

Software Requirements Specification for: Simulating the Inverted Pendulum system

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Revision History

Date	Version	Notes
February 1, 2023	1.0	First version of document
February 3, 2023	1.1	Complete the Description part
February 4, 2023	1.2	Update Requirements part
February 6, 2023	1.2	Update Specific System Description part

1 Reference Material

This section records information for easy reference.

1.1 Table of Units

Throughout this document SI (Système International d'Unités) is employed as the unit system. In addition to the basic units, several derived units are used as described below. For each unit, the symbol is given followed by a description of the unit and the SI name.

symbol	unit	SI
kg	mass	kilogram
N	force	newton
deg	angle	degree
m	distance	metre
τ	torque	newton.metre

1.2 Table of Symbols

The table that follows summarizes the symbols used in this document along with their units. The symbols are listed in alphabetical order.

symbol	unit	description
b	dimensionless	coefficient of friction for the cart
d_{py}	metre	distance traveled by the center of mass of pendulum in y direction
d_{px}	metre	distance traveled by the center of mass of pendulum in x direction
g	m s^{-2}	Acceleration due to gravity
$F(t)$	N	Horizontal force exerted on the cart
I	kg m^2	moment of inertia of the pendulum
ℓ	m	Length to pendulum center of mass
M_c	kilogram	Mass of cart
m_p	kilogram	Mass of pole
H	N	Horizontal reaction force of the cart or the pole
P	N	Vertical reaction force component of the cart or the pole
$x(t)$	metre	The distance which cart transfer during time (t)
\dot{x}	m s^{-1}	Velocity of cart
\ddot{x}	m s^{-2}	Acceleration of cart
$\theta(t)$	deg	Pendulum angle from vertical (down)

$\dot{\theta}$	deg/s	Angular velocity of the pendulum
$\ddot{\theta}$	deg/s ²	Angular acceleration of the pendulum

1.3 Abbreviations and Acronyms

symbol	description
A	Assumption
DD	Data Definition
GD	General Definition
GS	Goal Statement
IM	Instance Model
LC	Likely Change
PS	Physical System Description
R	Requirement
SRS	Software Requirements Specification
IP	Simulating the Inverted Pendulum
T	Theoretical Model

1.4 Mathematical Notation

In this document, we do not use any specific mathematical notation.

2 Introduction

The Inverted pendulum is a classical control problem used for illustrating non-linear control techniques. The system is motivated by applications such as control of rockets and anti-seismic control of buildings. The inverted pendulum system consists of a pendulum which is attached to a cart that can move horizontally. It is unstable because its center of mass is above its pivot point so without additional help will fall over. The cart move horizontally by an external. This force is the only control input to the system. By manipulating the force, the position of pendulum is to be controlled.

Considering the force, we would like to simulate the behaviour of the system and measure the position and the angle of the pendulum in the presence of the force. The following section provides an overview of Software Requirement Specification (SRS) for a pole-cart system. This section explains the purpose of the document, the scope of requirements, the characteristic of the intended reader, and the organization of a document.

2.1 Purpose of Document

The main purpose of this document is to describe the mathematical model of IP system. To clarify software requirements, detailed information about goals, assumptions, theoretical models, and definitions will be explained.

Therefore, this document will be the reference during producing the software. It will provide requirements of the software which will be used in planing for design stage. The following SRS document will remain abstract exploring what is being solved rather than how it will be solved.

2.2 Scope of Requirements

The problem is restricted to two dimensions. The pendulum is attached to the cart in such a way that it is free to rotate in the pivot. The cart can move horizontally, left or right. for more details, see the assumptions section (Section 4.2.1)

2.3 Characteristics of Intended Reader

Intended Reader(s) or Reviewer(s) should have knowledge about equations of motion in Physics. Good understanding of solving an ordinary differential equation (ODE) in Mathematics is also needed. Both of the topics are offered in the undergrad engineering courses or high school Mathematics and Physics subjects.

