# [Thesis Title]

Thesis by
[Your Full Name]

In Partial Fulfillment of the Requirements for the
degree of
[Name of Degree]

Caltech

CALIFORNIA INSTITUTE OF TECHNOLOGY
Pasadena, California

[Year Degree Conferred]
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# ACKNOWLEDGEMENTS

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# ABSTRACT

[This abstract must provide a succinct and informative condensation of your work. Candidates are welcome to prepare a lengthier abstract for inclusion in the dissertation, and provide a shorter one in the CaltechTHESIS record.]

# TABLE OF CONTENTS

# LIST OF ILLUSTRATIONS

# LIST OF TABLES

Start off all chapters with `chapter`. `\extrachapter` will give you an unnumbered chapter that's added to the Table of Contents.

Here's an example of a citation (**GMP81** ). Here's another (**PP98** ). These will appear in the big bibliography at the end of the thesis.

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You can define nomenclatures as you talk about key terms in your thesis. So what's a galaxy?

## 1.1 This is a Section

## 1.2 Obtaining lower bound to the performance index in an LQG control system with stochastic parameters

For the imperfect information case, as in , we aim to obtain a lower bound to the performance index without using the "enforced" separation method presented in which leads to a suboptimal controller. In Eq.(24) of , the term containing $\tilde{x}(N-1)$ has been ignored to enforce the separation principle which does not hold otherwise in this case. The equation is shown below:

$$\begin{aligned}
&\min_{u(n-2)} \{\mathbb{E}\left[x^T(N-1)W(n-1)x(N-1) + u^T(N-2)R(N-2)u(N-2)\right] \\
&\qquad + \mathbb{E}\left[\tilde{x}^T(N-1)M_1(N-1)\tilde{x}(N-1)\right]\}
\end{aligned}$$

Instead of ignoring the second part with the estimation error as in , we aim to find a lower bound to the above using the following.

$$\begin{aligned}
&\min_{u(N-2)} \{\mathbb{E}\left[x^T(N-1)W(n-1)x(N-1) + u^T(N-2)R(N-2)u(N-2)\right] \\
&\qquad + \mathbb{E}\left[\tilde{x}^T(N-1)M_1(N-1)\tilde{x}(N-1)\right]\} \geq \\
&\min_{u(N-2)} \left\{\mathbb{E}\left[x^T(N-1)W(n-1)x(N-1) + u^T(N-2)R(N-2)u(N-2)\right]\right\} + \\
&\qquad \min_{u(N-2)} \left\{\mathbb{E}\left[\tilde{x}^T(N-1)M_1(N-1)\tilde{x}(N-1)\right]\right\}
\end{aligned}$$

Minimization of the first part would be the same as in the “enforced" separation case in . The second part, the part with the estimation error needs to be minimized now as shown below:

$$\tilde{x}(N-1) = x(N-1) - \hat{x}(N-1)$$

where $\hat{x}(N-1)$ is the estimate of $x$ given the observations $y(0), y(1), ..., y(N-1)$ denoted as $Y_0^{N-1}$

$$\hat{x}(N-1) = \mathbb{E}\left[x(N-1)|Y_0^{N-1}\right]$$

Substituting for $x(N-1)$ from the system dynamics equations (Eq.(1) in ), we get for scalar case

$$\begin{aligned} x(N-1) &= A(N-2)x(N-2) + u(N-2) + w(N-2) \\ \tilde{x}(N-1) &= A(N-2)x(N-2) + u(N-2) + w(N-2) \\ &\quad - \mathbb{E}\left[A(N-2)x(N-2) + u(N-2) + w(N-2)|Y_0^{N-1}\right] \end{aligned}$$

