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Concepts for Sample Positioning using Industrial Robots at ISIS

Matt North[1]**,** Saurabh Kabra[1]
[1] STFC, ISIS, Rutherford Appleton Laboratory, UK

E-mail: matt.north@stfc.ac.uk, saurabh.kabra@stfc.ac.uk

Abstract. This paper offers a conceptual outline regarding the application of industrial robots for automated sample positioning activities at the ISIS Neutron & Muon source, located at the Rutherford Appleton Laboratory in the UK. Drivers for a change in the approach to traditional component positioning tasks are highlighted, from which the concept of applying an industrial robot platform for neutron camera positioning at the Imaging and Materials Science & Engineering (IMAT) instrument, automation of sample changes for top loading closed cycle refrigerators and the automation of sample changing and positioning for texture measurements on powder diffraction instruments is discussed.

1. Introduction

The ISIS neutron & muon source located at the Rutherford Appleton Laboratory in the UK. ISIS operates two targets stations, 30 beamline instruments with over 1800 domestic and international users per year. The facility comprises of a 70MeV LINAC feeding a dual harmonic proton accelerator, producing 200uA 800MeV protons to two independent targets. Proton extraction is such that TS1 operates at 40Hz and TS2 at 10Hz repetition rates, producing 128kW and 32kW respective target power.

ISIS has a total of 26 neutron and 4 muon instruments covering diffraction, spectroscopy, reflectometry and SANS techniques. On completion of the TS2 Phase-II construction project an additional four instruments will increase the SANS and reflectometry instrument suite with ZOOM[1] and LARMOR[2] whilst adding neutron chip irradiation with CHIPIR[3] and neutron imaging with IMAT[4].

2. Triggers for future development of sample positioning and manipulation systems

2.1. Increasing Experimental Throughput

Regardless of the measurement technique, a gain in neutron flux and associated reduction in measurement period is the primary driver for automating sample changes and sample positioning, to remove or reduce preparatory bottlenecks, reduce strain on human resource or streamline instrument operation.

ISIS target station one target is currently moving towards a future target and moderator upgrade which is estimated to increase the neutron flux by an average gain factor 3.4 across the instrument suite. [5] Coupling a source upgrade with beamline equipment upgrades such as the addition of modern neutron guides enables instruments to see potential neutron flux gain increases by an order of magnitude. [6]

A range of sample changers are currently used at ISIS to enable automation of sample changing tasks on select beamlines on both the first and second target stations. Typically diffraction and small angle neutron scattering measurements have the capacity for the highest experimental throughput with measurements durations as low as 15 minutes. Reflectometry measurements can be similar in period but experimental throughput is restricted by the sample alignment process. Spectrometry measurements require much greater periods to get useful data, for simple experiments where sample signature data is the primary requirement, such as with express access, the minimum measurement durations is around five hours.

The GEM[7] and POLARIS[8] high intensity diffraction beamlines at the first target station use a 20 position carousel sample changer, shown in figure 1, for automated measurements at room temperature, at atmospheric pressure, with samples contained in standard vanadium cans. Currently measurement durations are as low as 30 minutes, providing automated sample changes over a minimum 10 hour period. Looking to the future with higher neutron fluxes, both GEM and POLARIS will experience measurement durations in the 10 minute range at which point the current capacity of the existing sample changer limits its value and a new type of sample changer must to be developed to meet this high throughput future.

Figure 1: 20 Position Carousel Sample Changer

2.2. Beamline Access Routes

Express access to instruments is an important part of the range of ISIS access routes enabling a comparably simple route for users to quantify the value in neutron techniques. [9] ISIS is exploring the value and practicalities of a range of facility access models. In this context if there is significant growth in express access this could erode the value of existing sample changers to a level where changer capacity will not cover automation through an express period.