2.4 Organization of Document

The organization of the document follows the template for an SRS for scientific computing software proposed by [1] The template will present the system's goals, theories, definitions, and assumptions. Goals are good points to start. To be familiar with mathematical model,

Section 4.2.2 and then Section 4.2.2, Section 4.2.3, Section 4.2.6 can be explored. Readers interested in top-down reading can begin by reading the system's goal statements (Section ??). Subsequently, the theoretical models will elaborate on the goal statements. Lastly, readers can finish with a more understanding of the system by reading instance models of the system.

3 General System Description

This section provides general information about the system. It identifies the interfaces between the system and its environment, describes the user characteristics and lists the system constraints.

3.1 System Context



Figure 1: System Context

The interaction between the product and the user is through a user interface. The responsibilities of the user and the system are as follows:

- User Responsibilities:
 - Provide required inputs including cart and pole features.
- The Inverted Pendulum simulation software Responsibilities:
 - Ensure all inputs are in correct format and detect data type mismatch.
 - Calculate and show the outputs.

3.2 User Characteristics

The end user of the Inverted Pendulum simulation software should have an understanding of undergraduate Calculus and Physics.

3.3 System Constraints

There are no system constraints for this project.

4 Specific System Description

This section first presents the problem description, which gives a high-level view of the problem to be solved. This is followed by the solution characteristics specification, which presents the assumptions, theories, definitions and finally the instance models.

4.1 Problem Description

The inverted pendulum system inherently has two equilibrium points, one of which is stable while the other is unstable. The stable equilibrium corresponds to a state in which the pendulum is pointing downwards. In the absence of any control force, the system will naturally return to this state. The unstable equilibrium corresponds to a state in which the pendulum points strictly upwards and thus requires a control force to maintain this position.

The Inverted Pendulum simulation tool is intended to describe and simulate the behaviour of the system in the presence of different inputs. As the inverted pendulum is widely used as a benchmark to demonstrate concepts and test control strategies and algorithms in nonlinear control, the final tool can show system status and be a great help as an educational material for students and engineers.

4.1.1 Terminology and Definitions

This subsection provides a list of terms that are used in the subsequent sections and their meaning, with the purpose of reducing ambiguity and making it easier to correctly understand the requirements:

- **Inverted Pendulum:** An inverted pendulum is a pendulum that has its center of mass above its pivot point. It is unstable and without additional help will fall over.
- **Force equilibrium:** A body is in force equilibrium if the sum of all the forces acting on the body is zero.
- **Friction:** The force that resists the sliding or rolling of one solid object over another.
- **Moment:** The turning effect of a force is called the moment. The moment is the result of the force multiplied by the perpendicular distance from the line of action of the force to the pivot or point where the object will turn.

4.1.2 Physical System Description

The physical system of IP simulation Tool, as shown in Figure 2, includes the following elements:

- PS1: The cart
- PS2: The pendulum

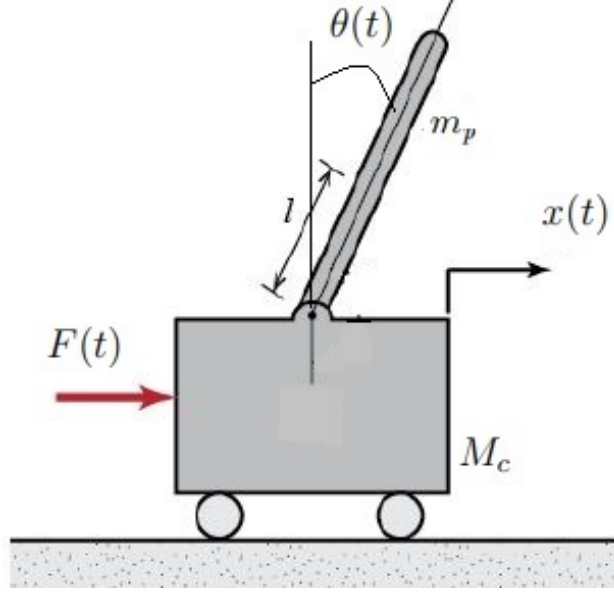


Figure 2: The physical system of IP simulation Tool

4.1.3 Goal Statements

Given the cart and pendulum features and external force, the goal statements are:

