### 3.7.2 Software

All data from the orthosis is collected using a data acquisition card (National Instruments™ NI-6251) installed in a target computer that interfaces with the host computer over an Ethernet connection. This setup allows for data collection within the MATLAB xPC Target framework (Mathworks™). Using Simulink, a data collection model was created, linking the DAQ within software and allowing real-time processing and routing of the data. All analog signals were subjected to digital low pass filtering (minimum order FIR, 2 Hz cutoff frequency, 60 dB stop band attenuation at 5 Hz), due to the small bandwidth of the signals of interest (0-2 Hz) and the high sampling rate (1000 Hz). All analog position data is passed through a unit conversion function, and digital encoder counts are converted to radian and degree measurements by relating counts per turn and gear reduction to physical angular displacement of the joints. Force and encoder data are transmitted to the control algorithm directly, while potentiometer data is applied to the forward kinematic equations that define the position of the mechanical system to provide wrist position information during movement through the workspace.

### 3.7.3 Position Tracking Using Forward Kinematics

As is common practice in robotic applications, a forward kinematic approach was used to locate the Cartesian space location of the end effector using the joint space position of each degree of freedom. Rotation about each degree of freedom was defined about the z-axis, and a coordinate frame was established around this. Translation between coordinate frames takes place about either the x-axis or z-axis, and is defined by the link length connecting the two joints. Frame assignments are displayed in Figure 11. This framework is defined by the Denavit-Hartenberg convention for kinematic analysis, which greatly simplifies the positioning process for a robot with several degrees of freedom. Transitions between frames of reference for each degree of freedom are represented by homogeneous transformations that are created from the product of four basic transformations characterized using four parameters; link length ($a_i$), link

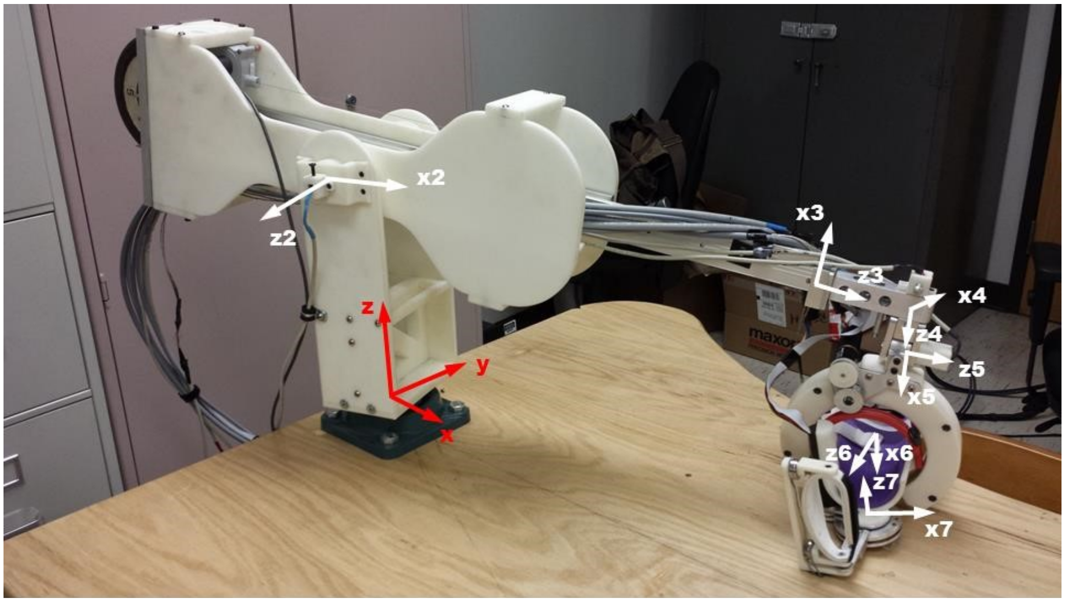


**Figure 11:** Movement frames for degrees of freedom (DOF) present in the orthosis. Full control of position and orientation is accomplished with 6 rotational DOF and 1 translational DOF.

