International Journal on Interactive Design and Manufacturing (IJIDeM) (2020) 14:1569–1575
https://doi.org/10.1007/s12008-020-00714-4

TECHNICAL PAPER

Industry 4.0: examples of the use of the robotic arm for digital manufacturing processes

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Received: 14 November 2019 / Accepted: 19 September 2020 / Published online: 27 September 2020
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Abstract

The use of robots for pick and place, welding, subtractive and additive manufacturing are spreading at the last years with the concept of industry 4.0. This paper presents all modifications, adjusts and applications of a KUKA KR16 robotic arm at PUC-Rio, using the robot at different forms (e.g. milling machine, styrofoam cutting machine, pick and place machine). The purpose is to demonstrate how a robot arm can be used by applying the concepts of industry 4.0, 3D printing techniques, milling and other tools, with the aim to verify the impact of these transformations and uses for engineering and industry in general.

Keywords KUKA KR16 · Milling robots · Visual servoing · Industry 4.0 · Digital manufacturing

1 Introduction

The evolution of the use of the robotic arms at manufacturing begins in 1937 with the first robot design by “Bill” Griffith P. Taylor with a “crane-like” design. In 1954, George Devol construct a robotic arm with hydraulic actuators that was able to pick one piece and place it in another defined place. In 1969 Victor Scheinman at Stanford University invent the first 6 axes robotic arm, called “Stanford Arm”, with electric motors and after that another plataforms called “MIT arm” and “PUMA” (Programmable Universal Machine for Assembly). In 1974 the KUKA robotics developed the robot called “Famulus”. In 1979 Japan introduce the SCARA (Selective Compliance Assembly Robot Arm) (Fig. 1).

At the 80’s with the improvement of the microprocessor technologies, the use of robotic arms in welding and mounting was spread, specially at the automotive industries and the robotic industry had a grown, with YASKAWA, FANUC, MOTOMAN, ABB, KUKA and another companies, as shown at [21][24][15]. In the 90’s and 2000’s the use of IoT (Internet of Things) at manufacturing [4], with the SCADA (Supervisory Control and Data Acquisition) systems has made manufacturing processes ever faster and more accurate. Thus, the use of robotic arms proved to be an effective way to increase productivity in the industry (Fig. 2).

Currently the concept of industry 4.0 extends to several branches of knowledge, so the workers should be prepared to

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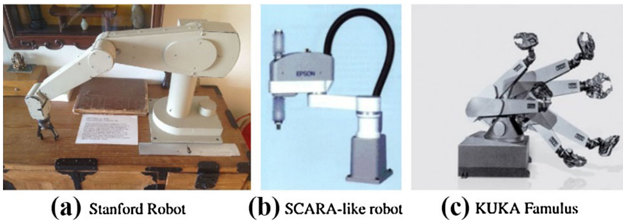


Fig. 1 First age of robotic arms

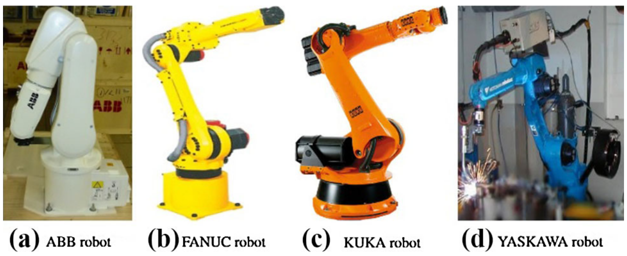


Fig. 2 Second age of robotic arms

merge such knowledge. It is a concept recently proposed and that mixes the main technological innovations of the fields of automation, control and information technology, applied to the manufacturing processes [20].

This means a new period in the context of the great industrial revolutions. With intelligent factories, a number of changes will take place in the way the products will be manufactured, affecting various market sectors. In the context of industry 4.0, the idea of changing paradigms of construction is interposed [18].