GS1: Present a mathematical model of IP

GS2: Calculate the position of the cart

GS3: Calculate the angle of the pendulum arm

4.2 Solution Characteristics Specification

4.2.1 Assumptions

This section simplifies the original problem and helps in developing the theoretical model by filling in the missing information for the physical system. The numbers given in the square brackets refer to the theoretical model [T], general definition [GD], data definition [DD], instance model [IM], or likely change [LC], in which the respective assumption is used.

- A1: The system is a two-degree of freedom system, so the pendulum is allowed to rotate in a two-dimensional plane.
- A2: The pendulum is smooth and friction-less.
- A3: The pendulum is unified and its moment of inertia is constant.

A4: The equations of the problem are non linear equations and to make them linear, we can assume that θ is small enough to have, $\cos(\theta) \approx 1$.

A5: According to previous assumption, for small angle of θ , $\sin(\theta)$ is equal to θ .

4.2.2 Theoretical Models

This section focuses on the general equations and laws that the tool is based on.

Number	TM1
Label	Newton's Second Law of Motion
Equation	$F = m.a$
Description	Newton's second law of motion pertains to the behavior of objects for which all existing forces are not balanced. The second law states that the acceleration of an object is dependent upon two variables, the net force acting upon the object which is a and the mass of the object that is m . The acceleration of an object depends directly upon the net force acting upon the object, and inversely upon the mass of the object. As the force acting upon an object is increased, the acceleration of the object is increased. As the mass of an object is increased, the acceleration of the object is decreased.
Notes	none.
Sources	https://www.physicsclassroom.com/class/newtlaws/Lesson-3/Newton-s-Second-Law
Ref. By	GD1,GD2,GD3, IM1

Number	TM2
Label	Newton's Second Law for Rotation
Equation	$\sum(\tau)=I.\alpha$
Description	<p>If more than one torque acts on a rigid body about a fixed axis, then the sum of the torques equals the moment of inertia times the angular acceleration.</p> <p>I is the moment of inertia for a point particle.</p> <p>α is angular acceleration of the object.</p>
Notes	none.
Sources	https://www.physicsclassroom.com/class/newtlaws/Lesson-3/Newton-s-Second-Law
Ref. By	IM2

Number	TM3
Label	Torque Definition
Equation	$\tau = rF \sin(\theta)$
Description	<p>Measure of the twisting action caused by a force that can cause an object to rotate about an axis.</p> <p>τ is torque</p> <p>F is applied force</p> <p>r is the radius from the axis of rotation to the location where the force is exerted</p> <p>θ is the angle between F and r</p>
Notes	none.
Sources	https://www.khanacademy.org/science/in-in-class11th-physics/in-in-system-of-particles-and-rotational-motion/in-in-torque-and-equilibrium-ap/a/torque-and-equilibrium
Ref. By	GD4

Number	TM4
Label	Force of Gravity
Equation	$W = m.g$
Description	<p>Gravity is a force that attracts objects toward the Earth. It is an approximation of the gravitational force that attracts objects of mass toward each other at great distances.</p> <p>g is the acceleration due to gravity</p> <p>m is the mass of the object</p>
Notes	none.
Sources	https://www.school-for-champions.com/science/gravity_overview.htm#.Y9-9ZXbMLs0
Ref. By	GD3

4.2.3 General Definitions

This section collects the laws and equations that will be used in building the instance models.