For scalar case, since $M_1(N-1)$ is constant (see ), we need to minimize $\tilde{x}^2(N-1)$ with respect to $u(N-2)$. Squaring, we get,

$$\begin{aligned} \tilde{x}^2(N-1) &= \{A(N-2)x(N-2) + u(N-2) + w(N-2)\}^2 \\ &\quad + \mathbb{E}\left[A(N-2)x(N-2) + u(N-2) + w(N-2)|Y_0^{N-1}\right]^2 \\ &\quad - 2\mathbb{E}\left[A(N-2)x(N-2) + u(N-2) + w(N-2)|Y_0^{N-1}\right] \\ &\quad . [A(N-2)x(N-2) + u(N-2) + w(N-2)] \end{aligned}$$

On differentiating the above expression for $\tilde{x}^2(N-1)$ with respect to $u(N-2)$ we get 0, as all terms cancel out. Here is the **expansion of $\tilde{x}^2(N-1)$**:

$$\begin{aligned} \tilde{x}^2(N-1) &= A^2(N-2)x^2(N-2) + u^2(N-2) + w^2(N-2) \\ &\quad + 2A(N-2)x(N-2)u(N-2) + 2u(N-2)w(N-2) \\ &\quad + 2A(N-2)x(N-2)w(N-2) \\ &\quad + \left\{\mathbb{E}\left[A(N-2)x(N-2) + u(N-2) + w(N-2)|Y_0^{N-1}\right]\right\}^2 \\ &\quad - 2\mathbb{E}\left[A(N-2)x(N-2) + u(N-2) + w(N-2)|Y_0^{N-1}\right] \\ &\quad . [A(N-2)x(N-2) + u(N-2) + w(N-2)] \end{aligned}$$

Now using the linearity property of expected value we write the following

$$\begin{aligned}
&\mathbb{E}\left[A(N-2)x(N-2)+u(N-2)+w(N-2)|Y_0^{N-1}\right] \\
&=\mathbb{E}\left[A(N-2)x(N-2)|Y_0^{N-1}\right] \\
&+\mathbb{E}\left[u(N-2)|Y_0^{N-1}\right]+\mathbb{E}\left[w(N-2)|Y_0^{N-1}\right]
\end{aligned}$$

Squaring we get,

$$\begin{aligned}
&\left\{\mathbb{E}\left[A(N-2)x(N-2)|Y_0^{N-1}\right]\right\}^2+\left\{\mathbb{E}\left[u(N-2)|Y_0^{N-1}\right]\right\}^2 \\
&+\left\{\mathbb{E}\left[w(N-2)|Y_0^{N-1}\right]\right\}^2+2\mathbb{E}\left[A(N-2)x(N-2)|Y_0^{N-1}\right].\mathbb{E}\left[u(N-2)|Y_0^{N-1}\right] \\
&+2\mathbb{E}\left[A(N-2)x(N-2)|Y_0^{N-1}\right]\mathbb{E}\left[w(N-2)|Y_0^{N-1}\right] \\
&+2\mathbb{E}\left[u(N-2)|Y_0^{N-1}\right]\mathbb{E}\left[w(N-2)|Y_0^{N-1}\right]
\end{aligned}$$

Substituting the above in the expression for $\tilde{x}^2(N-1)$ obtained above, we get

