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KUKA KR3 INDUSTRIAL ROBOT UNIT HMI DESIGN AND CONTROL WITH UNIVERSAL INDUSTRIAL PC IN SIPY DEVELOPMENT ENVIRONMENT

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Abstract

The challenges presented by Industry 4.0 require an innovative, new type of thinking from the engineers. Connecting old machines into a network presents significant problems, as the switch cabinets for these are obsolete and non-upgradeable. This has made developing a solution necessary, that is later universally applicable for scrapped, but mechanically intact robot arms. During the realization of the project such an IoT compatible graphical interface was developed, which can control a KUKA KR3 industrial robot unit and can also Real-Time simulate it in virtual reality. The security functions of the robot are provided by a Pycom SiPy developer panel.

Keywords: *KUKA KR3, C++, JavaScript, Pycom SiPy, HMI.*

1. Introduction

At the University of Debrecen, Faculty of Engineering, Department of Mechatronics, in the Cyber-Physical & Intelligent Robot Systems Laboratory, besides education, the testing and validation of research topics is also conducted **[1]**. One of the main aims of the projects is the complete reimagining of industrial robots and their control systems, as well as realizing the support of new network functions. Old robot units mechanically don't become obsolete, but their control systems do.

In the laboratory students take part in a practical education in the subject of „Robotics Knowledge", but the distribution of new knowledge also happens here, as any research that is finished has its discoveries added to the lessons. Many of the robots that are found in the laboratory are undergoing refurbishing, just like the robot KR3 that was made by the company KUKA **[2]**. These units are in a mechanically sound state, with working motor regulating circuitry, but their control through their original industrial computers is impossible, because they are inoperable and their parts cannot be repaired.

The reasons mentioned above made the development and programming of a new, unique HMI necessary for the KUKA KR3, which makes visualization of 3D position possible in a Real Time environment. The Dead-Man switch was also reimagined, considering the relevant security standard.

2. KUKA KR3 Industrial Robot

The KUKA KR3 industrial robot and its variants are six-axis industrial robots designed for precise handling of light payloads.

These are used in small workspaces, for the manufacturing of small parts, with a nominal payload of 3kgs and a maximum reach of 635mm. Its main applications are: arc welding, grinding, assembly, automation in laboratories and the moving and implanting of parts **[3]**.

The structure of the robot can be seen on **figure 1** where the axes, the angular ranges of rotations and also the directions of the rotations are depicted.

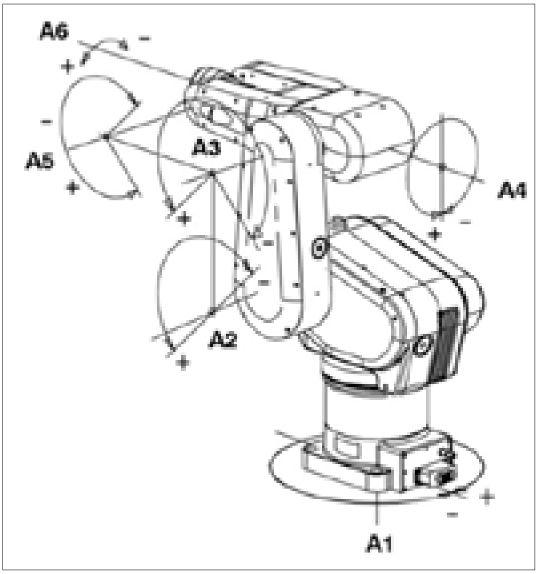

Figure 1. *Structure of a KUKA KR3 robot.* [3]

The robot itself is a 6R type robot, meaning, that every axis makes a rotational movement possible, resulting in a spherical field of action. It is also important to mention, that the actual field of action is influenced by the axis limitations of the robot unit in question.

1. táblázat. *KUKA KR3-axis-mozgástartományok* [3]

Maximum angular speeds of robot	Range of motion for axes in (degrees)
Axis 1 (A1) 240°/s	Axis 1: ±180º
Axis 2 (A2) 210°/s	Axis 2: -45º / +135º
Axis 3 (A3) 240°/s	Axis 3: -225º / +45º
Axis 4 (A4) 375°/s	Axis 4: ±180º
Axis 5 (A5) 300°/s	Axis 5: ±135º
Axis 6 (A6) 375°/s	Axis 6: infinite

An industrial computer is a PC made for use by the industry, that has to meet precise standards, has to provide great reliability, upgradeability and long-lasting technical support, besides being usually more expensive, than everyday consumer electronics.

