Appendix A

Description of Simulation models

A.1 Double-integrator model

A double-integrator model is chosen in this work due to its simplicity and fundamental nature in control theory. It serves as a baseline for testing control algorithms, allowing for clear and straightforward benchmarking. A double integrator system is inherently unstable thus this model helps isolate and understand the effects of the proposed methods, making it an ideal starting point. Additionally, many practical systems, such as rolling mill [1], can be approximated as double integrators in their initial response stages, making this model relevant for demonstrating general principles before moving on to more complex systems.

A double integrator system dynamics can be represented by [135, 136]:

$$\dot{x}(t) = A_c x(t) + B_c u(t) \tag{A.1}$$

$$y(t) = C_c x(t) + D_c u(t) \tag{A.2}$$

with

$$A_c = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, B_c = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, C_c = \begin{bmatrix} 1 & 0 \end{bmatrix}, \text{and} \quad D_c = 0. \tag{A.3}$$

The discretized system model with sampling period $T = 1\text{ms}$ can be represented as:

$$x_{k+1} = Ax_k + Bu_k, \qquad y_k = Cx_k. \tag{A.4}$$

with

$$A = \begin{bmatrix} 1.0000 & 0.0010 \\ 0 & 1.0000 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0.0010 \end{bmatrix}, C = \begin{bmatrix} 1 & 0 \end{bmatrix}. \tag{A.5}$$

A.2 DC motor model

A DC motor model is included due to its practical relevance and the ubiquity of DC motors in real-world applications, from industrial machinery to consumer electronics. Demonstrating control strategies on a DC motor model highlights the practical applicability of the proposed methods. This model introduces a higher level of complexity (although a stable one) compared to the double-integrator, involving both electrical and mechanical dynamics. Using a DC motor model validates the control methods in scenarios closer to many practical applications, ensuring that the solutions are not just theoretically sound but also practically viable.

The continuous-time dynamics of a DC motor can be represented by the state-space model following [24, 137] as:

$$\dot{x}(t) = A_c x(t) + B_c u(t) \tag{A.6}$$

$$y(t) = C_c x(t) + D_c u(t) \tag{A.7}$$

where $x(t) = \begin{bmatrix} i(t) & \omega(t) \end{bmatrix}^T$ is the state vector, $i(t)$ representing the armature current and $\omega(t)$ representing the angular velocity, $u(t)$ representing the input voltage applied to the motor, and $y(t)$ representing speed as the output of the system.

The system matrices are as:

$$A_c = \begin{bmatrix} -\frac{R}{L} & -\frac{K_e}{L} \\ \frac{K_t}{J} & -\frac{B}{J} \end{bmatrix}, B_c = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}, C_c = \begin{bmatrix} 0 & 1 \end{bmatrix}, \text{and} \quad D_c = 0.$$

where $-\frac{R}{L}$ represents the rate at which the current decays due to the armature resistance (R) and inductance (L), $-\frac{K_e}{L}$ represents the coupling between the electrical and mechanical dynamics, where K_e is the back EMF constant (V·s/rad), $\frac{K_t}{J}$ represents the relationship between the current and the generated torque, where K_t is the torque constant (N·m/A) and J is the moment of inertia (kg·m^2), $-\frac{B}{J}$ represents the damping effect due to viscous friction (B) in the motor, and $\frac{1}{L}$ represents the effect of the applied voltage ($u(t)$) on the rate of change of current, considering the armature inductance (L).

To implement the DC motor model in a digital control system, the plant dynamics for a sampling period of $T = 1$ ms, conforming to the system dynamics (A.4) as considered in this work, is given by [132]:

$$A = \begin{bmatrix} 1.0087 & -0.0051 \\ 0.0711 & 0.9667 \end{bmatrix}, B = \begin{bmatrix} 0.0581 & -0.1684 \end{bmatrix}^T, C = \begin{bmatrix} 4.2400 & 2.6720 \end{bmatrix}, \text{and} \quad D = 0.$$

A.3 Inverted pendulum model

The inverted pendulum system is considered since it is a challenging problem due to its inherently unstable nature. Successfully controlling an inverted pendulum demonstrates the robustness and effectiveness of the proposed control methods. Unlike the double-integrator and DC motor models, the inverted pendulum introduces significant nonlinearity, allowing the demonstration of the method's ability to handle nonlinear dynamics and more challenging control scenarios. Furthermore, the inverted pendulum is widely used in academic and research settings to teach and test advanced control concepts, ensuring that the work is relevant and impactful for both educational and research purposes.

