Chapter 2
Background

In this chapter, the joint torque loop of the ARTISAN manipulator will be described in terms of its generalized components. Additionally, the motor, current amplifier and transmission system will be described in detail. A summary describing the system equations of these components concludes this chapter.

2.1 ARTISAN Joint Torque Loop Design

In order to develop a high-bandwidth torque loop for the ARTISAN manipulator, one of two approaches can be used. The open-loop approach requires a hyper-accurate model of all the components that comprise the joint torque loop. This approach is often infeasible due to the non-linear, time-varying characteristics of components in the overall system. As shown in Table 2-1, the number of characteristics found in a typical manipulator are too numerous to be determined with confidence or certainty.

System Component	Non-linear, Time-varying characteristics
Motor and Current Amplifier	Commutation method, back EMF, heat, rotor acceleration/deceleration
Gearing mechanism	Gearing contact, backlash, stiction
Bearings	Viscous friction

Table 2-1: Loop Component Characteristics

The second approach is to develop a reasonable linear model of the loop's components and provide feedback control to improve the overall performance of the commanded link torque. This method provides a reasonable approximation to the physical system and allows for the impact of parameter variation to be reduced significantly.

The components of the generalized joint torque loop are shown in Figure 2-1

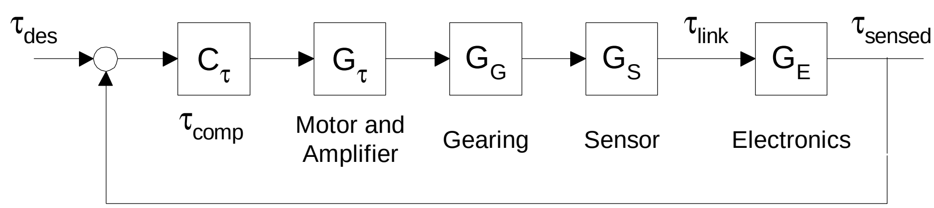

Figure 2-1: Generalized Joint Torque Loop

where G_τ represents the torque source, realized by the current amplifier and motor; G_G represents the transmission system that applies the torque from the motor to the link; G_S represents the mechanical torque sensor that converts the applied torque to a measurable quantity; G_E represents the sensor electronics that convert the measurable quantity to a electrical or digital quantity; and C_τ represents the controller that will operate on the error between the desired torque (τ_{des}) and sensed torque (τ_{sensed}).

In the ARTISAN project, two major design goals drove the design of the actuation system:

- the torque generated at each joint must be precisely controllable;

- the actuation system must be small, light, and powerful enough to work within the given configuration.

To achieve these design goals, the system components described in Figure 2-1 were selected in order to optimize the performance of the joint torque loop while remaining light and powerful. The design goals were created in order to develop a manipulator with the desirable characteristics described in Section 1.2 and without the limitations of position-based manipulators. The selection of the joint motor and current amplifier, represented by G_τ in Figure 2-1, attempts to address these goals.

2.2 Motors and Amplifier

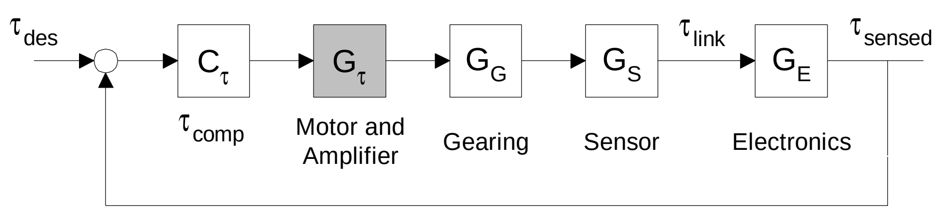

Figure 2-2: Generalized Joint Torque Loop

In order to provide a torque source with as few non-linear characteristics as possible, the ARTISAN wrist joint incorporates RBE(H) 1500 Brushless DC motors from Inland Motor. A brushless motor provides a number of improvements over brush-type motor systems used in typical actuation systems. With brushless DC technology, the rotor is actuated by electromagnetic fields that are generated by the current flowing through the windings of the stator. To generate the electromagnetic fields, the windings of the stator are energized through the use of positional information of the rotor magnets by the motor's Hall Effect sensors. The generation of these fields with regard to the rotor's magnets create the torque seen from the rotor. Placement of brushless windings in the outer stator and field magnets onto the inner rotor allows for significant reductions in motor inertia (smaller rotor) and the resulting improvement in acceleration. Additionally, brushless DC motors provide other benefits including reduction of the electromagnetic interference normally generated from arcing, and significantly reduced friction. These effects are achieved by removal of brushes which, in brush DC motors, are required to contact the motor's rotor windings.

