# PROGRESS TOWARDS A REVOLUTE-JOINT ROBOT FOR THE PRECISION POSITIONING OF MATERIAL SAMPLES OR AN X-RAY DETECTOR[#]

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*Abstract*

*At the Advanced Photon Source (APS), the desire to combine sample handling, sample positioning or goniometer functionality into one piece of equipment has provided the impetus for the development of a precision six degree-of-freedom robot with approximately 2 µm dynamic positioning uncertainty. This specification is driven by the need for a positioning uncertainty that should be 10 to 20 percent of possible x-ray detector resolution. Six-degree-of-freedom robots with 20 µm static positioning uncertainty are presently used at the APS in sample-changing applications. A history of these existing APS robotic sample-handling systems will be presented, along with discussion concerning the theoretical, computational and experimental issues associated with the design of a sample or detector manipulator with high trajectory precision. A computational model being developed is intended to capture the unique dynamics associated with the robot harmonic drive gearboxes. Incorporation of an accurate harmonic drive model into a multibody model is a novel approach to completely capturing the robot dynamics. The dynamic representation of the multibody model allows it to be used as a design tool and incorporated into a control architecture for use in the next-generation multi-degree-of-freedom manipulators for use on synchrotron beamlines. The successful operation of a multi-degree-of-freedom sample manipulator will represent a new paradigm in x-ray experimental sample positioning.*

## 1. Introduction

The engineers from the Advanced Photon Source (APS) Experimental Facilities Division (XFD) have been developing automated sample handling since the late 1990s. Increase in the synchrotron user base and a subsequent demand for more beam time has required a corresponding growth in automated sample handling. The current state of the art in robot sample handling is either a translational-cartesian or revolute-articulated industrial robot, mounting and dismounting samples attached to either standard or kinematically located sample holders. In the future, automated sample handling will still be driven by the requirement of high throughput but also by the necessity of reduced equipment size and controlled environment operation. These future needs are driving the current research into a small-footprint robot that can not only pick up a sample and bring it to the x-ray beam but also manipulate the sample during data collection, moving from a position-critical application to a trajectory-critical application.

## 2. History of robotic manipulators at the XFD/APS

Up until now, all previous XFD robotic systems were designed to fulfill x-ray sample transfer applications. Three of these sample-handling applications are detailed below. Two of the systems were based on systems of high-speed linear stages, the final result being cartesian robots. The third and most robust system was designed around an industrial revolute-joint, articulated robot. Work on each of these systems has helped build a foundation on which the next-generation robotic application can be built.

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### 3.2. Cartesian cryogenic sample changer

At the APS, initial work on an automated sample changer centered on a cartesian robot operating in a pick-and-place mode, handling samples holders that were precisely located by kinematic mounts [1], see ***Figure 1***. The APS-designed kinematic mounting system had two variations, one variant that constrained only position, while allowing rotation about the samples axis, and another that constrained position and orientation [2]. These kinematic mounts enabled sample placement repeatability within 5 μm, see ***Figure 2***. With this arrangement, robot repeatability could be in the 200 μm range, with the final positioning requirements controlled by the sample holder. While never implemented on a beamline, lessons learned here were used in other robot systems.

