University of Glasgow

James Watt School of Engineering

Simulation of Engineering Systems 3

Assignment: Position Control System of a Robotic Arm for Wind Turbine Blade Test

Part 1: Modelling, Simulation & Validation

Aim

Part 1 of this Simulation of Engineering Systems 3 Assignment involves the modelling, simulation and validation of a Position Control System for a Robotic Arm for Wind turbine Blade testing. This part of the assignment involves developing a mathematical model of the dynamics of a simple robotic arm and its position control system. This model will be implemented in Matlab code and as a Simulink block diagram. The responses from the Simulink block diagram will be used to analyse and validate the Matlab model and its associated simulation. This document provides background information about this system, followed by the problem specification for the mathematical model of the system and its simulation. Also, the Assignment Specifications are provided as a step by step guide for this part of the assignment.

Introduction

A robot for wind turbine blade testing is designed to automate inspection, measurement, and durability assessments of large turbine blades. It enhances precision by detecting micro-cracks, surface defects, and structural weaknesses that might be missed by manual inspection. By the robotic arm control and positioning, the test and inspection can be done, as shown in Figure 1.

Robotic Arms or *Manipulators* are used extensively in a number of industries e.g. manufacturing, testing, maintenance, exploration, including the large wind turbine blade testing. These robot arms are electro-mechanical systems that replicate the articulated motion of human arms. In certain cases this technology is used in prosthesis development for limb replacement. This assignment involves the development of a simulation of a position control system for a robotic arm as outlined in this document.

Fig. 1 Robot for wind turbine blade testing (Courtesy of Rope Robotics Ltd.)

Background

The development of robotic arms started in the manufacturing industries where the repetitive processes involved in production of goods (e.g. cars) required increased precision and articulation. Unfortunately these increases could not be achieved through human workers and programmable robot arms or manipulators were created (see Figure 2).

Figure 2: Industrial Robot Manipulator

The type of arm shown in Figure 2 replicates the anatomy of human arms with increased power provided by the actuation systems that drive each joint. Other types of robot manipulator have been refined from these industrial manipulators in order to serve other industries and performance needs. One such application of this technology has been in the development of articulated prostheses for limb replacement. In particular they have been used to develop actuated prosthetic arms as shown in Figure 3. This application is the focus of this assignment.

Figure 3: Prosthetic Arm

The motion of this 2 link arm is predominantly through the actuated elbow joint. This is usually driven by a d.c. motor controlled to give the correct position for the hand. The hand provides fine, dexterous motions for performing tasks, which is not considered in this assignment. The motion of the elbow is outlined in Figure 4 below.

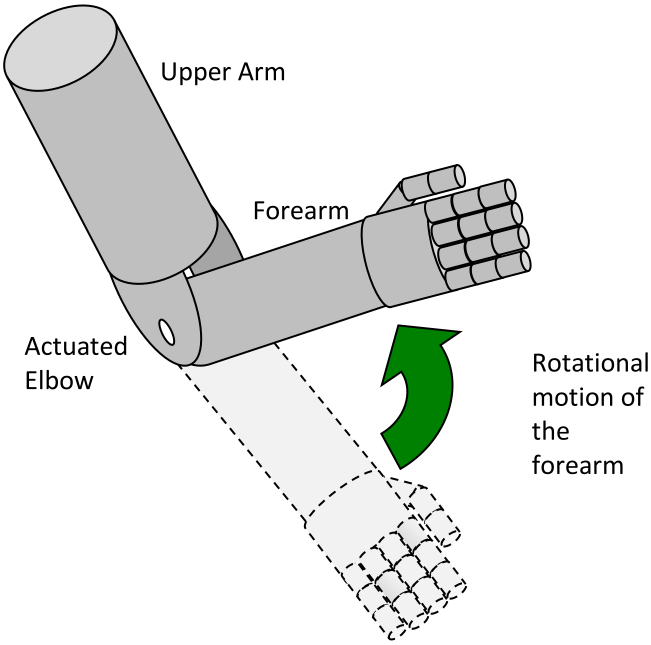

Figure 4: Prosthetic Arm Elbow Motion Schematic Diagram

The actuator (i.e. motor) is connected to the upper arm. For most of the assignment the upper arm is assumed to remain stationary at a specified angle. The actuator rotates the forearm by means of a set of gears. This controlled rotating motion described in Figure 4 is the focus of this assignment as outlined in the Problem Specification below.

