Chapter 4

Control Problem and Design

This chapter will discuss the performance requirements for the torque loop as well as the AD2S93 Converter. From these requirements, the design methodology for each compensator will be described.

4.1 Torque Loop Performance Requirements

Designing the torque loop for the ARTISAN wrist joint requires that the overall control system of the ARTISAN manipulator be taken into account. The ARTISAN control system operates on many different levels, incorporating position control, force control and path planning with each loop operating at different rates and managing different performance characteristics. Since each inner control loop operates as a component of the outer loop, the constraints of one loop can directly impact the other. As shown in Figure 4-1, the path planning control loop includes the kinematic control loop which, in turn, includes the torque loop.

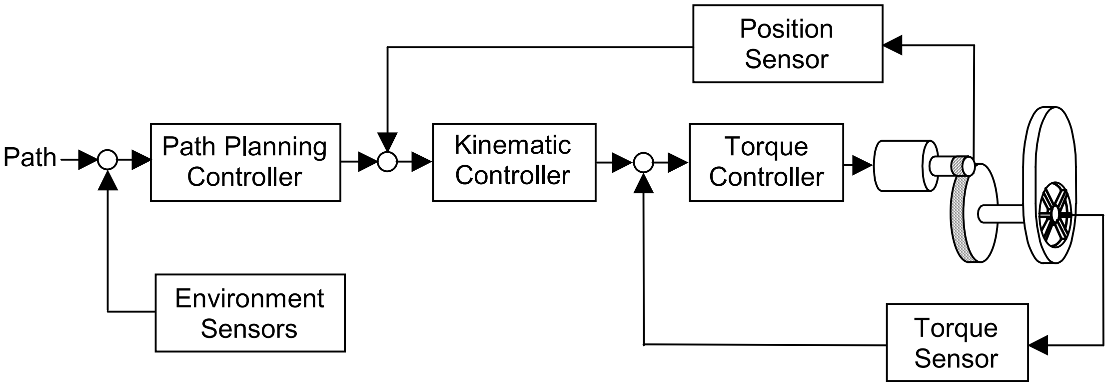

Figure 4-1: Successive Loops for ARTISAN Manipulator

Because of this multi-loop scheme, the design of the controller for each outer loop can be impacted by dynamics of the enclosed inner loop if the dynamics of the inner loop are "seen" by the outer loop. For example, given the system in Figure 4-2, the two plants P_1(s) and P_2(s) have particular, individual open-loop dynamics. If P_2(s) has a bandwidth that is five times greater than the bandwidth of P_1(s) ($\omega_2 \geq 5\omega_1$), the dynamics of P_2(s) would be fast enough to be imperceptible to the other components of the closed loop system. It could therefore be assumed, for the purposes of control design, that P_2(s) would not need to be taken into account in the design of the closed loop compensator *C*(s). This assumption helps to isolate the design of the compensator *C*(s) to focus on the system dynamics of P_1(s) and result in a simpler compensator design.

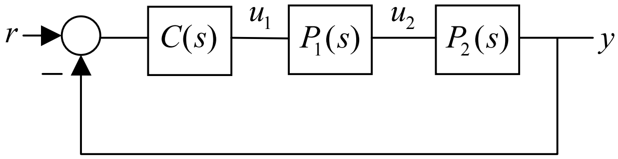

Figure 4-2: Example Control System

In addition, the bandwidth of the closed loop system can impose limits on the control signals at each point along the system. In the above case, the input u_2 is bandlimited by the transfer function $\frac{U(s)}{R(s)}$ which is defined:

$$\frac{U(s)}{R(s)} = \frac{C(s)P_1(s)}{1 + C(s)P_1(s)P_2(s)} \tag{4.1}$$

If the assumption holds that P_2(s) is significantly faster than P_1(s), then Equation (4.1) reduces to:

$$\frac{U(s)}{R(s)} = \frac{C(s)P_1(s)}{1+C(s)P_1(s)} = \frac{Y(s)}{R(s)} \tag{4.2}$$

which is essentially the closed loop response of the outer loop. Therefore, the bandwidth of the signal u_2 can be assumed to be the bandwidth of the closed loop system.

With this understanding, the multi-loop scheme can be visualized as Figure 4-2, where P_2(s) can be considered the inner loop, P_1(s) as the dynamics of the outer loop not addressed by the inner loop and C(s) as the outer loop compensator. Therefore, given the maximum frequency contained in each command signal, five times that frequency provides a rough estimate of the desired loop bandwidth for each inner loop. For the three control loops described in Figure 4-1, the desired loop bandwidths are listed in Table 4-1.

Type of Loop	Max Signal Frequency	Loop Bandwidth
Path planning	4 Hz	20 Hz
Kinematic	20 Hz	100 Hz
Torque	100 Hz	500 Hz

Table 4-1: Desired Loop Bandwidth Requirements

In regard to the torque loop, the motivation for development of a high-bandwidth torque sensor is the formulation of a *perfect torque source*. A perfect torque source is defined as a torque source that provides near-instantaneous response to any torque command with no torque loop dynamics perceivable to the commanding system. Based on the earlier discussion, the desired torque loop bandwidth listed in Table 4-1 should provide the requested system performance.