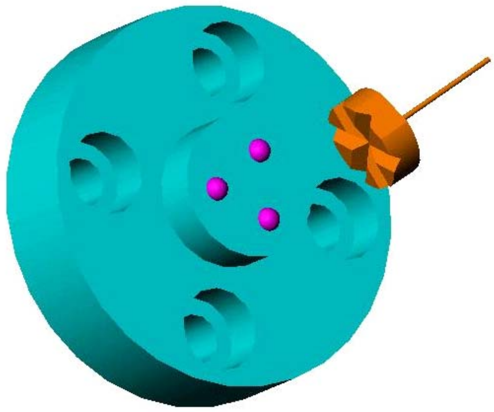


*Figure 1. Kinematically located sample holder.*

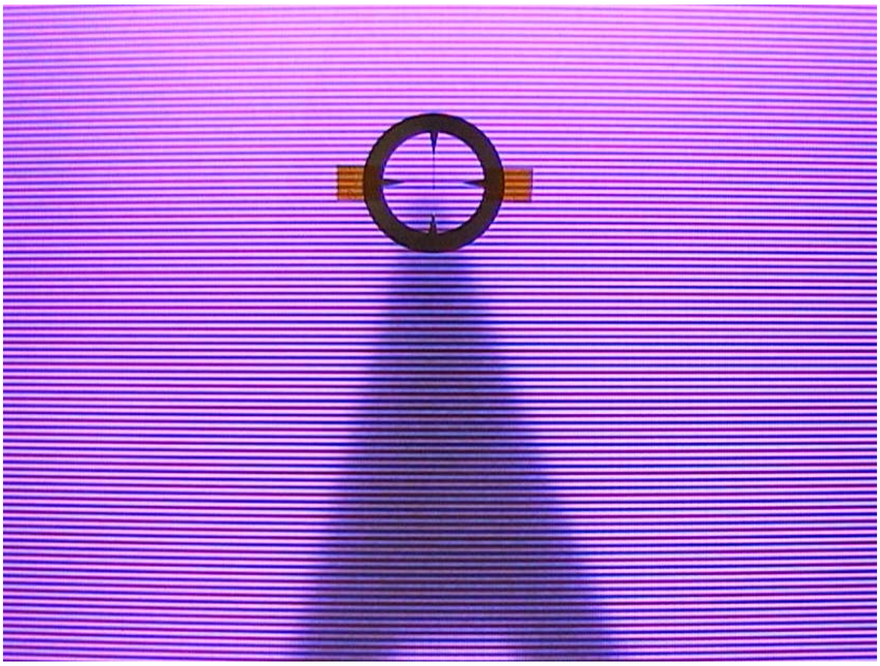


*Figure 2. Image from the cartesian robot repeatability test.*

### 3.2. Cartesian tomography sample changer

Another cartesian sample-changing robot was designed for a high-throughput microtomagraphy experimental station. This three-axis robot (***Figure 3***), was based on the work described in section 3.2. The robot moves samples from a 72 sample magazine and places it on the fine-motion stages located in the beam path. In this case, a commercially available kinematic sample holder was used. Both position and rotation of the sample were constrained.

