ISBN: 978-3-95450-221-9 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2021-FRBR01

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PROCESS AUTOMATION AT SOLEIL: TWO APPLICATIONS USING ROBOT MANIPULATORS

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Abstract

Robot manipulators are an important component in most autonomous systems in the industry. Arc welding, machine tending, painting, picking, are only some examples where the robot manipulators are widely employed. In Synchrotrons some process can benefit from robotic approaches in order to improve automation. Automatic Sample Changer on beamlines is the most common example of automation. This paper describes two robotic applications developed at Synchrotron SOLEIL. Both applications use the SOLEIL robotic standard introduced some years ago [1]. The first application aims to automate the exchange of samples for powder diffraction experiment on the CRISTAL beamline. Hence, a pick-and-place robot is used to automate the process of picking up the sample holders and placing them on the goniometer. The second application, also of the pick-and-place type, is dedicated to the automation of the magnetic characterization of magnet modules of an U15 undulator. These modules, built with a permanent magnet and two poles, are measured using a pulsed wire method [2]. In this case, the robot picks the modules stored in boxes to then place them on the test bench of the U15 undulator.

INTRODUCTION

According to the International Federation of Robotics (IFR) an industrial robot is an automatically controlled, reprogrammable multipurpose manipulator programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications (ISO 8373:2012). At the beginning, since manipulators had no external sensing, they were used for simple tasks as pick and place, mainly doing monotonous, repetitive and dangerous tasks for humans. As a result of technological advances, robots could handle more complex motion and had external sensors and then, more complex applications followed like welding, painting, grinding and assembly. Nowadays, the use of an industrial robot, along with Computer-Aided Design (CAD) systems and Computer-Aided Manufacturing (CAM) systems, not only characterize the latest trends in process automation in the industry [3], but the robot manipulators are becoming essential components in various growing sectors such as medical.

In a synchrotron facility, the most common application of industrial robots is to use the manipulator as a sample changer. The principle of a robotic sample changer is to take samples from one place and put them in another place with accuracy and repeatability. Thus, these robotic exchangers are widely used in experimental stations for Macromolecular Crystallography (MX), like is the case of the beamlines AMX and FMX at the National Synchrotron Light Source II (NSLS-II) [4], the beamlines I03, I04, I04-1 and I24 at Diamond Light Source (DSL) [5], the beamlines ID23-1 and ID23-2 at the European Synchrotron Radiation Facility (ESRF), among other MX beamlines. Some other techniques like biological Small-Angle X-ray Scattering (bioSAXS) at NSLS-II [4] and the powder X-Ray diffraction at the ESRF [6] integrate the sample changers to sample automation.

Nevertheless, the use of industrial robots is not limited to the sample changer, they can also be used to detector positioning: for Bragg CDI and Bragg-ptychography [7], to study structural dynamics with X-ray techniques [8], to enable coherent diffraction and SAXS experiments [9]; or even, robot manipulators can execute similar tasks to those present in the industry, such high precision manufacturing [10].

At Synchrotron SOLEIL, two robotic sample changers were installed on the beamlines PROXIMA-1 [11], and PROXIMA-2 [12], long before SOLEIL developed the robot standardization in 2019. This standardization, see Fig. 1, designed as part of a larger strategy in process automation, defines a robotic standard on both hardware and software which is versatile enough to cover the synchrotron requirements, while being easy to implement, to employ and to maintain in operation [1].

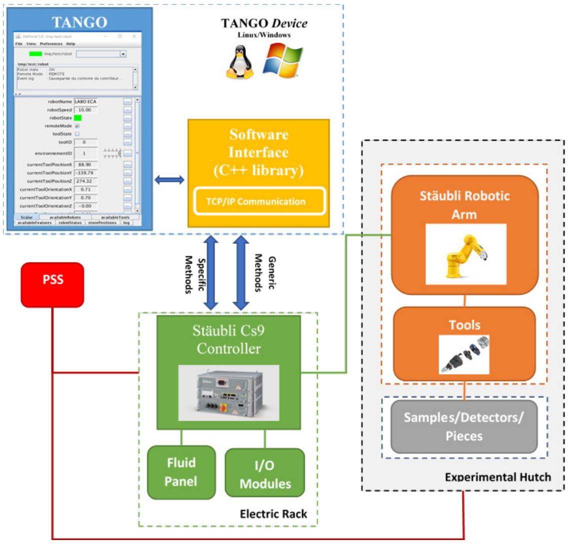

Figure 1: SOLEIL Robot Standardization Scheme.