Before the industry 4.0, the limit was the number of operations and types of machines, today is the assertiveness in relation to the final model [5]. The construction of complex parts became easier and with one unique machine, it is possible to build a prototype or final piece. Thus, with the aim to propose and demonstrate several applications of this concept, the PUC-Rio bought a robot KUKA KR16 arm.

In this paper will be described experiments made with this robot arm in four major areas: architecture, design, robotics and manufacturing processes, some focused on the teaching area and others focused on the industry and research.

2 Related works and background

The additive manufacturing is very versatile and can be applied at several areas. this section will describe some applications and recent works using this type of process. The 3D printers can be used for optimization of construction of complex pieces with the aim to minimize the weight, efforts and maximize the strength of the structures like at space applications [9] and robotics [13]. The structure of spacial pieces must be strong and light to resist to critical conditions.

Fig. 3 Heydar Aliyev center (extracted from [11])

Another application is at medical [6] [12]issues. In that cases the use of robotic arms and additive manufacturing has the aim to accelerate the confection of the first piece or prototype and are an important part, because the maximum precision and repetition accuracy is necessary.

Around the world, the concept of industry 4.0 has been spreading faster and faster, especially in the field of 3D printers and prototyping. According [19]:

“*Additive manufacturing is a fabrication technology that is rapidly revolutionizing the manufacturing and construction sectors.*”

In this regard, the use of a robotic arm as a tool for an additive manufacture is essential for the evolution of the process, allowing increasingly complex structures and more fluid and organic forms, as opposed to the conventional format, such as the “Heydar Aliyev Center”(Fig. 3):

Another aspect of the industry 4.0 is described at [22] and [3], in which the authors summarize the concepts and research at this field and draws a parallel with what has been and is being developed. At the field of engineering, the use of robotic arms is very common, however, this aspect including at industry 4.0 is new [14] and the improvements at productivity are significant (Fig. 4).

The new challenge of this application is: “*How to make flexible the use of the robot arm to improve the productivity?*” To answer that question, it is necessary that the controller of the robotic arm have the ability to modify his structure [17]. Thus, the electronic components and mechanical tools must be construct, according the application.

In terms of manufacturing and industry 4.0, two other very common concepts are introduced, which is product customization and user interaction. according [23]:

“*Interactive manufacturing is a new idea to cope with the difficulties caused by growing complexity of manufacturing activities.*”

Thus, using robotic arms, immersive virtual reality systems [8] or another way to break the “constructivity paradigm”

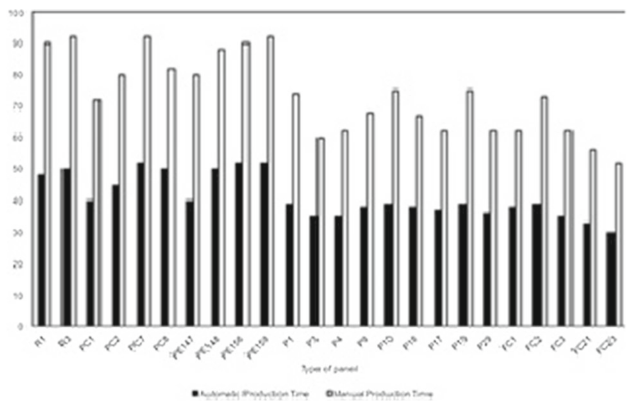


Fig. 4 Productivity for robot and manual projection (extracted from [1])