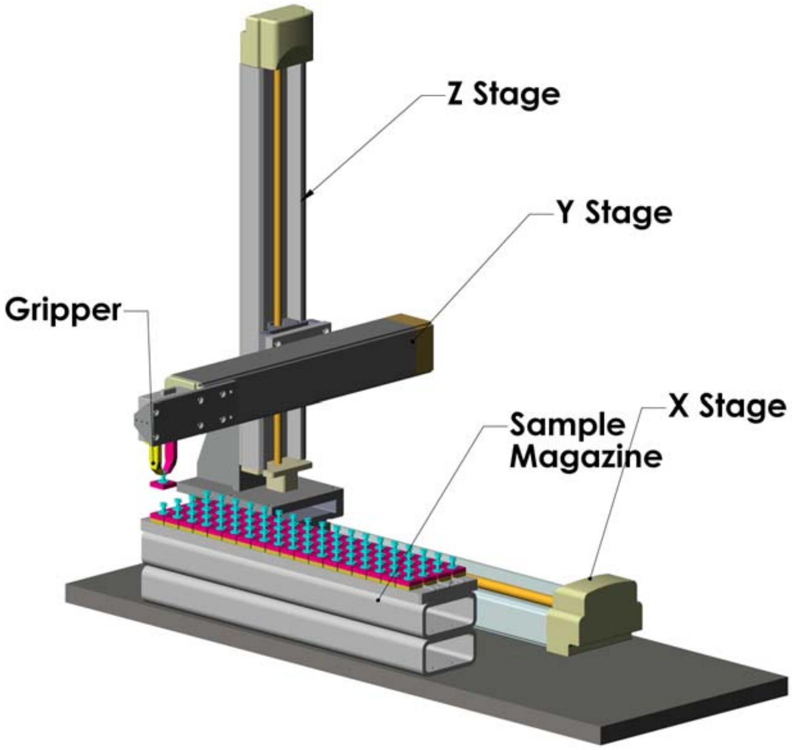



*Figure 3. Microtomography sample changing robot*

The kinematic mount defined the final location of the sample once again. The positioning capability of the robot did affect the final location of the sample on the experimental setup. However, experimental work indicated that, for this robot to be used in a more demanding positioning application, dynamic behavior would have to be considered [3]. Large displacements at the end effector could be excited through motion of the high-speed stages. While this behavior did not affect the microtomography application, it would be unacceptable in a sample, or detector-positioning application.

### 3.2. Revolute joint cryogenic sample changer

The revolute-joint cryogenic sample changer was the product of collaboration between XFD and the Argonne Structural Biology Center (SBC) [4]. The complete system is shown in ***Figure 4***. Designed around a Mitsubishi industrial robot with 20 μm position repeatability [5], this application called for the transport of cryogenically preserved protein samples from a liquid-nitrogen-filled storage dewar to a multi-axis kappa goniometer, used for protein crystallography.

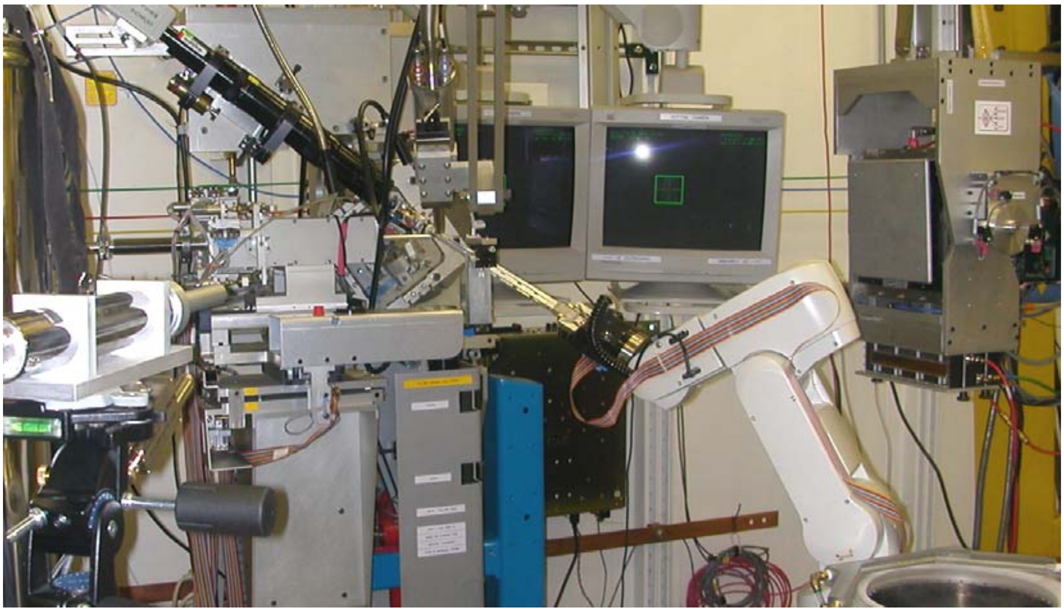


*Figure 4. The SBC cryogenic sample-changing robot in operation.*

Significant performance requirements included: the need for a long end effector to reach into the storage dewar and the goniometer, integrated force detection to prevent damage to beamline equipment in the event of a malfunction, and high-speed operation to minimize the amount of time a sample is in transit [2]. The long end effector placed tight requirements on the angular repeatability, as the fingertip location needed to be within ±200 μm. High-speed operation was critical to preserving cryosample integrity. This necessary combination of speed and accuracy could be met by the current state of the art in industrial articulated robots.
Work on the cryogenic crystallography robot provided insight into the behavior of a high-speed revolute joint robot. Once again, in the pick-and-place operation, the static positioning performance was important; however, dynamic performance characteristics that could affect a motion-, or path-critical application were observed. Practical experience with the dynamic performance characteristics of a small, articulated joint robot helped determine important aspects to consider for the application of similar systems in motion-critical tasks.

