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A robotic arm as a simple sample changer for a diffractometer with very low component costs

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Inexpensive model robots are a viable option for automation of simple, repetitive tasks and can be solutions when space restriction and funding are issues, both factors that may eliminate more advanced robots from consideration. A simple-to-program, inexpensive robotic arm has been integrated in a sample changer for room-temperature experiments on a neutron powder diffractometer. In spite of the limited precision inherent in a model, servo-controlled robot, a very reproducible overall system can be made. Simple 'tricks' such as incorporating self-centering mechanisms, *e.g.* mechanically self-centering designs and magnets, can produce central forces that eliminate the need for high precision from the robot arm.

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1. Introduction

Over the past few years, many central research facilities have greatly improved the efficiency of their diffractometers by incorporating commercially designed, industrial robots that are capable of acting as automated sample changers with high precision and reproducibility (Round *et al.*, 2008; Hiraki *et al.*, 2008; Ohana *et al.*, 2004; Viola *et al.*, 2007). These sample changers are often expensive, typically many tens to over 100 000 dollars, and moderate to large in size.

While many of these advanced robots are used for quite complicated tasks around a diffractometer, others are used as little more than the most basic sample changers. Here we show the possibility of producing a sample changer for a diffractometer that is both inexpensive and able to fit into a fairly constrained space. The C2 powder neutron diffractometer at the Canadian Neutron Beam Centre (Cranswick & Donaberger, 2008; Cranswick *et al.*, 2008) has very limited space both in the sample-space area and in the area immediately surrounding the diffractometer, and required an upgrade over the previous linear translator that could handle only seven samples reliably. The conclusion was that the best place to install a sample changer on the diffractometer would be in the square-shaped sample area itself.

Along with some minor modifications to increase its reproducibility, it was found that a basic robotic arm could be used as a reliable sample changer. Expensive, high-precision systems are not required, so long as the arm can attain a minimum level of reproducibility, as it is the reproducibility of the entire system that is most important. Self-centering forces (mechanical and magnetic) can be used: *e.g.* from conical mating surfaces and permanent magnets. These can ensure final reproducibility of an initially coarsely positioned sample.

A small five-axis, servo-controlled model robot arm was purchased from Lynxmotion for approximately \$500 CAD and was developed into a successful sample changer. The robot's cost is less expensive than a single linear drive and considerably more flexible.

In this paper, the description of the modifications to the hardware and the use of the control software are specific to the Lynxmotion robot. This does not imply recommendation or endorsement by the National Research Council for any other purpose other than in the specific situation and purpose to which it was applied here. The aim of the paper is to show that inexpensive model robots are a viable option for automation of certain simple tasks for crystallography.

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2. Description of design

2.1. Anatomy of the robotic arm

Lynxmotion is a company that manufactures robot-assembly kits intended for hobbyists and educational purposes. One great advantage to this system is that the kit includes easy-to-use software driven by a graphical user interface (GUI) for programming the arm (Gay, 2008). The arm's total lift capacity is approximately 0.25 kg.

The assembled arm contains a total of six motor servos of the kind used for the control surfaces of model aircraft. These servos control the movements in five major joints of rotation — the base, shoulder (which has two servos to support the lever action of the loaded arm),

Figure 1
The robot and the servos defining the five axes.

elbow, wrist and grip (Fig. 1). All servos are wired to an SSC32 servo-controller board and, in turn, this board is connected to a computer *via* an RS232 cable. The GUI allows users to move motors independently or in synchronization in absolute coordinates.

The SSC32 can control up to 32 servos and is also capable of handling analog or digital input and output signals (*e.g.* for triggers or inhibit functions to and from a control computer), and of being interfaced with Basic Stamp or Basic Atom microcontroller boards, so far more complex machines than the one described here could be built around one board.

2.2. Implementation and design

All the sample containers, in the form of V cans for our neutron powder diffractometer, and the arm sit on a common sample plate that can be bolted to the diffractometer; this design eliminates the need to calibrate the coordinate frame of the robot to that of the diffractometer. This also makes for simple storage when not in use. Such a design is about the simplest way of implementing a robot system and can be completely developed offline without ever interfering with beamline operation.

For this case, a pre-existing 20" (50.8 cm) diameter plate was the largest that could fit inside the sample area and therefore maximized the possible number of samples. The practical issues that needed to be dealt with involved determining how the samples will be stored on the sample plate, how the arm will most securely grip the canisters and how samples will be held in the beam during a measurement. Most of the additional pieces required to build such a changer were purchased from a hardware store, and machining was limited to drilling and tapping holes in the plate and making a few cylindrical posts.

