Software Requirements Specification for IP Simulator: A Tool for Simulating the Inverted Pendulum System

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Revision History

Date	Version	Notes
February 1, 2023	1.0	First draft of document
February 3, 2023	1.1	Complete the Description part
February 4, 2023	1.2	Update Requirements part
February 6, 2023	1.3	Update Specific System Description part
February 10, 2023	1.4	Refine Solution Characteristic Specification
February 15, 2023	1.5	Refine according to Dr.Smith comments
April 14, 2023	2.0	Update and check consistencies in all documents

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
rad	angle	radian
m	distance or length	metre
N m	torque	newton.metre
s	time	second
$\mathrm{m\,s^{-2}}$	acceleration	metre.second^{-2}
$\mathrm{m\,s^{-1}}$	velocity	metre.second^{-1}
$\mathrm{kg\,m^{2}}$	moment of inertia	kilogram.metre^{2}
$\mathrm{rad\,s^{-1}}$	angular velocity	radian.second^{-1}
$\mathrm{rad\,s^{-2}}$	angular acceleration	radian.second^{-2}

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
$d_p y$	m	Distance traveled by the center of mass of pendulum in y direction
$d_p x$	m	Distance traveled by the center of mass of pendulum in x direction
$F(t)$	N	Horizontal force exerted on the cart over time
g	$\mathrm{m\,s^{-2}}$	Acceleration due to gravity
H	N	Horizontal reaction force of the cart or the pole
I	$\mathrm{kg\,m^{2}}$	Moment of inertia of the pendulum
l	m	Length to pendulum center of mass
m_c	kg	Mass of the cart

m_p	kg	Mass of the pendulum
r	m	Radius from the axis of rotation to the location where the force is exerted for calculating torque
V	N	Vertical reaction force component of the cart or the pole
$x(t)$	m	The distance which cart transfer over time (t)
$\dot{x}(t)$	$\mathrm{m\,s^{-1}}$	Velocity of the cart over time
$\ddot{x}(t)$	$\mathrm{m\,s^{-2}}$	Acceleration of the cart over time
$\theta(t)$	rad	Pendulum angle from vertical over time
$\dot{\theta}(t)$	$\mathrm{rad\,s^{-1}}$	Angular velocity of the pendulum over time
$\ddot{\theta}(t)$	$\mathrm{rad\,s^{-2}}$	Angular acceleration of the pendulum over time

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	Inverted Pendulum
TM	Theoretical Model

1.4 Mathematical Notation

In this document, the common mathematical notation used in undergraduate-level mathematics will be used.

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 that is attached to a cart and can move horizontally. It is unstable because its center of mass is above its pivot point so without additional help it will fall over. The cart moves horizontally by an external force and by manipulating the force, the position of the pendulum is controlled. Considering the force, we would like to simulate the behavior of the system and measure the position of the cart and the angle of the pendulum in the presence of the external force. We called the software, IP Simulator. The final tool can also be incorporated into a control system to stabilize the inverted pendulum system.

The following section provides an overview of Software Requirement Specification (SRS) for a pendulum-cart system, discussing the scope and purpose of the work.

2.1 Purpose of Document

The main purpose of this document is to describe the mathematical model of the Inverted Pendulum (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 the 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, and the cart can move horizontally left or right. This project does not cover the control algorithms to stabilize the system and focuses only on simulating the behavior of the system. For more details, the reader can refer to the assumptions section (Section 4.2.1).

2.3 Characteristics of Intended Reader

Intended Reader(s) or Reviewer(s) should have knowledge of Physics and more specifically the equations of motion. A good understanding of solving an ordinary differential equation (ODE) in Mathematics is also needed, both of the topics are offered in undergraduate engineering courses or high school Mathematics and Physics subjects.

2.4 Organization of Document

This document follows the SRS template as specified by Smith and Lai[1]. It 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 4.2.3, Section 4.2.6 can be explored. Most of the material is referential and may be read as needed.

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 represents an abstract view of the software. The rectangular node represents the IP simulator tool, and the circular nodes are users who interact with the software through a user interface.

Figure 1: System Context

The responsibilities of the user and the software are as follows:

- User responsibilities:
  - Provide required inputs including cart, pole specifications, and initial conditions of the system.
- The Inverted Pendulum Simulator responsibilities:
  - Ensure all inputs are in the correct format and detect data type mismatch.
  - Calculate and show the expected outputs including the position of the cart and the pendulum over the simulation time .

