Human Transporter Project

UNIVERSITY OF Waterloo

Duncan VanPagee (21010547)

Izaac Mottiar (21017776)

Jarryd Ross (21003924)

Luke Wilbee (21004033)

Group 22

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MTE 351 – Systems Models

Dr. Charbel Azzi

Abstract

This report investigates the motion of a human transporter device using models built in two industry leading software: Simulink (MATLAB) and SimulationX. The system's equations of motion were derived from free body and kinetic diagrams to represent the motion of the system mathematically. These equations were linearized and used to develop a block diagram necessary to model the system in Simulink. While keeping a constant lean angle of 5° between the handlebar and the user, the Simulink model showed that the human transport device has a positive forward displacement when an external force between 65N and 82N acted one the center of the base parallel to the ground. After which a physical network version of the segway was built and modelled in SimulationX, using physical constraints and body elements. The Variants Wizard module in SimulationX was used to iteratively optimize the model. Key variables including handlebar tilt, user lean angle and input force were fine-tuned to maximize displacement while maintaining a speed below 20 km/h. The final optimized model predicted a maximum displacement of 5.1761 m while having a lean angle of 0.01 radians, tilt of the transporter be 0.24 radians and an external applied force of 294.4N. To thoroughly evalua

te the models built, a comparison between Simulink and SimulationX was carried out to highlight the discrepancies caused by the simplified Simulink model.

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1 Introduction

This project focuses on modeling the kinetics of a human transporter device, commonly known as a Segway. These low-speed, single user vehicles are commonly operated within a short range, powered by an electric source. The user stands on a base, which is then driven by two inline wheels that rotate at varying speeds based on direction commands. To control the speed and direction of the device, the operator leans on the handlebars and the electric motors drive in response. For the purposes of this project and ease of simulation, the movement of the segway will be simply limited to forward motion. Due to the dynamics of this device, the system will always fall over without proper control systems, so a goal for this project is to manipulate input parameters to maximize stability without said controls.

The first goal of this project is to develop a theoretical model of the human transporter. The general equations of motion of the segway base and the user was derived to complete the analytical model. The second part of this project was numerically simulating the system. To do so, the previously derived analytical model was linearized and then transformed into standard state-variable form. This simplified linearized model was then solved numerically in Simulink. The input thrust force of the device to maximum the uncontrolled forward motion and attempt to allow the transporter to move 5-10 meters before collapsing. The final task in this project was to animate and experimentally model the human transporter. A simple visual representation of the Segway was implemented in SimulationX, with input parameters tuned to achieve a maximum forward displacement. The Segway base, handlebars, and human user were represented with simple MBS blocks with set with the parameters defined in the project manual.

2 Background

Dicycles are a classification of personal transportation vehicles identified by two parallel inline wheels [1]. These devices have been available in many different forms since the mid 1800's and have undergone many advancements to modernize the technology into the 21st century. Originally, these vehicles comprised of two large wheels powered by the user with pedals like that found on a common bicycle as seen in Figure 1a) below [1]. In the present day, dicycles are more commonly called Segways, which is a trademark of the company that first brought the product to market, Segway Inc [1]. The dicycle technology has shifted away from its rudimentary past, becoming self-balancing scooters with a power system and manageably smaller wheels as seen below in Figure 1b) [1].

The initial design for the Segway was an exciting leap, adding a vast amount of technology to the personal mobility industry. Movement of the device is controlled by the user input to the handlebars [2]. To move forward or back, lean on the control stick, and to move left or right, direct the handles in this direction [2]. The stability of this movement is achieved by a system that acts like human responses [2]. When a person in leaning forward and unstable, a response is triggered to prevent a fall by stepping forward [2]. With Segways, gyroscopic sensors detect a change in pitch of the control handles, and drive the motors to compensate for this lean, thus preventing the vehicle from falling [2]. By using the Coriolis effect to determine the rotation of the handlebar, the wheels will rotate at a specific speed to maintain balance [2]. If the user is continually leaning forward, the wheels will drive the system in that direction to maintain balance.

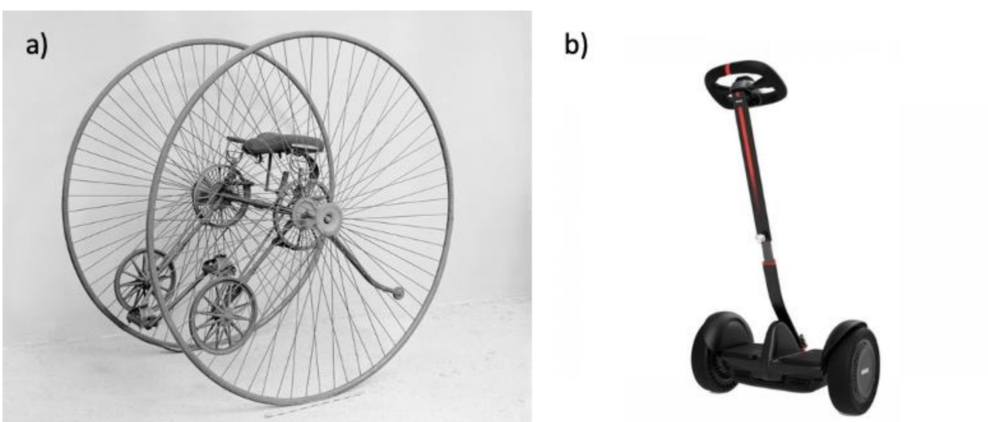

Figure 1: a) Otto Dicycle (1870's), b) Modern Segway

3 Methodology

3.1 FBD and KD of the Subsystems

Table 1: List of parameters and details of each

Parameter/Variable	Description
F_t	Thrust Force
F_f	Friction Force
N	Normal Force
M	Mass of the Base
g	Gravity
R	Radius of Wheel
O_y	Reaction Force of Pin at Point O (y-axis)
O_x	Reaction Force of Pin at Point O (x-axis)
x	Position of the Transporter
I_{G_w}	Inertia of the Wheel
α_w	Angular Acceleration of Wheel
M_u	Mass of the User
I_{G_u}	Inertia of the User
α_u	Angular Acceleration of User
L_G	Distance OG
θ	Tilt of the Transporter
β	User Tilt with respect to Transporter
a_{Gx}	Acceleration at Point G along x-axis
a_{Gy}	Acceleration at Point G along y-axis