Number	GD1
Label	Newton's second law of motion for cart in horizontal
SI Units	N
Equation	$M_c \ddot{x} = F - H_c - b\dot{x},$
Description	<p>Based on Newton's second law of motion, sum of all forces applied to the cart is equal to $M_c.a$.</p> <p>F is the external force exerted to the cart in N.</p> <p>H_c is the force component in x direction of the reaction force which pendulum applies on the cart and measured in N.</p> <p>b is coefficient of friction for the cart.</p> <p>\dot{x} is the velocity of cart and therefore \ddot{x} will be its acceleration.</p>
Source	https://ctms.engin.umich.edu/CTMS/index.php?example=InvertedPendulum&section=SystemModeling
Ref. By	IM1

Number	GD2
Label	Newton's second law of motion for pendulum in horizontal
SI Units	All forces are measured in N
Equation	$m_p \ddot{x} = H_p$
Description	<p>Based on Newton's second law of motion, sum of all forces applied to the pendulum in x direction is equal to $m_p \cdot a$.</p> <p>H_p is the force component in x direction of the force exerted by cart on the pendulum and measured in N.</p> <p>m_p is mass of pendulum.</p> <p>\ddot{x} is the pendulum acceleration.</p>
Source	https://ctms.engin.umich.edu/CTMS/index.php?example=InvertedPendulum&section=SystemModeling
Ref. By	IM2

Number	GD3
Label	Newton's second law of motion for pendulum in vertical
SI Units	All forces are measured in N
Equation	$m_p(l - l \ddot{\cos}(\theta)) = (m_p)g - V_p$
Description	<p>Based on Newton's second law of motion, sum of all forces applied to the pendulum in y direction is equal to $m_p \cdot a$. Because the second derivation of \ddot{l} as a constant values is zero, therefore the equation reduces to $m_p(-l \ddot{\cos}(\theta)) = (m_p)g - V_p$.</p> <p>$V_p$ is the force component in y direction of the force exerted by cart on the pendulum and measured in N.</p> <p>m_p is mass of pendulum.</p> <p>$l - l \cos(\theta)$ is the Vertical displacement of the pendulum.</p>
Source	https://ctms.engin.umich.edu/CTMS/index.php/example=InvertedPendulum&section=SystemModeling
Ref. By	IM2

Number	GD4
Label	Calculate angular displacement of the pendulum
SI Units	τ
Equation	$I.\ddot{\theta} = l.(V.\sin(\theta) - H.\cos(\theta))$
Description	<p>Let's take the center of mass of this pendulum as a center of rotation so this pendulum rotates about this center of mass. The torques due to forces exerted to pendulum will calculate as below: the torque of weight force of pendulum is zero since the perpendicular distance of this force uh from center of rotation is zero. For reaction forces V_p, H_p, we decompose these forces to components which are perpendicular to the pendulum which we have, $V.\sin(\theta)$ and $H.\cos(\theta)$.</p> <p>I is the moment of inertia of the pendulum.</p> <p>$\ddot{\theta}$ is pendulum angular acceleration.</p>
Source	https://ctms.engin.umich.edu/CTMS/index.php?example=InvertedPendulum&section=SystemModeling
Ref. By	IM2

4.2.4 Data Definitions

This section collects and defines all the data needed to build the instance models. The dimension of each quantity is also given.

Number	DD1
Label	Horizontal displacement of the pendulum
Symbol	d_px
SI Units	m
Equation	$d_px = l \sin(\theta) + x(t)$
Description	The distance traveled by the center of mass of the pendulum is due to two reasons, first, horizontal displacement of the cart, and second, due to angular rotation of the pendulum. The distance due to angular rotation in the pendulum will be $= l \sin(\theta)$ while the half length of the pendulum is l , and the angular rotation in the pendulum is $\theta(t)$. Therefore, the total distance traveled by the center of mass of pendulum is equal to $= l \sin(\theta) + x(t)$.
Sources	https://www.youtube.com/watch?v=c3z4eo6s0Ek
Ref. By	GD1