3.2 User Characteristics

The end user of the IP Simulator should have an understanding of first-level 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 Simulator tool is intended to describe and simulate the behavior of the system in the presence of different values of input. As the IP 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 educational material for students and engineers, It can also be incorporated into control software to stabilize the whole pendulum-cart system.

4.1.1 Terminology and Definitions

This subsection provides a list of terms that are used in the subsequent sections and their meanings, 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 it 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.
- Center of Mass: The center of mass is a position defined relative to an object or system of objects. It is the average position of all the parts of the system, weighted according to their masses. For simple rigid objects with uniform density, the center of mass is located at the centroid.
- Centroid: In mathematics and physics, the centroid, also known as geometric center or center of figure, of a plane figure or solid figure is the arithmetic mean position of all the points in the surface of the figure
- 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.

- Moment of Inertia: A quantity expressing a body's tendency to resist angular acceleration. It is the sum of the products of the mass of each particle in the body with the square of its distance from the axis of rotation.

4.1.2 Physical System Description

The physical system of IP Simulator, as shown in figure 2, includes the following elements:

- PS1: The cart
- PS2: The pendulum

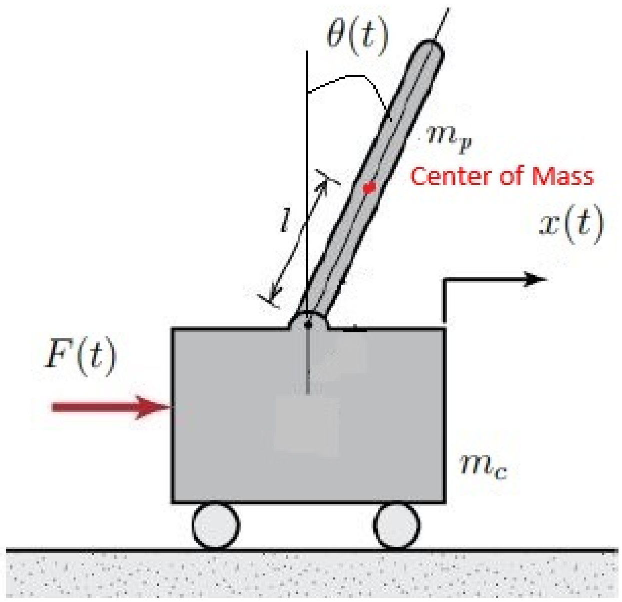

Figure 2: The Physical System of IP Simulator.

4.1.3 Goal Statements

Given the cart and the pendulum specifications, initial conditions and external force, the goal statements are:

GS1: Calculate the position of the cart over time.

GS2: Calculate the angle of the pendulum arm over time.

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], the general definition [GD], data definition [DD], instance model [IM], or likely change [LC], in which the respective assumption is used.

A1: The system has two degrees of freedom. The first degree of freedom is the horizontal motion of the cart and the second degree of freedom is the rotational motion of the pendulum.

A2: The pendulum is frictionless.

A3: The cart has friction.

A4: The moment of inertia of the pendulum is constant.

A5: The cart is allowed to move in a one-dimension plane, horizontally left or right.

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	$F = ma$
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 which 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. F is the net force acting upon the object in N, a is the acceleration of the object in $\mathrm{m\,s^{-2}}$, m is the mass of that object in kg.
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	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. τ is sum of the torques act on an object in $\mathrm{N\,m}$, I is the moment of inertia for a point particle in $\mathrm{kg\,m^2}$, α is angular acceleration of the object in rad/sec.
Notes	none.
Sources	`https://courses.lumenlearning.com/suny-osuniversityphysics/chapter/10-7-newtons-second-law-for-rotation/`
Ref. By	IM2

Number	TM3
Label	**Torque Definition**
Equation	$\tau = rF\sin(\beta)$
Description	Measure of the twisting action caused by a force that can cause an object to rotate about an axis. τ is torque, the rotational equivalent of linear force in $\mathrm{N\,m}$, F is applied force to an object that makes the object rotate around an axis and is measured in N, r is the radius from the axis of rotation to the location where the force is exerted in m, β is the angle between F and r in rad.
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, T2

Number	TM4
Label	**Force of Gravity**
Equation	$W = mg$
Description	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. g is the acceleration due to gravity in $\mathrm{m\,s^{-2}}$, m is the mass of the object in kg.
Notes	none.
Sources	`https://www.school-for-champions.com/science/gravity_overview.htm#.Y9-9ZXbMLs0`
Ref. By	GD3

