|  |
| --- |
| Constrained and Unconstrained Non-Linear Control RTGC with DC Motor Based on Sliding Mode Controller  Cristian MP Napitupulu1 Steven Bandong2 Yul Yunazwin Nazaruddin3  1 Engineering Physics Program, Faculty of Industrial Technology,  Institut Teknologi Bandung, Bandung, (40132), Indonesia (13319004@mahasiswa.itb.ac.id)  2 Engineering Physics Doctoral Program, Faculty of Industrial Technology,  Institut Teknologi Bandung, Bandung, (40132), Indonesia (bandong.steven@gmail.com)  3 Instrumentation and Control Research Group, Department of Engineering Physics,  Institut Teknologi Bandung, Bandung, (40132), Indonesia (yul@itb.ac.id) \* Corresponding author |
| **Abstract:** The increasing exchange of goods between countries and continents necessitates efficient transportation facilities, with cargo seaports playing a vital role. Within each cargo seaport, the Rubber Tyred Gantry Crane (RTGC) is a crucial heavy equipment that requires automation to handle heavy cargo traffic and eliminate bottlenecks. Although linear control methods are commonly employed to address this issue, the system behavior is inherently nonlinear. This paper focuses on designing a non-linear control method, namely the Sliding Mode Controller (SMC), to effectively control the position, cable length, and sway of the gantry crane system. Two DC motors are used as actuators for controlling the trolley position and cable length, which hoist the container. The nonlinear gantry crane model, integrated with the nonlinear DC motor model, is elaborately derived. The designed non-linear SMC control law and sliding surface are then simulated to evaluate the control performance. The results demonstrate that the proposed method yields excellent control performance.  **Keywords:** Nonlinear control, Sliding mode control, Nonlinear DC motor, RTGC automation, Sway reduction |

1. INTRODUCTION

The rapid advances in communication technology in this century have brought about market development, enabling sellers and buyers to make deals in just a few minutes. The increasing number of transactions demands better transportation technology to efficiently deliver goods to consumers across countries and continents. Sea transportation remains the dominant means of distributing goods in containers [1], making technology in cargo seaports a crucial aspect. The Rubber Tyred Gantry Crane (RTGC) is heavy equipment used for loading and unloading containers at container yards. Improving automation in RTGC operations is a major concern, as manual operation may lead to accidents due to lack of experience, illness, or fatigue. Furthermore, the volume of container trade worldwide has increased fourfold since 2000 [2] demonstrating its rapid growth.

Automation on RTGC focuses on two main objectives: sway control and position control. The container needs to be quickly moved to the desired position with minimal sway at the destination, ensuring ease and accuracy of placement. Some researchers have attempted to solve this problem using methods such as PID-PD [3], fuzzy-PID [4], and Robust PID based on the H-infinite method [5]. Others have aimed to optimize controller parameters through techniques like particle swarm optimization, genetic algorithms, and others [6]. However, these methods still employ linear controllers despite the RTGC system being nonlinear [7]. Therefore, it is necessary to control the RTGC using nonlinear methods.

One of the nonlinear control methods famous for its robustness against parametric uncertainties or disturbances is the Sliding Mode Controller (SMC). SMC is well-suited to solve the RTGC control problem as RTGC also encounters parametric uncertainties due to variations in container mass or wind disturbances during the container loading or unloading process. SMC has also proven to be effective in solving various control problems, such as robotic manipulator control combined with fuzzy logic [8], which performs well despite model parameter variations, and DC motor control with modified switching control to reduce chattering effects [9]. SMC has also been applied to boost converter control in PV systems under fast-varying environmental conditions [10].

In this paper, SMC will be utilized to address MIMO control problems on RTGC. The control objective encompasses not only moving the container to the desired position and minimizing sway but also controlling the cable length. The control action will be carried out by two motors that directly affect the trolley position and the cable length. Consequently, the problem falls under the category of underactuated control since the sway is not directly influenced by the actuator. The paper also provides a detailed derivation of the gantry model, considering the nonlinearities of the DC motor. The design of the sliding surface and SMC control law, based on the nonlinear model of the DC motor and gantry crane, yields good control performance, which can aid researchers and practitioners in the future development of RTGC automation.

2. SYSTEM ANALYSIS

A RTGC with DC motor system can be modelled with two masses: a trolley and a container. Trolley () is attached to Motor with pulley and belt mechanism and container () is attached to Motor by a cable. Both belt and cable are assumed to be massless and non-elastic. Meanwhile, the DC motor can be modelled into two parts: electrical part (coil equivalent circuit) and mechanical part (rotator and pulley body).

Look at Figure 1 and Figure 2. In these two figures, the direction of the arrows indicates the direction when the variable is positive. The line N is the normal line that passes vertically through the center of mass of the trolley .