The model of the inverted pendulum considered in this work is shown in Fig. A.1, with m and M as the masses of the pendulum and the cart, respectively, l as the length of the pendulum from the center of the rotational shaft to the centroid of the pendulum, u as the external force on the cart, s as the displacement of the cart, and θ as the pendulum angle from vertical [11]. It is important to mention that the system's equilibrium point is unstable and isn't easy to control in an NCS setup.

For the continuous-time model, we define the state vector as:

$$x(t) = \begin{bmatrix} s(t) & \dot{s}(t) & \theta(t) & \dot{\theta}(t) \end{bmatrix}^T$$

where $s(t)$ is the displacement of the cart (in meters), $\dot{s}(t)$ is the velocity of the cart (in meters per second), $\theta(t)$ is the angle of the pendulum from the vertical (in radians), $\dot{\theta}(t)$ is the angular velocity of the pendulum (in radians per second).

The continuous-time dynamics of the inverted pendulum [27, 138] can be represented by the state-space model

$$\dot{x}(t) = A_c x(t) + B_c u(t) \tag{A.8}$$

$$y(t) = C_c x(t) + D_c u(t) \tag{A.9}$$

where the system matrices are defined as follows:

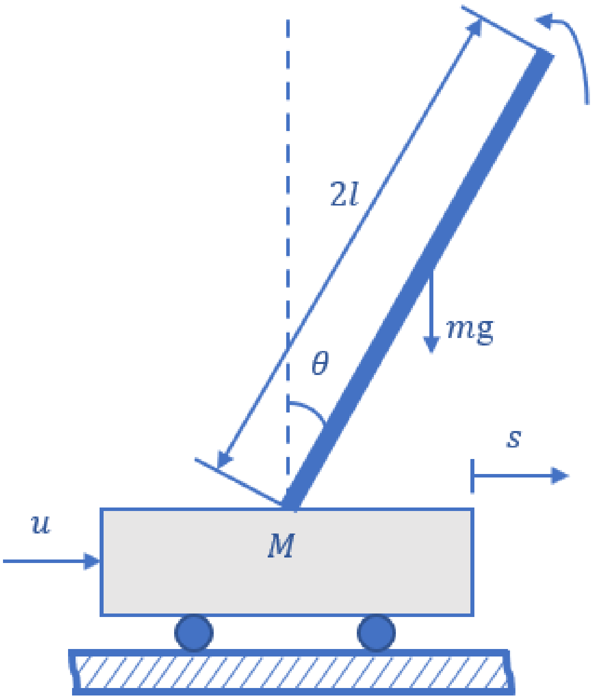

Figure A.1: The inverted pendulum model

$$A_c = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -\frac{I_p+ml^2}{I_p(M+m)+Mml^2}b & \frac{m^2gl^2}{I_p(M+m)+Mml^2} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & -\frac{ml}{I_p(M+m)+Mml^2}b & \frac{mgl(M+m)}{I_p(M+m)+Mml^2} & 0 \end{bmatrix}, B_c = \begin{bmatrix} 0 \\ \frac{I_p+ml^2}{I_p(M+m)+Mml^2} \\ 0 \\ \frac{ml}{I_p(M+m)+Mml^2} \end{bmatrix},$$

$$C_c = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \text{and} \quad D_c = 0$$

with M is the mass of the cart (kg), m is the mass of the pendulum (kg), l is the length of the pendulum from the pivot to the center of mass (m), g is the acceleration due to gravity (m/s^2), I_p is the moment of inertia of the pendulum about the pivot (kg·m^2), b is the Coefficient of friction for the cart (N·s/m), and where $u(t)$ represents the force applied to the cart (N).