Problem Specification

The motion of the arm is regulated by an automatic control system that determines the necessary rotational deflection of the forearm. In order to achieve this, the arm must be equipped with the necessary systems to ensure its automatic movement within it operating environment. The general principle of automated actuator systems is to feed information from joint rotation sensors to the arm's control system.

In this study we will consider the development of a simulation that represents the Elbow Control System only. This system changes the voltage applied to the elbow actuator to produce the required rotational motion and thus change the deflection angle of the forearm. For most of the assignment the Upper Arm is kept at a constant angle of deflection θ_U (set at a value of 7° initially).

The geometry of this rotational motion is shown in Figure 5.

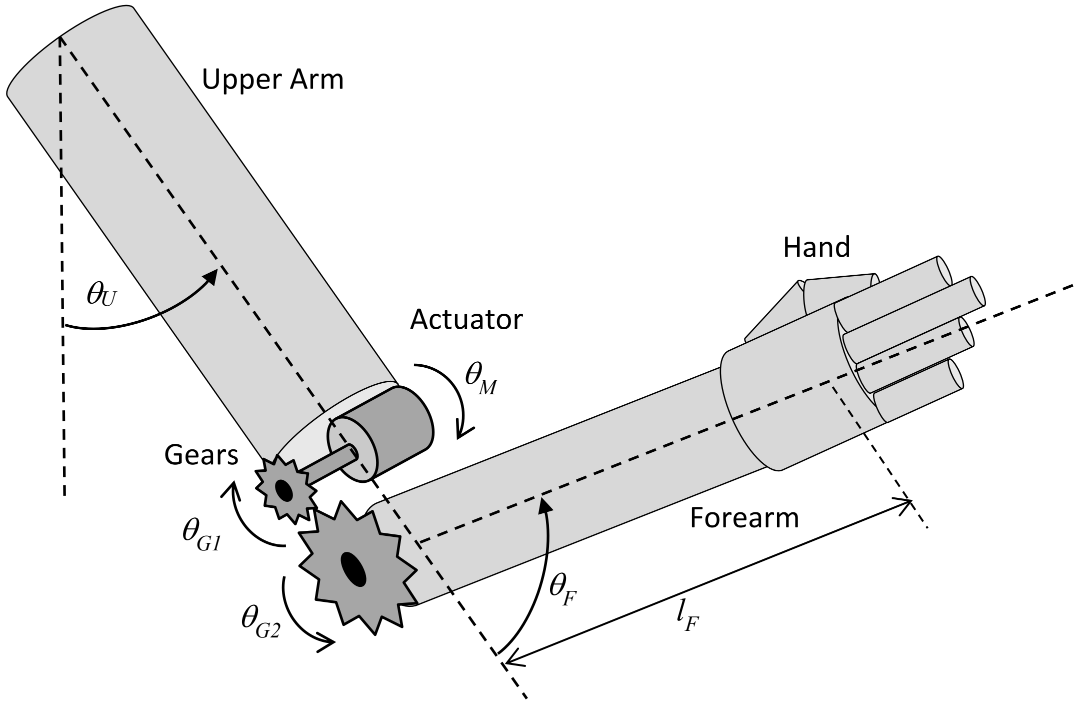

Figure 5: Geometry of rotating motion

The elbow control system produces the required actuator rotation to move the forearm to a reference angle. It achieves this by comparing the actuator deflection angle, θ_M (radians), with the reference angle, θ_{Fref} (radians). This provides indirect control of the Forearm's deflection angle, θ_F (radians). A diagram of the total system is shown in Figure 6.