An industrial PC is first and foremost used for process control and/or data collection or in some cases, if there is distributed processing, as a Front End for another controlling computer.

The control system managing the industrial robot consist of an industrial PC and the HMI control interface.

The above points are general expectations that need to be adhered to by the new control system of the KUKA KR3.

One of the main reasons for this is that although the complete control system is reimagined, in theory it still has to be able to perform the same functions as before, including a DeadMan Switch, Joint, World, Tool, Base coordinate systems, velocity control and axis End-Stops have to be usable.

The KUKA KR3 robot wasn't in sate at the beginning of the project to be used with an HMI, as it was missing one entirely. The robot was only moveable per axis. with the use of Step-Dir commands.

The main problem was presented by the fact, that the control systems or control racks present in the industry are usually company specific, meaning they are not interchangeable or repairable. The real life-cycle is defined by the support of the official manufacturer.

The original KR C3 controller used by the KUKA KR3 (Figure 2) is not being sold anymore and is inoperable. Since it is missing basic functions and the impossibility of a software update, in the case of a working control cabinet, would still present limitations in the performable tasks. The Embedded OS, which is available for it is Windows 95 - an earlier Microsoft development - which had its official support terminated on 31 December 2001. Of the supported ports at that time, the USB 1.0 was also only added with a later OSR 2.1 update, with a data transfer speed of 1,5Mbps. The use of broadband internet was also not possible [5].

Taking the above points into account, we can declare, that the KR C3 industrial control unit does not correspond to the expectations of Industry 4.0, nor to the network communication standards.

In essence, the control cabinet is capable of controlling the KR3 servo-motors, can run its manufacturer HMI, setting speed values and storing programs. In itself the industrial PC elements of it are the same as those of a general use Desktop PC, meaning it has basic hardware elements such as: CPU, RAM, HDD, Motherboard.

The parts cannot be replaced, as these also function as a type of hardware key for the original HMI.

In the original control unit is an MFC expansion card, this handles the I/O s; and also a DeviceNet/CAN bus to make communication between a teach pendant (KCP2) and the industrial PC possible.

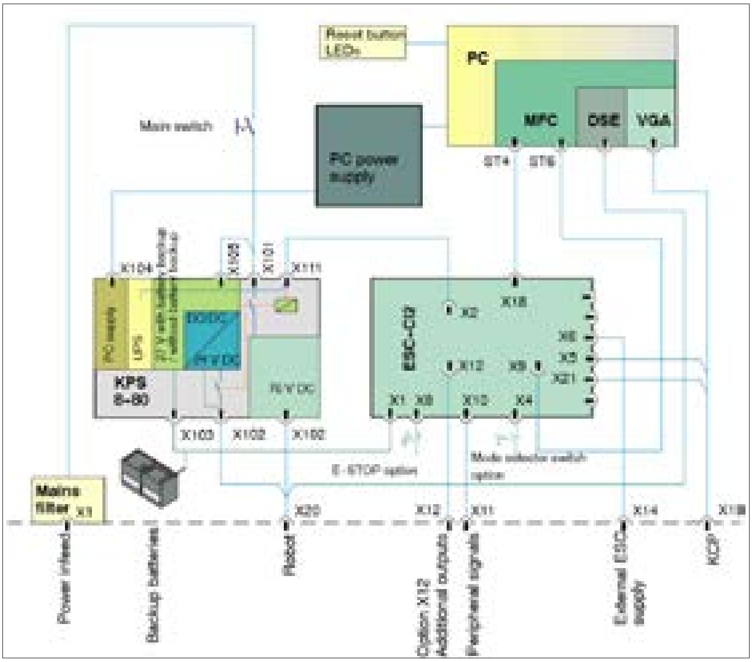

Figure 2. *Structure of KR C3 robot controller.*

3. Control of BLAC Motor

Inside the KUKA KR3 industrial robot there are several servo motors, which all perform rotational movements in every joint of the robot. These motors are all brushless AC motors, meaning that the spools are found on the stator and the magnets on the rotor.

For the precise operation of the servo motor, a HALL sensor is needed, so that the exact position of the motor can be determined at every moment of time. The current for the coils of the motors can be switched with the control of transistors, allowing for the creation of the electromagnetic fields needed for the rotation [6].

