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Modelling and control of neutron and synchrotron beamline positioning systems

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ABSTRACT

Measurement of residual stress using neutron or synchrotron diffraction relies on the accurate alignment of the sample in relation to the gauge volume of the instrument. Automatic sample alignment can be achieved using kinematic models of the positioning system provided the relevant kinematic parameters are known, or can be determined, to a suitable accuracy.

In this paper, the use of techniques from robotic calibration theory to generate kinematic models of both off-the-shelf and custom-built positioning systems is demonstrated. The approach is illustrated using a positioning system in use on the ENGIN-X instrument at the UK's ISIS pulsed neutron source comprising a traditional XYZΩ table augmented with a triple axis manipulator. Accuracies better than 100 microns were achieved for this compound system.

Discussed here in terms of sample positioning systems these methods are entirely applicable to other moving instrument components such as beam shaping jaws and detectors.

1. Introduction

Neutron and synchrotron diffraction are non-destructive methods of determining residual stress from measurements of strain within crystalline or polycrystalline materials. Residual stresses are those stresses present in an object in the absence of any external load or force. Such stresses can be very detrimental to the performance of a material, or the life of a component. Alternatively, beneficial residual stresses may be introduced deliberately [1]. Neutron and synchrotron beam line experiments, as used for residual stress measurements, rely on accurate alignment of the sample in relation to the beam and hence the instrument hardware. Such instruments often incorporate XYZΩ tables for positioning the sample in the beam, with additional hardware such as rotation tables or goniometers being added to meet particular requirements. Interest has also recently increased in exploring the use of industrial robotic arms as sample positioning systems, [2,3]. The motivation for the interest in robotic arms is the potential improvement in flexibility and the possibility of automation. For example, when controlled by suitable software, such systems may enable all required strain components to be obtained without manual intervention, even within large and geometrically complex samples.

Whatever positioning system is in use the motor positions (or, in robotics terminology, 'joint variables') required to bring the measurement point to the measurement position, with sufficient accuracy, will need to be determined. Traditionally this has been achieved by performing a series of 'wall scans' in which the sample surface is passed through the beam while the scattered intensity is recorded. The position of the sample in relation to the beam is then determined from the intensity profile. By repeating this process, using scans through different points on the sample surface, the sample alignment may be determined. This process however can take considerable time, particularly with a sample of complex geometry, thereby considerably reducing the time available for making scientifically useful measurements. For this reason other sample alignment methods have been developed. Ratel et al. [4] proposed doing sample alignment with a modular sample holder, coordinate measurement machine (CMM) and a XYZΩ positioning table. Their sample was mounted on the positioner and digitised with the CMM. Measurement points were specified using the model acquired from the CMM and the coordinate frame of the CMM was set as the inverse of the axes of the positioning table, enabling motor positions to be generated by simply inverting the coordinates of the measurement point. The solution proposed by Ratel requires samples to be mounted on sample holders which are then used to align the coordinate systems on the instrument and the CMM, the method also assumes that a

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standard XYZΩ positioning table will be used for sample alignment, which would not always be the case. Altenkirch et al. [2] proposed the use of a Stäubli RX90L robotic arm for sample positioning. They rely on the control unit supplied by the manufacturer for robot control but tested the accuracy of the robot using ISO standard testing procedures and found it to be sufficient. They scan the sample along with the attached sample holder. The scanned samples were used to generate scripts that placed the specified measurement points in the gauge volume of the instrument. Their solution relies on the Stäubli control unit to compute the motor positions and therefore is not easily extendable to other neutron diffractometers using different positioning systems. A Stäubli RX160 six axis robot which was previously installed on the STRESS-SPEC instrument at FRM II, but deemed to be accurate enough only for texture measurements, has recently been used for stress measurement [5]. Here a ring of six retro-reflective targets are mounted on the robot and measurements of at least three targets, with a laser tracker, are used to improve positioning accuracy. Ensuring that three reflectors are visible each time is acknowledged as an issue with this approach, which also relies on the manufacturer's control unit to compute the motor positions for the robot. James et al. [6] developed the Strain Scanning Simulation Software (SScanSS) which is currently used on ENGIN-X and at several other neutron facilities. SScanSS is based on a virtual laboratory and incorporates three dimensional models of the sample and the instrument in order to simulate many aspects of the stress measurement process. SScanSS uses techniques from robot kinematics [7,8] to model the positioning systems of the instruments as kinematic models; building on the observation that many positioning systems used by neutron diffractometers can be classified as serial robots, with the exemption of the Hexapod at ILL [9] which is a parallel robot.