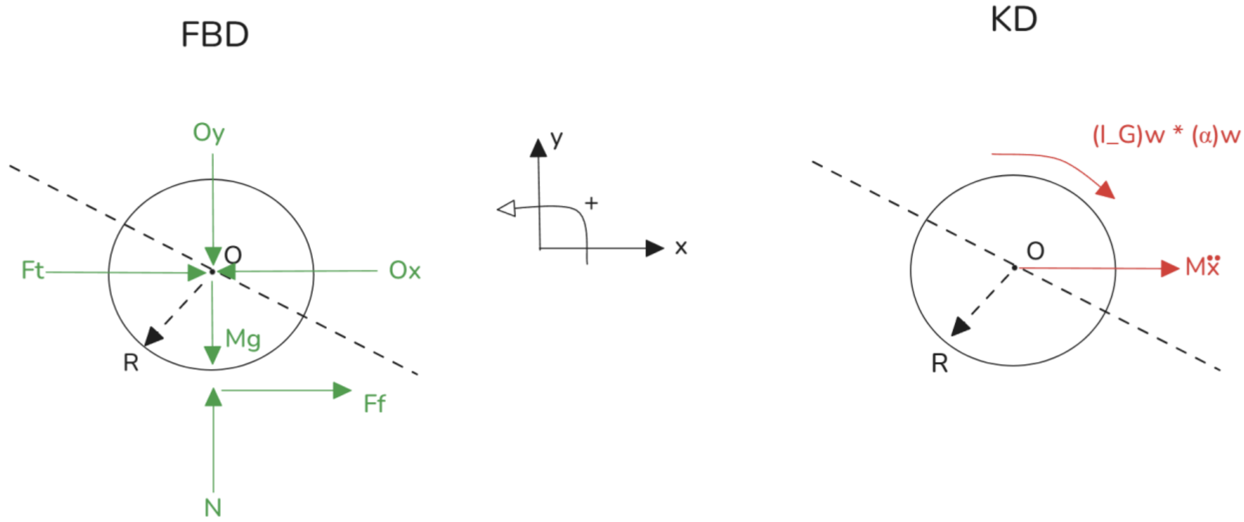

Figure 2: FBD and KD of Wheel

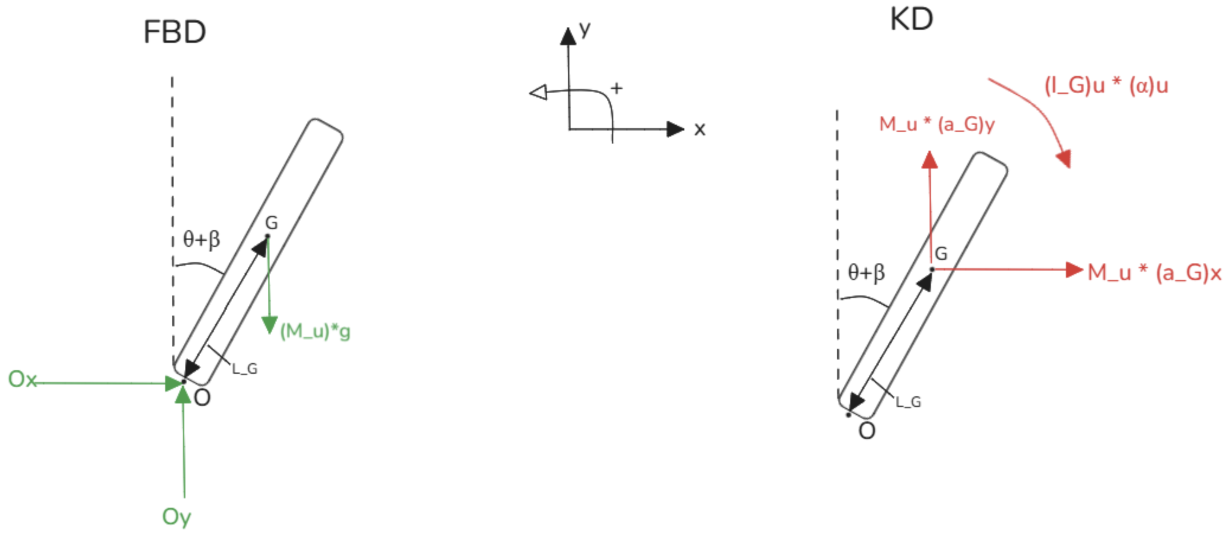

Figure 3: FBD and KD of User

3.2 Mathematical Model of the Transporter

Applying Newton’s second law to the wheels/base of the segway:

$$\sum F_x = m\ddot{x}$$

$$F_T + F_f - O_x = M\ddot{x} \ldots \ (1)$$

$$\sum F_y = 0$$

$$N - Mg - O_y = 0 \ldots \ (2)$$

$$\sum M_o = I_G\alpha$$

$$F_f \cdot R = -\, I_{G_w}\alpha_w$$

As no slip condition is assumed, $\alpha_w = \frac{\ddot{x}}{R}$

$$F_f \cdot R = -\, I_{G_w}\frac{\ddot{x}}{R} \dots \ (3)$$

Applying Newton's second law to the user:

$$\sum F_x = M_u a_{Gx}$$

$$O_x = M_u\left[\ddot{x} + L_g\cos(\theta+\beta)\,\ddot{\theta} - L_g\sin(\theta+\beta)\,\dot{\theta}^2\right] \dots (4)$$

$$\sum F_y = M_u a_{Gy}$$

$$-M_u g + O_y = M_u\left[-L_g\sin(\theta+\beta)\,\ddot{\theta} - L_g\cos(\theta+\beta)\,\dot{\theta}^2\right] \dots \ (5)$$

$$\sum M_G = I_G\alpha$$

$$O_x L_g\cos(\theta+\beta) - O_y L_g\sin(\theta+\beta) = -I_{G_u}\ddot{\theta} \dots \ (6)$$

Solving Equations (1)-(6) to end up in desired form:

Rearranging (3):

$$F_f = -\, I_{G_w}\frac{\ddot{x}}{R^2} \dots \ (7)$$

Sub (7) into (1):

$$F_T - \ I_{G_w}\frac{\ddot{x}}{R^2} + O_x = M\ddot{x}$$

Sub in (4):

$$F_T - \ I_{G_w}\frac{\ddot{x}}{R^2} - M_u\left[\ddot{x} + L_g\cos(\theta+\beta)\,\ddot{\theta} - L_g\sin(\theta+\beta)\,\dot{\theta}^2\right] = M\ddot{x}$$

$$\ddot{x}\left(M + \frac{I_{G_W}}{R^2} + M_u\right) + M_u L_g\cos(\theta+\beta)\,\ddot{\theta} - M_u L_g\sin(\theta+\beta)\,\dot{\theta}^2 = F_t \dots \ (A)$$

From (A),

$$C_1 = M + \frac{I_{G_w}}{R^2} + M_u$$

$$C_2(\theta) = M_u L_g\cos(\theta+\beta)$$

$$C_3(\theta) = -M_u L_g\sin(\theta+\beta)$$

$$C_7 = F_t$$

Rearranging (5):

$$O_y = M_u\left[-L_g \sin(\theta+\beta)\,\ddot{\theta} - L_g \cos(\theta+\beta)\,\dot{\theta}^2\right] + M_u g \ \dots\ (8)$$

Sub (4) and (8) into (6):

$$(M_u\left[\ddot{x} + L_g\cos(\theta+\beta)\,\ddot{\theta} - \cancel{L_g \sin(\theta+\beta)\,\dot{\theta}^2}\right]) \cdot L_g\cos(\theta+\beta)$$

$$- (M_u\left[-L_g\sin(\theta+\beta)\,\ddot{\theta} - \cancel{L_g\cos(\theta+\beta)\,\dot{\theta}^2}\right] + M_u g\ ) \cdot L_g \sin(\theta+\beta) = -I_{G_u}\ddot{\theta}$$

$$(L_g^2\cos^2(\theta+\beta) + L_g^2\sin^2(\theta+\beta))\ddot{\theta} + M_u L_g\cos(\theta+\beta)\,\ddot{x} - M_u L_g g\sin(\theta+\beta) = -I_{G_u}\ddot{\theta}$$

$$(I_{G_u} + M_u L_g^2)\ddot{\theta} + M_u L_g\cos(\theta+\beta)\,\ddot{x} - M_u L_g g\sin(\theta+\beta) = 0\ \dots\ (B)$$

From (B),

$$C_4(\theta) = I_{G_u} + M_u L_g^2$$

$$C_5(\theta) = M_u L_g \cos(\theta+\beta)$$

$$C_6(\theta) = -M_u L_g g\sin(\theta+\beta)$$

3.3 Linearization of System Model and State-Variable Model

The small angle approximation assumes that $\sin(\theta+\beta) = \theta+\beta$, $\cos(\theta+\beta) = 1$, and $\dot{\theta}^2 = 0$.