## 3. Current work: sample *or* detector positioning application development

The constantly expanding field of x-ray science drives APS x-ray instrumentation innovation. Scientists are applying standard x-ray techniques, like scattering and imaging, to new types of experiments, especially in the microfocusing and small-sample areas. These new applications place additional requirements on the support equipment, such as spatial constraints and controlled experiment environments. In addition, the desire to reduce the quantity of positioning equipment along with the need for high throughput have pushed forward the idea of providing for sample transfer and positioning with one device.

### 3.1 New requirements for path-critical applications

In contrast to the previously mentioned robot systems described in section 2, the new application will feature a small-footprint robot, used to position the sample in the x-ray beam during experiments. The most important requirement for this new application of sample or detector positioning is high trajectory accuracy. Additionally, the experimental conditions will be controlled, with the robot operating in a partial vacuum or clean-room conditions. Data collection will be performed nearly "on-the-fly," with the robot pausing briefly before moving to the next point. In order to achieve this method of operation, the end-effector path will need to be precisely controlled, and the robot should have a positioning uncertainty of 2.0 μm, along with a short settling time. Detector spatial resolution constrains the positioning uncertainty of the robot, which should be 10 to 20 percent of the detector spatial resolution. A review of the literature indicates that the unique requirements of this application, controlled environment, small size, and high accuracy, necessitate the development of a new type of robot [6-8].

## 3.2 Design methodology

### *3.2.1 Background*

In order to progress towards a new type of articulated sample/detector positioning robot, we are establishing an engineering tool that can be used to analyze and simulate the performance of the proposed detector-positioning robot. We are approaching the problem in two steps, construction of a multibody dynamic model of an existing six degree-of-freedom robotic arm and the subsequent use of the model as a design tool. At later steps, the accurate modeling of the dynamics will play an important role in the control architecture [6]. Key information required to build a useful model include identification of system parameters, such as the mass matrix, stiffness, and damping. Experimental measurement of the characteristics of the existing robot system allows for the verification of the computational multibody dynamic model. Once the ability of the model to capture actual system dynamics has been confirmed, proposed designs for the new sample manipulator can be evaluated with confidence.

We are using a robot similar to the SBC cryogenic sample changer for testing and model validation purposes. It makes an ideal subject, as the system topology is the same as that proposed for the small, high-precision, highly repeatable robot. The test robot is a Mitsubishi industrial robot arm, model: RV-1A, shown in ***Figure 5***. It consists of seven links or bodies, interconnected via harmonic drive transmissions, and supported on a combination of ball and cross-roller bearings. As with any mechanical system, the dynamics are determined by the inertial, stiffness and damping properties. The sources of damping and compliance of the robotic system originate from three sources: the bodies, the support bearings, and the harmonic drive transmissions. Most of the system mass is concentrated in the links that form the robot structure. The experimental testing of the RV-1A will include measurements made on the complete robot and measurements made on disassembled components.