Number	DD2
Label	Vertical displacement of the pendulum
Symbol	d_py
SI Units	metre
Equation	$d_py = l - l \cos(\theta)$
Description	When the pendulum rotates, the center of mass of the pendulum travels a vertical displacement, and as the half length of the pendulum is l , so the vertical distance travelled by the center of mass of the pendulum will be equal to $l \cos(\theta)$ hence the total displacement is equal to $l - l \cos(\theta)$
Sources	https://www.youtube.com/watch?v=c3z4eo6s0Ek
Ref. By	GD2

Number	DD3
Label	The moment of inertia of the pendulum
Symbol	I
SI Units	kgm^2
Equation	$I = \frac{1}{12}(m_p \cdot l)$
Description	The moment of inertia of a rod is related to its mass and length. the mass of rod is denoted by m and its length is denoted by l .
Sources	https://www.vedantu.com/question-answer/moment-of-a-rod-of-mass-m-length-l-about-class-12-physics-cbse-5f471db855e
Ref. By	GD4

4.2.5 Data Types

This section collects and defines all the data types needed to document the models.

Type Name	Name for Type
Type Def	
Description	
Sources	

4.2.6 Instance Models

Number	IM1
Label	Equation of motion for the cart
Input	F, M_c, m_p, b, l from IM??
0	The input is constrained so that θ is small
Output	$x(t)$, such that $F = (M_c + m_p)\ddot{x} + b\dot{x} + m_pl\ddot{\theta}\cos\theta - m_pl(\dot{\theta})^2\sin\theta \rightarrow$ $\ddot{x} = \frac{F - b\dot{x} - m_pl\ddot{\theta}\cos\theta + m_pl(\dot{\theta})^2\sin\theta}{(M_c + m_p)}$
Description	M_c is the mass of the cart (kg). m_p is the mass of the pendulum (kg). b is the coefficient friction of the cart (dimensionless). l is the length of pendulum.
Sources	https://www.mathworks.com/help/control/ug/control-of-an-inverted-pendulum-on-a-cart.html
Ref. By	

Number	IM2
Label	Equation of motion for the pendulum
Input	M_c, m_p, b, l
Output	$\theta(t)$, such that $(I + m_pl^2)\ddot{\theta} + m_pl\ddot{x}\cos\theta - m_pgl\sin\theta = 0 \rightarrow$ $\ddot{\theta} = \frac{m_pgl\sin\theta - m_pl\ddot{x}\cos\theta}{(I + m_pl^2)}$
Description	M_c is the mass of the cart (kg). m_p is the mass of the pendulum (kg). l is the length of pendulum.
Sources	https://www.mathworks.com/help/control/ug/control-of-an-inverted-pendulum-on-a-cart.html
Ref. By	

4.2.7 Input Data Constraints

Table 1 shows the data constraints on the input output variables. The column for physical constraints gives the physical limitations on the range of values that can be taken by the variable. The column for software constraints restricts the range of inputs to reasonable values. The software constraints will be helpful in the design stage for picking suitable algorithms. The constraints are conservative, to give the user of the model the flexibility to experiment with unusual situations. The column of typical values is intended to provide a feel for a common scenario. The uncertainty column provides an estimate of the confidence with which the physical quantities can be measured. This information would be part of the input if one were performing an uncertainty quantification exercise.

The specification parameters in Table 1 are listed in Table 2.

Table 1: Input Variables

Var	Physical Constraints	Software Constraints	Typical Value	Uncertainty
m_p	$m_p > 0$	$m_p > 0$	0.2 kg	
M_c	$M_c > 0$	$M_c > 0$	0.5 kg	
b	$b > 0$	$b > 0$	0.1(dimensionless)	
l	$l > 0$	$l > 0$	0.3 m	
I	$I > 0$	$I > 0$	0.006 kg m ²	

Table 2: Specification Parameter Values

Var	Value
-----	-------

4.2.8 Properties of a Correct Solution

Table 3 shows the physical constraints on the output.

5 Requirements

This section provides the functional requirements, and the business tasks that the IP simulation software is expected to complete, and the nonfunctional requirements, the qualities that the software is expected to exhibit.