Applying to (A) and (B) yields:

$$\ddot{x}\left(M + \frac{I_{G_W}}{R^2} + M_u\right) + M_u L_g \ddot{\theta} = F_t\ \dots\ (9)$$

$$(I_{G_u} + M_u L_g^2)\ddot{\theta} + M_u L_g \ddot{x} - M_u L_g g(\theta+\beta) = 0 \dots\ (10)$$

Using MATLAB's Symbolic Toolbox to solve isolate for $\ddot{x}$ and $\ddot{\theta}$ yields:

$$\ddot{x} = \frac{R^2(F_t I_{G_u} + F_t L_G^2 M_u - L_G^2 M_u^2 \beta g - L_G^2 M_u^2 g\theta)}{I_{G_u}I_{G_w} + I_{G_w}L_G^2 M_u + I_{G_u}R^2 M + I_{G_u}R^2 M_u + L_g^2 R^2 M M_U}$$

$$\ddot{\theta} = \frac{L_g M_u g(\theta+\beta)\left(I_{G_w} + MR^2 + M_u R^2\right) - L_g M_u F_t R^2}{I_{G_u}I_{G_w} + I_{G_w}L_G^2 M_u + I_{G_u}R^2 M + I_{G_u}R^2 M_u + L_g^2 R^2 M M_U}$$

Let $x_1(t) = x,\ x_2(t) = \dot{x_1}(t) = \dot{x},\ x_3(t) = \theta,\ x_4(t) = \dot{x_3}(t) = \dot{\theta}$

$$\dot{x_1}(t) = x_2(t)$$

$$\dot{x_2}(t) = \frac{L_G^2 M_u^2 g}{I_{G_u}I_{G_w} + I_{G_w}L_G^2 M_u + I_{G_u}R^2 M + I_{G_u}R^2 M_u + L_g^2 R^2 M M_U} x_3(t)$$

$$+ \frac{R^2(F_t I_{G_u} + F_t L_G^2 M_u - L_G^2 M_u^2 \beta g)}{I_{G_u}I_{G_w} + I_{G_w}L_G^2 M_u + I_{G_u}R^2 M + I_{G_u}R^2 M_u + L_g^2 R^2 M M_U}$$

$$\dot{x_3}(t) = x_4(t)$$

$$\dot{x_4}(t) = \frac{L_g M_u g\left(I_{G_w} + MR^2 + M_u R^2\right)}{I_{G_u} I_{G_w} + I_{G_w} L_G^2 M_u + I_{G_u} R^2 M + I_{G_u} R^2 M_u + L_g^2 R^2 M M_U} x_3(t) + \frac{L_g M_u g \beta\left(I_{G_w} + MR^2 + M_u R^2\right) - L_g M_u F_t R^2}{I_{G_u} I_{G_w} + I_{G_w} L_G^2 M_u + I_{G_u} R^2 M + I_{G_u} R^2 M_u + L_g^2 R^2 M M_U}$$

State Equation Matrix

Let $A_1 = \frac{L_G^2 M_u^2 g}{I_{G_u} I_{G_w} + I_{G_w} L_G^2 M_u + I_{G_u} R^2 M + I_{G_u} R^2 M_u + L_g^2 R^2 M M_U}$,

$$A_2 = \frac{L_g M_u g\left(I_{G_w} + MR^2 + M_u R^2\right)}{I_{G_u} I_{G_w} + I_{G_w} L_G^2 M_u + I_{G_u} R^2 M + I_{G_u} R^2 M_u + L_g^2 R^2 M M_U}$$

$$B_1 = \frac{R^2 (F_t I_{G_u} + F_t L_G^2 M_u - L_G^2 M_u^2 \beta g)}{I_{G_u} I_{G_w} + I_{G_w} L_G^2 M_u + I_{G_u} R^2 M + I_{G_u} R^2 M_u + L_g^2 R^2 M M_U}$$

$$B_2 = \frac{L_g M_u g \beta\left(I_{G_w} + MR^2 + M_u R^2\right) - L_g M_u F_t R^2}{I_{G_u} I_{G_w} + I_{G_w} L_G^2 M_u + I_{G_u} R^2 M + I_{G_u} R^2 M_u + L_g^2 R^2 M M_U}$$

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & A_1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & A_2 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ B_1 \\ 0 \\ B_2 \end{bmatrix}$$

3.4 Simulink System Model

Equations (9) and (10) were used to simulate the system in MATLAB's Simulink due to their linear nature. The following conditions were assumed for preliminary testing:

- $F(t)$ was tested at a range of values ranging from $F(t) = 65 * u(t)[N]$ to $F(t) = 83 * u(t)[N]$.
- $\beta = 5°$. A value greater than 0 was assumed to keep β significant while under the conditions of small angle approximation.
- $M_u = 50 + \frac{22}{2} = 61[kg]$.
- The user has fallen once the angle $\theta >= 90°$.

3.4.4 Equation Manipulation

Following the steps presented during lectures. The linear equations (9) and (10) were rearranged as follows to isolate for $\ddot{x}$ and $\ddot{\theta}$.

$$\ddot{x} = \frac{1}{\left(M + \frac{I_{G_W}}{R^2} + M_u\right)} (F_t - M_u L_g \ddot{\theta})$$

$$\ddot{\theta} = \frac{1}{\left(I_{G_u} + M_u L_g^2\right)}(M_u L_g g(\theta + \beta) - M_u L_g \ddot{x})$$

The following constants were assigned to simplify the equations and used in the Simulink system model:

$$A = M + \frac{I_{G_W}}{R^2} + M_u = 96.000124$$

$$B = M_u L_g = 61$$

$$C = I_{G_u} + M_u L_g^2 = 81$$

The final modified equations used to build the block diagram in Simulink are as follows:

$$\ddot{x} = \frac{1}{A}(F_t - B\ddot{\theta}) \ldots (11)$$

$$\ddot{\theta} = \frac{B}{C}(g\theta + g\beta - \ddot{x}) \ldots (12)$$

Figure 6 shows the completed block diagram built in Simulink using equations (11) and (12). The input block F(t) is a step function with a step at $t = 0s$ to the varied force input. The simulation stops when $\theta > 1.57\ rad$ or when the user is considered to have fallen. A scope has been placed to monitor both x and θ on the same plot.

3.5 SimulationX Design

Table 2: SimulationX Component Design Table

SimulationX Component Name	Dimensions
Wheels: wheel1, wheel2	Cylinder: Radius = 0.127m Height = 0.127m Weight: 15kg each
Wheel Axel: base	Cuboid: Lx = 0.254m Ly = 0.6m Lz = 0.0635m Weight: 5kg
Human Body: body	Cuboid: Lx = 0.127m

	Ly = 0.45m Lz = 0.5m
Handlebar: handlebar1	Cylinder: Radius = 0.01m Height = 1m Weight = 1.5kg
Human Legs: leg1, leg2	Cuboid: Lx = 0.127m Ly = 0.127 m Lz = 0.9167m
Human head: head	Cuboid: Lx = 0.127m Ly = 0.08467m Lz = 0.167m
Human Center of Mass: body1	General RB: Location: G Weight 61kg
Input Force: bodyForce1	Body Force: Input: step function to a constant input force at time = 0s
Input Theta: theta	Step Function: Input: keeps revoluteJoint3 offset angle constant
Input Beta: beta	Step Function: Input: keeps handlebar1 offset angle constant

Before discussing the simulation model the coordinate system must be defined. In this system, the x-axis is directed parallel to the ground, in the direction of motion. The y-axis is parallel to the ground, directed perpendicular to the motion of the transporter. Finally, the z-axis is perpendicular to the ground.