2.3. Widening Technical Capabilities

Measurements at cryogenic temperatures and texture measurements are two types of measurement that currently have the potential for associated short measurement durations but are not currently catered for by the existing set of sample changers at ISIS. Texture measurements can be completed in the carousel style sample changer if the changer is lifted out of the instrument and rotated, however this methodology deviates from automated instrument operation.

3. Industrial Robots vs. Traditional Sample Positioners

Traditionally the solution to sample positioning has been the in house development of bespoke motion systems. This methodology produces systems that vary significantly with little scope for shared deployment across beamlines. Consequentially development costs and commissioning times are amplified and varying levels of support and maintenance are required. As previously described the inflexibility of the traditional sample changer model means that step changes in beamline neutronic performance, such as instrument or source upgrades requires settling with non-optimal operation or complete redesigns.

With this in mind a major advantage of applying an industrial robot system is the flexibility of motion and subsequent increased scope in motion solutions that can be delivered. Hardware costs can be up to an order of magnitude lower in comparison to in house designs. Industrial robot system operation is also reliable with mean time between failure rates generally around 80,000 hours with low associated maintenance frequencies. [10]

Figures 2 and 3 show two common types of industrial robot. SCARA robots are commonly used for high throughput pick and place whereas the 6 axis robotic arms are used where a greater degree of flexibility is required for component or tool positioning tasks. Repeatability of the robot end effector is a key factor of a robot system and repeatability in the order of 100µm is not uncommon with many off the shelf systems. Positional accuracy is not so easily defined and is dependent on many factors including robot pose, payload weight, end effector working volume, joint paths, operating environment, robot manufacturing quality and the kinematic model referenced by the robot controller. For these reasons robot manufacturers do not freely quote positional accuracies which can be as high as 15mm in some cases. [11]

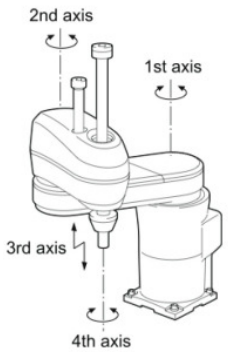

Figure 2: SCARA Robot Schematic

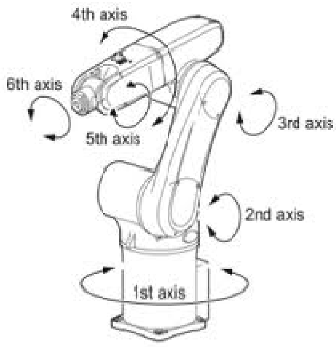

Figure 3: 6 Axis Robot Arm Schematic

Improving the kinematic model of a robot provides a generic approach to improving positional accuracy of industrial robots. Many robot manufacturers can provide an absolute robot which is shipped with a calibrated kinematic model specific to the robot arm. The calibration process utilises a laser tracker system to plot the errors between the standard kinematic model and the robot end effector over a number of points through the working volume. The kinematic model is then adjusted to take account of the difference. The level of improvement in positional accuracy provided by robot calibration is not standard across the board but can increase absolute positional accuracy in the 120µm region for a robot working in a restricted $0.4m^3$ volume with a 1.3kg payload. [12]

4. Conceptual Applications for Industrial Robotics at ISIS

4.1. Camera Positioning System

IMAT (Imaging and Materials Science & Engineering) is a neutron imaging and diffraction instrument for materials science, materials processing and engineering being constructed as part of the ISIS

second target station phase-II project. The special features of the instrument will be energy-selective neutron imaging and the combination of neutron imaging and neutron diffraction. It is expected that IMAT will start operating in September 2015. [4]
Neutron imaging measurements on IMAT will require different neutron cameras to be positioned accurately beyond the sample. Imaging requirements define the automation of neutron camera selection and positioning. Integrating this requirement on an instrument with wide detector coverage, as shown in figure 4, dictates the need for imaging equipment to be completely removed from the sample area. These needs could not be adequately met through traditional positioning systems.