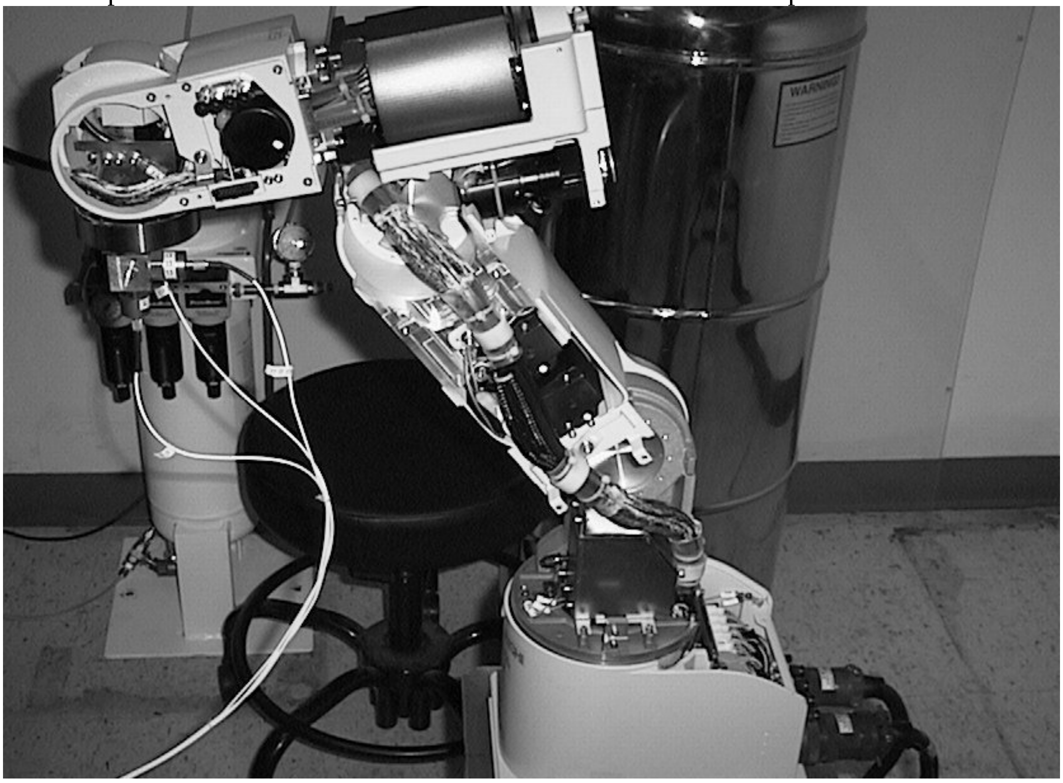


*Figure 5. Mitsubishi industrial robot, Model RV-1A.*

### *3.2.2* Experimental approach

*Complete system testing*

As mentioned, a six-degree-of-freedom robot was available for testing. We experimentally tested the complete robot system for two reasons: (1) to quantify the overall performance of the RV-1A, and (2) to attempt to identify component mass, stiffness and damping properties based on these tests of the whole system. Item one concentrates on the most important aspect of a path-critical robot system, the behavior of the end effector, or interface between the robot and the surroundings. These measurements are crucial for computer model verification. Measurements of the displacement and acceleration of a chosen point on the end-effector, while the robot executes a specific set of motions, are used to assess the dynamic performance of the robot system. Initially, simple straight-line trajectories were used; these quantitative measurements of the RV-1A dynamic performance provided for computer model verification.
While the end effector path is important for model verification, item two, the identification of the dynamic characteristics of the components that make up a robotic system, is crucial to constructing a computer model that exhibits representative dynamic behavior. As compared to quantifying the complete system behavior, component identification while the whole system is assembled is more involved experimentally. The main advantage of the assembled system approach is the ability to perform the necessary tests *in situ* without system disassembly. A literature review revealed some useful methods to identify component parameters from a complete manipulator system [9-16].

*Component level testing*

As compared to system level testing, component level testing can yield more accurate information, with less computational work. The main disadvantage is the need for access to subassemblies of the robot. Fortunately, one link, bearing set, and harmonic drive transmission are available for testing. The goal for experimentally testing the support bearings, harmonic drive, and linkage is to determine the stiffness and linear viscous damping coefficients of the bearing, the transmission characteristics of the harmonic drive, and the inertial properties of the body. We will input these data into the computer model, along with data from the system-level tests.
Three different types of experiments were identified to determine the bearing stiffness, transmission drive characteristics and the body inertia. The translational stiffness and linear viscous damping coefficients can be quantified by using an experimental method similar to that described by Wyatt-Becker et al. [17]. Experimentally determined frequency response functions (FRFs) are used to calculate the stiffnesses based on measured force and displacement. Inertial parameters were estimated by constructing a CAD model of the link structure.
Torque transmission characteristics of the harmonic drive transmission are one of the most important contributors to overall manipulator behavior. The high reduction ratios and compact size of harmonic drives make them excellent transmissions for robot systems. However, the drive output contains high frequency torque variations. Explained by Tuttle and Seering [18], who state "Since kinematic inaccuracies in the transmission cause velocity fluctuations which excite system resonance, a substantial portion of the operating range of each harmonic drive is contaminated by serious vibration." In an articulated robot, these drive fluctuations are manifest as trajectory errors due to the resonance of the whole robot structure. Experimental measurements of the harmonic drive while mounted on a torque-meter will relate the input torque to the output torque through a series of nonlinear equations that are described by Tuttle and Seering [18].