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The robotic standard has allowed a rapid development and deployment of two new applications at SOLEIL. The first one, integrated by IRELEC company, is dedicated to accomplishing powder X-Ray diffraction measurements, where the robot is in charge of automating the sample changer. The second one, developed entirely in-house, differs from the application examples given above, since in this application the robot manipulator is used to automate the magnetic characterization of the modules of an U15 Undulator. Since measuring the magnetic field each of the modules is time-consuming and is often a repetitive and tedious task for human operators, the automation of this task can be perfectly achieved by an industrial robot.

In the following sections these two robotic applications are described in detail.

CRISTAL BEAMLINE ROBOTIC APPLICATION

CRISTAL is an Undulator-based X-ray multi-technique diffraction beamline, which delivers high-brightness beam in the 5 to 30 keV energy range. It is dedicated to study single crystals and powders. All the standard techniques for structural analysis on single crystals and powders are implemented, as well as more advanced techniques like coherent diffraction imaging and time-resolved diffraction in a pump-probe scheme [13].

To improve the efficiency of powder diffraction measurements, the process has been automated using an industrial robot:

1. Automatic mounting of capillaries. The robot is in charge of mounting the capillaries to be studied on a 2-circle diffractometer, following the workflow shown in Fig. 2.

2. Sample self-centering task. The diffractometer is equipped with a spinner and a Y-Z translation stage. Both of them serve to the sample self-centering[1].

3. Diffraction measurements. Measurements are performed by scanning the 2-circle diffractometer. The diffractometer includes two detectors. In order to obtain high-angular-resolution diagrams in less than one hour for ab-initio structure determinations a multi-crystal analyzer detector (21-Si(111) crystals) is employed. For phase analysis, in-situ or operando studies, a Mythen (from Dectris) curved pixel detector is used.

4. Automatic dismounting of capillaries. The robot returns the samples to their place in the sample store.

This process can be repeated without entering the experimental hutch as many times as necessary until the maximum capacity of the sample store is reached.

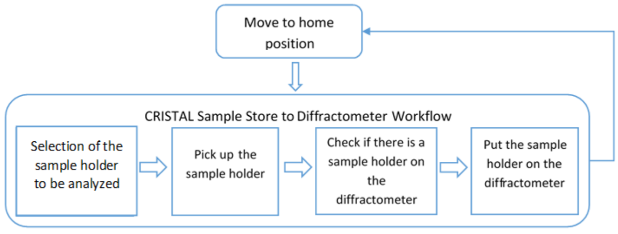

Figure 2: Robot Workflow: Sample Store to Diffractometer.

Robotic Sample Changer

The robotic platform, shown in Fig. 3, is based on a Stäubli TX2-60L robot with six degrees of freedom, which is mounted on a mobile chassis and integrates the Cs9 robot controller, the electric rack, the fluid panel and the input/output modules. The TX2-60L was chosen for its radius of work of 920 mm and the load capacity of 3.7 Kg. sufficient enough to carry the robot end-effectors. The main end-effector is composed of a pneumatic tool changing system, a 3-finger centric gripper, a collision and an overload protection system and a laser sensor. The manipulator is equipped with solenoid valves that operate the gripper, the tool changing system and the collision device without external devices. The robot controller is interlocked with the beamline Personnel Safety System (PSS) such that no robotic movements are allowed unless the hutch has been locked.

The sample store is placed next to the robot base and it has a capacity of 36 samples. The samples are mounted on 17mm diameter cylindrical sample holders. It can be observed from Fig. 4 that the lower part of the sample holder has a female cone that is used to place it on the sample store. The TX2-60L robot has a positioning repeatability of 30 μm and combined with a magnet housed in the bottom of the female cone, allows the accurate location of the sample holder on the diffractometer.

Although the position of the diffractometer is known, it has 1 degree of freedom (translation), thus the robot must be able to detect if it has been displaced. Furthermore, since the robot can be itself moved, a calibration process had to be implemented.

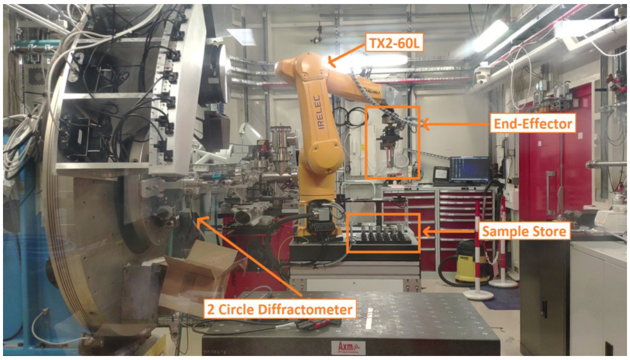

Figure 3: CRISTAL Robotic Sample Changer.

