ME 5659 Term Project Part I

Due: See Gradescope.

In this project, we will develop and test various controllers for the Segway vehicle depicted in Figure 1. Students will use the fundamental tools covered in the course, such as stability analysis, root locus design, frequency response tools, as well as state space techniques. Furthermore, students will use MATLAB/SIMULINK, and a symbolic manipulation software such as MATLAB, MAPLE, or MATHEMATICA. Some of the numerical values are to be chosen by the students based on the last digit of their NUID number and some others are free to chose. Unless you can justify the need, please do not ignore any parameters in the analysis. If you are more comfortable with the US customary units, please feel free to adopt them in your work.

On the Segway, there are two DC servo motors where each one powers one of the wheels. The controllers that are responsible to command these motors need the measurements $\dot{\theta}$ and θ in order to adjust those commands, and these measurements here are assumed to be available.

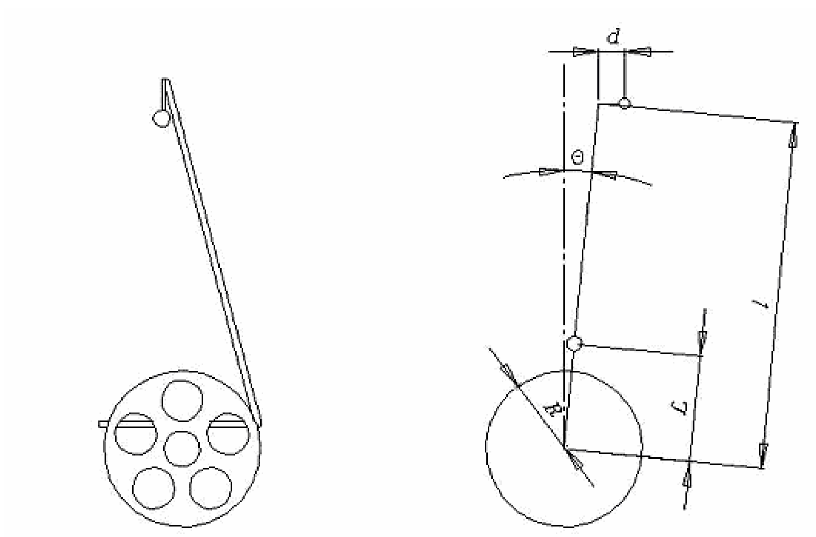

Figure 1: Segway vehicle with critical dimensions.

Governing dynamics along with some simplifying assumptions are given as follows:

$$\sum M_o = J\ddot{\theta}(t) = MgL\theta(t) + mg\ell\theta(t) - T - c_1\dot{\theta}(t) + mgd, \tag{1}$$

$$\sum F_x = (M+m)\ddot{x}(t) = \frac{T}{R} - c_2\dot{x}(t), \tag{2}$$

where

$$\sin(\theta) \approx \theta, \tag{3}$$

$$T = \alpha V - \beta\dot{x}, \tag{4}$$

$$\alpha = \frac{k_T}{r_a}, \tag{5}$$

$$\beta = \frac{k_T k_{bemf}}{R r_a}. \tag{6}$$

Table 1: Nomenclature.

$\theta(t)$, platform deviation from vertical
$x(t)$, Horizontal displacement of Segway vehicle
R, wheel radius*
L, distance from wheel centerline to center of mass*
ℓ, distance from wheel centerline to rider (load) mass*
d, $[m]$, horizontal displacement of rider (load) mass
J, moment of inertia related to all the mass rotating around the wheels (to be calculated)
α, motor constant
β, motor constant
M, system (vehicle) mass*
m, rider (load) mass*
T, motor torque
k_T $[Nm/A]$, torque constant*
k_{bemf} $[V \cdot sec]$, back emf constant*
r_a $[\Omega]$, armature resistance*
V, motor voltage
$c_1 = 0.1$, rotational damping with appropriate units
$c_2 = 0.1$, linear damping with appropriate units
$g = 9.81\, m/sec^2$, gravitational acceleration.

Simplification of governing dynamics yields,

$$\ddot{\theta}(t) = \frac{MgL + mg\ell}{J}\theta(t) + \frac{\beta}{J}\dot{x}(t) - \frac{\alpha}{J}V + \frac{mg}{J}d - \frac{c_1}{J}\dot{\theta}(t), \tag{7}$$

$$\ddot{x}(t) = \frac{\alpha}{R(M+m)}V - \frac{\beta/R + c_2}{M+m}\dot{x}(t). \tag{8}$$

Important: Before you begin, please read this:

(a) Please see Canvas/Modules/Project Part 1 for the numerical values you will need to use for this project. Each student's NUID number will determine which numerical values the student must use. We will carefully check this while grading. When submitting your project by email, please make sure you insert your NUID number on the cover sheet of your project.

(b) Please do NOT copy the numerical choices from someone else. Please follow Step (a) carefully. Projects that do not follow (a) will not be graded.

(c) Please solve all the questions on your own. The work must be 100% your own/creative work. Do NOT share, email, show your software codes and handwritten notes. If you want to help someone, you can still help them without showing your own work. If students are found to copy from each other, all students will be held responsible including the student(s) who actually solved the question(s).

(d) If you got help, and/or discussed with, or solved some part of the problems together with a student or students, you must list these students' names on your project report. If you did not collaborate with anyone, then you must state this in your report. If this information is missing we will NOT grade the project.

(e) All the work must be merged into a single PDF file and submitted to Gradescope. This file should include all possible details for a convincing argument that you have solved the steps by applying course materials. Please make sure you include screenshots of your code, your plots, derivations, etc. Separately, please ZIP all the original software codes and email them to our grader Uday by Project Part 1 deadline (see Gradescope). Sufficient detail and discussion must be provided to demonstrate that the material has been properly learned. Correct results without any explanation/justification will not earn points.

Tasks to be completed:

1. Find the Laplace representations of the outputs $\theta(t)$ and $\dot{x}(t)$ in terms of both voltage input V and disturbance d.
2. Analyze the stability of the outputs found in the previous step.
3. Since the sensors on the vehicle can measure only θ and $\dot{\theta}$, the state $\dot{x}$ is not available. Without using $\dot{x}$ in the control design, construct a controller using θ, $\dot{\theta}$ and integral of θ for stabilizing the output $\theta(t)$ around the vertical (i.e., you are designing a PID controller). This PID controller regulates the voltage inputs to the motor. Using Routh's array, find a set of controller gains k_p, k_I and k_D with which $\theta(t)$ is asymptotically stable.
4. With the PID gains found in Step 3, show whether or not $\dot{x}$ is stable.
5. Using Root Locus analysis, tune either one of the PID controller gains in Step 3, such that system's settling time is reduced as determined by dominant poles.
6. Simulate the time domain behavior of $\theta(t)$ and $\dot{x}(t)$ with the implemented PID controller at Step 3 and assuming the following conditions separately hold: (i) the disturbance is a unit impulse, (ii) the rider leans forward and keeps a constant disturbance d.
7. Assume that the motor can deliver only ∓ 15 Volts. Connect a 'saturation block' to the output of your controller in your simulation and compare Segway's responses with those in Step 6. Use the PID design from Step 3 for this analysis.

Distribution of points: Each step has the same points. Once Part II of the project is assigned, the total number of steps assigned in Part I and Part II will determine the point of each step over a total of 100 pts.

Any evidence of copying from someone else's work will be penalized in accordance with the policies in NU Student Handbook.