In general, BLAC type motors operate with better efficiency, since they are brushless and produce lesser thermal losses (Figure 3).

The outlets of the coils are designated with U, V, W, while those for the HALL sensor are VCC, GND, HU, HV, HW. Data provision regarding the positions from the motor side are made possible by Tamagawa TS5643 N 100 (11/24 bit) encoders [7].

The KUKA KR3 robot arm uses Inertia Dynamics M1701-2221 (FSB series) brakes, that operate with 24V DC current, but not on all 6 axes (A1, A2, A3, A4, A5 applies brakes).

The role of these brakes in the case of industrial robots is to make sure, that if the supply voltage ceases, the position and torque values are kept [8].

In the case of the KR3 robot the former motor controllers were changed out for the industrial

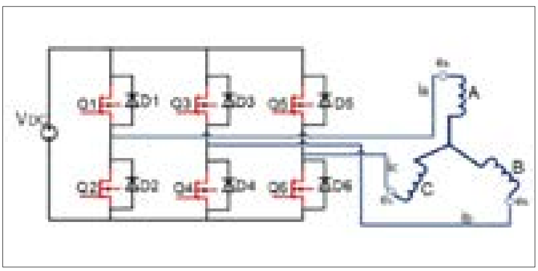

Figure 3. *Circuit of BLAC motors.* [4]

Figure 4. *LeadShine ACS606 servo controller* [9]

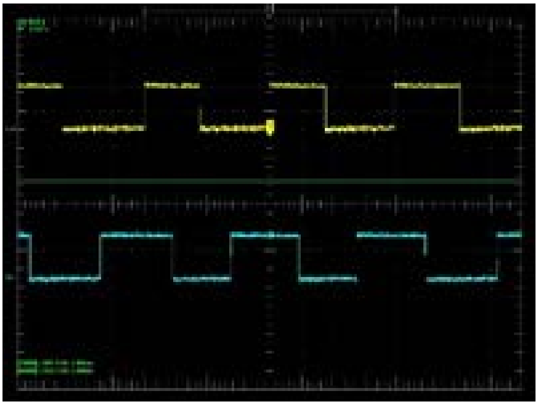

Figure 5. *Signals EA+ és EB+ .*

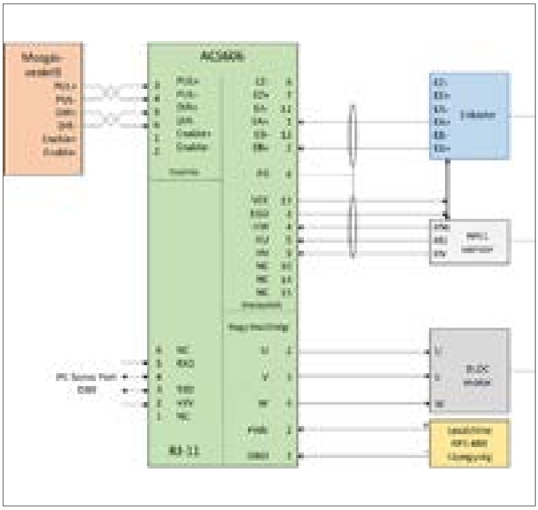

Figure 6. *ACS606 servo controller & sensors* **[9]**

Figure 7. *Block diagram of the system.*

type Leadshine AC606 **[9]** servo motor controllers. These are used for multiple axis industrial milling machines, for purposes of production, primarily for brushless (BLAC) motors (**Figure 4**).

The direct current supplied for the motors by the controller ranges from +18V up to +60V. On the outlets of U, V, W the supplying of current to the motors is made possible. Processing of the positions of each axis controlling motor happens through a 15-pin unique connector.

A rectangular signal is provided on the encoders EA+ and EB+, and on the HALL sensor's HU, HV and HW outlets (**Figure 5.**).

AThe encoders were validated with an oscilloscope before the new HMI was engineered. The complete rotation of an axis consists of 8192 impulses. In **Figure 5** on the X-axis of the oscilloscope is a „t"-time depicted (2ms), while on the Y-axis the current. The RPM set for the motors was 0,915 rotations/minute.

The cable type used for wiring was a twisted pair wire that was routed in a hose.