The two wheels for the human transporter were modeled with cylinders. The radius of these components was set to 12.7cm as defined in the problem definition. The thickness of these wheels was also set to 12.7cm to have a 2:1 ratio of diameter to width. The total weight of the base, 35kg, was provided. To achieve this, the mass of the two wheels was set to 15kg each, leaving 5 kg for the base. The wheels are connected to the base about the middle of its thickness and rotates about axles as the system translates. The wheels are aligned along an axis parallel to the y-direction. The moment of inertia of the wheels was set with the inertia tensor of the cylinder blocks, rotating about the y axis.

The base of the transporter was modeled with a cuboid. The dimensions of this cuboid were selected based on proportions that were visually appealing. The length of the board was 0.6m (y-direction), plenty of space for a human to stand on. The width was selected to be 0.254m (x-direction) to match the diameter of the wheels, and the thickness (z-direction) was 0.0635m, or half the wheel radius. The mass of the base was 5kg to complete the 35kg required and was centered within the cuboid.

The handlebar of the Segway was modeled with a long slender cylinder. The length of the rod was defined as 1m. One end of the handlebar was fixed to the base located at its center of mass and was leaned an angle of β away from the user. Its mass was set to the specified 1.5kg and was distributed evenly along its length.

The human was modeled with a composition of 4 cuboids. Two for the legs, one for the body, and one for the head. The legs were fixed at one end to the base and leaned at an angle θ initially. The body was fixed to the other end of the legs and aligned with the same tilt angle as the legs. The head was fixed upon the top of the body. The dimensions selected for the human composition were based on proportions that were visually acceptable. These 4 cuboids were set as massless objects.

To efficiently locate the center of mass at the desired position of the human, a general rigid body set to a mass of 61kg was fixed to the end of the handlebar at an angle of $\theta+\beta$. This allowed for the desired physical characteristics to be simulated while also providing a visual representation of the user. The moment of inertia of the user was set with the inertia tensor of the rigid body rotating about the y axis.

Table 33: SimulationX Joint Design Table

SimulationX Joint Name	Justification
revoluteJoint1, revoluteJoint2	- Used to allows wheel1 and wheel2 to rotate about the Z axis and with respect to the base. Allows the base to act as an axel.
revoluteJoint3	- Used to allow the human and handlebar rotate about the Y axis at a fixed point on the base.
prismaticJointX1	- Used to allow the entire model to translate in the X direction.
prismaticJointZ1, prismaticJointZ2	- Used to allow wheel1 and wheel2 to translate in the Z direction. It is necessary to allow the mass of the wheel to act on the ground and the wheel to rotate.

The offset angles of revoluteJoint3 and handlebar1 reference step function blocks, theta and beta respectively. This modification allows beta, theta, and force to be varied in the variant wizard in one cycle, decreasing optimization time.

