Table of Contents

[1 Table of Figures 1](#_Toc515884610)

[2 Table of Tables 1](#_Toc515884611)

[3 Table of Equations 1](#_Toc515884612)

[4 Subsystem Three: Controls and Decision Making 3](#_Toc515884613)

[4.1 Requirements and Functional Decomposition 3](#_Toc515884614)

[4.2 Background and Prior Art 4](#_Toc515884615)

[5 Bibliography 9](#_Toc515884616)

# Table of Figures

[Figure 1: SS3 Breakdown 3](#_Toc515884617)

# Table of Tables

No table of figures entries found.

# Table of Equations

[Equation 1: Jacobian 4](#_Toc515884618)

[Equation 2: Relationship between q and x 4](#_Toc515884619)

[Equation 3: Euler–Lagrange equations (Khatib, 2008) 5](#_Toc515884620)

[Equation 4: The Lagrangian (Khatib, 2008) 5](#_Toc515884621)

[Equation 5: Kinetic Energy (Khatib, 2008) 5](#_Toc515884622)

[Equation 6: Kinetic Energy Partial Derivative 5](#_Toc515884623)

[Equation 7: Kinetic Energy Time Derivative 5](#_Toc515884624)

[Equation 8: Inertial Forces 5](#_Toc515884625)

[Equation 9: Vector of centrifugal and Coriolis forces 5](#_Toc515884626)

[Equation 10: Explicit form of EOM 6](#_Toc515884627)

[Equation 11: Kinetic Energy of Link i 6](#_Toc515884628)

[Equation 12: Kinetic energy of System 6](#_Toc515884629)

[Equation 13: Kinetic Energy of Total System 6](#_Toc515884630)

[Equation 14: Explicit form of Manipulator Mass Matrix 6](#_Toc515884631)

[Equation 15: mijk 7](#_Toc515884632)

[Equation 16: Christoffel Symbols 7](#_Toc515884633)

[Equation 17: Coefficients associated with centrifugal forces 7](#_Toc515884634)

[Equation 18: Coefficients associated with Coriolis force 7](#_Toc515884635)

[Equation 19: Potential Energy of the System 7](#_Toc515884636)

[Equation 20: Gravitational Potential Energy of Each Link 8](#_Toc515884637)

[Equation 21: Vector of Gravity Force 8](#_Toc515884638)

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# Subsystem Three: Controls and Decision Making

This section details the analysis, design, implementation, and results of the subsystem responsible for determining the actions required by the actuation system.

## Requirements and Functional Decomposition

The overarching purpose of subsystem three (SS3) was to determine the action that should be taken by the actuator system to minimise the error in the system.



Figure 1: SS3 Breakdown

As seen in Figure 1: SS3 Breakdown, to determine the action required in a state (given by the values determined by SS1, SS2, and SS4) the action required in any given state must be known.

To determine the general solution of what actions should be taken at any given state the controls parameters and method for the system should be derived, and then this model should be refined by practically tuning the solution.

The methodology for tuning the controls parameters of the system is discussed in kt, but the initial values to be refined are best source directly from the theory.

To determine the control parameters for the system the following method is employed:

1. Derive the equations of motion (EOM) for the system;
2. From the EOM derive the transfer function (TF) of the system (torque () with respect to angle ());
3. Transform the TF into the Laplace Domain; and,
4. Derive the PID parameters from the Laplace Domain TF.

Ultimately, five sets of controls were derived during the project: three for the 3 Degree of Freedom (DOF) lower extremity system (each joint had its own parameters), one for the continuous servomotor (which was abandoned as discussed in kt), and the positional servomotor.

The 3 DOF system was to control the lower extremity exoskeleton being constructed by the actuators and structural side of the project. However, as actual values for system parameters (masses, dimensions, moments of inertia, etc…) were never confirmed the solution had to be found algebraically.

The two systems used in testing featured their own embedded control systems, and their torque, angle, velocity, and acceleration could not be directly controlled. As such precise controls could not be derive from first principles. Instead the controls systems would need to be tuned empirically to achieve the desired system response.