To implement the inverted pendulum model in a digital control system, the continuous-time dynamics is to be discretized. The discrete-time representation is obtained using a specific sampling period to ensure the system can be modeled at distinct time intervals suitable for digital control.

With a sampling period of $T = 0.01$s, the discrete-time system matrices of the inverted pendulum, corresponding to the model (A.4), are given by:

$$A = \begin{bmatrix} 1.0000 & 0.0100 & 0.0001 & 0 \\ 0 & 0.9982 & 0.0267 & 0.0001 \\ 0 & 0 & 1.0016 & 0.0100 \\ 0 & -0.0045 & 0.3119 & 1.0016 \end{bmatrix}, B = \begin{bmatrix} 0.0001 \\ 0.0182 \\ 0.0002 \\ 0.0454 \end{bmatrix}, C^T = \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}, \text{and} \quad D = 0$$

This discrete-time model is leveraged to implement control strategies for the inverted pendulum within the scope of this thesis.

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Responses to Examiner's Comments

Thesis title: Event-triggered Predictive Control of Networked Control Systems with Output Transmission

Haritha Mittapally

Examiner ♯1

R1.1

Comment: The abstract mainly focuses on the motivation, mentions broadly the techniques used, and says that these methods are innovative, Beyond this, it says very little about the techniques used and why they are innovative. The abstract should be a comprehensive account of the main contributions of the thesis and not just on motivation and claims of innovation, which are repeated several times in the abstract. The phrase ”limited communication bandwidth, network delay, and packet dropouts” is repeated in different forms throughout the abstract. Please rewrite the abstract so that it reflects the contributions well.

Response: Thank you for the suggestion. The abstract has now been rewritten to reflect the newness of the work. Now, the main contributions of the proposed work are mentioned clearly. Please see the updated abstract in the revised thesis. For convenience, it is reproduced below as well.

The Abstract is reproduced here

Abstract: Networked Control Systems (NCS) have emerged as a prominent field of research due to their potential to revolutionize various applications, including automation, energy management, and healthcare. By integrating control systems with communication networks, NCS offers enhanced flexibility, scalability, and distributed control capabilities. However, several challenges need to be addressed to ensure efficient and reliable control in networked environments. NCSs are known to offer control design challenges involving network-induced time delays, packet dropouts, packet size, and limited bandwidth resources in NCS. While the first two are often addressed using predictive controllers, the limited bandwidth issue is addressed by using event-triggering mechanism. However, the issue of packet size is limitedly addressed in literature. It is known that larger data packets also deteriorate the network bandwidth leading to more delays and packet losses. In order to reduce the size of the data packets, output transmission over the network for an NCS is considered in this thesis and new solutions to overcome its limitations are proposed.

As a first problem, an event-triggered NCS with output transmission instead of state transmission is considered. The NCS is considered to be having conventional event-triggering mechanism in both the feedback and forward channels. Such a situation is helpful in improving the network bandwidth when shared network channels are used for both the forward and feedback channels. A predictive controller with an observer to estimate the states from delayed event-triggered output

is developed to take care of the random delays and dropouts in the NCS. Stability analysis of the predictive controller is studied and effectiveness of the proposed scheme is shown through numerical examples.

Since output transmission deteriorates the system performance by trading off the network bandwidth improvement, the next problem is considered to study if sequential output transmission through a single packet can be potentially used to improve the performance of such NCS. A sequential observer-based predictive controller is proposed for such an NCS to utilize the sequential output information transmitted in a single packet. It is shown that the proposed predictive controller improves the performance of the NCS as more sequential information is transmitted in a single packet even in presence of event-triggering in both the feedback and forward channels.

While conventional event-triggering works well for NCS, it is well known that predictive triggering can further optimize the network utilization. A predictive controller is then designed for the NCS in the presence of predictive triggering with output transmission. It is seen that the predictive controller works as expected in the presence of predictive triggering as well.

R1.2

Comment: The first two chapters take up about 40 percent of the thesis and cover known concepts and definitions. There are not even mathematical formulations that can help in understanding the formulation of the problem later. This part contributes very little to the thesis except for the literature survey which is cursory and provides very little insight into the novelty (if any) of the approach. I would advise the student to rewrite these two chapters and make them more compact by combining them, if possible.