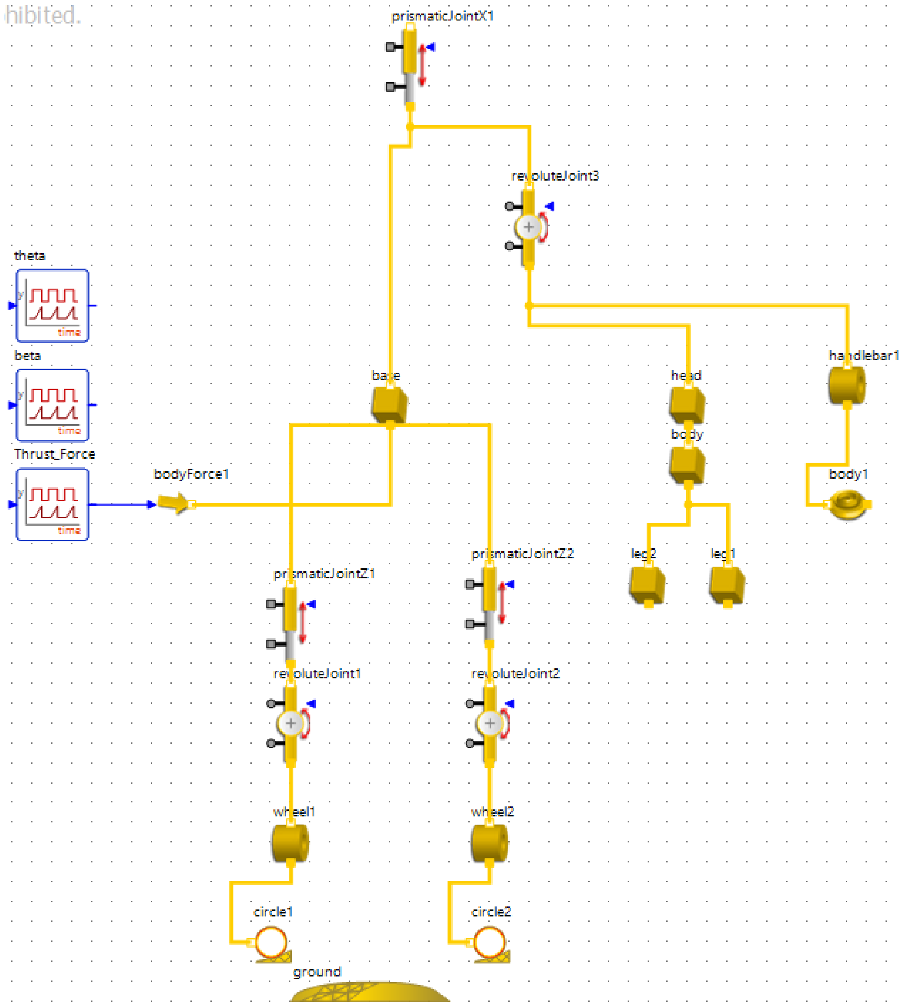

Figure 4: SimulationX Design

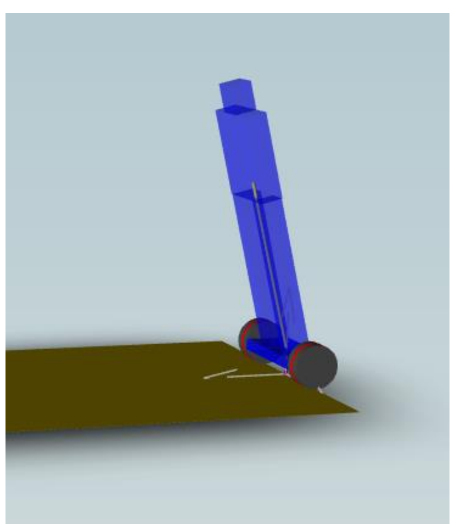

Figure 5: SimulationX 3D model

4 Results and Discussion

4.1 Linearized Simulink Results

4.1.1 – Simulink Model

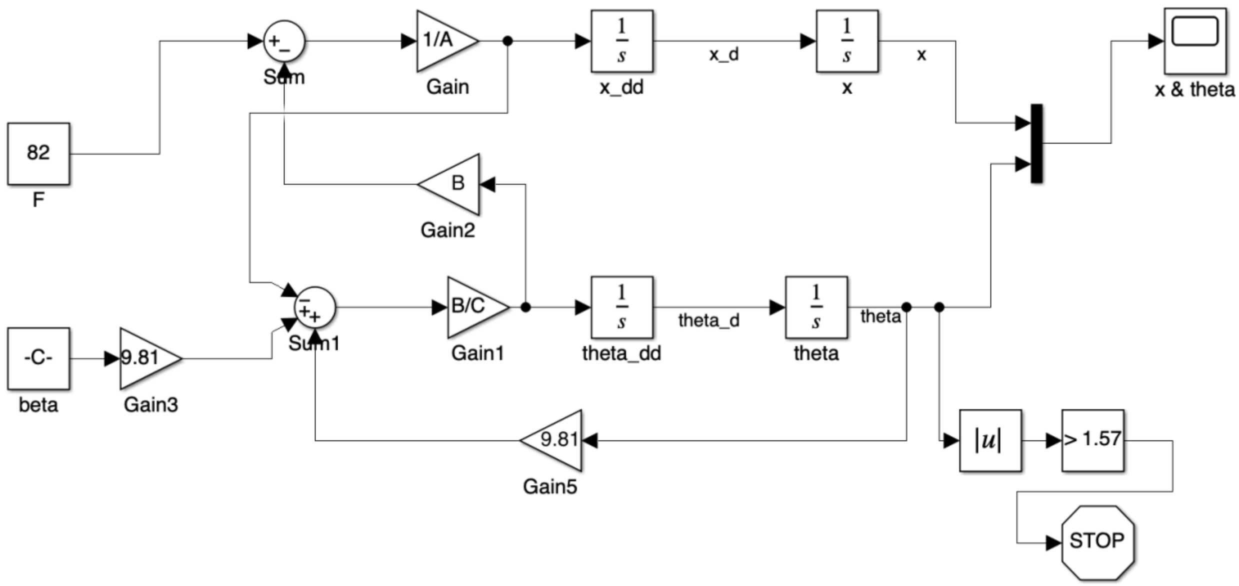

Figure 6: Simulink Model

4.1.2 Observations

The variables β and M_u are held constant while the forced input, $F(t)$, is varied to observe different system responses. There were three prominent resulting scenarios with the system model in Simulink outlined in Table 4.

Table 44: Simulink Scenarios

Input Force Range (N)	Distance Observation	Primary User Angle Observation
< 65	An immediate negative exponential.	An immediate positive exponential.
65 - 83	A negative exponential with an initial positive region.	A positive exponential.
> 83	A positive exponential.	An immediate negative exponential.

1. Both Figure 7 and Figure 8 show the system's responses when an input force of 65 N and 82 N was applied respectively. All the plots show a $\theta > 90°$ stopping the simulation once the user has

fallen. It is noted that as the input force increased in the range of 65 N to 82 N the displacement increased. This scenario is the desired system response. This input range allows for enough balance for the user/handlebar to stay upright long enough for the segway to move forward.

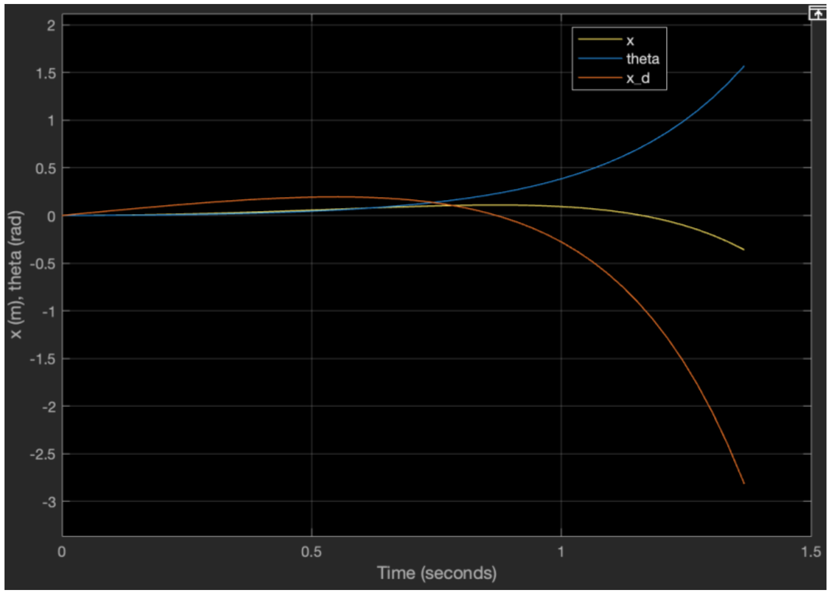

Figure 7: Simulink Plot F(t) = 65 N

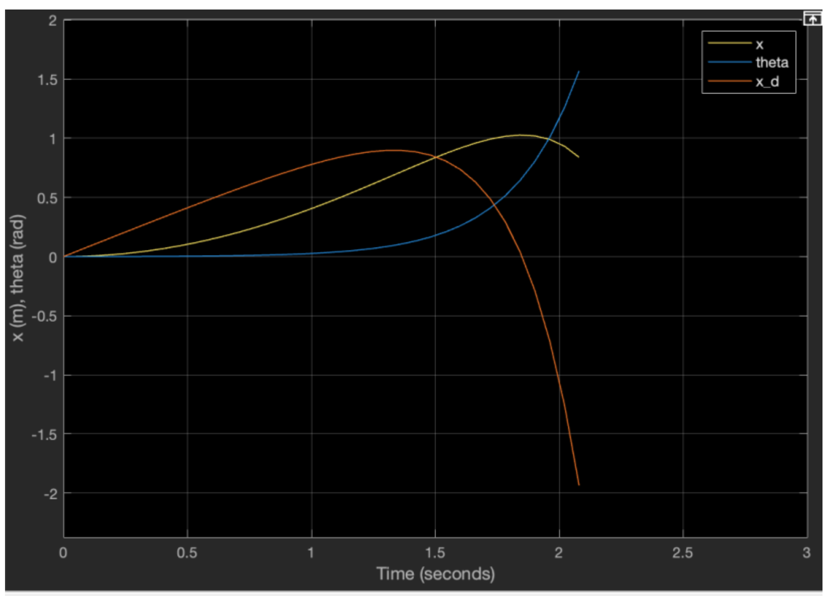

Figure 8: Simulink Plot F(t) = 82 N

2. The second system response scenario is when the input force was less than 65 N. A force of 50 N is shown in Figure 9. In this range, there was no noticeable displacement for the duration of the simulation. The displacement quickly increased in the negative direction. This case is when there

is not enough input force to keep the user/handlebar upright, causing the handlebar to fall forward. The user/handlebar falling forward, forces the wheels in the reverse direction overcoming the input force and this is why the simulation models an immediate negative displacement and velocity.

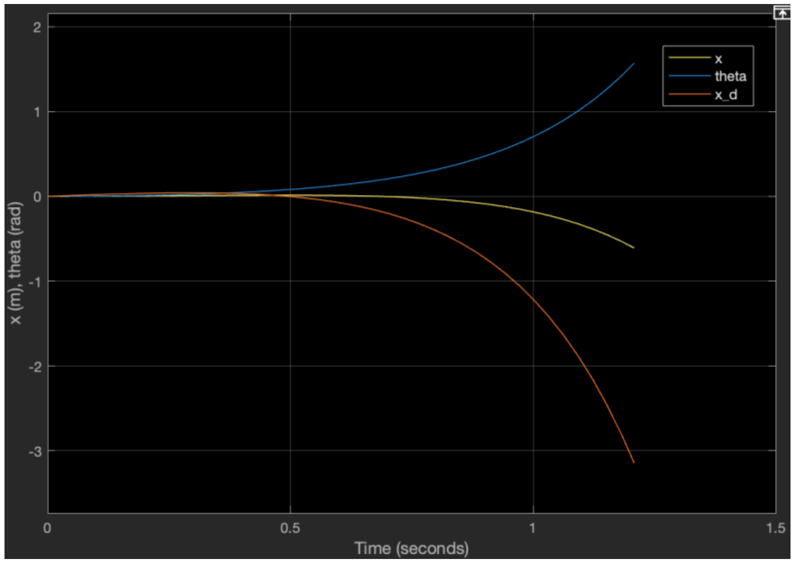

Figure 9: Simulink Plot F(t) = 50 N

3. The final system response scenario observed was as the input increased past ~83 N the θ value immediately became negative, evident in Figure 10. Conceptually, this is likely because the magnitude of the applied force causes the handlebar to fall backward (negative) and shoots the base forward which is why there is a spike in the velocity and displacement as θ becomes negative.