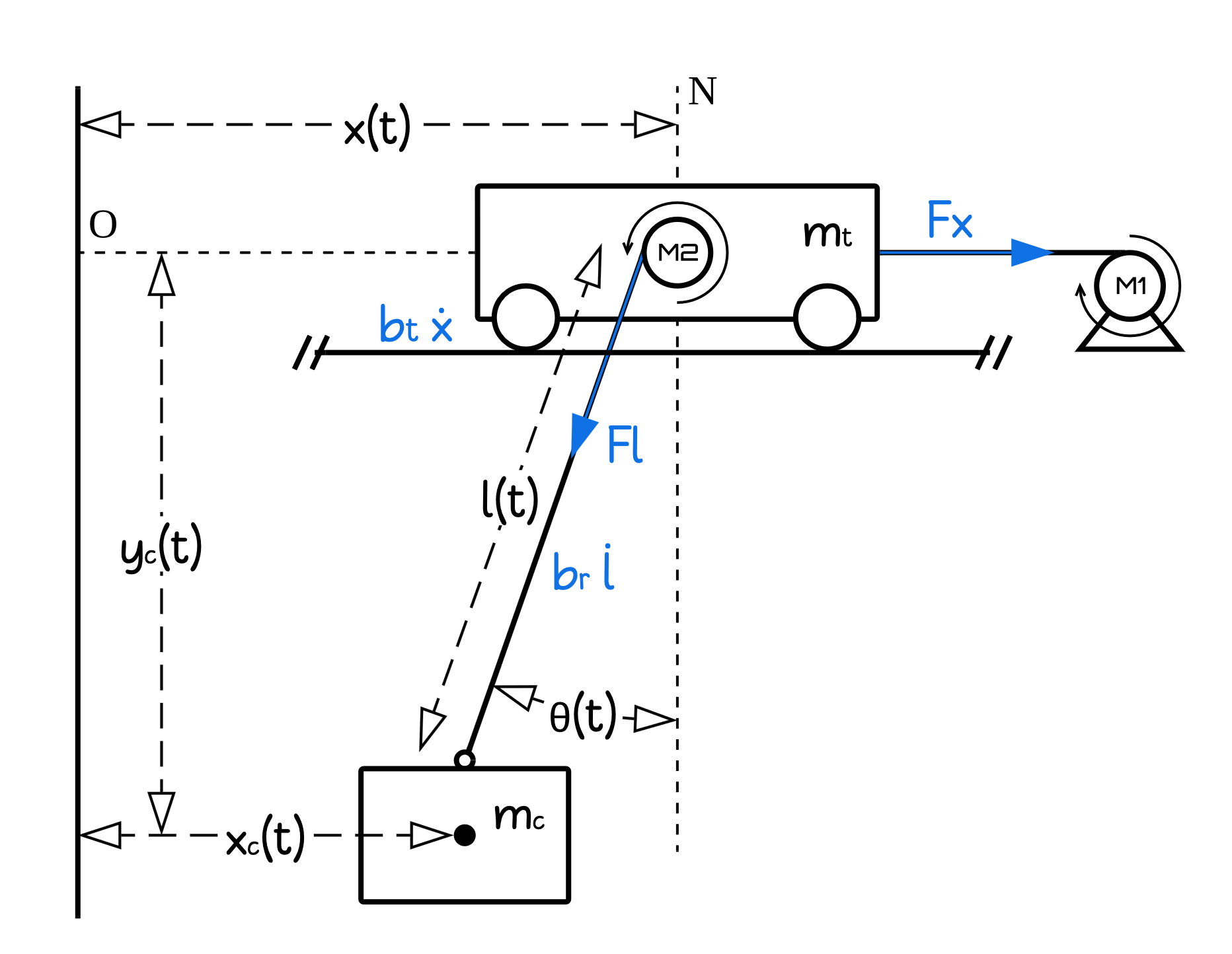


Figure RTGC with DC Motor System

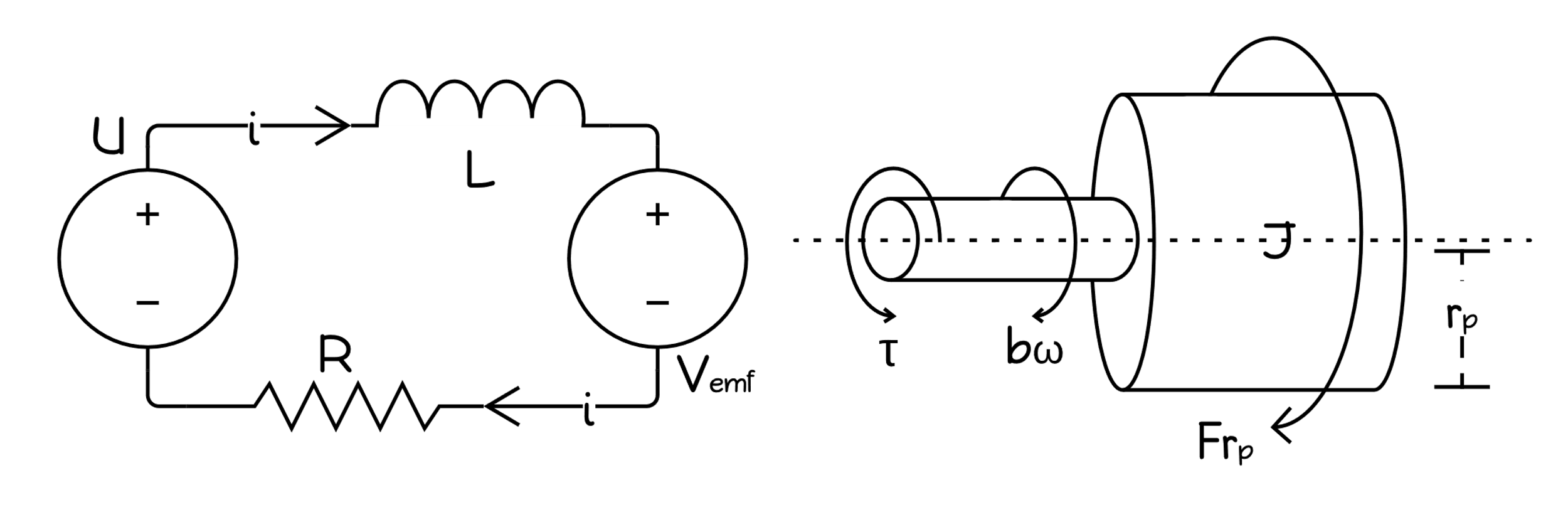


Figure DC Motor Model

The displacement of trolley denoted by and the displacement of container of container denoted by and . is the length of the cable and is the angle that is created by the cable and vertical line N while the container swaying freely along XY plane.

While active, motor and are generating torque and converted into force () via pulley (pulley radius ): and respectively. Both and control the movement of trolley and container. There are also damping forces that opposing the movement of each body with damping coefficient and . The motor also has angular damping with coefficient .

Each motor in the system ( and ) will have input voltage () and intrinsic parameters such as coil inductance (), coil resistance (), armature inertia (), angular damping coefficient (), back-EMF constant (), torque constant () and pulley radius () respectively.

3. SYSTEM DYNAMICS

To minimize writing, from now on will be written as , as , and as .

3.1 Gantry crane

For each body, , we can get their position (), speed (), kinetic energy (), and potential energy () as follows.

Trolley ():

|  |  |  |
| --- | --- | --- |
|  |  | () |
|  |  | () |
|  |  | () |
|  |  | () |

Container ():

|  |  |  |
| --- | --- | --- |
|  |  | () |
|  |  | () |

|  |  |  |
| --- | --- | --- |
|  |  | () |
|  |  | () |

From all kinetic and potential energy, we get Lagrangian as follows:

|  |  |  |
| --- | --- | --- |
|  |  | () |

Also, we can get Lagrange Equation for each coordinate , , and as follows:

|  |  |  |
| --- | --- | --- |
|  |  | () |
|  |  | () |
|  |  | () |

After substituting eqs. (3), (4), (7), (8) into eq. (9) and solve for for eqs. (10), (11), and (12) respectively, we will get these following equations:

|  |  |  |
| --- | --- | --- |
|  |  | () |
|  |  | () |
|  |  | () |

Rewrite eq. (15) to get as follows:

|  |  |  |
| --- | --- | --- |
|  |  | () |

Substitute eq. (16) into eq. (13) and we get:

|  |  |  |
| --- | --- | --- |
|  |  | () |

3.2 DC motor

From now on, symbol is not representing Lagrangian but the coil inductance of DC motor instead.

From Figure 2 we can get two equations:

|  |  |  |
| --- | --- | --- |
|  |  | () |
|  |  | () |

When the rotator of DC motor is rotating, magnetic field of the permanent magnet inside the stator will induces back-EMF in the coil that is proportional with the angular speed of rotator. Also, electric current inside the coil creates magnetic field that generate force while interacting with the magnetic field of permanent magnet inside the stator that will result in torque on the rotator. These relations can be written as:

|  |  |  |
| --- | --- | --- |
|  |  | () |
|  |  | () |

is the input voltage, is coil inductance, R is coil resistance, is the electric current inside the coil, is the back-EMF, is torque on rotator, is damping coefficient of the DC motor, is angular speed of rotator, is load force, is pulley radius, is inertia of rotator and pulley, is EMF constant, and is torque constant.

Substitute eq. (20) into eq. (18) and eq. (21) into eq. (19). Then, perform a Laplace transform on the resulting two equations to get:

|  |  |  |
| --- | --- | --- |
|  |  | () |
|  |  | () |

Substitute eq. (23) into eq. (22) and rewrite to get:

|  |  |  |
| --- | --- | --- |
|  |  | () |

On pulley, applies equation , where is tangential velocity of the pulley. Perform Laplace transform to that equation and solve for to get:

|  |  |  |
| --- | --- | --- |
|  |  | () |

Substitute eq. (25) into eq. (24) and perform inverse Laplace transform into resulting equation to get:

|  |  |  |
| --- | --- | --- |
|  |  | () |

3.3 Gantry crane and DC motor integration

For motor set , , , , , , , , and .

For motor set , , , , , , , , and .

Then, substitute eq. (14) and (17) into eq. (26) such that we get the following equations:

|  |  |  |
| --- | --- | --- |
|  |  | () |
|  |  | () |

Each for motor and respectively.

We can rewrite eq. (27) and (28) into matrix form as follows:

|  |  |  |
| --- | --- | --- |
|  |  | () |

Or:

|  |  |  |
| --- | --- | --- |
|  |  | () |

Rewrite eq. (30) into:

|  |  |  |
| --- | --- | --- |
|  |  | () |

Where:

4. SLIDING MODE CONTROLLER

The RTGC with DC motor system will have 3 main objectives: (1) get the container into certain position (), (2) hoist or lower the container (), and (3) make sure that the container not swaying too much.