4. Designing the HMI & Requirements

As was earlier described, most of the elements of the KUKA KR3 are not changeable, as they also function as a sort of hardware key in regards to this system, while the KR C3 control cabinet found in the laboratory was also in an inoperable state. However, during the engineering of our HMI (Human Machine Interface) there were certain points, that, if implemented correctly in our own HMI would mean, that in theory, the original HMI would be reproduced. Therefore, so that the new HMI corresponds to the requirements of Industry 4.0, the system depicted in **Figure 7** was developed **[7]**.

To each axis of the robot, one by one a servo controller is connected, depicted in **Figure 6.** **[9]** each of these are also connected to a computer. This computer can be an industrial PC as well, just as it was in our case. On this computer a Linux OS is running that was modified so that it could run our own application in real time. Furthermore, it also houses a webserver, on which the 3D model of the KUKA robot, as well as the website responsible for the HMI can be stored, thus providing a flexible solution for the user. Unlike an industrial PC which only has one given hardware key, inside a network we can run our HMI on basically any computer, as long as that computer possesses a JavaScript enabled browser.

If a client wants to connect to the webserver, it first checks whether the Real-Time application is running, afterwards providing the files of the 3D model and the JavaScript program code necessary to run the HMI to the client.

This means, that the Human Machine Interface runs completely on the client, it sends the commands through the network to the Real-Time application, that executes those.

5. Industrial Compute Engine

For the realization of the project a one-card computer was selected, which is present as an embedded system during its application. The Strato Pi Base Board **[10]** was applied together with a Raspberry Pi **[11]** (**Figure 8**), that makes RS-232 as well as RS-485 communication possible.

With the help of the extra expansion card, it is now possible to use the Raspberry Pi to complete industrial tasks. The webserver and the Linux OS itself run on the Raspberry Pi, in turn the Strato Pi Base Board **[7]** sends signals to the servo controllers. Before replacing the old industrial PC, it proved necessary to test the waveforms sent to the motor control electronics.

The motor controller receives a STEP/DIR type signal, that means to every axis there are two corresponding signal cables. On the cable connected to the DIR input, depending on the direction of the motor steps, either 0V or 5V current is present (**Figure 9**).

A 5V peak voltage pulse with a 16us period is connected to the STEP input to move a unit in the direction specified by the DIR signal. The step unit depends on the range of motion of the respective axis and the resolution of the position encoder and the gear ratios of the motor.

6. Real Time Application

The version number of the Linux kernel of the applied operating system is 5.4.51-v8+, a Preemptive type kernel, which is key for running the application in real time.

The „core” program starts as a system level service, after initializing the network interfaces. The program is based on the principle that the specific position of the axes is given as a digital code, i.e. we know exactly how many steps are allowed due to the digital encoder. After starting it, the „core” program reads the saved maximum position numbers, then the initialization process happens, where it creates the corresponding POSIX socket resources for the network communication. In the background 6 threads are created, each of those corresponding to ‘on’ of the axes of the KUKA KR3 industrial robot. In the event that an inbound connection occurs, a new thread is created that executes it. The threads corresponding to the axes

8. ábra. *Strato Pi Base Board & Raspberry Pi* **[11]**

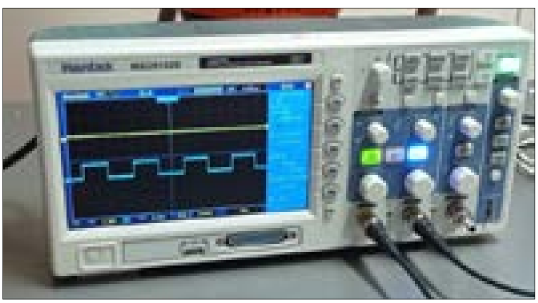

Figure 9. *Waveforms sent to motor controllers.*

Figure 10. *Pycom SiPy Pinout*

check whether there is a change in the incoming information compared to that which is stored. Additionally, the state of the DeadMan Switch is also checked, which happens over the network as well (Figure 10.).

7. Developing the Dead Man's Switch

A problem encountered during design was that if the HMI is accessible from anywhere on the network, the robot operator may not always be near the emergency stop button, which is dangerous. Starting from Murphy's Law, which reads, "What can go wrong, will go wrong" [12], the implementation of a simple emergency stop button accessible from anywhere under the network was necessary.