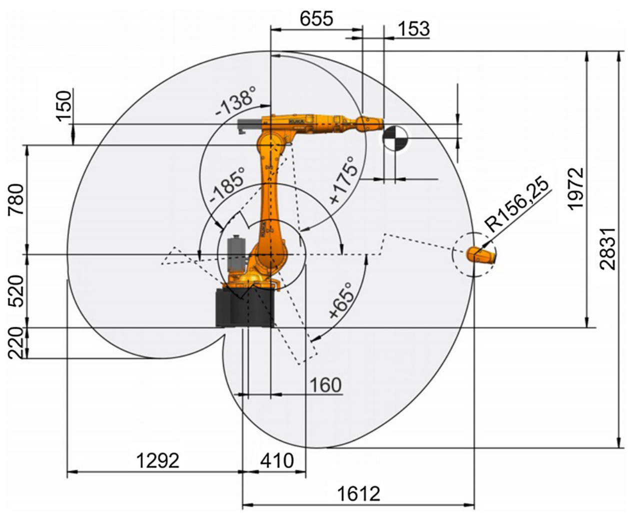


Fig. 5 Dimensions and ranges

make Industry 4.0 an interdisciplinary union of knowledge and applications to make manufacturing even more flexible [10].

3 Proposed work

The robotic arm used at this work is KUKA KR16 model, with following dimensions and ranges (Fig. 5) and With the aim to evaluate several uses of robotic arms at manufacturing, the KUKA KR16 robot arm purchased by PUC-Rio was modified for some purposes.

This is a general-purpose robot arm commonly used for medium weight operations such as pallet handling, welding, and milling of soft materials (wood, acrylic, PVC, uriol, styrofoam, polyethylene and others) and has with main characteristic speed and accuracy. The controller used by this robot arm is KUKA KRC 4, that have some characteristics:

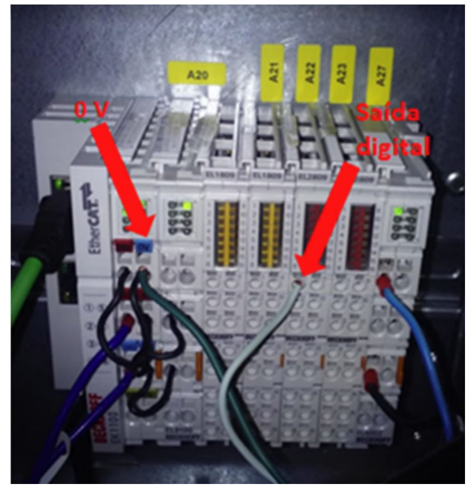


Fig. 6 Drivers I/O Beckhoff

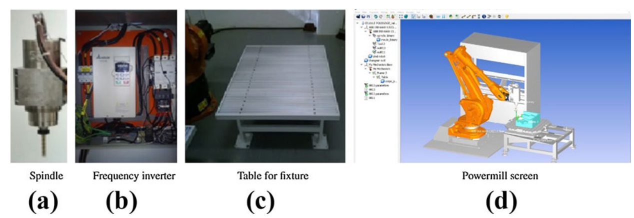


Fig. 7 Adaptations to milling

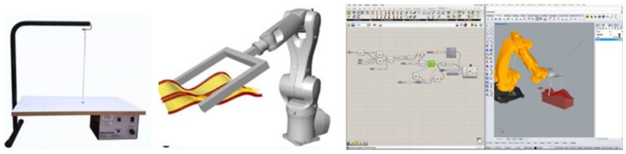
- Optional “KUKA.CNC control”: Enables direct programming and operation of KUKA robots via G-code;
- Optional “High-end PLC support”: Allows full access to the entire controller I/O system and has a high runtime performance.
- Fully integrated safety controller: Integrates the complete safety controller into the control system without proprietary hardware.

In addition, control systems with analogic and digital outputs and inputs from beckhoff have been specified, which enable a generic interface with any external system (Fig. 6).