To power the motor, the ARTISAN wrist joint uses the Inland Motors BDA3 Current Amplifier to drive the motors to the desired torque and/or position. These amplifiers are designed to energize the three phases of the rotor through a proprietary commutation pattern called Sinusoid Commutation developed at Inland Motor [McCormick90].

The most common method of controlling the current applied to the stator windings is through six-step commutation. Commutation is the powering of the three-phases of the motor stator with three different waveforms, each 120 degrees out of phase with each other. In six-step commutation, the three phases of the stator windings (designated A, B, and C) are energized using one of three states - either "fully positive", "fully negative" or zero. As the rotor rotates, the three phases of the stator are energized in a six-step, square wave pattern. As shown in Figure 2-3, Phase A goes positive, zero, negative, negative, zero then positive in the six-step cycle while Phase B goes negative, negative, zero, positive, positive, zero and Phase C goes zero, positive, positive, zero, negative, negative.

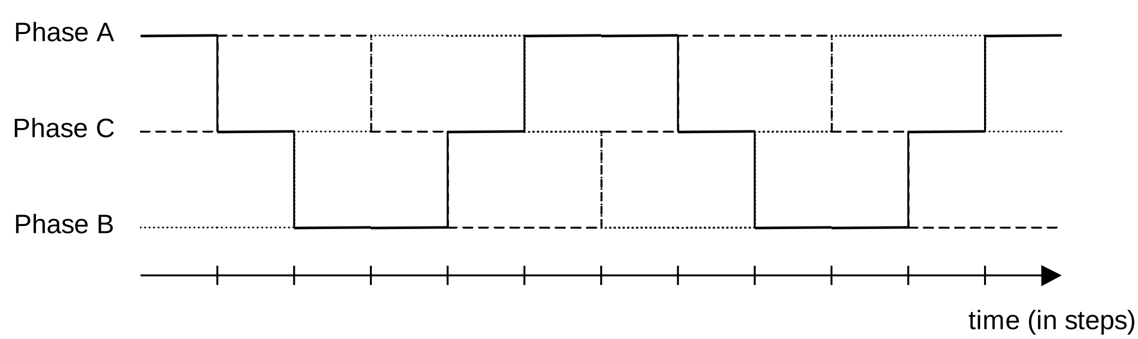

Figure 2-3: Six-Step Commutation Excitation of Stator Windings

The "positive" or "negative" current applied to the phases generates an electric field that creates either a repelling force in one direction or an attracting force in the other direction. These fields interact with the rotor's field magnets to generate the desired torque. Six-step commutation works very well in a stalled motor situation since the torque generated is proportional to the current being applied to the windings. In a dynamic situation when the rotor is moving, six-step commutation can generate undesirable torque ripple. This disturbance torque results from the discontinuous switching between states. Therefore, the forces which generate torque on the rotor are not constant throughout the full rotation.

Sinusoidal Commutation is a variation of the six-step commutation process that Inland Motor has pioneered. This method employs a sinusoidal waveform for its commutation, rather than a discontinuous step function. Using Hall Effect sensors and accurate position information through encoders or resolvers, the commutation waveform is transformed into a sinusoid which smoothly energizes the stator winding in relation to the rotor magnets. By smoothing out the transitions between the different states, torque ripple and “ratcheting” transitions from one state of the waveform to the next are significantly reduced. The result is a cleaner torque source from the motor.

2.2.1 Motor and Amplifier System Equations

The BDA3 Current Amplifier and the HBE Motor can be modeled as a plant controlled by a proportional-integral (PI) controller with a current sensor converting the maximum current (14A) to the maximum voltage (10V). Using Figure 2-4, the transfer function of the current loop in terms of the amplifier and motor components is represented in Equation (2.1).

$$\frac{i_m}{v_c} = \frac{R_{43}C_{17}s + 1}{R_1 C_{17} L_m s^2 + \left(R_1 R_{43} R_m + \frac{10}{14} R_{43} C_{17}\right)s + \frac{10}{14}} \tag{2.1}$$

where v_c is the command voltage, i_m is current applied to the motor and all other values are defined by Inland Motor and are listed in Table 2-2.