To achieve this goal, we will set desired value and . From this desired value, we can get error functions for each parameter as follows:

For sliding mode control to work, we need to set sliding surface. For this system, we will choose sliding surface as follows:

|  |  |  |
| --- | --- | --- |
|  |  | () |

Where:

To get the control law , we need from eq. (32) as follows:

|  |  |  |
| --- | --- | --- |
|  |  | () |

Then, substitute eq. (31) into eq. (33) to get:

Set then solve for as follows:

For sliding mode controller, we also need a reaching mode () as the initialization step to guide the system onto the chosen sliding surface. For this system we will use sliding surface as follows:

Where and is a function that return the sign of every element of .

Finally, we get the full control law for non-linear RTGC with DC motor system as follows:

|  |  |  |
| --- | --- | --- |
|  |  | () |

5. RESULT AND DISCUSSION

To test the model and sliding mode controller performance, we will use 2 scenarios: unconstrained and constrained control law. Both scenarios will move the container from initial position to desired position and cable length . Initial and desired position are set so that we can see the control law action when moving the trolley () and hoisting the container simultaneously while maintaining the sway angle () as small as possible. The constrain value for the control law in constrained is scenario is which is a typical value for single celled Li-Po battery at fully charged to simulate real life problem. Other than that, the two scenarios will use the same set of parameters as follows:

Figure 3 to Figure 12 are showing all visualizations of the simulations. The first scenario, unconstrained control law, is shown in Figure 3 to Figure 7 and the second scenario, constrained control law, is shown in Figure 8 to Figure 12, in total 5 figures for each scenario. First three figures from each set of figures will show the and their respective rate of change and last two figures will show the control law and their own sliding surface .

For the first scenario we can see that SMC managed to make the system achieve the desired value and make sure that the sway angle and its settling time were as small as possible. The control law in Figure 6 seems to be trying to reduce the sway angle by oscillating its value. We can also see that , a few seconds before settling, has a negative value which means the container is oscillating to the right of the normal line N in Figure 1. This is caused by deceleration of the trolley as shown in Figure 3.

For the second scenario, unconstrained control law, control law also seems to be trying to reduce the sway angle by oscillating its value but and are clipped at as shown in Figure 11 and Figure 12. In Figure 9, the rate of change in the length of the cable is stuck at a value of so that the duration of hoisting the container becomes longer. This makes the performance of the sliding mode controller not as good as the unconstrained scenario. Even so, the system can still go to the desired value properly.

For both scenarios we can see that doesn't settle at 0 like did, but it does settle at around -3V. This is in accordance with our expectations where the motor must continue to be active to maintain the position of the container so it doesn't fall.

Even though both scenarios show good results, of course the unconstrained scenario’s result are better. As a form of quantification of the performance of the two scenarios, a performance table has been presented in Table 1. This table shows the rise time for and , settling time for , , and , as well as the RMSE of the three at steady state. Rise time is calculated as the time difference when and reach a value of 10% and 90% error at time . Settling time is calculated as the time required to have a stable value below 2% of the setpoint . For , because the value of is 0, a maximum error limit of 0.057 degrees (0.001 rads) is created. Then, RMSE at steady state is calculated since of , , and enter the steady state phase .

From Table 1 we can infer that the performance of Sliding Mode Controller in the unconstrained scenario is much better than the constrained scenario. Even though it has almost the same RMSE value, the rise time and settling time in the unconstrained scenario are much faster.

Table Sliding Mode Controller Performance for Each Scenario

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Variation | Displacement *(x)* | | | Rope length *(l)* | | | Swing angle *(θ)* | |
| Rise time *(s)* | Settling time *(s)* | RMSE *(m)* | Rise time *(s)* | Settling time *(s)* | RMSE *(m)* | Settling time *(s)* | RMSE *(degree)* |
| unconstrained | 2.2489 | 3.8636 | 0.0028 | 2.0566 | 4.0759 | 0.0038 | 4.8271 | 0.00822 |
| constrained | 6.3271 | 8.7158 | 0.0039 | 6.4337 | 8.7582 | 0.005 | 9.7526 | 0.01154 |