Response: Thank you for your valuable feedback. In response to the suggestion, Chapters 1 and 2 have been thoroughly revised and condensed into one chapter to focus on the most pertinent aspects of the thesis.

R1.3

Comment: The claim of novelty in Chapter 3 is in the placement of the observer on the controller side of the network and the inclusion of passive dropouts. The novelty of using the observer after the communication network is not very clear. I believe most observer designs in communication networks do consider packet drops and other disturbances introduced by the network.

Response: Thank you for the critical observation.

The newness in this thesis work lies in placing the observer on the controller side instead of the conventional approach of placing it on the plant side. Placing the observer on the plant side means states are observed first before transmission using instantaneous input and output of the plant and requires observed state information to be transmitted through the network that increases packet lengths and induces comparatively more delays and drops than the case when only output is transmitted through the network. This strategic choice conserves packet length and network bandwidth, directly addressing one of the primary challenges in networked control systems.

What sets this work apart from the existing literature is the complex task of estimating state information from the delayed or dropped output information without direct access to the control input. Additionally, the observer design uniquely considers the impact of delays and packet drops in both the feedback and forward paths of the network, including those introduced by

event-triggering mechanisms. The observer design is pivotal here, overcoming these multifaceted challenges and ensuring robust communication, an accomplishment not typically addressed in existing observer designs for communication networks.
Please see the Abstract and Section 1.7 on pages 24 - 26 where contributions are written.

R1.4

Comment: Event triggering is applied in Chapters 3 and 4. I am not sure if the issues related to event-triggering are even discussed. See the papers [X. Wang and M.D.Lemmon, "Event-Triggering in Distributed Networked Control Systems," in IEEE Transactions on Automatic Control, Vol. 56, n0.3, pp.586-601, March 2011, doi: 10.1109/TAC.2010.2057951.][Feng-Lin Qu, Zhi-Hong Guan, Ding-Xin He, Ming Chi, Event-triggered control for networked control system with quantization and packet losses, Journal of the Franklin Institute, Volume 352, Issue 3, 2015, Pages 974-986, doi.org/10.1016/j.jfranklin.2014.10.004.] These and many similar papers which are very relevant to the work reported in the thesis are not cited.

Response: Thank you for the suggestion to include more relevant references related to event-triggering. The mentioned works and other pertinent literature have now been cited in the thesis.

The following references have been included and discussed: [2] on page 2, [20] on page 7, [24-31] on page 8, [37] and [41] on page 9, [60-65] on pages 11 and 12, [67-69] on page 13, [70] and [75] on page 14, [81] and [90] on page 15, [113-115] on page 18, [121-123] on page 29, [129] on page 56, [132] on page 71, [134] on page 77, [135-136] on page 103, [137] on page 104, and [138] on page 105.

R1.5

Comment: Figs. 3.8 and 3.11 show very high frequency switching at some patches. What is the frequency in these regions? Will the system be able to take this kind of switching? Are there any dynamics that will prevent this?

Response: Thank you for the critical observation. Figs. 3.8 and 3.11 earlier are now Figs. 2.8 and 2.13. The sampling period for the system is $T = 0.01$ second. The maximum switching frequency is at 0.01 sec (the sampling interval), though it may look like high-frequency switching due to the large time duration of the simulation. The switchings are the transmission instants of the output or input information, and these are exclusive switching inputs to the system. For example, there could be a transmission corresponding to a switching instant, but the data could be the same as the previous instant. This has been taken care of by the stability of the overall system. Hence, the system is well remain stable even if the data transmission is with high frequency (at most equal to the sampling frequency). The low-frequency data shows that event-triggering is active with few data transmissions.
Two new figures have been included with less simulation duration after each of Fig. 2.8 and Fig. 2.13, please see Figs. 2.8 - 2.10 on pages 44 and 45, and Figs. 2.13 - 2.15 on pages 47 and 48 where the data transmission intervals are better visible.