4.1.1 Time Domain Specifications

Converting the torque loop bandwidth into time-domain specifications, a bandwidth of 500 Hz results in a rise time of less than 2ms. Additionally, the system designer specifies the maximum overshoot of the torque loop to be less than 5% of the commanded torque to minimize control efforts to compensate for sensor overshoot. These specifications are listed Table 4-2.

Characteristic	Parameter	Value
Bandwidth	ω_{BW}	500Hz
Rise Time	t_r	< 2 ms
Overshoot	M_p	< 5%

Table 4-2: Desired Torque Loop Characteristics

4.2 Physical Torque Loop System

In the ARTISAN wrist joint, the physical system can be mapped to the generalized control loop listed in Figure 2-1. The compensator includes the computer, the digital-to-analog converter, and the digital input port, while the sensor electronics consists of the LVDT and the AD2S93 Converter. As shown in Figure 4-3, two controllers are required: one compensator for the AD2S93 and one overall Torque Controller for the torque loop.

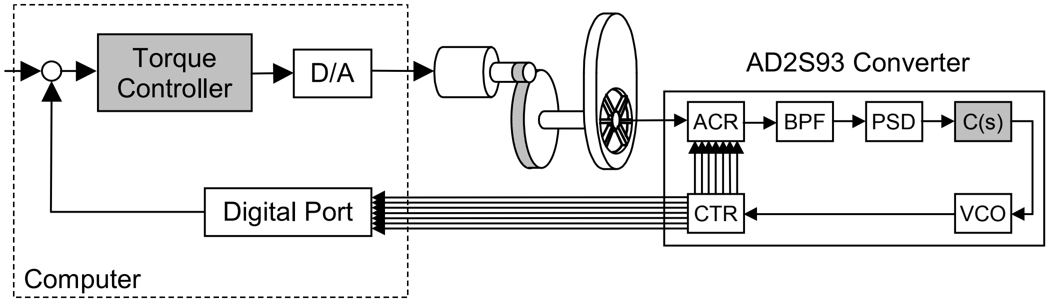

Figure 4-3: Physical Torque Loop System

The torque loop represented in Figure 4-2 is another example of a multi-loop scheme where the bandwidth of the inner loop (the AD2S93 Converter) can impact the resulting bandwidth of the outer loop (the torque loop) and vice versa. Based on the design requirement that the torque loop have a bandwidth of 500Hz, the command signals (sensed torques from the mechanical sensor) will also be comprised of signals up to 500Hz. Using the specification that the converter be invisible to the torque loop, the AD2S93 Converter is required to have a bandwidth five times greater than the torque loop, or 2.5KHz. Due to component limitations, the AD2S93 Converter has a dynamic range no greater than 1.25KHz. In order to make the AD2S93 invisible to the torque loop, the desired bandwidth on the torque loop would need to be reduced to 250Hz. Since 250Hz is lower than the desired 500Hz for the bandwidth of the torque loop, the AD2S93 dynamics will have to be included in the design of the torque loop control law in order to reach the desired bandwidth.

4.3 AD2S93 Converter Control Design

In developing the control law for the AD2S93, a number of system constraints exist that limit the scope of compensators that can be implemented. These constraints include:

- **Limited compensator realizations**
  Due to the structure of the AD2S93 layout, only a small set of compensators that use a single operational amplifier can be implemented. This limitation is imposed by the placement of an on-chip amplifier that is hard-wired in the control path of the converter.
- **Limited performance on internal components**
  Since all of the components already onboard the AD2S93 have been specified by the original designers, performance limitations and design flaws that exist in the component place bandwidth limitations on the closed loop performance.

Because of these limitations, the limited number of possible compensators listed in Table 4-3 were tested using the system approximation shown in Figure 4-4.

Compensator	Parameter
Pure Gain	K
Single Pole	$\frac{K}{s+p}$
Lead Compensator	$\frac{K(s+z)}{s+p}$

Table 4-3: Candidates for AD2S93 Compensator

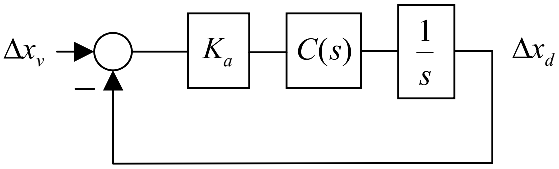

Figure 4-4: AD2S93 System Approximation

Along with the Analog Devices suggested compensator described in Section 3.2.4.1, the final compensator is chosen to generate a response with the highest bandwidth and smallest overshoot possible.

4.4 Torque Loop Controller Design

Once the AD2S93 has been properly configured, each component of the ARTISAN wrist joint will be identified and simulated using SIMULINK. Using the design specifications listed in Table 4-2 as a guide, state feedback gains are designed using the techniques for designing a Linear Quadratic (LQ) Regulator using the LQ performance index shown in Equation (4.3).

$$J = \int_0^\infty \left[\rho y^2(t) + u^2(t) \right] \qquad (4.3)$$

where y(t) is the closed-loop response, u(t) is the control effort and ρ is the weighting factor that weights the closed-loop response with respect to the control effort. Once the state feedback gains have been selected, a state estimator is designed using Kalman estimation techniques to maximize the ratio between the slowest estimator pole and the slowest desired closed loop system pole. Finally, the addition of the command input will be incorporated and the entire system simulated.

4.5 Summary

The control design methodology has been created in this chapter, Chapter 5 will discuss the results of the system identification analysis of each of the components, the resulting open loop system and the final closed loop response in simulation.