### *3.2.3* Computer simulation

We based the first model of the robot system on rigid body dynamics; that is, a set of equations were derived for a system consisting of undeformable masses connected by discrete stiffness and damping elements. In deriving the equations, Newton's second law is cumbersome when applied to a complex multibody system. Instead, a Lagrangian approach was used. In short, the method described by Shabana "Dynamics of Multibody systems" was used to write the system equations of motion in terms of a number of redundant generalized coordinates. The equations for any multibody system can be written in the following form:

$$\begin{bmatrix} M & C_q^T \\ C_q & 0 \end{bmatrix} \begin{bmatrix} \ddot{q} \\ \lambda \end{bmatrix} = \begin{bmatrix} Q_e + Q_v \\ Q_d \end{bmatrix},$$

where $M$ is the mass matrix, $q$ is the vector of generalized coordinates, $C(q,t)$ is a matrix of kinematic constraints on the bodies, $Q_e$ is a vector of externally applied forces, $Q_v$ is a quadratic velocity vector, and $\lambda$ is a vector of Lagrange multipliers. This form of the equations of motion can be systematically solved using a multibody computer code. The multibody code used to model the robotic manipulator is a program created by Dr. Ahmed A. Shabana at the University of Illinois at Chicago. It is called SAMS, an acronym for **S**ystematic **A**nalysis of **M**ultibody **S**ystems.

A schematic of the model is shown in ***Figure 6***. A model topology that could replicate the actual system dynamics was developed, accounting for joint compliance through the addition of massless bodies connected to stiffness and damping elements. Once verification of the basic model is completed the intention is to incorporate an accurate model of the harmonic-drive transmission dynamics.

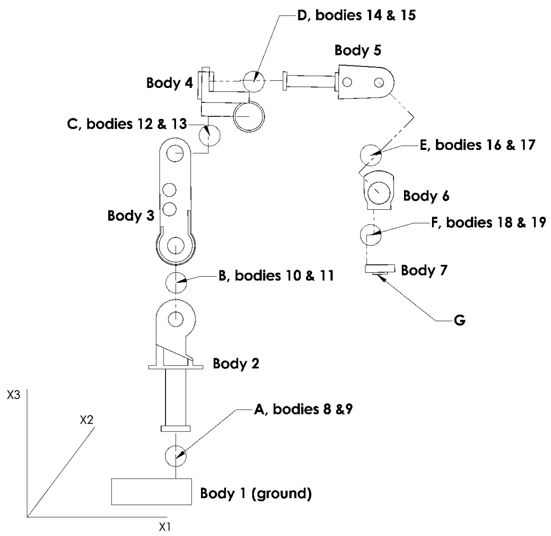



*Figure 6. Schematic of the robot computer model.*

In the initial simulations, the en-effector displacement was constrained to a straight line path, ***Figure 7***. During this constrained motion, the moments acting on the joint axes were calculated. These moments are the actuator torques necessary to produce the constrained motion. These actuator torques will then be used as input for another simulation that combines the Tuttle and Seering harmonic drive model with the multibody robot model. In addition, at the starting point and endpoint of the trajectory, the system equations were linearized, allowing for determination of eigenvalues and eigenvectors. These data were compared to experimentally determined natural frequencies and modeshapes, an indication of how well the models inertia, stiffness, and damping properties match the actual system.