R1.6

Comment: It is not clear what is being shown in Fig. 3.9. Is one better than the other? And, if so, then why? The caption also does not match the legend in the figure. One needs to find the discussion to make any sense.

Response:
Thank you for the observation and suggestion. the Fig. 3.9 is now Fig. 2.11 in the revised thesis. The title of the figure has been modified to match the legend in the figure. The comparison aims to highlight the performance difference between the proposed system and an ideal case where network issues are absent. Specifically, the figure contrasts the proposed networked control system with a state feedback controller implemented as a local controller without network constraints.
The corrected Figure 2.11 can be found on page 46.

R1.7

Comment: In Fig.3.10. what is the unit on the Y-axis? Note that unclear identification of quantities is a problem in many figures.

Response:
The figure in the revised thesis is Fig. 2.12. Thank you for the comment. The Y-axis in Fig. 2.12 represents the 2−norm of the observer error vector e_k, as defined in (2.4). This value quantifies the magnitude of the observer error, denoted by $||e_k||_2$. Since the individual states are in different units, this error can not be represented with an appropriate unit.
The corrected Fig. 2.12 can be found on page 47.

R1.8

Comment: In Fig.4.6, ϕ shows a downswing but $\dot{\phi}$ still shows positive values. Why?

Response:
The figure is now Fig. 3.6. Thank you for the observation. The labels in Fig. 3.6 were mistakenly labeled as ϕ and $\dot{\phi}$; they have now been corrected to x_1 and x_2, and $x_2 \neq \dot{x}_1$; this can be seen from the system dynamics in Example 2 in page 71. We have cross-verified the simulation result, and the result is correct.
The figure with correct notations can be found on page 74.

R1.9

Comment: Fig.5.7 needs to be explained better. What is being shown in the Y-axis?

Response:
Thank you for the comment. The figure is now Fig. 4.7. The title of the figure is rewritten to reflect the individual values. The figure illustrates the variable prediction horizon for state transmissions in the Predictive Triggering (PT) mechanism discussed in the chapter. The Y-axis represents the prediction horizon values, M, which denote the number of intervals until the next triggering. Due to the long text, the Y-axis label is not used, rather it is represented as the legend. Each triggering instant with $\gamma_k = 1$ (value 1 represents triggering occurs and value 0 represents no triggering) corresponds to the transmission instant.
For example, a value of $M = 1$ indicates that the next triggering will occur after one interval,

represented by $\gamma = 1$. Similarly, $M = 2$ suggests that the next triggering will occur after two instants and $M = 9$ indicates that triggering will happen nine instants later. This mechanism helps in efficiently allocating network resources by informing the network operator about the intervals between triggering instants and optimizing channel usage.
The explanation can be found on page 91 and Fig. 4.7 on page 93.

Examiner ♯2

R2.1

Comment: There are minor grammatical or presentational errors in the text and references.

Response: Thank you for pointing out the minor grammatical and presentational errors. The entire thesis has been thoroughly reviewed and revised to address these issues, ensuring improved clarity and accuracy.

R2.2

Comment: Chapter 1: This chapter is very big with information that may not be related to the works completed in the thesis and can be shifted to the appendix. The thesis should have aims first then objectives. I also think that the motivation for doing this research should be in the beginning to justify this work. Thesis outlines and objectives should be related. Now it looks like separate identities. Maybe explain inside objectives where these are met in the thesis. The list of publications from this work should also be included in this chapter.

Response: Thank you for the valuable feedback. In response to your suggestions, Chapter 1 has been reorganized to present the motivation, aims, and objectives in a logical sequence, followed by the thesis outline. The aims and objectives are now more clearly linked to the content of the thesis. Additionally, the list of publications related to this work has been included in this chapter.

R2.3

Comment: Chapter 2: The title of the chapter should be changed to reflect the contents of the chapter. One suggestion will be to remove section 1.5 (Literature review) from Chapter 1 and change the name of Chapter 2 to Literature Review. Much information in section 1.5 is repeated in this Chapter. Figure 2.2- Change the notion of u(k) and y(k) after the network to make it distinguished from the original controller action and the sensor output. Provide a reference for the Luenberger observer and Kalman filter on page 33.