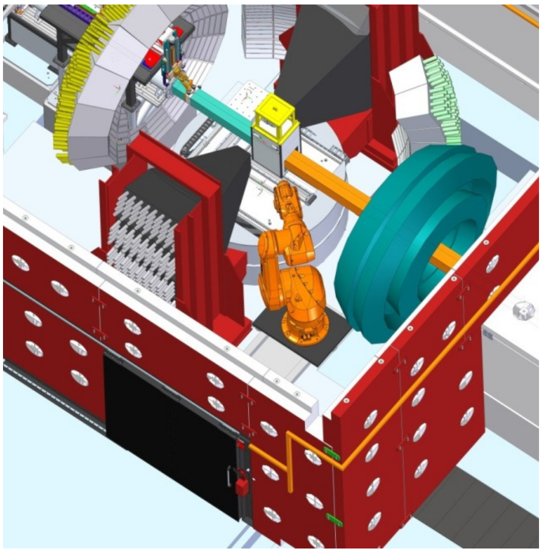

Figure 4: 3D representation of the IMAT blockhouse

A 6 axis robot arm provides the level of kinematic flexibility required to meet the motion requirements, however to ensure a high quality of measurement there is a requirement for the robot arm to hold a neutron camera with positional stability better than 40μm for periods up to an hour. The working volume constraints require the robot arm to hold pose, reaching out in the order of 2m from the base with up to a 70kg payload. A feasibility study was performed showing that, without application specific robot calibration or positional tracking feedback, typical repeatability with a 70kg load was in the order of 70μm with drift in the order of 10μm to 150μm over a 30 minute period. [12] This drift envelope can be significantly reduced to sub 10μm by employing a peripheral laser tracking device as a positional sensor to enable closed loop control of the robot end effector.

4.2. Cryogenic Sample Changer

A similar approach to automated sample changes on x-ray diffraction beamlines can be adapted to neutron sources; applying an industrial robot to move samples between a precooled sample rack and a closed cycle refrigerator (CCR). A novel approach has been developed to position vanadium cans in a CCR without the need to use the traditional method of mounting sample and associated thermometry wiring on sample stick mechanics. The addition of baffles and thermometry to the sample can and the inclusion of a positioning seat in the CCR insert are the only modifications required. Figure 5 shows vanadium can including thermometry contact PCB and baffles. Figure 6 shows the fixed sample seat ready for mounting in a CCR insert complete with sprung contacts to complete the temperature sensing circuit.

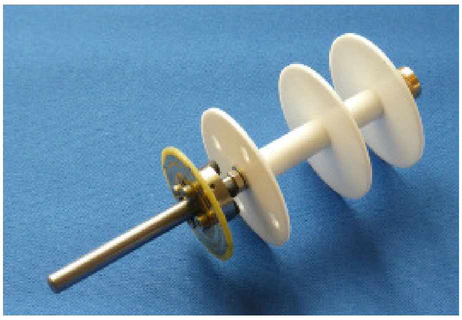

Figure 5: Sample Can with Integrated Baffles

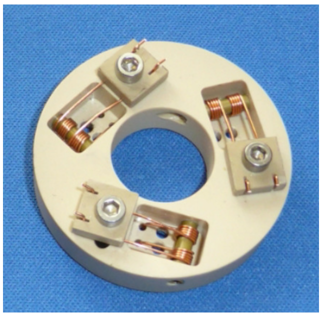

Figure 6: Insert seat showing sprung contacts

By ensuring that the sample can baffle dimensions are similar in diameter to the CCR insert a controlled flow of gas through the insert produces enough pressure to move the vanadium can through the insert. Offline experimentation has proven that this method provides robust control of sample position and robust, repeatable connections have been made for sample thermometry as the can is seated in the operating position.

Sample precooling is an essential component of an automated cryogenic sample changer for high throughput experiments. In general precooling samples to liquid nitrogen temperature halves the total time to cool a sample to 4K. An important aspect of automating cold samples changes is to ensure that there is no ice deposition on the sample can or inside associated sample environment during the movement and positioning of the sample can.