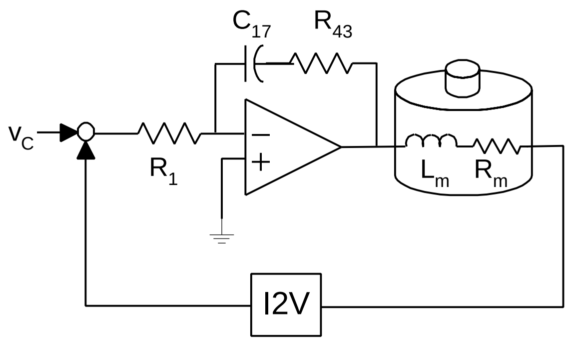

Figure 2-4: BDA3 Amplifier and RBE Motor

Component	Value
R_1	$44k\Omega$
R_{43}	$49.9k\Omega$
C_{17}	$4.7\,pF$
L_m	$1.3mH$
R_m	1.3Ω

Table 2-2: Motor Components

The motor's system equation, which defines the relationship between input current, i_m and applied torque, t_m is represented by a simple gain term. As shown in Equation (2.2), the expression is equal to the torque constant of the RBE motor, K_τ.

$$\frac{t_m}{i_m} = K_t \tag{2.2}$$

2.3 Transmission System

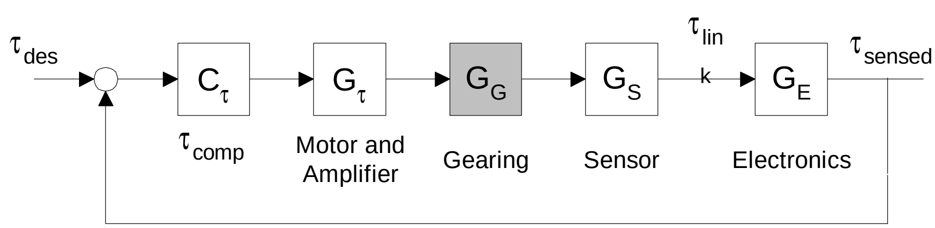

Figure 2-5: Generalized Joint Torque Loop

In any manipulator, the transmission system seriously impacts the torque characteristics and physical dimensions of the manipulator. Direct drive actuators, which do not require a separate transmission system, were not incorporated into the design because of their bulky size and weight. Multiple stage transmission systems can provide excellent torque amplification but were ruled out due to their poor backlash and compliance characteristics. Single stage gearing has less backlash and less compliance than similar multi-stage gearing, resulting in fewer non-linearities in the transmission. Therefore, a single stage transmission system using evoloid gears is employed in the ARTISAN wrist joint.

2.3.1 Evoloid Gearing

Evoloid gears [Berlinger75] are similar in tooth profile to typical helical spur gears except that coarser pitches are normally used. As with helical gears, evoloid gear sets transmit torque in both directions and have smooth torque transfer characteristics. Evoloid pinions, however, are noticeably different from helical spur gear pinions. Much higher gear ratios are possible because these pinions have only a small number of thick teeth. Because of the thickness of the teeth on the pinion, evoloid gear sets also have higher load capacities and better resistance to shock loads than helical gears. Due to the pinion's line contact with the spur gear, torque transmission is smoother than the point contact transmission usually found in helical gears. Based on these strengths, the evoloid gearing provides the best solution given the design goals for ARTISAN.

2.3.2 Transmission System Equation

The dynamic equation for the transmission system is a simple gain which represents the gear ratio of the spur gear to the pinion. In the case of the ARTISAN wrist joint, the gear ratio, N, is 13.5.

$$\frac{t_o}{t_i} = N \tag{2.3}$$

where t_i is the input torque and t_o is the output torque from the transmission system.

2.4 Summary

Table 2-3 summarizes all of the system equations of the mechanical components of the joint torque loop. Chapter 2 will discuss the development for the torque sensor and the system components that make up the sensor itself.

Subsystem	System Equation	Bandwidth
Current Amplifier	$\frac{i_m}{v_c} = \frac{R_{43}C_{17}s+1}{R_1C_{17}L_m s^2 + \left(R_1R_{43}R_m + \frac{10}{14}R_{43}C_{17}\right)s + \frac{10}{14}}$	1Khz
Motor	$\frac{t_m}{i_m} = K_T$	Infinite
Transmission	$N = 13.5$	Infinite

Table 2-3: Summary of System Equations