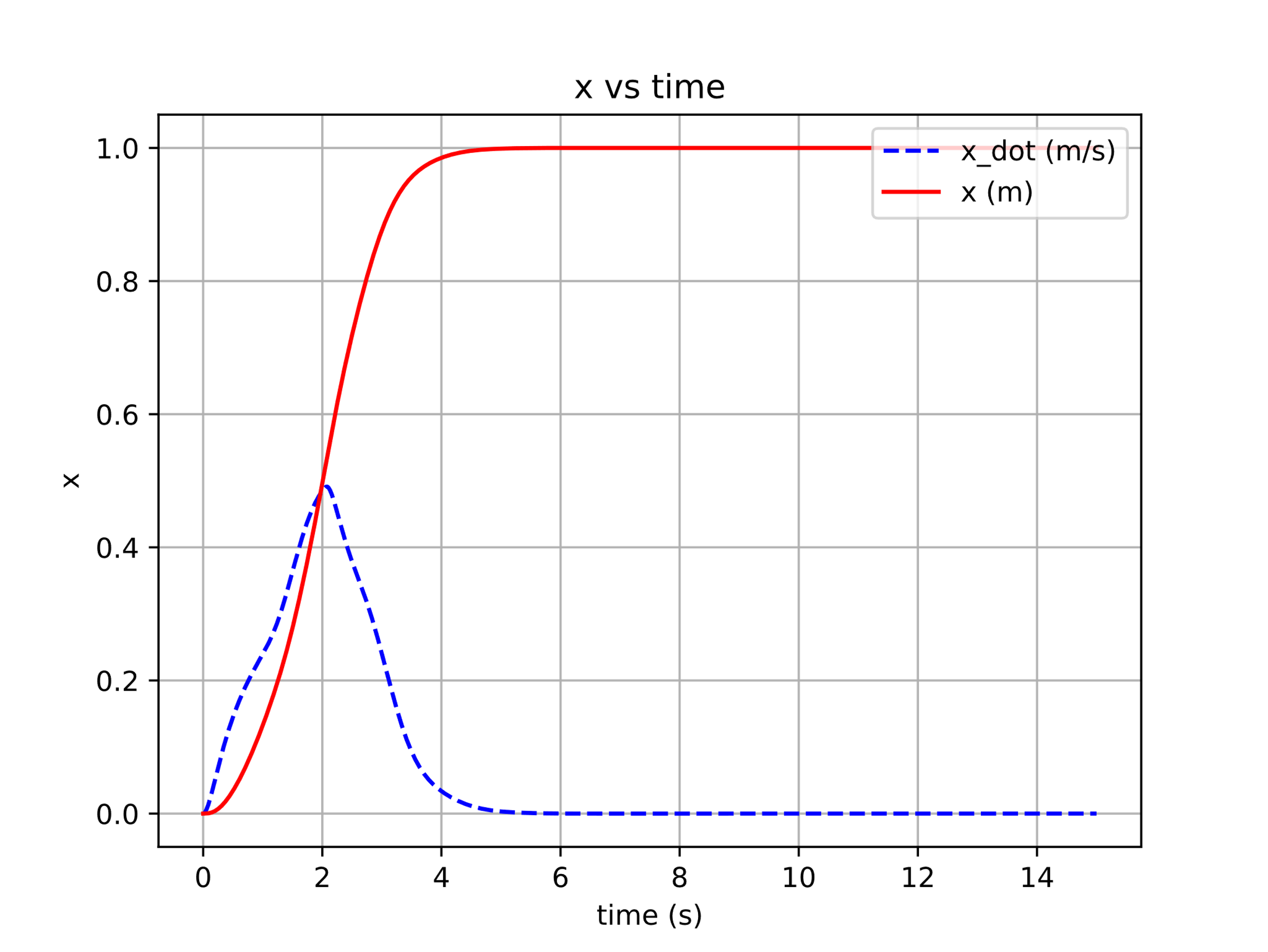


Figure Unconstrained x vs time

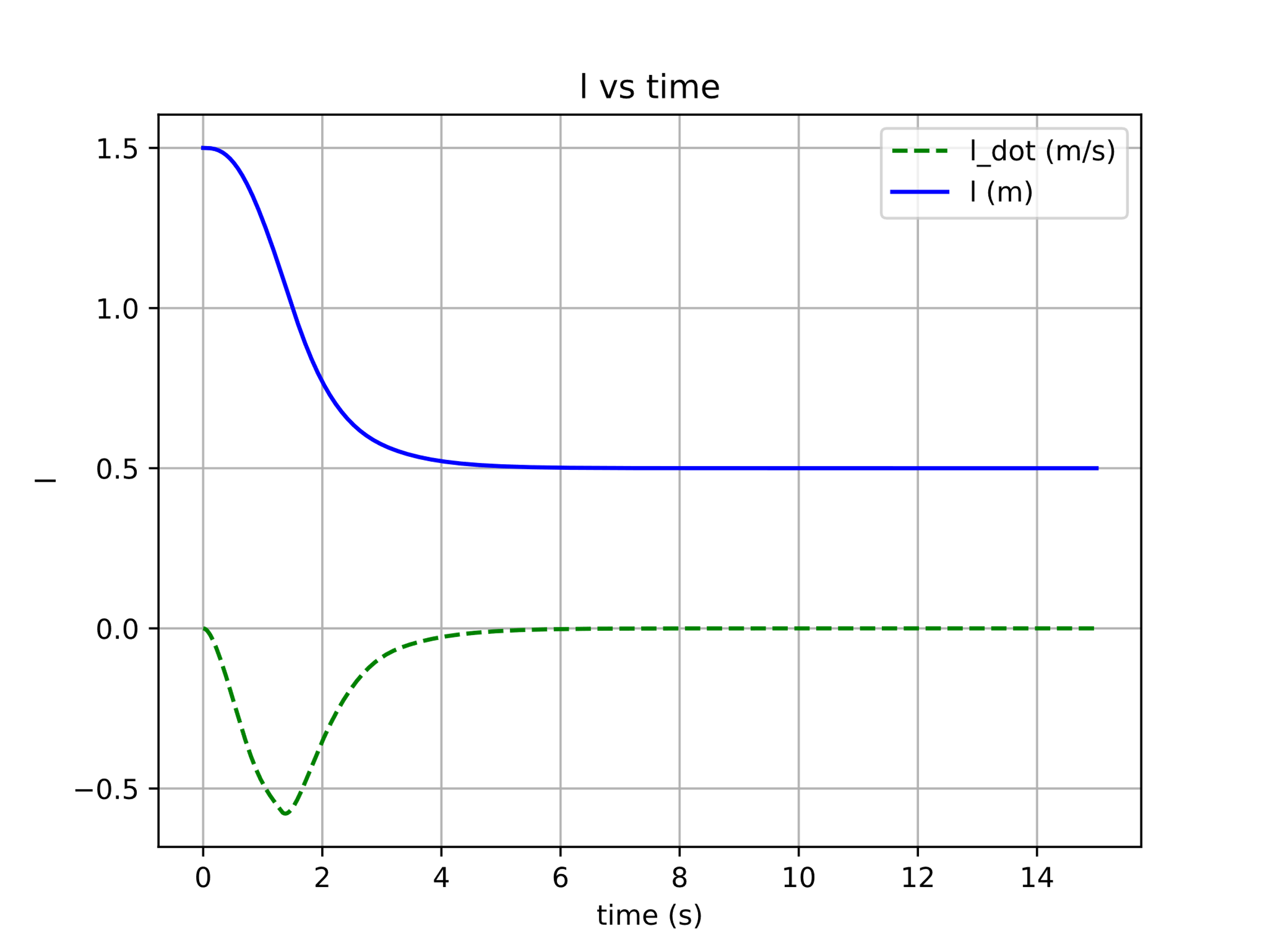


Figure Unconstrained l vs time

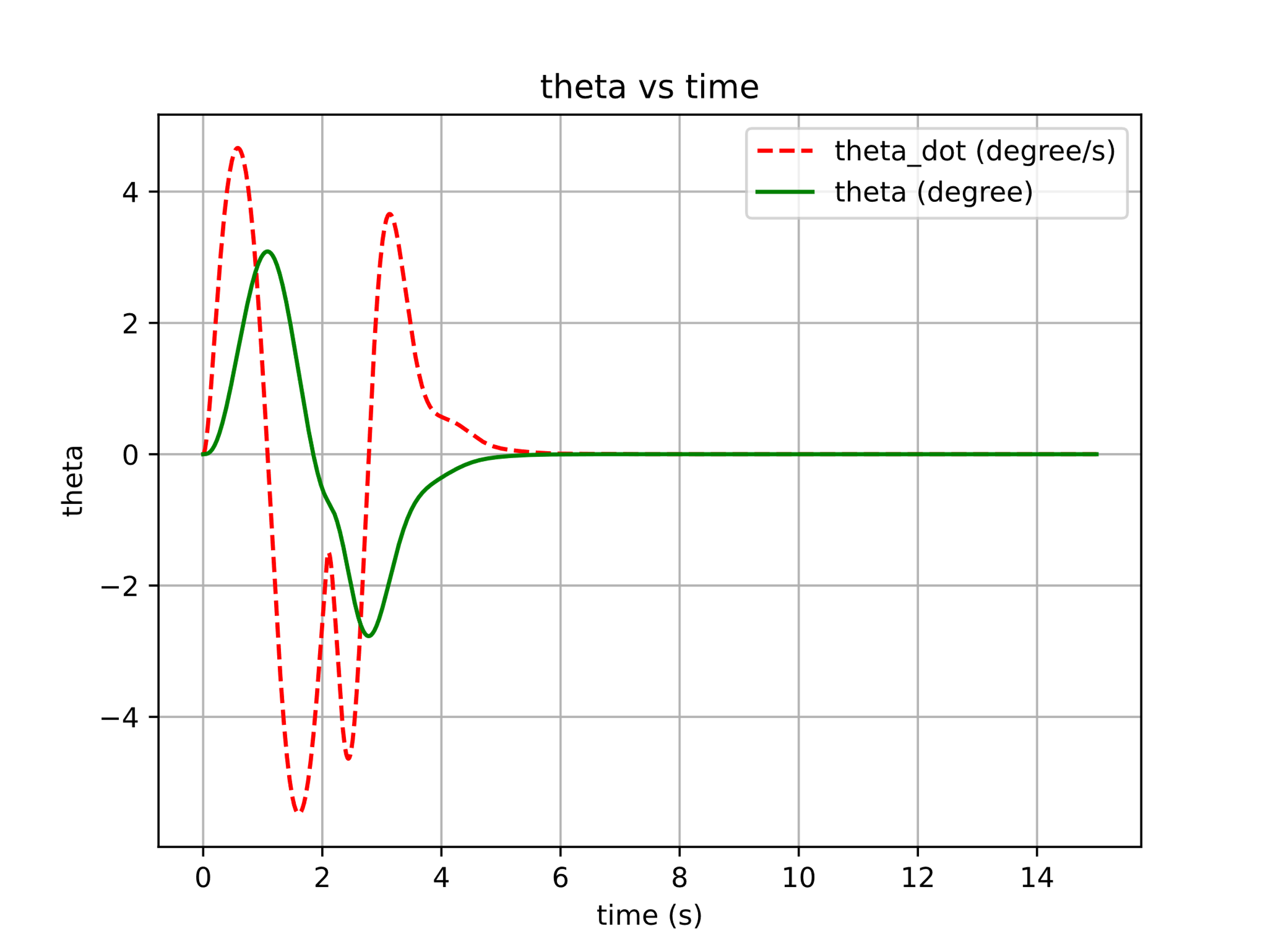


Figure Unconstrained theta vs time

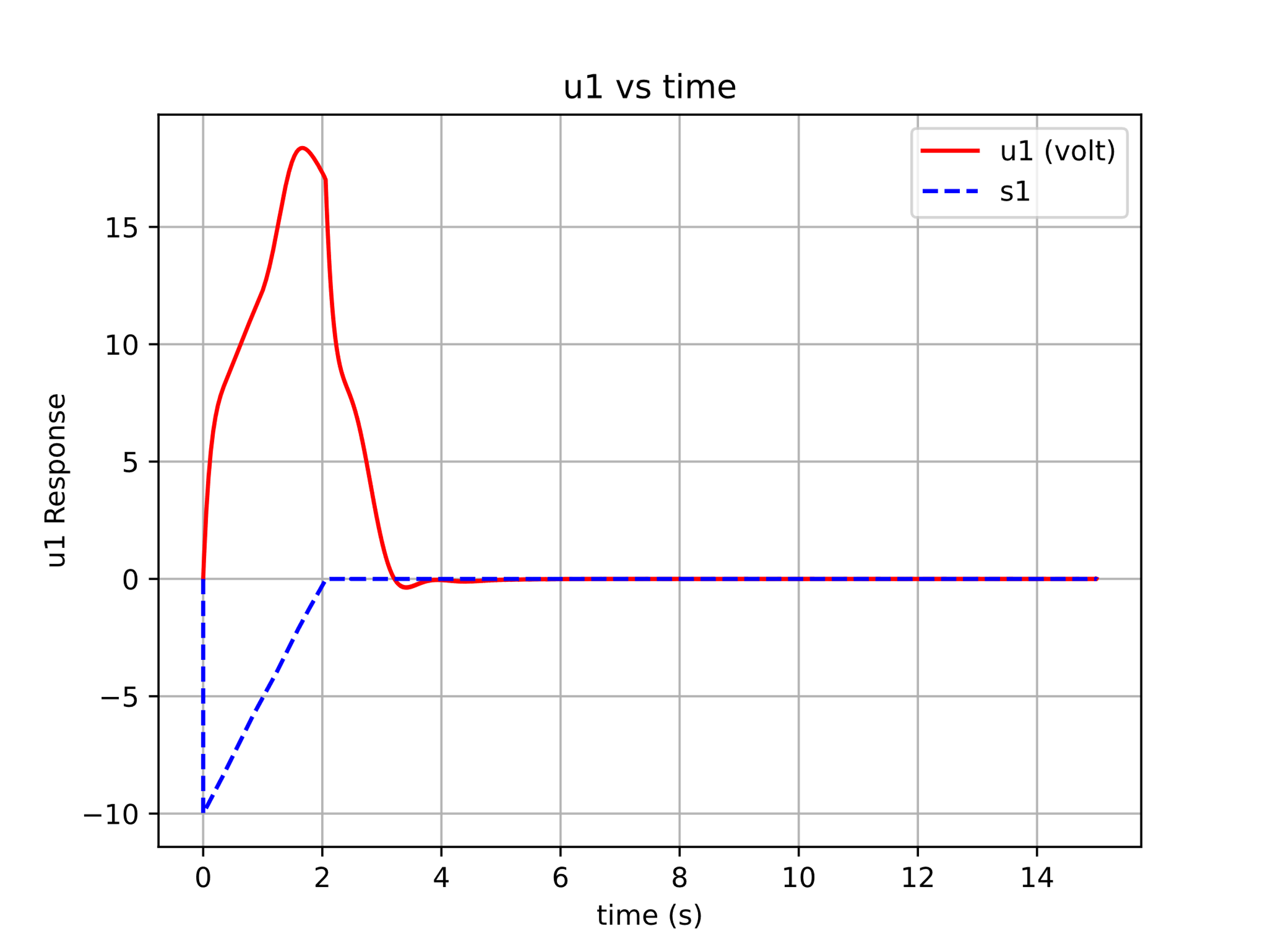


Figure Unconstrained U1 vs time

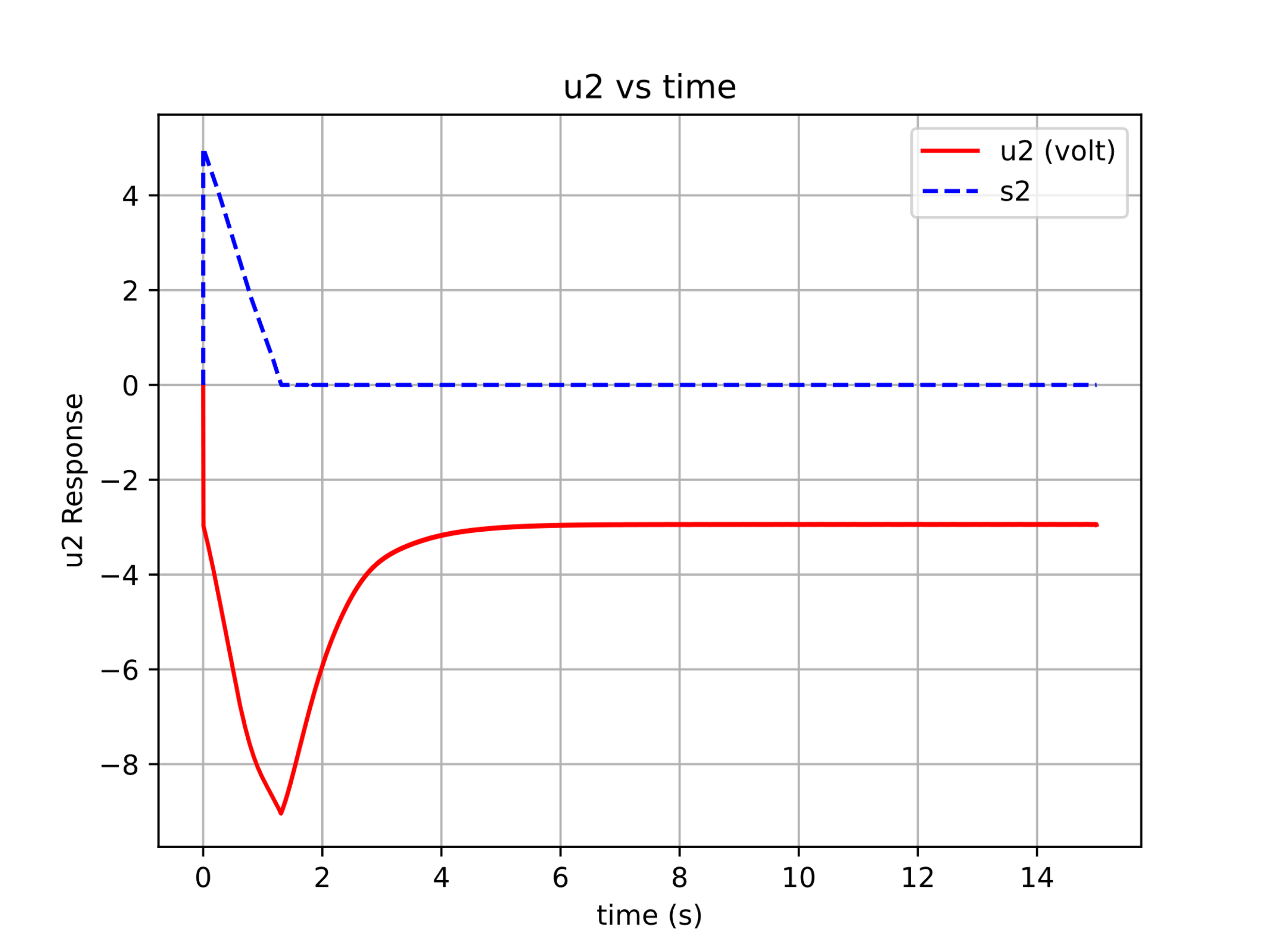


Figure Unconstrained U2 vs time

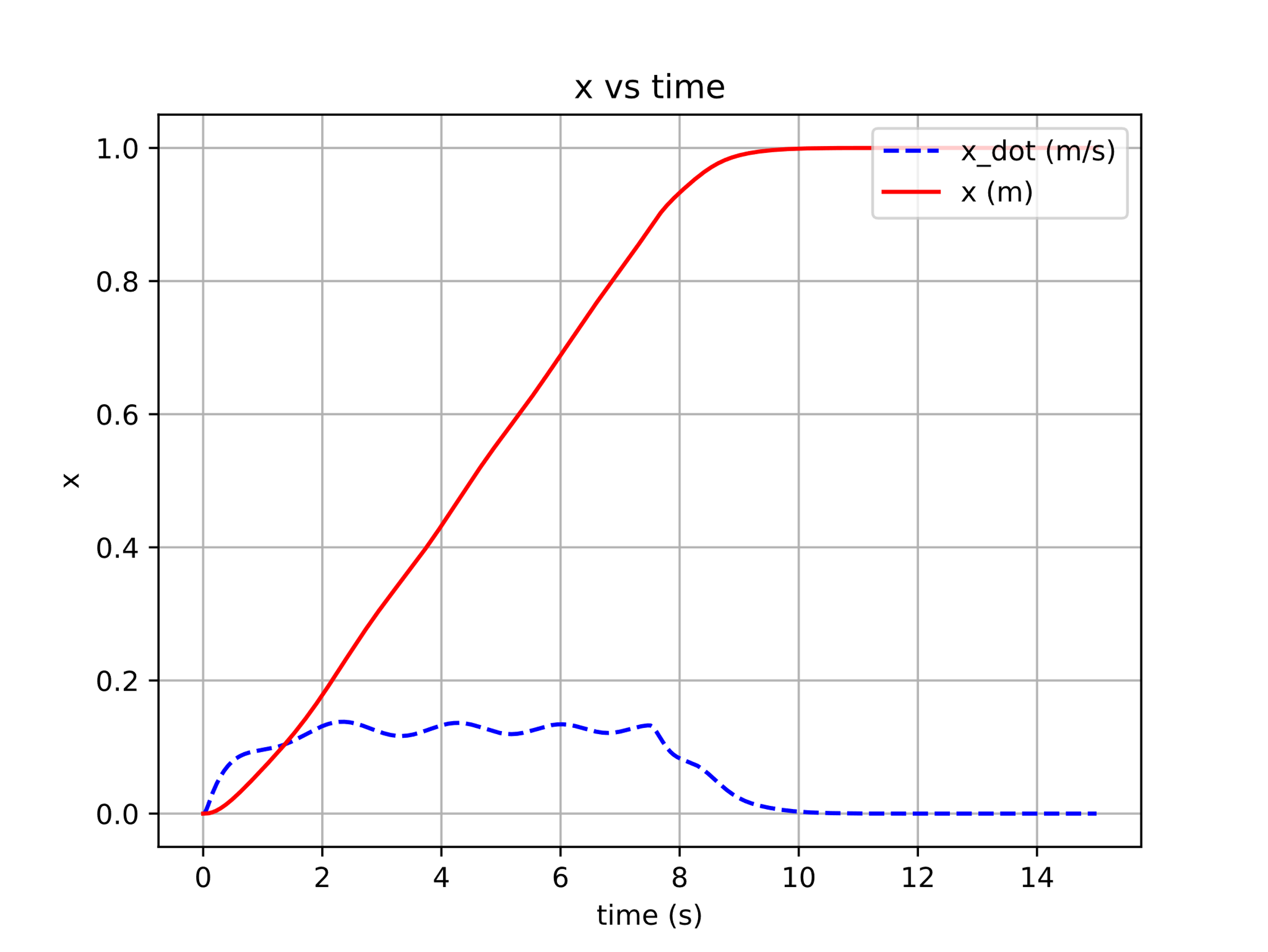


Figure Constrained x vs time

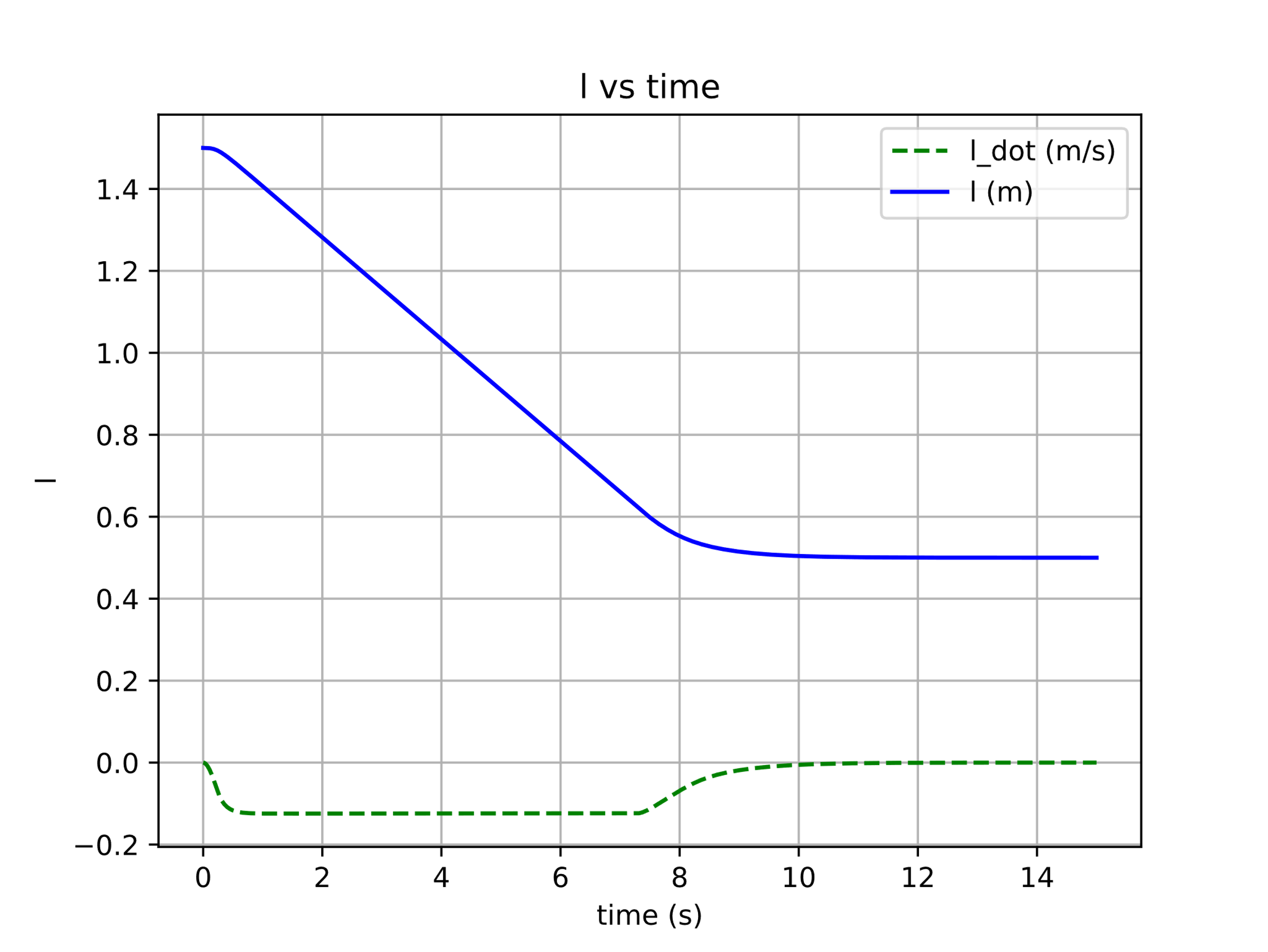


Figure Constrained l vs time

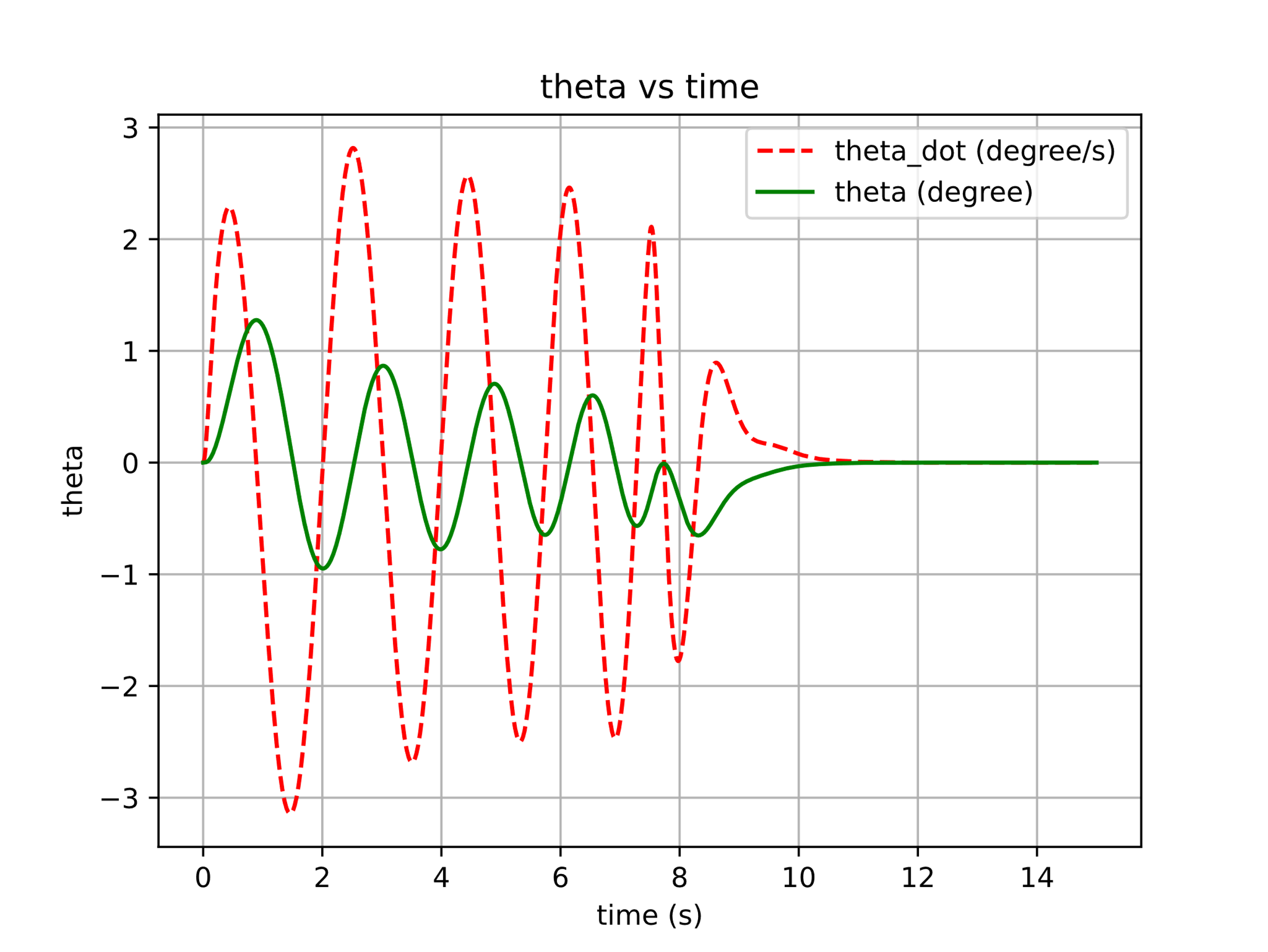


Figure Constrained theta vs time

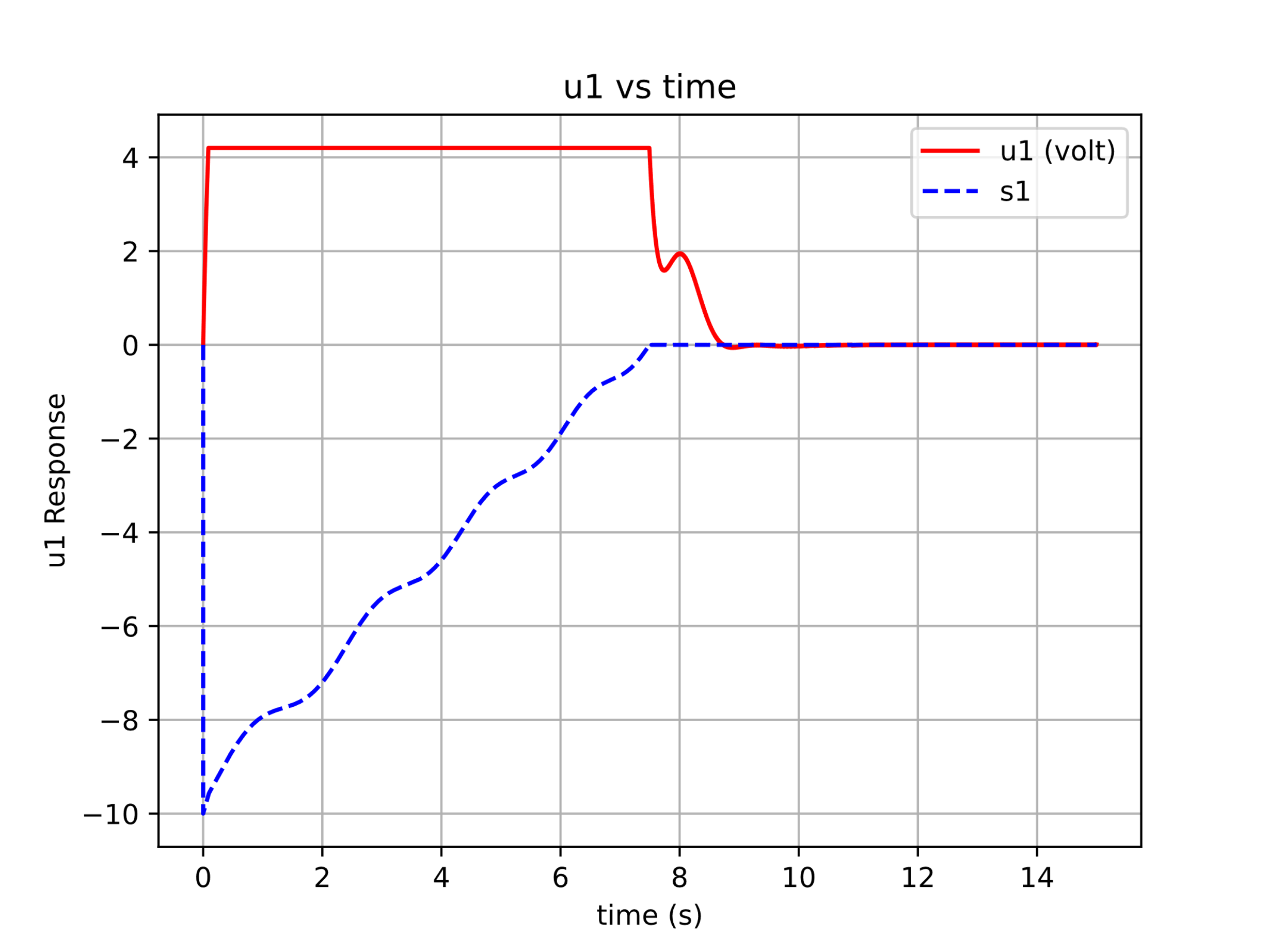


Figure Constrained U1 vs time

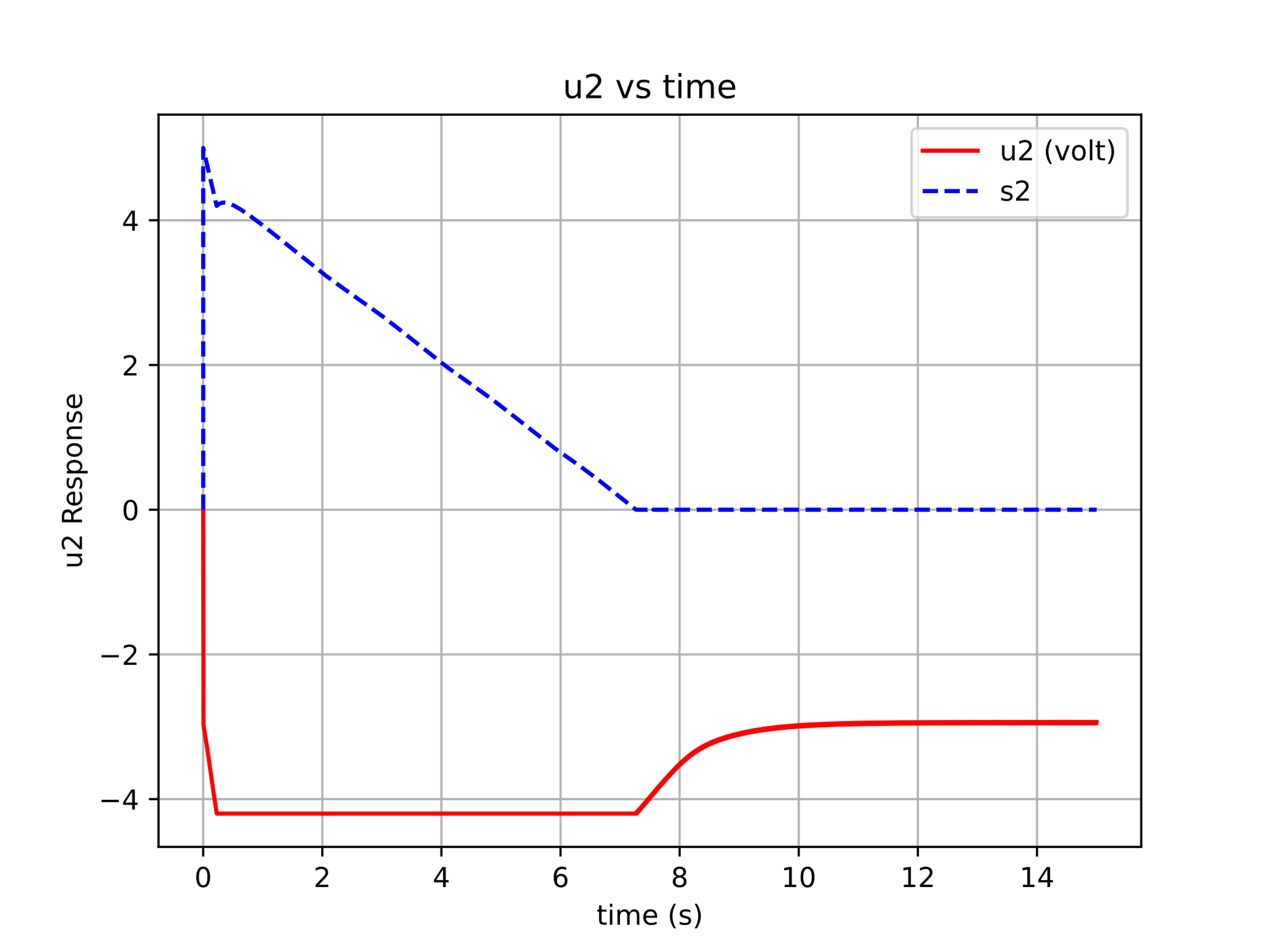


Figure Constrained U2 vs time

CONCLUSION