For a CCR the greatest risk of ice deposition in the insert is during entry and egress of the sample into the insert volume. This is can be managed by isolating the insert volume from the outside environment via an automated gate valve and controlling the flow of exchange gas through the insert volume during a sample change. For the sample can the greatest risk of ice deposition is during the pick and place task between the precooled location and the CCR. By integrating pipework onto the robot arm end effector, adequate control of precooled gas flow across the sample during the pick and place task can ensure that the sample can is kept in a dry cold environment.

4.3. Ambient Sample Changer

The principles outlined in the cryogenic sample changer concept can be applied to provide improvements to the existing carousel sample changer used for powder diffraction by providing scope for increased sample capacity. Enabling operation in a vacuum environment; reducing background scatter. The capability to monitor sample temperature and the possibility to control sample temperature by filling the insert with cooled or heated exchange gas.

4.4. Automated Texture Measurements

6 axis articulated arms have the kinematic freedom, using the axis convention provided in figure 7, to move a sample through 360° in φ, χ and Ω. Both φ and Ω can be mapped to a single revolute axis; J1 and J6 respectively using the convention shown in figure 3. To ensure that χ is kept perpendicular to φ throughout the range of motion, χ is potentially a composite motion of axis J2 through to J5.

Controlling from a calibrated kinematic model of the robot can provide positional accuracy better than 500μm with rotational resolution of 1° from a single axis making a 6 axis arm an ideal candidate for texture measurements on powder samples where the neutron beam size is larger than the sample size.

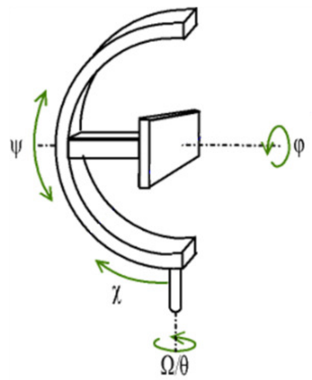

Figure 7: Eulerian Cradle Schematic

The operating environment required for texture measurements produces greater challenges. Mounting the sample to the end of a robot arm requires the robot to operate inside an evacuated volume in the instrument tank during a measurement. Robot operation in a vacuum is possible with minor modification to a robot arm to ensure that pressure differentials across robot joints are managed and heat from motor operation is dissipated into a peripheral heat sink. [12]

The physical constraints dictated by the working volume are a significant concern as the range of robot motion and pose required for a texture measurement may, if unconstrained, need an operating volume greater than the physical constraints of the instrument tank, posing a significant hazard to damaging the instrument, robot arm or sample can. DENSO produces one of the smallest 6 axis robot arms on the market with a radial reach of just 430mm [13] This small robot still exceeds the extents of most instrument tank working volumes at ISIS. Parasitic scattering and detector shadowing by the robot arm as it moves inside the working volume is also a concern, having a detrimental effect on the quality of the measurement.

Many robot manufacturers provide 3D environments as part of robotic motion design environments enabling the design to simulate control programs, mapping the path and pose of the robot arm and identifying potential collisions. Integrating 3D models of the instrument infrastructure into the 3D design environment provides a precise indication to the extent of the physical constraints posed by tank apertures and the position of the robot arm referenced to instrument detector positions allowing working volumes to be constrained and robot arm motion and position refined. Parasitic scatter can also be reduced by employing classic material shielding methods, with an emphasis on ensuring that the additional weight does not have detrimental impact on positional accuracies.

With respect to automating sample changes with texture measurements mounting the 6 axis arm in an evacuated volume has the major drawback of isolating the arm from the sample rack. The application of two robotic arms in cooperative motion is a viable solution with one robot performing a pick and place task outside of the instrument tank, passing the sample through an air lock to the second robot performing the sample positioning task in the instrument tank.