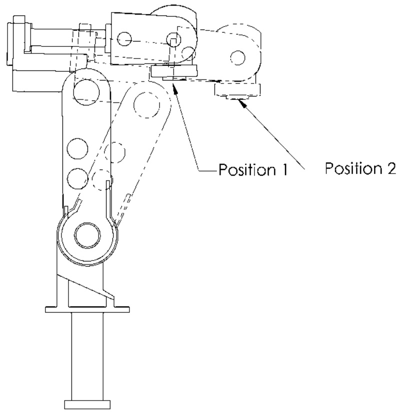



*Figure 7. Constrained path of end effector during simulation.*

### 3.3 Some results

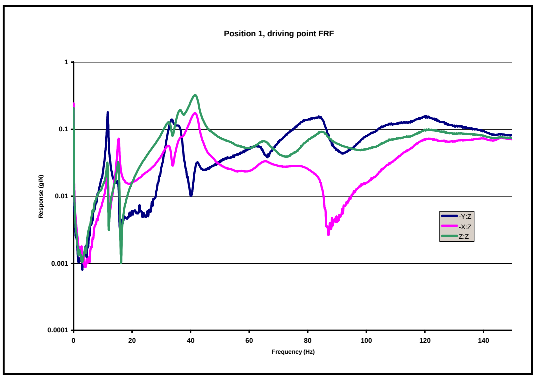
***Figure 8*** and Figure 9 show the driving point response, as measured at the end effector. A comparison of the data reveals two modes, below 20 Hz in both positions. While there are changes in the relative amplitudes of the modes the location in the spectrum remains constant when comparing position 1 to position 2. For this small change in position, these two modes do not seem affected by the change in robot configuration. Both sets of FRFs exhibit a well-damped mode above 80 Hz, primarily excited by Y direction input. Between 30 Hz and 50 Hz, there is a group of three modes that appear less coupled when the robot arm is in position 2. These three groups, consisting of two low modes, three modes between 30 and 50 Hz, and a mode close to 100 Hz are similar to the results obtained with SAMS and shown in Table 1 and Table 2.

*Table 1. Eigenvalues at position 1 configuration.*

| Mode | Natural Frequency (Hz) | Damping Ratio |
|---|---|---|
| 1 | 19.6 | 0.321 |
| 2 | 24.5 | 0.394 |
| 3 | 41.0 | 0.321 |
| 4 | 48.3 | 0.373 |
| 5 | 54.2 | 0.909 |
| 6 | 114 | 0.821 |

*Table 2. Eigenvalues at position 2 configuration.*

| Mode | Natural Frequency (Hz) | Damping Ratio |
|---|---|---|
| 1 | 19.5 | 0.317 |
| 2 | 25.5 | 0.411 |
| 3 | 36.8 | 0.308 |
| 4 | 54.2 | 0.400 |
| 5 | 54.2 | 0.904 |
| 6 | 107 | 0.765 |



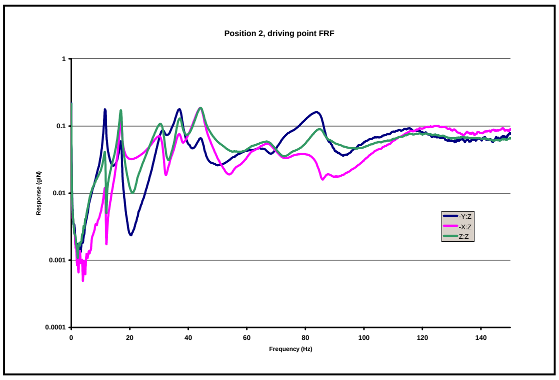




*Figure 8. Position 1 driving point FRFs. Figure 9. Position 2 driving point FRFs.*

The experimentally obtained acceleration during RV-1A movement from position 1 to position 2 is shown in Figure 10. The data are indicative of a non-constant acceleration profile. A period of increasing acceleration is followed by a period of decreasing acceleration, superimposed is a high-frequency oscillation.