3.1 Milling machine

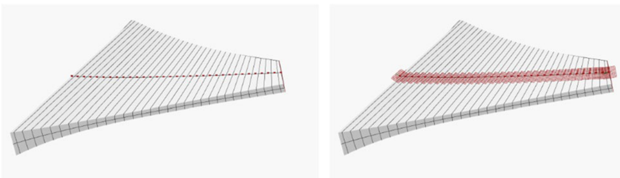
The first use of KUKA KRC 4 was as a milling machine. For that purpose, was made the following adaptations of hardware:

- Insertion of a spindle of 4500 W of power, air-cooled, 380V (Figure 7 (a));
- Insertion of a frequency inverter (Fig. 7b);
- Table for fix the pieces for milling (Fig. 7c);
- Enable of analogic output channel of Beckhoff board;



(a) Table to hot wire cut **(b)** Example of wire cut adaptation **(c)** Rhinoceros with Grasshopper plugin for KUKA

Fig. 8 Adaptations to wire cut



(a) Piece at grasshopper - points **(b)** Piece at grasshopper - planes

Fig. 9 trajectory done at grasshopper

After all adaptations, was used the software KUKA KRC to configurate all tools, movements and I/O of the robot arm. This is a slow process descript by KUKA to put any robot at all functionalities. For simulations and milling trajectory generation, was used first the software *Sprutcam* (for 3D milling and some primary tests) and after that the software was changed by *Robotmaster* Software and now the software used to generate the milling trajectory is *Powermill* (Fig. 7d)—extracted from [2]).

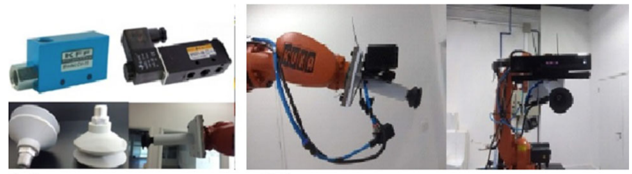
The aim of this application is show to the students another use of robot arm and test a different form of milling. Another objective of KUKA KR16 is making complex pieces to researchers of PUC-Rio and other laboratories.

3.2 Styrofoam cutting machine

The second use of KUKA KR16 was as a styrofoam cutting machine. For that purpose, was made the following adaptations of hardware:

- Adaptation of the table for fix the pieces for milling (Fig. 8a);
- Insertion of a stem to fix the hot wire on the end effector of the robot arm (Fig. 8b);
- Insertion of a 24V font;
- Enable of digital output channel of Beckhoff board;

After all adaptations, was used the software Rhinoceros with Grasshopper plugin to KUKA KRC to configure all tools, movements and simulations of trajectory generation (Fig. 8c). The virtual robot was configured at the plugin and after that the user create the path that the robot must follow and after all trajectories are done, the plugin generates the robot language, with all movements of the axes (Fig. 9).



(a) Suction tool and another device **(b)** Camera positioning at end effector of robot arm

Fig. 10 Adaptations to pick and place

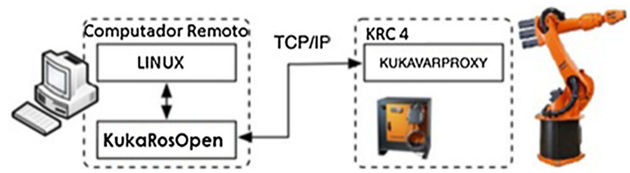


Fig. 11 KUKA-ROS communication

The aim of this application is show use of robot arm and test a different form of modelling. At this configuration, the robot made some pieces like a mold of concrete bench.

3.3 Pick and place machine

The third use of the robot arm was pick and place with visual servoing. For that purpose, the following changes was made:

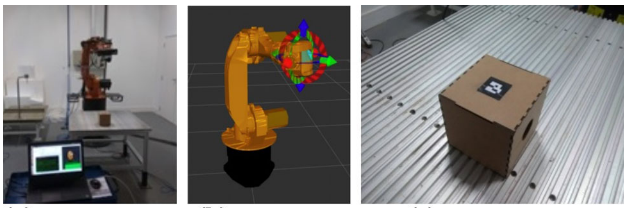
- Construction of suction tool (Fig. 10a);
- Insertion of a solenoid valve (Fig. 10a);
- Insertion of vacuum pump (Fig. 10a);
- Insertion of camera at the robot (Fig. 10b);