From Figure 5 it can be seen that the Elbow Control System uses the error difference between the reference deflection angle and the actuator's deflection angle. In this case the value for θ_{Fref} (the reference angle) is taken to be 55°. The reference deflection passes through the Reference Amp which is represented by a simple gain K_R. Also, the motor deflection is measured by the Actuator Sensor, which is represented by a simple gain K_S.

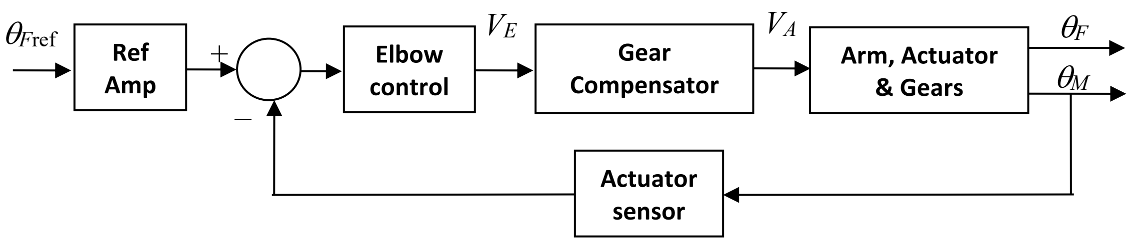

Figure 6: Elbow Control System

The control system itself is a proportional controller of the following form:

$$V_E = G_c \Delta\theta \quad (1)$$

Here G_C of the controller and $\Delta\theta$ is a function related to the difference between the reference angle and the actuator deflection angle. The resulting commanded voltage V_E (volts) then passes through the Gear Compensator, which is simply a gain, K_G. The compensated voltage, V_A (volts), is used to control the elbow actuator to drive the gears and thus indirectly generate an appropriate forearm deflection (θ_F). It achieves this by means of a proportional gain G_C and an integral term with gain K_I (this is assumed to be zero in the initial stages of the assignment). These gains determine the performance of the control system. This is an overview of the entire system.

A key part of the overall Elbow Control System is the arm and its interaction with the actuator and gears. In Figure 5 this part of the system is regarded as the conversion process between the actuator voltage, V_A, and the forearm deflection, θ_F. This process is more involved than this simplified system diagram would lead you to believe.

The actuator voltage is used to drive the actuator i.e. a d.c. motor) to deflection θ_M (radians) by means of its generated torque T_M (Nm). The drive shaft of the actuator is connected to Gear 1 (radius r_1 meters), which acts as a load on the motor. As Gear 1 rotates it transfers torque T_F (Nm) to Gear 2 (radius r_2 meters), which in turn rotates the forearm to the desired deflection angle. The gear ratio GR is calculated in the following manner:

$$GR = \frac{r_2}{r_1} \tag{2}$$

This ratio can be used to calculate the torque relationship between the gears i.e.

$$T_F = GR \times T_M = GR \times K_F \theta_{G1} \tag{3}$$

Here θ_{G1} is the angular deflection of Gear 1 (radians) and K_F is a torque gain. A detailed description of this system and how it interacts with the robot arm can be seen in Figure 7.

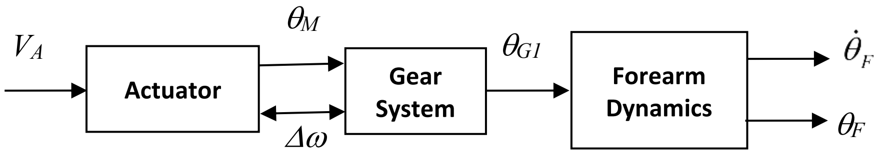

Figure 7: Actuator, Gears and Arm

As mentioned previously, the actuator in this case is a d.c. motor and its electro-mechanics can be represented by the following relationships:

$$L\frac{di}{dt} + Ri + K_E \frac{d\theta_M}{dt} = V_A \tag{4}$$

$$J_M \frac{d^2\theta_M}{dt^2} + B_{SM}\Delta\omega = K_T i \tag{5}$$

Here i is the motor current (A), $\Delta\omega$ is the difference in speed between the motor and Gear 1 (rad/s), J_M is the moment of inertia for the motor armature (kgm^2), L is the inductance (H), R is the resistance (Ω), B_S is the damping coefficient, K_T is the torque constant and K_E is the back emf constant.