This paper concerns constrained and unconstrained sliding mode controller on RTGC with DC motor system. The RTGC with DC motor system has been modelled and the sliding mode controller has been designed. The system model and controller that have been designed have been simulated and provide results that are in line with scientific expectations. Of the two simulated control scenarios, the unconstrained scenario gives better results. This shows that the physical limitations of the system greatly affect the resulting performance. This limitation can be predicted using the model that has been made in this paper.

ACKNOWLEDGEMENTS

Akan diisi nanti...

REFERENCES

1. R. J. Sanchez, J. Hoffmann, A. Micco, G. V Pizzolitto, M. Sgut, and G. Wilmsmeier, “Port efficiency and international trade: port efficiency as a determinant of maritime transport costs,” Maritime economics & logistics, vol. 5, pp. 199–218, 2003.
2. 2023 The World Bank Group, “Container port traffic (TEU: 20-foot equivalent units),” https://data.worldbank.org/indicator/IS.SHP.GOOD.TU, Jun. 29, 2023.
3. S. Y. Syed Hussien, H. I. Jaafar, R. Ghazali, and N. R. Abdul Razif, “The effects of auto-tuned method in PID and PD control scheme for gantry crane system,” International Journal of Soft Computing and Engineering (IJSCE), vol. 4, no. 6, 2015.
4. F. Zheng, C. H. Yang, G. Hao, K. C. Wang, and H. L. Hong, “Vision-based fuzzy proportional–integral–derivative tracking control scheme for gantry crane system,” Sensors and Materials, vol. 33, no. 9, 2021, doi: 10.18494/SAM.2021.3403.