Kinematic models are commonly used in the field of robotics to compute the position and orientation of objects mounted on the 'end effector' of a robotic manipulator. Positioning a specimen with high accuracy can be accomplished given an accurate knowledge of the kinematic parameters of the relevant positioning system. The kinematic parameters used to design a serial manipulator would typically be provided by the manufacturer, but insufficient construction tolerance typically leads to the real kinematic parameters of the manipulator being different from the manufacturer design parameters. In the case of positioning systems built in-house, such as many of the XYZΩ tables used for sample positioning on engineering diffractometers, or bricolage systems where components such as goniometers are mounted on top of XYZΩ tables, the kinematic parameters of the manipulator may be unknown. Even when the kinematic parameters are initially accurately known, they may change with time, following repairs to the manipulator or after years of wear and tear. The effect of using inaccurate kinematic parameters can be very significant, particularly in relation to the use of more complex positioning systems.

In this paper, the use of calibration techniques from the field of robotics to extract the kinematic parameter of both off-the-shelf and custom built positioning systems is proposed. These methods are directly applicable to positioning systems ranging in complexity from the simple XYZΩ systems to industrial robots. Other items of moving hardware, such as beam shaping jaws, collimators or detectors, may also be accurately modelled and hence controlled using these same techniques.

The prime driver of this work is to extend the ability of the SScanSS simulation software to accurately model more complex positioning systems or similar items of instrument hardware, however the methods developed are generally applicable.

2. Calibration theory

Robot calibration is an attempt to obtain a functional relationship between the joint sensors and the actual pose of the manipulator. In this paper, the four standard robot calibration steps [10] of; modelling, measurement, parameter identification and implementation are followed.

The first step, modelling, is where a mathematical scheme, or notation, is chosen to represent the manipulator. In the second step, measurements of the manipulator's end effector position and orientation are taken. The third step is the determination of the actual kinematic parameters and in the final step, the identified kinematic parameters are implemented into the manipulator control software or the instrument simulation software. These steps are introduced briefly below, but more complete descriptions of each step can be found in [10,11].

2.1. Modelling

Several notations have been proposed for modelling robotic manipulators, the most widely used of which is the Denavit–Hartenberg (DH) notation, [7,12]. The DH notation is a systematic notation, commonly used to assign coordinate frames to a serial manipulator. The DH notation uses four parameters to model the relationship between a pair of coordinate frames $i-1$ and i placed on the robot. These parameters are the joint angle (θ_i), the link twist (α_i), the link length (r_i), and the link offset (d_i), (Fig. 1). Only one of these parameters is variable for each joint, with either θ or d being the 'joint variable' depending on whether the joint in question is revolute or prismatic.

A serial manipulator with n joints therefore requires $n+1$ coordinate frames and $4\times n$ parameters for its representation. Since six numbers are required to specify the position and orientation of an arbitrary coordinate frame in space, the DH notation requires the additional constraints that (i) the x_n axis intersects both z_{n-1} and z_n axes and (ii) that the axis is perpendicular to both the and axes.

Industrial robots are typically designed to respect these constraints, but calibration can reveal that such constraints are broken [13]. Some neutron beam-line positioning systems are designed without reference to these constraints so that the standard DH parameters would not be sufficient to represent these systems. To solve this problem, a modified DH notation is utilised which was first introduced by Hayati and Mirmirani [13] in which an extra

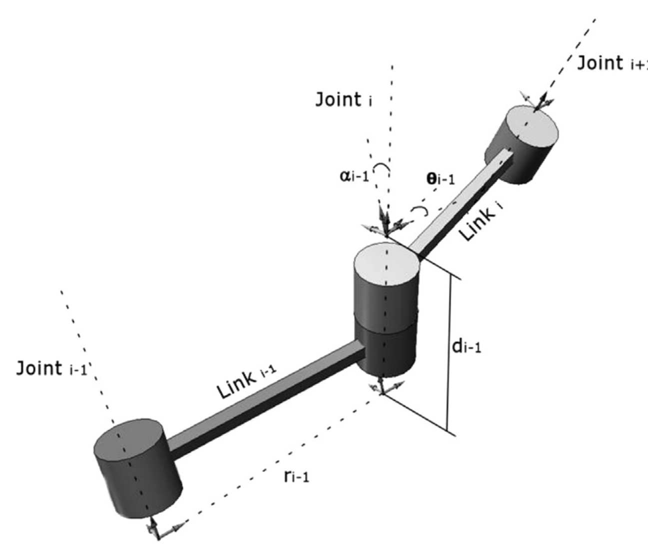

Fig. 1. A simple two link system showing the standard DH parameters.