The KUKA robot was originally controlled using the KUKA Robot Controller (KRC) by KUKA Robot Language (KRL). To make the connection with the ROS [7] and the robot, was used a package called KUKAVARPROXY [16]. The process of transmitting commands works in a client-server architecture with the ROS of a remote computer and the KUKAVARPROXY acting as a server in the KRC. The ROS interacts locally with the user program and remotely communicates with the KUKAVARPROXY server via TCP / IP. The KUKARosOpenCommunication package was used to make the ROS communication with the KUKAVARPROXY (Fig. 11).

The KRC allows the creation of global variables by editing the "config.dat" file inside the robot console, and Boolean, integer, real variables can be inserted as well as specific structures in command format of axes, such as E6POS and E6AXIS. In the case of the system used, a variable type "MYAXIS" was inserted in the robot, which executes a movement in the six axes of the robot, given a position received in the KUKAVARPROXY. This variable allows the controller to read commands without quaternion transformation (ROS

```
INI
PTP HOME  Vel= 100 % DEFAULT;
LOOP
     $VEL.CP=0.2
     $OUT[1]=TRUE
     PTP MYAXIS C_PTP
$OUT[1]=FALSE
ENDLOOP
PTP HOME  Vel= 100 % DEFAULT;
END
```

Fig. 12 KUKA program



(a) Robot arm configuration **(b)** Moveit planning **(c)** Object with QR code

Fig. 13 Adaptations to pick and place 2

program send a quaternion transformation that is translated to "myaxis" variable type).

To configure the server, a service under ip 192.175.0.20 and port 8000 was created in the robot, thus opening an external communication. After this a network cable with the Linux PC (Fig. 13a) was connected and a fixed IP with address 192.175.0.21 was configured, so that one connected with the other. After this variable was created and the communication process was done, the following program was created to execute continuously in the robot (Fig. 12):

To control and send the movements to the robotic arm, a ROS-industrial experimental KUKA repository package was used to obtain URDF of the specific robot model, seen in (Fig. 13b), and how to configure joint, link and collision settings was used the package called MOVE IT with the ROS. So was created some nodes (package of commands at ROS) to control and search a specific object with a QR code (Fig. 13c):

To guarantee the movement, was used some packages of ROS, like "Kinect V2 driver" and "artrackalvar". The "kinect2 bridge" package is used as a link between the Kinect V2 driver called "libfreenect2" and ROS. The launcher publishes camera information, color images, depth and also the point clouds at 30 fps. Kinect calibration was done previously, so the intrinsic and extrinsic parameters were already known. The "artrackalvar" package was used to get the camera distance to the QR code pasted on the object. The node of this package receives the camera information and point clouds topics and publishes a topic called "arposemarker" that contains the distance from the QR code to the stipulated frame. In this case, we chose the distance to baselink.

Some nodes (command packages) was created to do the movements safely, as "environment" node, "initial position" node, "final position" node and "pick and place" node. The "environment" adds the table in front of the robot to the planning scene. The "initial position" node do the planning and send action to the robot to go to the first determined position, from view. The "final position" node does the planning and sends action to the robot to go to the final position determined. The "pick and place" node receives the "AlvarMarkers" topic that contains the QR code position based on the link, makes the trajectory planning up to that point and sends it to the robot. In addition to these, a launcher was created that initializes the kinect driver, the with the robot's URDF, the "environment" node, the air track valve and a static transform publisher from the camera frame to the robot tip frame (end effector).