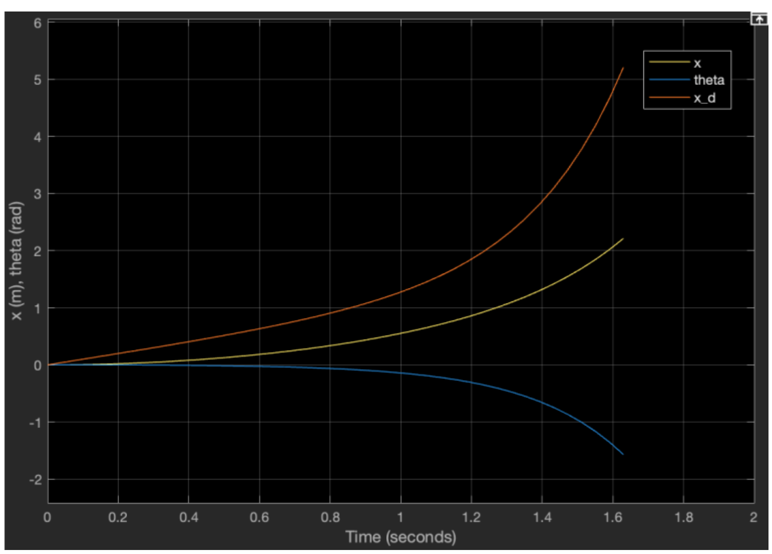

Figure 10: Simulink Plot F(t) = 90 N

Concluding the system response modeled using Simulink, the range of input values 65 N – 85 N is where the handlebar is balanced, and the wheelbase moves forward for a period of time before the user has fallen.

4.2 SimulationX Results

4.2.3 Initial Testing of the SimulationX Model

After the development of the SimulationX Model described in Section 3.5 SimulationX Design, the optimal values from the Simulink model (discussed in section 4.1.2 Observations), were used for initial testing of the SimulationX Model. As θ had not been optimized in Simulink, an initial value of 15° was chosen for the model. The results of running the SimulationX model with the optimal Simulink values are shown in Figure 11 below.

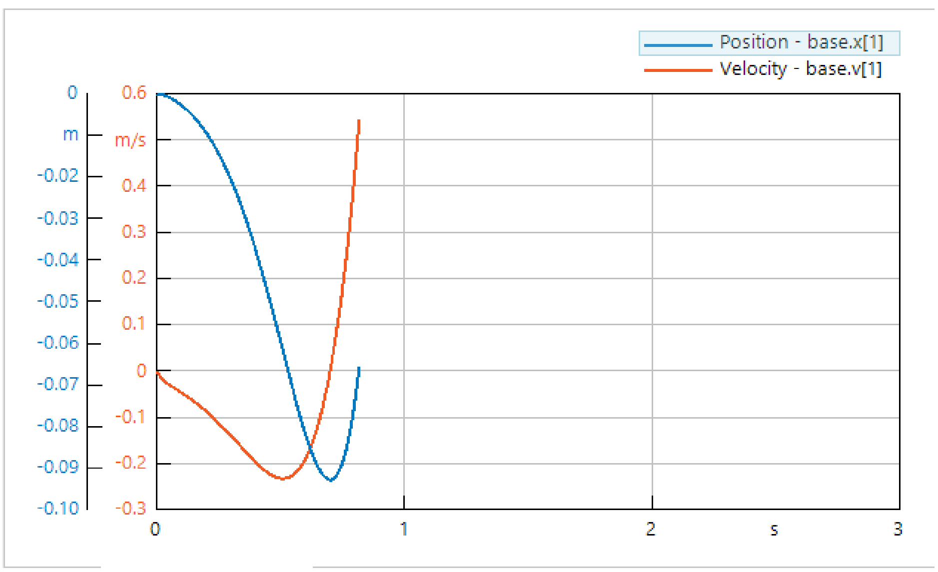

Figure 11: SimulationX Model with Initial Unoptimized Values for Variables

From Figure 11, it was determined that a larger initial F_t would be required to optimize for distance travelled. With the optimal Simulink values, there wasn't enough force to propel the segway forward, and resulted in the user simply falling due to the initial Inertia. Additionally, from Figure 11, the max velocity the segway reached was about 0.6 m/s, meaning that there was room for F_t to be increased without breaking the speed limit of 20 km/h (5.56 m/s).

4.2.2 Optimization of SimulationX Model

To optimize the distance that the user travels on the segway, θ, β, and F_t were all varied. It was noted that as the angle β decreased, it would directly increase the final distance of the user. The motivation behind this decision was a result of the simulation termination logic. The termination condition is when $(\theta + \beta) > \frac{\pi}{2}$ or, in words, when the handlebar hits the ground. Based on this logic, the smaller the β value, the longer before the simulation terminates. A value of $\beta = 0.01\ rad$ was chosen and held constant through the optimization of θ and F_t.

Table 55: Variants Wizard Optimizations

Testing Iteration	Range of θ (rad)	Incrementation Step Size θ (rad)	Range of Ft (N)	Incrementation Step Size Ft (N)	Max Distance with an Allowable Speed
1	[0.1:0.3]	0.01	[250:310]	5	4.45372 m
2	$\theta = 0.24$	n/a	[290:300]	0.01	5.1761 m

The Variants Wizard in SimulationX was used to optimize θ and F_t. Table 55 shows the different iterations of optimizations ran using the Variants Wizard. The first iteration was used to find a θ value that could be held constant so the input force could be fine-tuned. $\theta = 0.24\ rad$ was chosen as it yields the furthest distance in the first iteration data with a speed less than 5.55 m/s (20 km/h). The results of this test are displayed in Figure 1212 with the maximum allowable speed line as the constraint. The chosen point that yields the maximum distance from this test is labeled on the graph. This point yielded an input force of $\approx 300\ N$ with an increasing distance as the F_t decreased. This led to the determination of our next iteration range of [290:300].