5. Challenges for Industrial Robot Application

As previously highlighted industrial robots currently have the capabilities to meet the positioning and working environment requirements of a range of applications at ISIS. To truly capitalise on the flexible, standardised, robust motion system that a 6 axis robot provides is to apply a standard robot platform to a range of applications. Taking sample changing as an example, there is a wide variety of in house designed sample changers at ISIS used for a particular type of sample can on a particular beamline. Amalgamating these to a single entity which has the flexibility to be deployed across many beamlines for many different types of samples and environments is a valuable goal. However, the greatest barrier to realising this is the variation in working volumes around the instrument sample areas.

Figure 8 highlights the diverse range of sample areas at ISIS. Deploying a standard robot cell at each of these locations is not trivial, it can be seen that there is a varying amount of area for deploying the robot system and it's peripheral components and the final position the robot arm must deliver the sample to ranges from deep wells as seen in WISH, to moderate heights on sample positioners, LARMOR.

One viable option is to design a standard robot cell which is incorporated with instrument specific mechanics defining the location of the robot arm and associated equipment. Using modern 'teach by hand' robot arms [14] in conjunction with mechanical reference dowels could provide a flexible and user friendly method for managing the variation in equipment position across the beamlines, with robot automated control tasks being defined as a standard and remaining unchanged at each location.

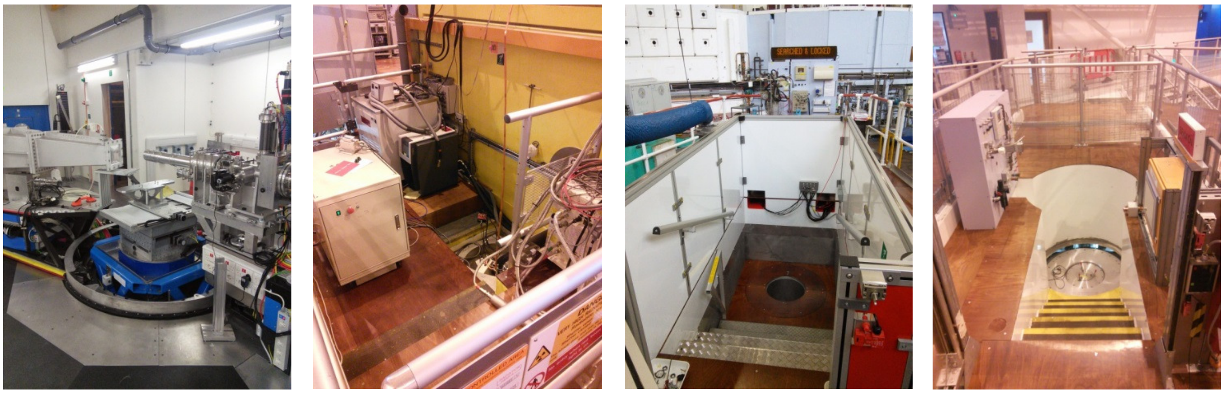

Figure 8: ISIS Instrument sample areas. From left to right: LARMOR, NIMROD, POLARIS, WISH.

6. CONCLUSIONS

It is clear that industrial robots can provide a low cost, reliable and flexible platform to develop solution to automate a variety of sample and beamline equipment positioning tasks. The series of revolute joins that makes up a robot provides essentially open loop control of the end effector which limits the robots positional accuracy, however there are well established methods to improve positional accuracies to the extent that they meet the requirements for sample changing and component positioning tasks.

The traditional methodology of designing one off sample changers and associated control systems in house for a specific beamlines is resource heavy, expensive and complicates operational support and equipment maintenance. Using a robotic arm as a generic standard to develop from is very attractive proposition; however the differing working environments found across beamlines makes this difficult in practical terms and further work is required to understand the management of these differences in detail.

7. ACKNOWLEDGEMENTS

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Thanks to Dr Oleg Kirichek information and images relating to the cryogenic sample changer concept.

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