## Background and Prior Art

The goal of SS3 is to model the dynamics expected of the system, establish the manipulator equations of motion, and derive the appropriate controls structure to create the behaviour required, in a stable fashion.

### Jacobian

For a system, in this case a manipulator, in the configuration given by the vector there is corresponding psotion for the end-effector given by the vector . The Jacobian matrix, , describes the relationship between the time derivatives of and ( and respectively). The Jacobian matrix, or simply the Jacobian, given by Equation 1, allows use to describe the system by Equation 2.

Equation 1: Jacobian

Equation 2: Relationship between q and x

Where .

### Dynamics

#### Explicit Form of the Equations of Motion

We begin with the Euler–Lagrange equations, or Lagrange's equations of the second kind, Equation 3.

Equation 3: Euler–Lagrange equations (Khatib, 2008)

Where is the vector of applied generalised torques. The Lagrangian, L, is given by Equation 4.

Equation 4: The Lagrangian (Khatib, 2008)

Where V is the potential energy of the system, and K is the kinetic energy of the system. As seen in Equation 5, K may be given in terms of the generalised velocities, (as seen in Equation 3: Euler–Lagrange equations) and the manipulator mass matrix M.

Equation 5: Kinetic Energy (Khatib, 2008)

Through Equation 3 we may say that

Equation 6and Equation 7 hold.

Equation 6: Kinetic Energy Partial Derivative

Equation 7: Kinetic Energy Time Derivative

Thus the inertial forces of Equation 4 may be expressed as Equation 8, where is the vector of centrifugal and Coriolis forces, Equation 9.

Equation 8: Inertial Forces

Equation 9: Vector of centrifugal and Coriolis forces

Through Equation 8 we may yield the explicit form of the equations of motion (EOM), see Equation 10. Where is the vector of gravity force and is the vector of centrifugal and Coriolis forces. Equation 10, once found, may be used to map the relationship between the torque applied by the systems actuators and the resulting system configuration.

Equation 10: Explicit form of EOM

#### Explicit form of Manipulator Mass Matrix

Kinetic energy is subject to the adaptive property (Siciliano & Khatib, 2016), and thus the total kinetic energy of a system is the summation of the kinetic energy of its links. Links here refers to the actuated limb segments of the exoskeleton correlating with the thigh, shin, and foot.

The kinetic energy of each link is comprised of a rotational and linear motion component. For a link with linear motion of , an angular motion of , and an inertia tensor of , the kinetic energy of the link , , is given by Equation 11Equation 11. Where refers to the centre of mass of the link.

Equation 11: Kinetic Energy of Link i

Given Equation 11 and the additive property it may be said that the kinetic of the system in total is given by Equation 12

Equation 12: Kinetic energy of System

Using Equation 11 and Equation 12, factoring out , we develop Equation 13

Equation 13: Kinetic Energy of Total System

Equating Equation 13 to Equation 5 we find the Explicit form of Manipulator Mass Matrix, Equation 14.

Equation 14: Explicit form of Manipulator Mass Matrix

#### Vector of centrifugal and Coriolis forces

We begin with Equation 9: Vector of centrifugal and Coriolis forces.

Sparing the derivation, we can say that givem Equation 15 and Equation 16, that Equation 17 and Equation 18 hold true.

Equation 15: mijk

Equation 16: Christoffel Symbols

Equation 17: Coefficients associated with centrifugal forces

Equation 18: Coefficients associated with Coriolis force

Where

#### Vector of gravity force

The vector of gravity force, , represents the gravitational potential energy of the system. The gravitational potential energy of the system is given by the gravitational potential energy of every link in the system, see Equation 19.

Equation 19: Potential Energy of the System

The gravitational potential energy of each link is given by Equation 20, where is the height of the centre of mass of the link relative to the origin (pelvis).

Equation 20: Gravitational Potential Energy of Each Link

Thus, we may say (using the Jacobian to map the location) the vector of gravity force, , is given by Equation 21.

Equation 21: Vector of Gravity Force

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