Fig. 14 Sequence of milling test

4 Discussion

At beginning of the first application, happened some problems, such as zeroing of the pieces to be milled, adjustment of the length of the cutting tool, adjustment of the movements made by the robot arm to avoid collisions between the spindle and the part, among others. These problems were solved by making changes in the configuration of the robot and at the CAM software, changing parameters and modifying the generator of post processor. Another action taken was the exchange of the CAM software, because the previous one could not execute satisfactory trajectories in 6 interpolated axes, which guarantees greater flexibility for the robot arm. Significant results were obtained, as can be seen in the following figure (Fig. 14). In this project a fan propeller model was milled using three and five interpolated axes strategies, guaranteeing fidelity and precision in the execution of this process.

The challenges of the second application was divided into three stages: *"What is the best type of tool?"*, *"Should the gross block be stationary or in motion?"* and *"How to make the grasshopper cut right?"*. To cut styrofoam, it is necessary to heat a stainless steel or nickel wire through the passage of a controlled electric current. In this case, because the parts to be cut were very large, was made a estimation of the power

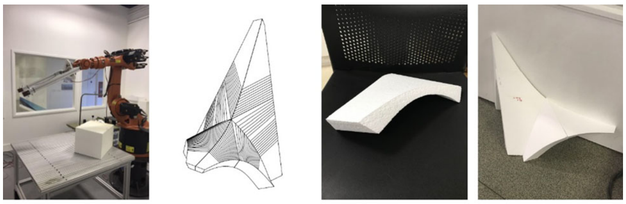


Fig. 15 Sequence of styrofoam cutting test

Fig. 16 Sequence of movements pick and place test

consumed during the cut and, thus, choose the source power needed to perform the service. After choosing the source and type of wire for the system, the next step was to choose whether it was best for the rough block to move (as it is done manually) or if it was best to leave the block fixed and place the hot wire on the arm robot. Then after several tests it was decided that the best configuration would be the second one. The grasshopper plugin of has a scheme for the KUKA KR16 robot, however for the execution to be perfect it was necessary to draw and insert in the scheme of the robot the table and the cutting tool. After this, parameters such as tangents and normal of the surface, safety planes and points of entry and exit of the cut were adjusted.

After all adaptations and adjusts, a chair projected by Zaha Hadid was made, as show in (Fig. 15).

In the third application, there were three challenges: *" Preparation and activation of the suction tool."*, *"Identification of the position and orientation of the object."* and *"Strategies of movement."*. To collect any piece size, a suction tool was designer. Became necessary to use a vacuum pump, which turns the compressed air blow from the building network into suction. Still within these modifications, a solenoid valve with 24V drive compatible with the hardware of the robot was placed. To identify the position and orientation of the object, as previously mentioned, a tag with a QR code was inserted in the object of interest and, using the programming in ROS, the camera read the position of the object and convert it into a vector of coordinates of the robot. To move the robot arm safely, the following ROS subroutine was created: the moveit always calculates the smallest distance between the position of the end effector and the position of the object, so the object was collected and taken to a determined position (Fig. 16).

5 Conclusions and remarks

Observing all the modifications, it can be concluded that all the applications were effective, demonstrating the versatility of robotic systems and their use for industry and research. In addition to demonstrating that the use of a robotic arm fits very clearly within the presented concepts of industry 4.0, since its practical approach impacts the breaking of several proposed paradigms, such as manufacturing interaction and manufacturing customization. Another point to be mentioned was that the first and second applications had the feedback of the students, who were motivated. Still speaking of results, the third application (the most used in the industry) has shown to be promising and versatile, because the ROS is an open language and have great possibility of spread.

It is possible to observe during the article, that the industry 4.0 goes through several areas of knowledge and the applications described have brought professionals from the area of design, architecture, control and automation and mechanics, all united in order to execute the objectives and to increase their knowledge.

In the future we intend to expand a number of tools by automating the exchange of tools, in addition to welding tools and injection of plastic and other materials. With respect to the pick and place problem, we intend to insert more sophisticated control algorithms that compensate parametric uncertainties and disturbances.

Acknowledgements The authors are grateful to the Brazilian Research Funding Agencies, CNPq, CAPES and TECGRAF Institute (PUC-RIO) for the support.

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