic Name and Description	Description	Example
JointPosition [A1, A2, A3, A4, A5, A6, A7] time	Joint position (in degrees), reading time-stamp	JointPosition [0.0, 0.17, 0.0, 1.92, 0.0, 0.35, 0.0] 1459253274.1
ToolPosition [X, Y, Z, A, B, C] time	Tool/end effector position (in cartesian space), reading time-stamp	ToolPosition [433.59711426170867, 0.028881929589094864, 601.4449734558293, 3.1414002368275726, 1.0471367465304213, 3.141453681799645] 1459253274.11
ToolForce [X, Y, Z] time	External force on tool/end effector in different directions, reading time-stamp	ToolForce [13.485958070668463, 0.3785658886199012, 5.964988607372689] 1459253274.11'
ToolTorque [A, B, C] time	External torque on tool/end effector in different directions, reading time-stamp	ToolTorque [13.485958070668463, 0.3785658886199012, 5.964988607372689] 1459253274.11'
JointAcceleration Float time	Joint acceleration value, reading time-stamp	JointAcceleration 0.4 1459253274.11'
JointVelocity Float time	Joint velocity value, reading time-stamp	JointVelocity 1.0 1459253274.11'
JointJerk Float time	Joint Jerk value, reading time-stamp	JointJerk 1.0 1459253274.11'
isCompliance Boolean time	Robot compliance status, reading time-stamp	isCompliance off 1459253274.11'
isReadyToMove Boolean time	Robot motion status; True if the robot can move or if the robot performed all the motion in its queue, reading time-stamp	isReadyToMove true 1459253274.11'
isCollision Boolean time	True if a collision has detected.	isCollision false 1459253274.11'
isMastered Boolean time	True if is mastered, reading time-stamp	isMastered true 1459253274.11'
isJointOutOfRange Boolean time	True if any joint is out of its range.	isJointOutOfRange false 1459253274.11'
OperationMode String time	Operation Mode T1/T2/AUT	OperationMode T1 1459253274.11'

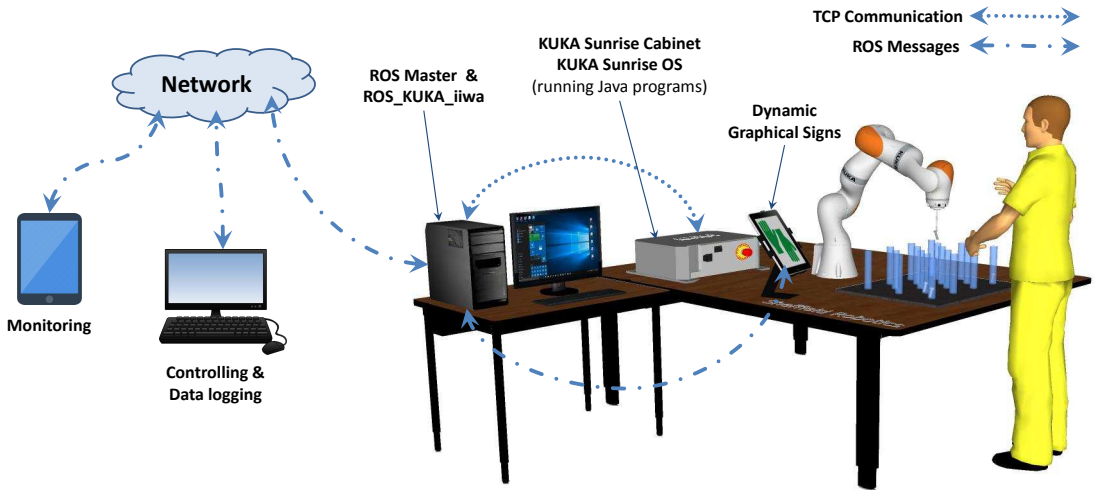

Fig. 2. *An example of the general structure of the KUKA iiwa ROS interface to Multiple Mobile Devices, exploited in the Assessing Graphical Robot Aids for Interactive Co-working (A-GRAfIC) project.*