Number	TM5
Label	**Acceleration Definition**
Equation	$a = \ddot{x}$
Description	Velocity is the derivative of position concerning time and acceleration is the derivative of velocity for time, so acceleration is the second derivative of position to time. a is the acceleration of the object in $\mathrm{m\,s^{-2}}$, x is the position of the object in m.
Notes	none.
Sources	`https://web.ma.utexas.edu/users/m408n/CurrentWeb/LM3-7-2.php`
Ref. By	GD1, GD2

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 Direction**
SI Units	N
Equation	$m_c\ddot{x}(t) = F(t) - H - b\dot{x}(t)$,
Description	Based on Newton's second law of motion, the sum of all forces applied to the cart in x direction is equal to $m_c a$, so the velocity of the cart is $\dot{x}$ and its acceleration will be $\ddot{x}$, therefore a is equal to $\ddot{x}$. $F(t)$ is the external force exerted to the cart over time and in N, H is the force component in x direction of the reaction force which the pendulum applies on the cart and measured in N, b is the coefficient of friction for the cart, $\dot{x}(t)$ is the velocity of the cart and therefore $\ddot{x}$ will be its acceleration.
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 the Pendulum in Horizontal Direction**
SI Units	All forces are measured in N
Equation	$m_p\ddot{x}(t) = H$
Description	Based on Newton's second law of motion, the sum of all forces applied to the pendulum in x direction is equal to $m_p a$. H is the force component in x direction of the force exerted by the cart on the pendulum and measured in N, m_p is the mass of the pendulum, $\ddot{x}$ is the pendulum acceleration.
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 Direction**
SI Units	All forces are measured in N
Equation	$m_p(l - l \ddot{\cos}(\theta)) = m_p g - V$
Description	Based on Newton's second law of motion, the sum of all forces applied to the pendulum in y direction is equal to $m_p a$. The total displacement traveled by the center of mass of the pendulum is equal to $l - l\cos(\theta)$ because the second derivation of l as a constant value is zero, therefore the equation reduces to $m_p(-l \ddot{\cos}(\theta)) = m_p g - V$. V is the force component in y direction of the force exerted by the cart on the pendulum and measured in N. m_p is the mass of the pendulum. $l - l\cos(\theta)$ is the vertical displacement of the pendulum.
Source	`https://ctms.engin.umich.edu/CTMS/index.php/example=InvertedPendulum&section=SystemModeling`
Ref. By	IM2 , DD2

Number	GD4
Label	**Calculate Angular Displacement of the Pendulum**
SI Units	τ
Equation	$I\ddot{\theta}(t) = l(V\sin(\theta)$ - $H\cos(\theta))$
Description	Let's take the center of mass of the pendulum as a center of rotation so the pendulum rotates about its center of mass. The torques due to forces exerted on the pendulum will calculate as below: the torque of the weight force of the pendulum is zero since the perpendicular distance of this force from the center of rotation is zero. For reaction forces V, H, we decompose these forces to components that are perpendicular to the pendulum which we have, $V\sin(\theta)$ and $H\cos(\theta)$. I is the moment of inertia of the pendulum. $\ddot{\theta}$ is pendulum angular acceleration.
Source	`https://ctms.engin.umich.edu/CTMS/index.php?example=InvertedPendulum&section=SystemModeling`
Ref. By	IM2, DD1, T3

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	$d_p x$
SI Units	m
Equation	$d_p x = l \sin(\theta) + x(t)$
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, 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 the pendulum is equal to $= l \sin(\theta) + x(t)$. l is the half length of the pendulum in m, $x(t)$ is the horizontal distance traveled by the center of mass of the pendulum in m, $\theta(t)$ is the angular rotation in the pendulum in rad.
Sources	`https://www.youtube.com/watch?v=c3z4eo6s0Ek`
Ref. By	GD1

Number	DD2
Label	**Vertical Displacement of the Pendulum**
Symbol	$d_p y$
SI Units	m
Equation	$d_p y = l - l\cos(\theta)$
Description	When the pendulum rotates, its center of mass travels a vertical displacement, and as the half length of the pendulum is l, the vertical distance traveled by the center of mass of the pendulum will be equal to $l\cos(\theta)$, hence the total displacement is equal to $(l - l\cos(\theta))$. l is the half length of the pendulum in m, $\theta(t)$ is the angular rotation in the pendulum in rad.
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	$I = m_p l^2$
Description	The moment of inertia of a rod is related to its mass and length. Its center of mass is located in the middle of its length. the mass of rod is denoted by m_p and is measured in kg, and its length is denoted by l and is measured in m.
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 is not applicable for the problem.