The solution is provided by Pycom's SiPy [13] development module, a Micropython-programmable microcontroller based on the Espressif ESP32 chipset (Figure 11).

Inside it are two processors: a network processor, that handles the WiFi radio connection and a main processor that runs a user installed program. Pycom's SiPy features include ultra-low power consumption, the implementation of a 1Km Wifi radio between Pycom devices, and SigFox communication with other IoT devices.

The wireless Dead Man's Switch only turns the power on or off from the SiPy panel.

The program running on the microcontroller will definitely try to connect to the real-time application on the network, which will detect the status of the connection and the MAC address of the device (Figure 12).

8. 3D KUKA KR3 HMI

One of the basic conditions of the HMI was to display the given robot unit in 3D. There were several reasons for this, one of which was to make it easier to track changes in the positions of individual axes and to allow easier user coordination.

The 3D model of the KUKA KR3 industrial robot arm was designed in 3D CAD (Computer Aided Design) program.

One solution to this is provided by SketchUp [14] which allows us to model 3D spatial shapes with a low polygon number, making it not only easier to slice 3D models during 3D printing, but also to design different simulation models.

The HMI interface was produced with the help of the JavaScript based ThreeJS 3D graphical engine. The functions of the HMI, such as calculations of coordinates, positioning of the robot, has

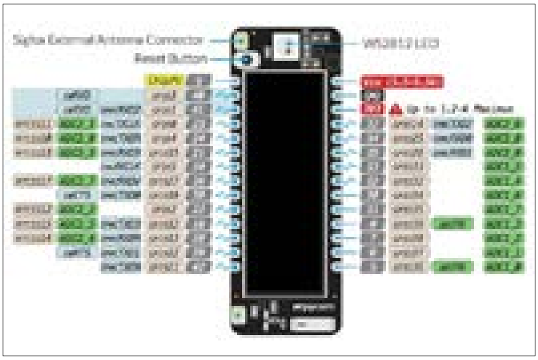

Figure 11. *Pycom SiPy Pinout.* [13]

Figure 12. *Pycom SiPy Deadman Switch.*

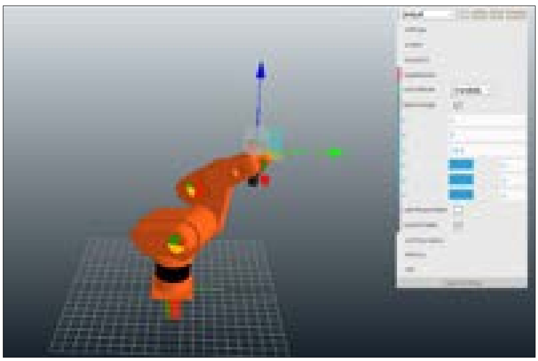

Figure 13. *KUKA KR3 3D HMI.*

14. ábra. *3D vs Real KUKA KR3 HMI*

also been written in JavaScript, as such the HMI runs in its entirety on the client computer (**Figure 13**).

Through the HMI the sending of signals towards the real KR3 industrial robot is possible, thus that will follow the position designated in the HMI. Positions can be reached through the velocities allowed by the robot's settings (**Figure 14**).

During the tests, the used client PC was and industrial Panasonic Toughbook Toughbook CF-C2, with 8 GB DDR3 RAM, Intel Core i5 4300U CPU.

The Cyber-Physical & Intelligent Robot Systems Laboratory previously provided opportunities for other types of research tasks as well. Whether it was image analysis for detection of specific elements in work stations **[15]**, creation of virtual environments **[16]** or conducting measurements related to singularities **[17]**. In addition to the aforementioned, the HMI design and control task mentioned above further strengthens this laboratory.

9. Conclusion

This project was fully realized and everything within it was also fully engineered. The KUKA KR3 industrial robot had its HMI engineered, for which a 3D model of the robot unit was also made that was integrated into a virtual reality environment. For the Dead Man's switch a SiPy controller developed by Pycom was used, while for the PC a Linux based OS, a once-card computer, a Strato Pi Base Board and Raspberry Pi were applied.

With the help of the 3D KUKA KR3 HMI, we can exactly track the changing of positions and also make the coordination of the real KUKA KR3 possible. As further possibilities for development, the integration and 3D modeling of a gripper tool for the virtual reality environment were considered.

Acknowledgements

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