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[1] How self-centering is implemented is outside the scope of this paper.

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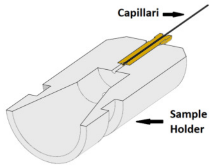


Figure 4: CRISTAL Sample Holder.

Calibration consists of measuring, with the help of a robot's tool equipped with a laser sensor (Keyence IL-30), the center of the placement area of the sample holder, located in the center of the diffractometer. If there is any difference between the calculated value and the value saved in the memory of the controller, the value save in memory is updated.

As it is described below in the **SOFTWARE INTEGRATION** Section, the robotic standard guarantees some flexibility in integration. Therefore, the calibration of the position of the diffractometer can be carried out when some movement in the translation of the diffractometer is performed or systematically at the beginning of a measurement campaign, i.e. before the execution of the 4 steps introduced above.

It is noteworthy that the execution time of the two first steps is about 1 minute and 30 seconds. This allows saving 5 minutes to 10 minutes if a human operator performs these tasks. In addition, the automated process gives the opportunity to almost uninterrupted use the beam 24 hours a day during the experiments.

MAGNETIC CHARACTERIZATION ROBOTIC APPLICATION

In order to achieve high-performance Undulators, a magnetic characterization of the modules (a hybrid magnetic structure, made out of permanent magnets and iron poles) that compose the insertion device have to be accomplished. For each module, the magnetic field is measured with a Hall effect probe mounted on a trolley which moves on a rail, and a rotating coil, supported by a set of motorized stages, is responsible of the magnetic field integral measurements. These two measuring instruments are placed next to the magnetic measurement bench, where each module is positioned on the internal girder for the purpose of being measured. Despite the fact that the magnetic field measurements are done automatically, the positioning of the module on the magnetic measurement bench was effectuated until now, by a human operator. Performing this task is time-consuming and it becomes repetitive for the operator due to the hundreds of modules that have to be characterized. Hence, to fully automate the magnetic characterization, a robotic solution to position the modules was implemented. The simplify workflow of the automated process is shown in Fig. 5. Where the orange dotted-line blocks are the tasks performed by the robot and the blue dashed-line blocks by the other devices of the test bench.

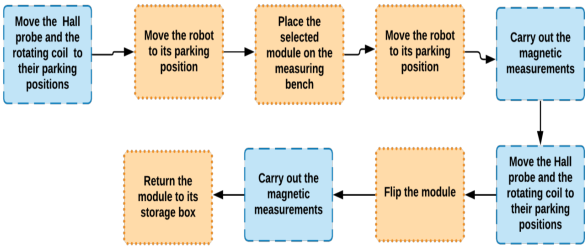


Figure 5: Automatic Magnetic Measurements Workflow.

Robotic Platform

The robotic platform is composed of a robot Stäubli TX2-60L mounted on a pedestal. The end-effector is formed by an electric 2-finger parallel gripper, a manual changing system and an ATI Force/Torque sensor system. The electric rack, the Cs9 robot controller and the Input/Output modules are placed in a separate bay. An optical table located next to the robot supports four boxes where 120 modules (30 per box) are arranged vertically. This optical table also supports a drop-off area that had to be implemented to be able to place the modules correctly on the measurement bench, see Fig. 6.

Since there are magnetic constraints, both the mechanical design and the design of the robot trajectories, were conceived taking into account these constraints. In addition, the gripper jaws were designed to be able to grasp the modules in two different ways, as it can be observed in Fig. 7. The "first configuration", Fig. 7a, takes place when the modules are taken out of the boxes and positioned on the drop-off area; while the "second configuration", Fig. 7b, is used when the robot takes the modules from the drop-off area and places them on the measurement bench and vice versa.

The Force/Torque sensor is used to ensure the accurate positioning of the module on the measurement bench. Once the module is released from the gripper, a series of movements is performed by the robot in such a way that the jaws push the module in the $X - Y$ direction until a $X - Y$ force threshold is reached.

The characterization of a module takes around 15 min, therefore the robot-based bench can work up to 30 hours without the need for human intervention.