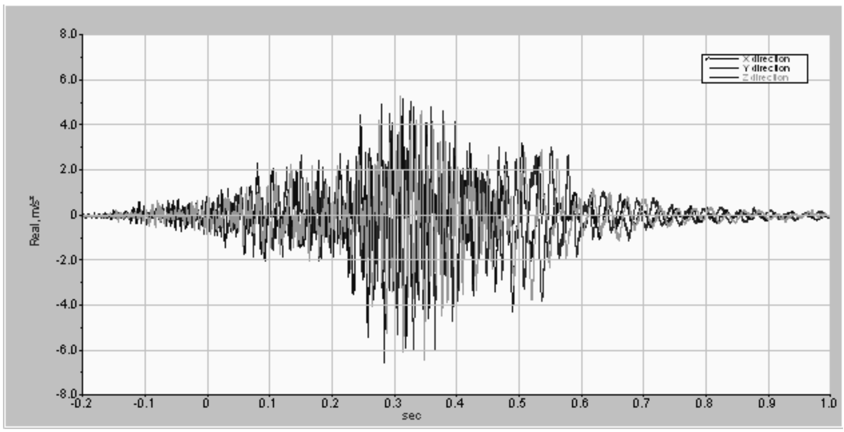



*Figure 10. Acceleration as measured at the end-effector during a straight line trajectory.*

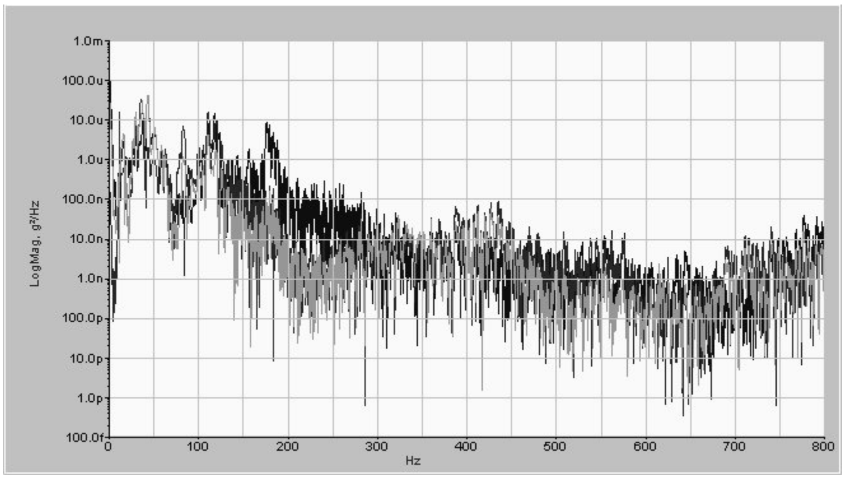



*Figure 11. Power spectrum of a straight line trajectory.*

The high-frequency behavior, shown in ***Figure 11*** between 0 and 200 Hz, is most likely due to harmonic drive excitation. Due to the constant-velocity constraint imposed on the end effector and lack of a harmonic drive transmission model, the SAMS model captured neither the change in acceleration nor the high-frequency behavior. Two changes need to be made the SAMS model to account for this. First, the end-effector velocity constraint should start and end at zero velocity. Second, joint torques need to be calculated such that the harmonic drive model can be implemented.

## 4. Accomplishments and continuing work

We have designed the basic structure of a tool to aid in the development of the robotic sample manipulator. We have also identified additional techniques that can generate the accurate inertia, stiffness and damping data that are required by the multibody dynamic model. A modeling scheme has been proposed that can capture the relevant dynamics of the RV-1A revolute-joint manipulator. Initial simulations using the proposed model indicate behavior similar to the RV-1A. Key features include the use of redundant revolute joints to model joint stiffnesses and incorporation of a harmonic drive response model. Initial literature review indicates that the current work may be unique with respect to integrating an accurate harmonic drive model into a multibody model of a revolute-joint manipulator.

We want to fine tune the current model in order to continue moving towards a design tool that can correctly model the performance of the proposed x-ray detector/x-ray sample manipulator. We will supply accurate information for stiffness and damping parameters. Additional experiments should be performed to identify key harmonic drive parameters: the stiffness of the assembly, with support bearings, and the kinematic and compliance properties in the driven axis. Model performance should be verified with experimental measurements of the robot response through various trajectories. We will be able to use the tool to predict the behavior of the new robot design when the model performance captures the existing RV-1A behavior.

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