5. S. Bandong, Y. Y. Nazaruddin, and E. Joelianto, “Optimal RTGC Controller using Robust PID H∞ Integral-Backstepping under Payload Mass and Rope Length Uncertainties,” in 2022 17th International Conference on Control, Automation, Robotics and Vision (ICARCV), 2022, pp. 18–23.
6. S. Bandong, R. C. Kirana, Y. Y. Nazaruddin, and E. Joelianto, “Optimal Gantry Crane PID Controller Based on LQR with Prescribed Degree of Stability by Means of GA, PSO, and SA,” in 7th International Conference on Electric Vehicular Technology, ICEVT 2022 - Proceeding, 2022. doi: 10.1109/ICEVT55516.2022.9925018.
7. H. I. Jaafar, Z. Mohamed, J. J. Jamian, A. F. Z. Abidin, A. M. Kassim, and Z. A. Ghani, “Dynamic Behaviour of a Nonlinear Gantry Crane System,” Procedia Technology, vol. 11, 2013, doi: 10.1016/j.protcy.2013.12.211.
8. A. Ashagrie, A. O. Salau, and T. Weldcherkos, “Modeling and control of a 3-DOF articulated robotic manipulator using self-tuning fuzzy sliding mode controller,” Cogent Eng, vol. 8, no. 1, 2021, doi: 10.1080/23311916.2021.1950105.
9. A. Ma’arif and A. Çakan, “Simulation and arduino hardware implementation of dc motor control using sliding mode controller,” Journal of Robotics and Control (JRC), vol. 2, no. 6, 2021, doi: 10.18196/jrc.26140.
10. R. S. Inomoto, J. R. B. D. A. Monteiro, and A. J. S. Filho, “Boost Converter Control of PV System Using Sliding Mode Control With Integrative Sliding Surface,” IEEE J Emerg Sel Top Power Electron, vol. 10, no. 5, 2022, doi: 10.1109/JESTPE.2022.3158247.J.