Treating the first gear as a load on the motor's shaft allows its own dynamics to be defined. This can be represented by the following equation.

$$J_{G1}\frac{d^2\theta_{G1}}{dt^2} - B_{SM}\Delta\omega = 0 \qquad (6)$$

Here θ_{G1} is the deflection of the gear (radians) and J_{G1} is the moment of inertia for the gear (kgm^2).

Since the second gear is attached to the forearm they both have the same dynamics (i.e. $\theta_F = \theta_{G2}$). The transfer of torque from Gear 1 to Gear 2 provides the following dynamic relationship for the forearm i.e.

$$J_F\frac{d^2\theta_F}{dt^2} + B_{SF}\frac{d\theta_F}{dt} + \frac{m_F l_F}{2} g\sin\left(\theta_U + \theta_F\right) = T_F \qquad (7)$$

Here J_F is the total moment inertia of the forearm and hand (kgm^2), B_{SF} is the viscous damping coefficient for the forearm, m_F the masses of the forearm and hand (kg), l_F is of the length of the forearm (m) and g is the acceleration due to gravity (m/s^2). These equations represent the dynamics of the prosthetic robot arm and its related systems.

Assignment

The combination of all these elements produces a mathematical model for the Elbow Control System for the Robot Arm. Using this description as a basis, follow the steps outlined below to complete the first part of your assignment for this course:

Mathematical Modelling & Continuous Time Simulation

1. Use the description given above to derive the state space model for the Robot Arm System.
2. Use this model and the parameter values given in the Appendix A to produce an equation or script based simulation of the Robot Arm System in Matlab.
3. Employ a suitable initial conditions and numerical integration solver with a suitable step-size in the simulation of your system. Justify your choice of the initial conditions, solver and step-size. **Do not** use the in-built Matlab integration functions.
4. Analyse the dynamic response of the system. Do you think this a good design for the Elbow Control System? Explain your answer.

Block Diagram & Validation

5. Using basic, commonly used blocks in Simulink, construct a block diagram simulation of the Robot Arm System.
6. Use the responses from this block diagram simulation to validate your Matlab model from steps (1) & (2) and simulation responses from step (3).

Report Part 1 Specifications

Once you have finished this part of the assignment, complete the report form for the first part of the assignment. This report form should outline the development of your mathematical model for this system, your Matlab and Simulink Simulations, your analysis of this system and the validation of your model responses. The part 1 report form template can be found on the moodle page for this course. Your completed report for this initial part of the assignment should not exceed 6 pages in length and it should be submitted through the moodle submission portal for part 1 of the assignment before 4:30pm on **25th November 2025**.

Appendix A: Parameter Values

The following parameters are typical for the Robot Arm and its Elbow Control System:

B_{SM} = 0.03Nm/rad/s
B_{SF} = 1.5Nm/rad/s
J_M = 0.003 kgm^2
J_{G1} = 0.001 kgm^2
J_F = 0.0204 kgm^2
g = 9.81 m/s^2
G_c = 3.5
GR = 1.5
K_E = 0.35 V/rad/s
K_F = 0.5
K_G = 3
K_R = 1.2;
K_S = 1.3;
K_T = 0.35 Nm/A
L = 0.12 H
l_F = 0.35 m
m_F = 0.5 kg
R = 4 Ω

Typical initial conditions are:

$\theta_{Fo} = 7°$
$\theta_U = 7°$

Dr Wenjuan Song
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