twist ($\alpha_i$), link offset ($d_i$), and joint angle ($\theta_i$). Link length is the measured distance along the x-axis between two frames, link twist is the rotation about the x-axis between two frames, link offset is the translation along the z-axis between two frames, and joint angle is the rotation about the z-axis between two frames. Joint angle or link offset, depending on whether it's a rotational or prismatic joint, acts as the joint variable. This is the variable that changes with joint movement while the other three parameters remain constant. The full derivation of the kinematic equations can be found in Appendix A, and are summarized in Equations 1-9 below. An "s" or "c" with a subscript number represents the sine or cosine of the specified joint variable.

**Table 3:** D-H parameters for determining robot forward kinematics. Joint transitions relate to the reference frames described in Figure 11.

| Joint Transitions | $\theta_i$ | $d_i$ | $a_i$ | $\alpha_i$ |
|---|---|---|---|---|
| **1-2** | $\theta_1$ | $d_1$ | - | -90° |
| **2-3** | $\theta_2$ - 90° | - | $a_2$ | -90° |
| **3-4** | -90° | $d_3^*$ | - | +90° |
| **4-5** | $\theta_4$ - 90° | $d_4$ | - | -90° |
| **5-6** | $\theta_5$ | - | $a_5$ | +90° |
| **6-7** | $\theta_6$ + 90° | $d_6$ | $a_6$ | -90° |

Position Kinematics:

$$x = d_3c_1c_2 + a_2c_1c_2 \tag{1}$$

$$y = d_3s_1c_2 + a_2s_1c_2 \tag{2}$$

$$z = -d_3s_2 - a_2s_2 + d_1 \tag{3}$$

Orientation Kinematics:

$$x = a_6(c_4s_5c_6 - s_4s_6) - d_6c_4c_5 + a_5c_4s_5 \tag{4}$$

$$y = a_6(s_4s_5c_6 + c_4s_6) - d_6s_4c_5 + a_5s_4s_5 \tag{5}$$

$$z = a_6c_5c_6 + d_6s_5 + a_5c_5 + d_4 \tag{6}$$

System Kinematics:

$$x = -a_6c_6\big(c_1s_2c_5 + s_5(s_1c_4 - c_1c_2s_4)\big) + a_6s_6(s_1s_4 + c_1c_2c_4) - d_6\big(c_1s_2s_5 - c_5(s_1c_4 - c_1c_2s_4)\big) - a_5c_1s_2c_5 - a_5s_5(s_1c_4 - c_1c_2s_4) - d_4c_1s_2 + c_1c_2(a_2 + d_3) \tag{7}$$

$$y = -a_6c_6\big(s_1s_2c_5 - s_5(c_1c_4 + s_1c_2s_4)\big) - a_6s_6(c_1s_4 - s_1c_2c_4) - d_6\big(s_1s_2s_5 + c_5(c_1c_4 + s_1c_2s_4)\big) - a_5s_1s_2c_5 + a_5s_5(c_1c_4 + s_1c_2s_4) - d_4s_1s_2 + s_1c_2(a_2 + d_3) \tag{8}$$

$$z = -a_6c_6(c_2c_5 + s_2s_4s_5) - a_6s_2c_4s_6 - d_6(c_2s_5 - s_2s_4c_5) - a_5(c_2c_5 + s_2s_4s_5) - d_4c_2 - s_2(a_2 + d_3) + d_1 \tag{9}$$

## 3.8 Force-based Compensation for Minimal Friction Movement

To achieve the torque specifications for actuation with motors that fit well within the orthosis design, the addition of planetary gearheads was required. One drawback to increasing torque through these means is that planetary gearheads are never 100% efficient, and often waste energy due to small misalignments between the gears. This setup created a system that provided limited backdriveability with noticeable resistance present when trying to move the actuated joints back and forth. This lack of backdriveability could cause the user to adopt an abnormal movement to overcome the resistance and complete the task. Since the goal was to create a system to facilitate the restoration of normative movement profiles, it was necessary to minimize the resistance so that an individual's movement was not impacted.