Response:
Thank you for your critical observations and suggestions. To eliminate redundancy, Section 1.5 has been removed from Chapter 1. Additionally, the content of Chapter 2 has been condensed and incorporated into Chapter 1, with all sections rearranged accordingly, in alignment with comment R2.2.

The figure is now Fig. 1.3. The notation for u(k) and y(k) after the network has been updated to avoid confusion with the original controller actions and sensor outputs. In the same line, Fig. 1.4 is also updated. These updated figures can be found on page 6.

References for the Luenberger observer and Kalman filter have been added and can be found on page 8.

R2.4

Comment: Chapter 3: This chapter provides a good review of the predicting control of NCS. Very good chapter with case studies and comparisons justifying the contributions of the thesis. Section 3.6 should be changed to Summary rather than Conclusion and should be followed in every chapter for consistency. The results shown in section 3.6 should be analyzed before maybe in the new section/subsection (i.e. Results and Discussions). The summary section should summarize the important outcomes in this chapter and make a connection with the next chapter with no results.

Response:
Thank you for the valuable feedback and suggestions. In response to the comments, the section title “Conclusion” in Chapters 3, 4, and 5 has been revised to “Summary” to ensure consistency across the thesis.

The figures of each section are rearranged such that they do not appear in other sections and the chapter summaries have been rewritten to effectively summarize key outcomes and establish a clear connection with the subsequent chapter. The same is followed in subsequent chapters as well.
Please find the Summary of Chapter 2, 3, and 4 on pages 54, 74, and 97, respectively.

R2.5

Comment: Chapter 4: The two examples inverted pendulum and DC motor considered as case studies are not explained well and there is no justification for why these two examples are only considered. Maybe a small description of the system in the appendix will be useful for the readers. Please follow the same instructions for section 4.6 as provided in Chapter 3.

Response: Thank you for the suggestion. The detailed descriptions of the systems that are considered for simulations, including the double-integrator system, the DC motor system, and the inverted pendulum system, have been included in the thesis as an Appendix.

Section 4.6 is now section 3.6. The instructions for Section 3.6 have been revised to align with the formatting and structure improvements implemented in Chapter 2, ensuring consistency throughout the thesis.

R2.6

Comment: Chapter 5: This is an important chapter and provides convincing results. The only drawback is the systems considered in the case studies. Although the inverted pendulum is a nonlinear system, the results are shown on a linearised one. It would be good if nonlinear state equations were used instead or explained the effect of NCS on the nonlinear systems. Section 5.6 should be changed as suggested before.

Response: Thank you for the valuable feedback and suggestions regarding the consideration of nonlinear dynamics in the case studies.

We have attempted to consider nonlinear system dynamics in simulations in our work earlier, but not been successful yet. This may be due to not incorporating the time-varying nature of the system dynamics due to the nonlinearity and mismatch in the corresponding predictions. This

would be a future work for us.
Please see third point in the future work list in page 100.

R2.7

Comment: Chapter 6: The title should be Conclusions and Future Scopes. Conclusions are okay but there are many future scopes. I think the future scopes should only list those items that are not possible to complete in the short duration and will require extensive research. If it is doable then it should have been done in this thesis and included in the chapters. Normally 3-4 major related works are enough for the future scope.

Response: Thank you for the suggestion. The title of the chapter has been changed to "Conclusions and Future Scopes." Additionally, it is ensured that the future scopes discussed are those that have been previously explored and where insights have already been formed.

R2.8

Comment: Appendix A: The list of publications should be included in Chapter 1. The status of the last paper should also be indicated if known (i.e. under review).

Response: Thank you for the suggestion. The list of publications has been moved to Chapter 1 as recommended. Additionally, the status of the third paper has been updated to "Under review" in the revised Chapter 1.

Besides the modifications suggested by the examiners, some changes have been made to improve the consistency of the notations and clarity of presentation. At this moment, it is emphasized that all the major changes are indicated in blue color in the revised version of the thesis. I thank the examiners for all the comments/suggestions and contributions to improving the quality and readability of the thesis.