Table 3: Output Variables

Var	Physical Constraints
θ	$0 \leq \theta \leq 360$
x	$0 \leq x$

5.1 Functional Requirements

R1: Provide input values.

R2: Calculate horizontal position of the cart from IM1

R3: Calculate the angular position of the pendulum from IM2

5.2 Nonfunctional Requirements

The nonfunctional requirements are listed below:

- NFR1: Accuracy: The accuracy of the computed solutions should meet the level needed for engineering or scientific application and have the properties described in Section 4.2.8.
- NFR2: Usability: The properties of the software should be able to tested easily through verification and validation plan (VnV Plan).
- NFR3: Maintainability: The effort required to make any of the likely changes listed for IP simulation software should be less than 50% of the original development time.
- NFR4: Portability: IP simulation software can be run on all of the possible operating environments, such as Windows, Mac-OS, and Linux.

6 Likely Changes

LC1: The software may be changed to consider friction of the pendulum [A2]

LC2: The software may be changed to consider non- linear equations and all values of the angle ot the pendulum [A4],[A5]

7 Unlikely Changes

ULC1: The system has two-degree of freedom [A1].

8 Traceability Matrices and Graphs

The purpose of the traceability matrices is to provide easy references on what has to be additionally modified if a certain component is changed. Every time a component is changed, the items in the column of that component that are marked with an “X” may have to be modified as well. Table 4 shows the dependencies of theoretical models, general definitions, data definitions, and instance models with each other. Table 5 shows the dependencies of theoretical models, general definitions, data definitions, instance models, and likely changes on the assumptions. Table 6 shows the dependencies of instance models, requirements, and data constraints on each other.

	T1	T2	T3	T4	GD1	GD2	GD3	GD4	DD1	DD2	DD3	IM1	IM2
T1					X	X	X					X	
T2													X
T3											X		
T4								X					
GD1												X	
GD2													X
GD3													X
GD4					X								
DD1						X							
DD2						X							
DD3						X							
IM1													
IM2													

Table 4: Traceability Matrix Showing the Connections Between Items of Different Sections Assumptions and Other Items

	T1	T2	T3	T4	GD1	GD2	GD3	GD4	DD1	DD2	DD3	IM1	IM2
A1												X	X
A2						X	X					X	
A3								X					X
A4												X	X
A5												X	X

Table 5: Traceability Matrix Showing the Connections Between Assumptions and Other Items

	IM1	IM2	4.2.7
R1			X
R2	X	X	
R3	X	X	

Table 6: Traceability Matrix Showing the Connections Between Requirements and Instance Models

9 Development Plan

10 Values of Auxiliary Constants

Show the values of the symbolic parameters introduced in the report.

The definition of the requirements will likely call for SYMBOLIC_CONSTANTS. Their values are defined in this section for easy maintenance.

The value of FRACTION, for the Maintainability NFR would be given here.

References

- [1] W. Spencer Smith and Lei Lai. A new requirements template for scientific computing. *In conjunction with 13th IEEE International Requirements Engineering Conference*, In J. Ralyt'ė, P. Agerfalk, and N. Kraiem, editors, Proceedings of the First International Workshop on Situational Requirements Engineering Processes – Methods, Techniques and Tools to Support Situation-Specific Requirements Engineering Processes, SREP'05: 107–121, Paris, France, 2005.

Appendix — Reflection

The information in this section will be used to evaluate the team members on the graduate attribute of Lifelong Learning. Please answer the following questions:

1. What knowledge and skills will the team collectively need to acquire to successfully complete this capstone project? Examples of possible knowledge to acquire include domain specific knowledge from the domain of your application, or software engineering knowledge, mechatronics knowledge or computer science knowledge. Skills may be related to technology, or writing, or presentation, or team management, etc. You should look to identify at least one item for each team member.
2. For each of the knowledge areas and skills identified in the previous question, what are at least two approaches to acquiring the knowledge or mastering the skill? Of the identified approaches, which will each team member pursue, and why did they make this choice?