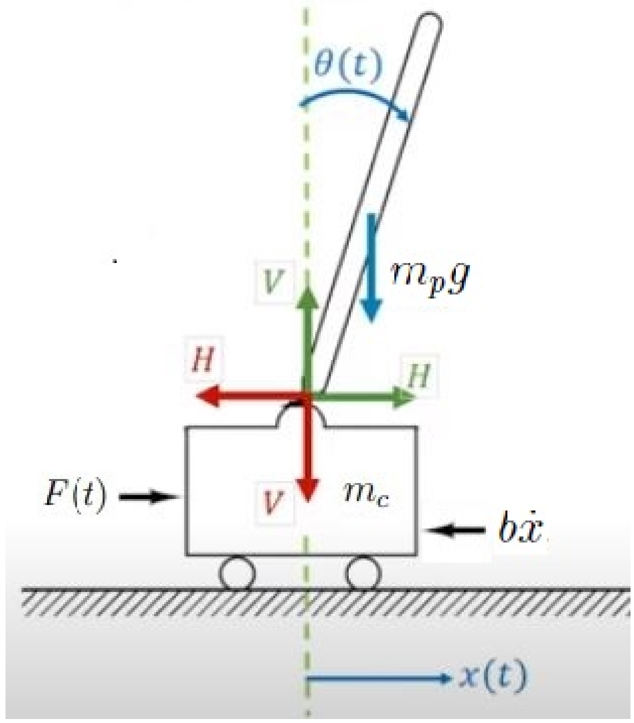

Figure 3: The Free Body Diagram of the Cart-Pendulum System

4.2.6 Instance Models

This section describes the instance models and figure 3 depicts the free body of the system, so the forces applied to the cart and the pendulum is shown.

Number	IM1
Label	**Equation of Motion for the Cart**
Input	$F(t)$, m_c, m_p, b, l
Output	$x(t)$ in m, such that $F(t)= (m_c + m_p)\ddot{x} + b\dot{x} + m_p l\ddot{\theta}\cos\theta - m_p l(\dot{\theta})^2 \sin\theta \rightarrow$ $\ddot{x}(t) = \dfrac{F(t) - b\dot{x}(t) - m_p l\ddot{\theta}\cos\theta + m_p l(\dot{\theta})^2\sin\theta}{(m_c + m_p)}$
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 in m. $\theta(t)$ is the pendulum angle from vertical in (rad) over time. and by writing equation of motion for the cart, the relationship between inputs and cart motion is clarified.
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 $(I + m_p l^2)\ddot{\theta}(t) + m_p l\ddot{x}(t)\cos\theta - m_p gl\sin\theta = 0 \rightarrow$ $\ddot{\theta}(t)= \dfrac{m_p gl\sin\theta - m_p l\ddot{x}(t)\cos\theta}{(I + m_p l^2)}$
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 in m. b is the coefficient friction of the cart (dimensionless). This equation show the relationship between motion of pendulum and the system.
Sources	`https://www.mathworks.com/help/control/ug/control-of-an-inverted-pendulum-on-a-cart.html`
Ref. By	-

4.2.7 Derivation of Instance Models

- Finding IM1: This subsection shows how the IM1 is derived. We should start from GD4, where we have this equation, $I\ddot{\theta} = l(V\sin(\theta)$ - $H\cos(\theta))$, we need to substitute V and H in this equation. Therefore, we have the value of H form GD2, consider that we also calculate x in the DD1, so we will have the H as $m_p\ddot{x}(t){+}m_p l\ddot{\sin}\,\theta$.
  For finding V, we use GD3, when we have $m_p(l - l\ddot{\cos}(\theta)) = (m_p)g - V$, so $V = (m_p)g - m_p(l - l\ddot{\cos}(\theta))$. The point is that the force that the cart applied to the pendulum is equal to the force exerted on the cart by the pendulum. Hence, by substituting V and H in GD4, the IM1 is obtained.

- Finding IM2: This subsection shows how the IM2 is derived. In GD1, we have $m_c\ddot{x}(t) = F(t) - H - b\dot{x}$, by writing Newton's second law of motion for the pendulum in the vertical direction. As $F(t)$ in the input of the system and we also have the value of H form GD2, consider that we also calculate $x(t)$ in the DD1, so we will have the H as $m_p\ddot{x}(t) + m_p l\ddot{\sin}\,\theta$.
  Therefore, by substituting H, we will reach $(I + m_p l^2)\ddot{\theta}(t) + m_p l\ddot{x}(t)\cos\theta - m_p gl\sin\theta = 0$. The point is that the force that the cart applied to the pendulum is equal to the force exerted on the cart by the pendulum.