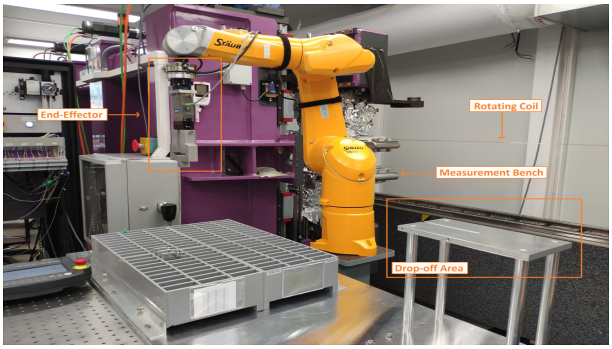
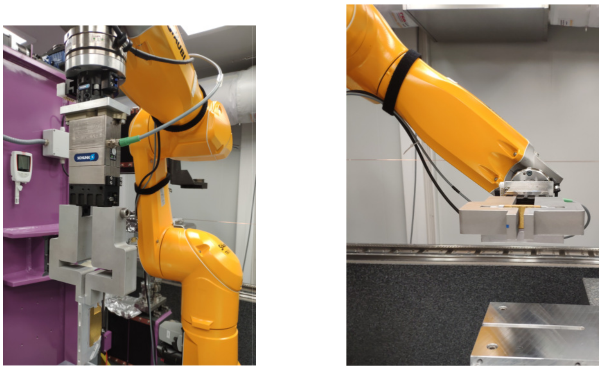


Figure 6: Robotic Platform.



(a) Gripper Configuration 1. (b) Gripper Configuration 2.

Figure 7: Two-in-one Gripper.

SOFTWARE INTEGRATION

It can be observed in Fig. 1 that a C++ library interface was developed to enable communication between TANGO and the robot controller. The library integrated into the TANGO Device communicates with the Cs9 controller via the Ethernet network using TCP/IP.

In order to facilitate the integration into the control system, a series of methods or routines are used to communicate and act on the physical environment of the robot. The so-called generic methods are instructions that can be applied to any robotic application, such as, turn the robot on/off, sending the robot to a parking position or home position. On the other hand, the specific methods are instructions dedicated to an application, i.e., they execute functionalities or features developed for a single application.

For the CRISTAL robotic application some of the implemented features are: *put* (take the sample from the sample store at coordinates *row,column*, and mount it on the diffractometer), *get* (take the sample from the diffractometer and put it back at its position in the sample store), *teachgonio* (launch the automatic teaching of the diffractometer position, i.e. the calibration process). For the magnetic characterization some of the implemented features are: *put* (take the module from the selected box at coordinates *box,row,column*), *get* (take the module from the measurement bench, flip it, and put it back at its position), *flip* (take the module from the measurement bench, flip it, and put it back on the measurement bench).

TANGO allows to individually manage each component of the experimental setups, i.e. the translation of the diffractometer, the spinner, and so on, in the case of the CRISTAL application; the Hall probe and the rotating coil in the case of the magnetic measurements. Thus, the whole process is manage at a higher level using the different TANGO bindings to other languages, see Fig. 8. This approach then provides that the process can be adapted and can evolve according to the needs, without having to modify the code programmed in the robot controller.

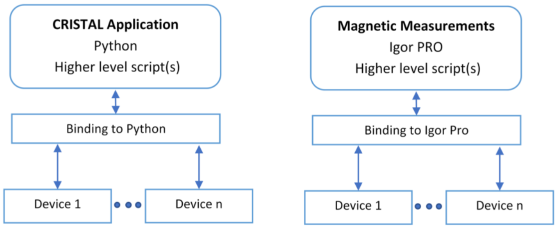


Figure 8: Software Integration Schematic.

CONCLUSIONS

The standardization of robots has made possible to develop robotic applications in a relatively short period of time, considering that one of them was completely designed and developed in-house. These two applications have established the technical basis for the future development of robotic applications. Ten other applications have already been identified to include industrial robots in the automation of experiments. These identified applications are not only of the pick-and-place type, but also include the positioning of detectors and new assembly methods for SOLEIL future upgrade, which means that new challenges must be faced in the short and long term, notably avoiding obstacles. Besides, the sample environments are increasingly complex and more demanding in performance, reliability and safety. The integration of robot manipulators in the sample environments therefore becomes another challenge.

In order to better address the aforementioned challenges, SOLEIL is already working on some Collision Avoidance Systems (CAS) approaches, especially for systems who involves in limited workspaces, such as the sample environments. In the near future, adding CAS to the industrial robots will be an important step to accomplish.

AKNOWLEDGEMENTS

The authors thank all SOLEIL staff who have participated in one way or another in the development of the robotic applications.

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