3.3 Exploiting the API

The API has been used to support human-robot interaction experiments in collaborative working on the A-GRAfIC project (Eimontaite et al., 2016). In the A-GRAfIC scenario, a worker is required to remove bolts from perspex tubes with the assistance of a collaborative robot. The robot is aware of the tube locations but cannot detect which contain bolts, thus requiring collaboration with a human user: the human worker decides which tube to remove a bolt from and moves the robot, in compliant mode, to the tube location; the robot switches to autonomous mode, retrieves the bolt, and presents it to the worker; the task is then repeated for further bolts. An overview of the process is given in Figure 3. The algorithms to control this process using the API are given in Algorithms 1 and 2.

Algorithm 1, sets the KUKA iiwa to the home position and activates compliance of the arm in only the x-y plane (so that the operator can manually push it into the required pick up position). Algorithm 2 allows the operator a short time to change their mind, detecting if a force is applied to the arm within a 3 second window. If a force is detected, the compliance is re-enabled to allow the user to adjust the position of the end effector. Once a position is confirmed, the arm switches to autonomous operation and undertakes a motion to retrieve the bolt and return it to the user. The process is then repeated.

Table 2. Topics available through KUKA iiwa ROS interface.

Topic Name and Description	Description	Example
setJointAcceleration F	Setting/changing the joint acceleration value	'setJointAcceleration 0.4'
setJointVelocity F	Setting/changing the joint velocity value	'setJointVelocity 1.0'
setJointJerk F	Setting/changing the joint jerk value	'setJointJerk 1.0'
setCartVelocity F	Setting/changing the cartesian velocity (mm/s) value	'setCartVelocity 100'
setPosition A1 A2 A3 A4 A5 A6 A7	Moving the robot arm based on joint position. Angular values (in degrees) of type float can be replaced in A1-7. In case any axis doesnt need to be moved, a - can be used instead of a value. The example assigns new positions for each axis except A2 which doesnt move.	'setPosition 0 - 0 -100 0 60 0'
setPositionXYZABC X Y Z A B C ptp/lin	Moving the robot end effector in the robot cartesian space. Point-to-point (ptp) or linear (lin) motion can be selected. This moves the robot end effector to a particular location [x,y,z] orientation [a,b,c] (values in float). In case any parameter doesnt need to be changed, a - can be used instead of a value.	'setPositionXYZABC 700 290 - -180 0 -180 lin'
MoveXYZABC X Y Z A B C	Moving the robot end effector in the cartesian space with linear (lin) motion only. This moves the robot end effector in certain direction [x,y,z] and/or orientation [a,b,c] for the given values (in mm and degrees).	MoveXYZABC 10 20 0 30 0 0
MoveCirc X1 Y1 Z1 A1 B1 C1 X2 Y2 Z2 A2 B2 C2 BlendingOri	Moving the robot end effector in a arch/circular motion from its current position passing from a first one ([x1 y1 z1 a1 b1 c1]) to a second position ([x2 y2 z2 a2 b2 c2]) with a given blending value.	MoveCirc 700 0 290 -180 0 -180 710 0 300 -180 0 -180 0.1
setCompliance X Y Z A B C	Activates the robot Compliance mode with particular stiffness in each x,y,z,a,b,c. The given example activates the Compliance with a very low stiffness in x and y cartesian plain only.	'setCompliance 10 10 5000 300 300 300'
resetCompliance	Deactivates the robot Compliance mode.	resetCompliance
setCartImpCtrl X Y Z A B C Damping	Activates the robot cartesian impedance control mode with particular impedances in each x,y,z,a,b,c. The given example activates the cartesian impedance control with a very low impedance in z cartesian axis only.	'setCartImpCtrl 5000 5000 100 300 300 300 1.0'
resetCartImpCtrl	Deactivates the robot cartesian impedance control mode.	resetCartImpCtrl
resetCollision	Resets a Collision if any collision was detected.	resetCollision
forceStop	Stops the robot and removes all the robot motion queue.	forceStop
setWorkspace xmin ymin zmin xmax ymax zmax	Defining a cubic workspace boundaries.	setWorkspace 100 -300 0 600 300 500
setTool ToolName	Switching between any number of predefined tools. "tool1" is selected by default.	setTool gripper
sleep T	Suspending execution for the given number of seconds. The argument may be a floating point number to indicate a more precise sleep time.	sleep 2.5