4.2.8 Input Data Constraints

Table 1 shows the data constraints on the input and 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.

4.2.9 Properties of a Correct Solution

Table 3 shows the physical constraints on the output.

Table 1: Input Variables

Var	Physical Constraints	Software Constraints	Typical Value	Uncertainty
m_p	$0 < m_p$	$m_{\text{pmin}} \leq m_p \leq m_{\text{pmax}}$	0.2 kg	–
m_c	$0 < m_c$	$m_{\text{cmin}} \leq m_c \leq m_{\text{cmax}}$	0.5 kg	–
b	$0 \leq b$	$0 \leq b$	0.1(dimensionless)	–
l	$0 < l$	$l_{\text{pmin}} \leq l \leq l_{\text{pmax}}$	0.3 m	–
I	$0 < I$	$0 < I$	$0.006\ \text{kg}\,\text{m}^2$	–
$F(t)$	$0 < F(t)$	$0 < F(t)$	20 N	–
x_i	$0 \leq x_i$	$0 \leq x_i$	0 m	–
$\dot{x}_i$	$0 \leq \dot{x}_i$	$0 \leq \dot{x}_i$	0 m/s	–
θi	$0 \leq \theta i$	$0 \leq \theta i$	0.2 rad	–
$\dot{\theta} i$	$0 \leq \dot{\theta} i$	$0 \leq \dot{\theta} i$	$0\ \text{rad}\,\text{s}^{-1}$	–

Table 2: Specification Parameter Values

Var	Value
θ	0

Table 3: Output Variables

Var	Physical Constraints
$\theta(t)$	$0 \leq \theta(t) \leq 2 \cdot \pi$ rad
$x(t)$	$0 \leq x(t)$ m

5 Requirements

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

5.1 Functional Requirements

R1: Provide input values such as the cart specification, the pendulum features, and initial conditions according to Table1.

R2: Check the validity of input parameters.

R3: Calculate the horizontal position of the cart and the angular position of the pendulum from IM1 and IM2 over the time specified.

R4: Check the validity of outputs.

R5: Visualize the outputs.

5.2 Nonfunctional Requirements

The nonfunctional requirements are listed below:

NFR1: Portability: IP Simulator can run on all different operating environments, such as Windows, Mac-OS, and Linux.

NFR2: Usability: The properties of the software should be able to be tested through section 5.2.2 in the verification and validation plan.

NFR3: Accuracy: The level of accuracy achieved by IP Simulator shall be described following the procedure given in section 5.2.3 of the verification and validation plan.

6 Likely Changes

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

7 Unlikely Changes

ULC1: The system has two degrees 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 is 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 in the assumptions. Table 6 shows the dependencies of instance models, requirements, and data constraints on each other.

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

	T1	T2	T3	T4	T5	GD1	GD2	GD3	GD4	DD1	DD2	DD3	IM1	IM2
T1					X	X	X	X					X	
T2			X						X					X
T3		X							X					X
T4								X					X	
T5	X					X	X							X
GD1	X				X								X	
GD2	X				X				X				X	X
GD3	X			X										X
GD4		X	X				X							X
DD1														X
DD2														X
DD3														X
IM1	X			X		X	X							
IM2		X	X	X			X	X	X	X	X	X		

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

	T1	T2	T3	T4	T5	GD1	GD2	GD3	GD4	DD1	DD2	DD3	IM1	IM2
A1							X	X	X				X	X
A2							X	X	X	X	X	X		X
A3						X							X	
A4												X		X
A5						X							X	

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

	IM1	IM2	4.2.8
R1			X
R2			X
R3	X	X	
R4			X
R5			X

9 Development Plan

Not Applicable.

10 Values of Auxiliary Constants

Table 7: Auxiliary Constants

Symbol	Description	Value	Units
m_{pmin}	minimum value of the pendulum mass	0.01	kg
m_{pmax}	maximum value of the pendulum mass	50	kg
m_{cmin}	minimum value of the mass of the cart	0.01	kg
m_{cmax}	maximum value of the mass of the cart	50	kg
l_{pmin}	minimum value of the length of the pendulum	0.01	m
l_{pmax}	maximum value of the length of the pendulum	10	m
g	Acceleration due to gravity	9.8	$\mathrm{m\,s^{-2}}$

References

[1] W. Spencer Smith and Lei Lai. A new requirements template for scientific computing. In J. Ralyté, P. Ȧgerfalk, 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*, pages 107–121, Paris, France, 2005. In conjunction with 13th IEEE International Requirements Engineering Conference.