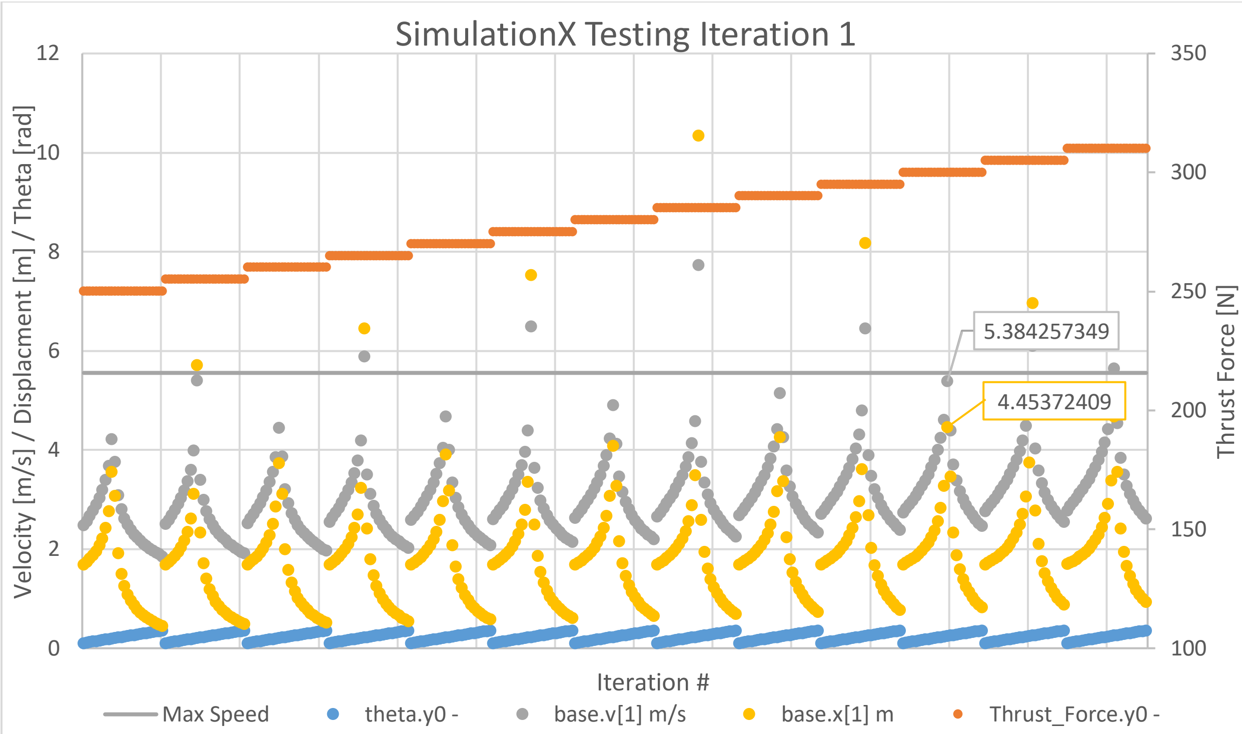

Figure 1212: SimulationX Testing Iteration 1

For the second iteration, $\theta = 0.24\ rad$ was held constant and the input force (Ft) was varied to optimize the distance and, in turn, bring the speed closer to 5.55 m/s (20 km/h). The labelled point in Figure 1313 yields the greatest distance while staying below the speed limit. This point yields an input force of 294.4 N.

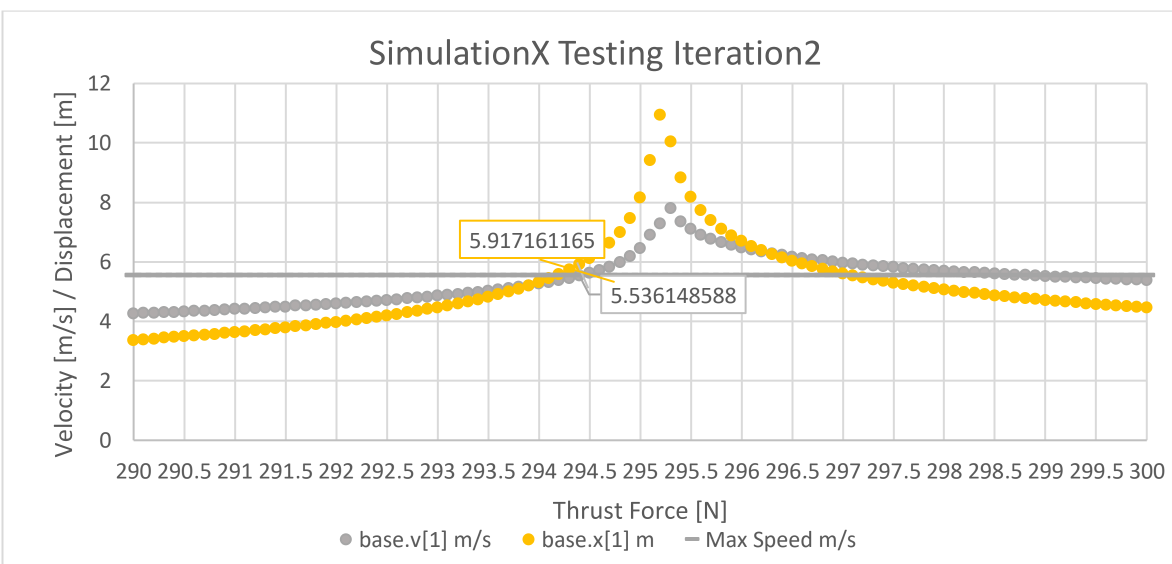

Figure 1313: SimulationX Testing Iteration2

To further verify that a smaller β value yields a greater final distance, a final test using the Variants Wizard was carried out. Figure 1414 shows a decreasing function where distance is a function of β and increases the closer β is to $0°$.

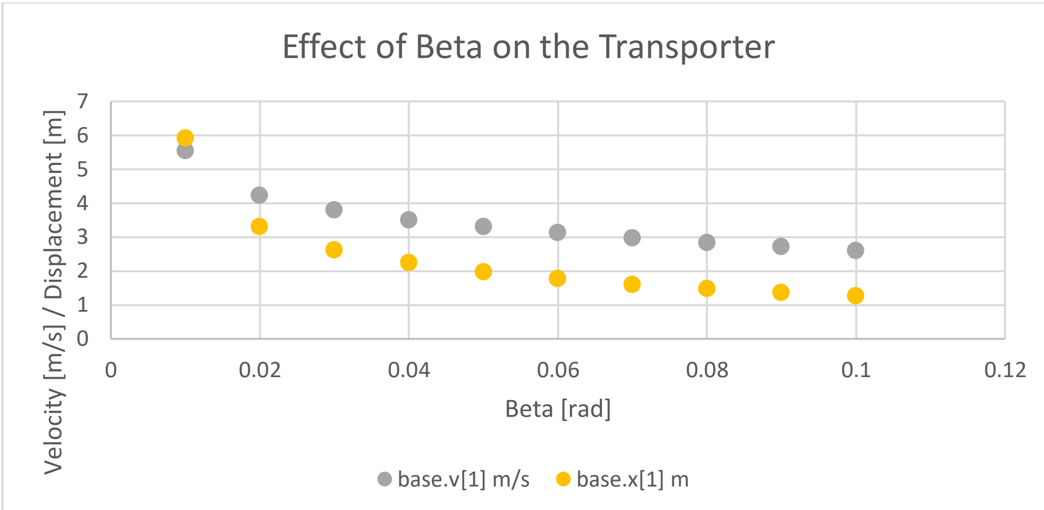

Figure 1414: Effect of Beta on the Transporter

4.3 Comparison of Simulink Model and SimulationX Model

To compare the Simulink and SimulationX models, the optimized SimulationX values ($\beta = 0.01\ rad$ and $F_t = 294.4\ N$) were used in the Simulink model. Figure 1515 shows the results of the Simulink after the SimulationX values were substituted into the model. The observed behaviour is that the segway falls backward, ($\theta < 0$) pushing the base forward ($x > 0$) while simultaneously breaking the speed limit. This is a result of an input force that is larger than the observed forces noted in the original Simulink experiments: 4.1.2 Observations. Both the SimulationX and Simulink models have very different acceptable input forces, and this is likely due to the system that they are modelling and how they model those systems. Simulink is modelling a linearized version of the equations of motion that don't reflect the entirety of the system. On the other hand, SimulationX considers many more variables by modelling the entire acausal system as a physical network. In Figure 16, the final optimized results from SimulationX that the segway behaves as expected with the distance the distance, velocity, and the user angle all increasing until the user has fallen.