Algorithm 1 goToStart() pseudocode

setJointAcceleration $\leftarrow 0.4$
setJointVelocity $\leftarrow 1.0$
setJointJerk $\leftarrow 1.0'$
Set initial position as point to point movement
setPositionXYZABC $\leftarrow$ *700 0 290 -180 0 -180 ptp*
while *ToolPositionError* > 10 **do**
  Wait until tool is in required position
end while
while No force is applied to tool **do**
  Wait until co-worker pushes tool
end while
Set compliance in x-y plane
setCompliance $\leftarrow$ *10 10 5000 300 300 300*

4. CONCLUSIONS

This paper has detailed a new API for the KUKA iiwa LBR, which is compatible with ROS and provides control capability across a distributed network. The API requires installation of a standard Sunrise-based application, and forms a wrapper that does not compromise existing safety features. This supports fast development of collaborative processes, and facilitates integration with other digital systems.

The API has been used to support human-robot interaction experiments in collaborative working, and we have summarised the A-GRAfIC demonstrator as an indication of the flexibility that the API provides. The operational modes of the KUKA iiwa can be quickly switched from fully-compliant to fully-autonomous programatically from within a distributed network around the robot arm. This allows full sensor suites to be quickly deployed and integrated into the system, providing capability but preserving safe operation.

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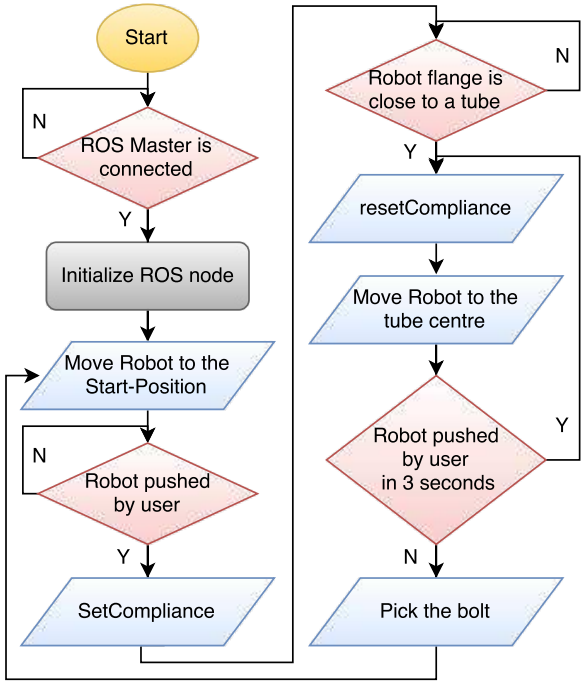

Fig. 3. Experimental Process

Algorithm 2 Pick up bolt pseudocode

Turn off compliance
resetCompliance
Center on the tube
setPositionXYZABC ← x_p y_p *290 -180 0 -180 ptp*
while do3*sTimerActive*
  if Co-Worker Applies Force to the Arm **then**
    Turn on compliance
    setCompliance ← *10 10 5000 300 300 300*
  end if
end while
Turn off compliance
resetCompliance
Center on the tube
setPositionXYZABC ← x_p y_p *290 -180 0 -180 ptp*
Lower into the Tube as a linear movement
setPositionXYZABC ← x_p y_p *120 -180 0 -180 lin*
Rise from the Tube as a linear movement
setPositionXYZABC ← x_p y_p *290 -180 0 -180 lin*
Return to home position presenting bolt
goToStart()

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