Although this arm is capable of performing the tasks of a sample changer as-built, it had a difficult time doing it reproducibly. The major issue associated with the selected robot's low cost is that of slop and backlash in the servos. Backlash is a common phenomenon in all geared systems (Norton, 2004). Harmonic drives that minimize this effect (Lauetta, 2006) are used in some more advanced robotics. Nevertheless, taking some simple steps can minimize backlash even in a system prone to it.

2.3. Antibacklash hardware modification

Of all the motors in the robot, backlash is most significant in the base rotation motor. One of the most effective ways to correct backlash is by applying a load in one direction to a motor (Jensen, 1991). Unlike the base motor which rotates the arm about the vertical axis, the shoulder, elbow and wrist motors all experience a natural load due to gravity, as they generally have components of motion in the vertical. To reduce the backlash in the base rotation, a spring was sufficient to provide a permanent directional load onto the base servo (Fig. 2).

2.4. Description of the sample-plate layout

The constricted sample area of C2 also contains a neutron camera mounted on a linear drive. The camera's height is such that it would sweep off any V sample cans placed vertically on the plate when the base plate was rotated, so the cans were constrained to lie in the horizontal. The bottoms of our V cans have a 4/40-threaded hole, usually used to attach thermocouples. Sets of magnetic latches, typically used for securing cupboard doors, were purchased. These latches consist of $\frac{1}{2}$ " (1.27 cm) diameter magnets inside fitted steel cups. A corresponding $\frac{1}{2}$ " torroidal magnet was screwed to a small steel bracket. These steel brackets hold the samples horizontally, $\frac{1}{4}$ "

(0.64 cm) above the sample plate. Weak ceramic magnets were chosen over rare earth magnets because they provided enough force to hold sample canisters at a desired location.

A cylindrical Al post was machined of appropriate height to place the V cans in the middle of the neutron beam and was mounted in the center of the plate. The top of the post had a dish-shaped recess and a $\frac{1}{2}$ " ceramic magnet was placed at the bottom of the dish. The combined actions of the dish-shaped funnel and the ceramic magnet guide samples to the center of the post with good reproducibility.

When placing the V cans onto the magnetic holders, the arm was programmed so that the two magnets contacted on an incline. Cans were released from the grip while only a mechanical slight contact existed between magnets, ensuring the maximum self-centering action as the can is pulled into place.

The arm was mounted on an elevated stand above the plate. This extends the range of motion of the arm across the plate. The sample plate's final design consisted of 22 cans. The total mass of the system is around 7 kg, mostly that of the Al plate, and is readily portable.

3. Programming

A sequence of motions, such as picking up a particular sample, may be broken down into many steps and the sequence saved, played and tested (Gay, 2008). The sequences can be exported from the GUI software for an optional Basic Stamp controller board. Basic Stamp code was exported, and a Tcl/Tk script stripped out the control strings. These are ultimately sent *via* RS232 to the SSC32 servo-controller board. Therefore, all the development can take place with the GUI on a PC, and the final servo-control sequences may be exported so that any diffractometer control computer capable of RS232 communication, in our case an Alpha/VMS system, can control the arm.

In addition to the spring loading of the base motor, programming can also reduce backlash effects. The arm was programmed always to drive from a common position in space before picking up a sample. This position was near the edge of the base plate, and all base rotations towards sample cans were done in a single motion, with the restoring force of the spring acting against it.

The servos can be powered on and off by software. Thus, the servos are only on for the few seconds it takes to retrieve and reposition a can, which prevents heat build-up in the motors. They are turned off

Figure 2
Front profile of the finished sample changer. Inset: magnified view of antibacklash spring. One end of the spring is attached to a stationary point while the other is attached to the base of the rotating arm.

during the diffraction measurement, which typically lasts more than an hour. The robot was then integrated into the VAX control system. Neutrons can be used to align the can even more precisely in the beam (Cranswick & Donaberger, 2008).

4. Conclusions

A sample changer for room-temperature measurements was designed using a model robotic arm, a pre-existing sample plate and a few inexpensive materials purchased from a hardware store, with a total component cost well under \$1000 CAD. While model robots are usually sold with a specific disclaimer that they are not intended for industrial use, the low duty cycle of such an arm for changing samples on a medium-flux neutron source is not much higher than that of hobby use. Backlash can be sufficiently overcome by a combination of programming and minor hardware modifications. Typical samples are well within the lifting capacity. Programming of the particular robot described here was made almost trivial by the GUI-driven software. Trials have proven that the arm is able to perform to required standards and highlights the point that simple robotics can be solutions when both space restriction and funding are issues, both factors that may eliminate more advanced robots from consideration.

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