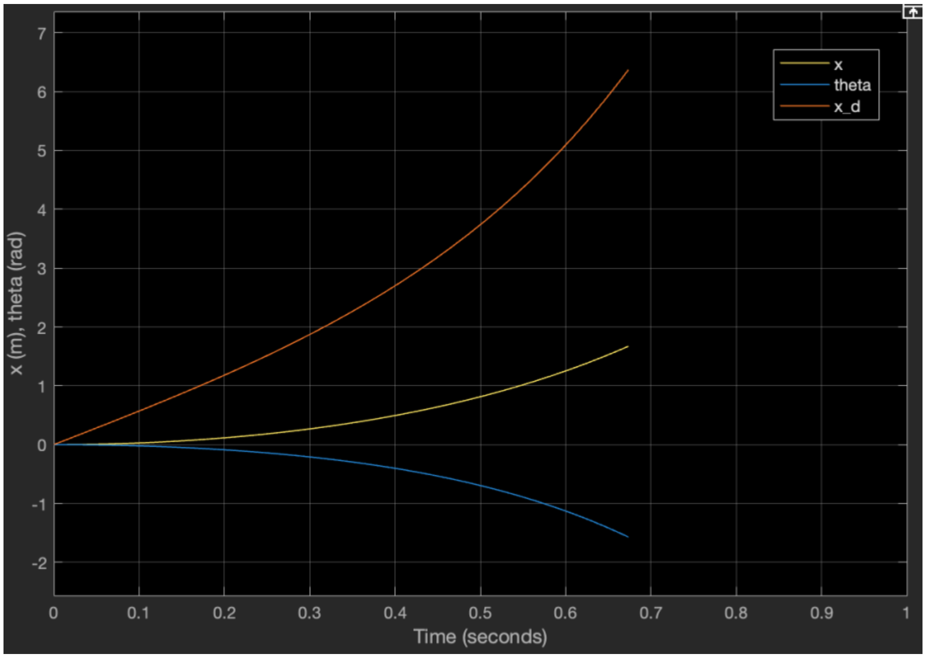

Figure 1515: Simulink with SimulationX values

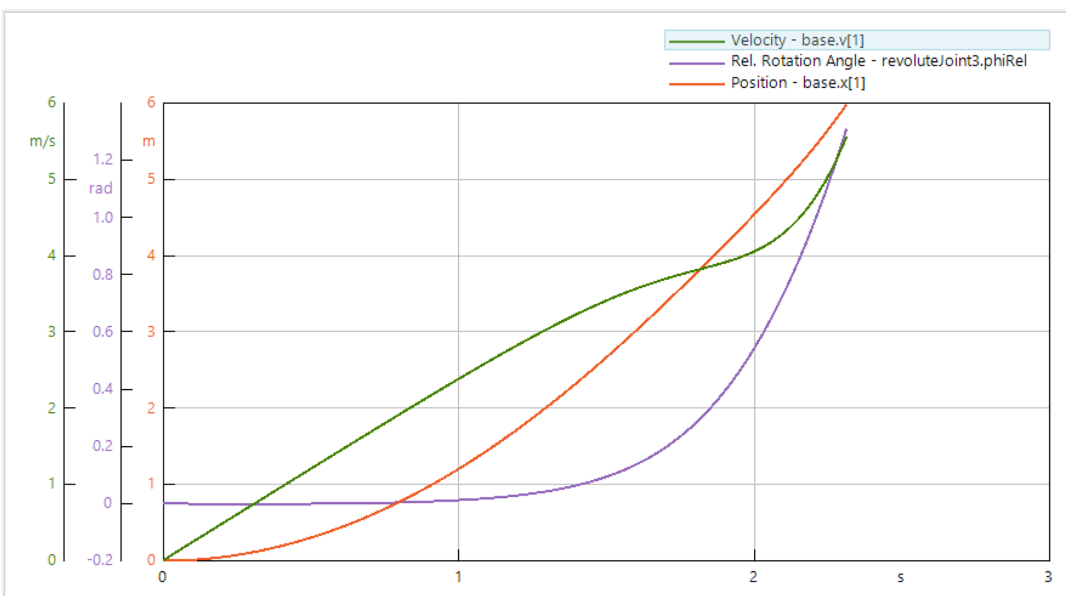

Figure 16: Final Optimized SmulationX

5 Conclusions and Recommendations

Throughout this project the forward motion of a two wheeled personal human transporter was studied. This was completed over a total of three steps with an analytical, numerical, and experimental model. The 2D free body diagrams and kinetic diagrams of the system were drawn to understand the kinetic behavior of the transporter. From these diagrams the two general equations of motion required to solve the remaining aspects of the system were derived. The output parameters of the two functions were the displacement of the transporter (*x*) and the tilt angle of the base (θ).

To numerically solve the forward motion of the system, the two general equations of motion were linearized using small angle approximation. With the linearized system, equations for $\ddot{\theta}$ and $\ddot{x}$ were derived, and the corresponding block diagram was entered into Simulink. By running the linear block diagram in this software, the approximated behavior of the forward motion of the transporter was modeled. After initial tuning it was identified that with a tilt angle β equal to 5° the ideal input thrust force was 82 N. As an additional task, the state variable model from the linearized equations was found, although this had no further input to the project.

The experimental model of the human transporter was created using the MBS Mechanics (3D) library in SimulationX. A rudimentary visual representation of the vehicle and human were modeled with cuboid, and cylinder blocks. The proper rotation and translation of the system was achieved with the use of revolute and prismatic joints allowing for the correct degree of freedom of motion of the transporter. Three test iterations using the variants wizard were performed when tuning the input thrust force F_T, initial transporter tilt θ, and user tilt β. The first iteration confirmed that the smaller the user tilt angle, the greater the displacement of the system. From this observation a user tilt angle of 5.73° (0.1 radians) was selected. The second test was performed to identify the ideal initial tilt of the transporter. Ranging from 0.1 to 0.3 radians, it was observed that the maximum displacement that adhered to the 20 km/h speed limit occurred at 13.75° (0.24 radians). The final test completed to determine the ideal input thrust force. It was observed that at an initial tilt angle of 13.75°, the maximum displacement was occurring between 290-300N. Running the simulation within this range, it was found that the maximum displacement occurred at 294.4N. In conclusion, the final displacement of the human transporter after tuning was determined to be 5.1761m.

5.1 Test Conclusions

To further increase the accuracy of the simulation it is recommended that the physical SimulationX model be further developed to better represent a real-life transporter. In this project the cuboid block used for the base did not rotate with the human and rather stayed parallel with the ground. To better simulate the segway, the base should rotate with the handlebars and the human. Additionally for ease of modeling the system, the handlebars were fixed to the center of the segway base. This would have ideally been fixed to the front edge of the base in front of the user.

5.2 Recommendations

To allow the simulated transporter to stay upright it is recommended that a controller be implemented in the system. This would behave similarly to the Segway solution outlined in section 2

Background. The input thrust force from the electric motors must be variable based on a feedback loop from the tilt angle of the transporter. As the user leans forward, the thrust force must increase to counteract this lean and keep the user upright. In addition, there must be a controller that can limit the speed of the device. This will vary the input force to maintain rotational stability, while also adhering to the desired maximum speed that is possibly attainable by the vehicle. While proper operation of a marketable product will certainly require a much more complex control system, implementing a variable force based on the handlebar position is a good starting point.

7 References

[1] "Dicycle," Wikipedia, 3 2025 February. [Online]. Available: https://en.wikipedia.org/wiki/Dicycle. [Accessed 10 March 2025].

[2] T. Harris, "How Segways Work," How Stuff Works, [Online]. Available: https://science.howstuffworks.com/transport/engines-equipment/ginger.htm. [Accessed 10 March 2025].