$$\begin{aligned}
\tilde{x}^2(N-1) &= A^2(N-2)x^2(N-2)+u^2(N-2)+w^2(N-2)+2A(N-2)x(N-2)u(N-2) \\
&+2u(N-2)w(N-2)+2A(N-2)x(N-2)w(N-2) \\
&+\left\{\mathbb{E}\left[A(N-2)x(N-2)|Y_0^{N-1}\right]\right\}^2+\left\{\mathbb{E}\left[u(N-2)|Y_0^{N-1}\right]\right\}^2 \\
&+\left\{\mathbb{E}\left[w(N-2)|Y_0^{N-1}\right]\right\}^2+2\mathbb{E}\left[A(N-2)x(N-2)|Y_0^{N-1}\right].\mathbb{E}\left[u(N-2)|Y_0^{N-1}\right] \\
&+2\mathbb{E}\left[A(N-2)x(N-2)|Y_0^{N-1}\right].\mathbb{E}\left[w(N-2)|Y_0^{N-1}\right] \\
&+2\mathbb{E}\left[u(N-2)|Y_0^{N-1}\right].\mathbb{E}\left[w(N-2)|Y_0^{N-1}\right] \\
&-2\mathbb{E}\left[A(N-2)x(N-2)|Y_0^{N-1}\right]A(N-2)x(N-2) \\
&-2\mathbb{E}\left[u(N-2)|Y_0^{N-1}\right]A(N-2)x(N-2)-2\mathbb{E}\left[w(N-2)|Y_0^{N-1}\right]A(N-2)x(N-2) \\
&-2\mathbb{E}\left[A(N-2)x(N-2)|Y_0^{N-1}\right]u(N-2)-2\mathbb{E}\left[u(N-2)|Y_0^{N-1}\right]u(N-2) \\
&-2\mathbb{E}\left[w(N-2)|Y_0^{N-1}\right]u(N-2)-2\mathbb{E}\left[A(N-2)x(N-2)|Y_0^{N-1}\right]w(N-2) \\
&-2\mathbb{E}\left[u(N-2)|Y_0^{N-1}\right]w(N-2)-2\mathbb{E}\left[w(N-2)|Y_0^{N-1}\right]w(N-2)
\end{aligned}$$

Now differentiating with respect to $u(N-2)$, we get

$$\begin{aligned}
&0+2u(N-2)+0+2A(N-2)x(N-2)+2w(N-2)+0+0 \\
&+2\mathbb{E}\left[u(N-2)|Y_0^{N-1}\right].\mathbb{E}\left[1|Y_0^{N-1}\right]+0+2\mathbb{E}\left[A(N-2)x(N-2)|Y_0^{N-1}\right].\mathbb{E}\left[1|Y_0^{N-1}\right] \\
&+0+2\mathbb{E}\left[w(N-2)|Y_0^{N-1}\right].\mathbb{E}\left[1|Y_0^{N-1}\right]-0-2A(N-2)x(N-2)\mathbb{E}\left[1|Y_0^{N-1}\right] \\
&-2\mathbb{E}\left[A(N-2)x(N-2)|Y_0^{N-1}\right].1-2\mathbb{E}\left[u(N-2)|Y_0^{N-1}\right].1 \\
&-2\mathbb{E}\left[1|Y_0^{N-1}\right]u(N-2)-2\mathbb{E}\left[w(N-2)|Y_0^{N-1}\right].1 \\
&-0-2\mathbb{E}\left[1|Y_0^{N-1}\right]w(N-2)-0
\end{aligned}$$

Using $\mathbb{E}\left[1|Y_0^{N-1}\right] = 1$, we have

$$\begin{aligned}
&2u(N-2) + 2A(N-2)x(N-2) + 2w(N-2) \\
&+ 2\mathbb{E}\left[u(N-2)|Y_0^{N-1}\right] + 2\mathbb{E}\left[A(N-2)x(N-2)|Y_0^{N-1}\right] \\
&+ 2\mathbb{E}\left[w(N-2)|Y_0^{N-1}\right] - 2A(N-2)x(N-2) \\
&- 2\mathbb{E}\left[A(N-2)x(N-2)|Y_0^{N-1}\right] - 2\mathbb{E}\left[u(N-2)|Y_0^{N-1}\right] \\
&- 2u(N-2) - 2\mathbb{E}\left[w(N-2)|Y_0^{N-1}\right] - 2w(N-2)
\end{aligned}$$

As we can see, all the terms cancel out and hence the derivative is zero.

Figure 1.1: This is a figure

**This is a subsection**

| Area | Count |
|---|---|
| North | 100 |
| South | 200 |
| East | 80 |
| West | 140 |

Table 1.1: This is a table

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### 1.3 This is Another Section

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If you'd like to have separate bibliographies at the end of each chapter, put a `refsection` around the material of each chapter, then cite as usual – e.g. (**GMP81**; **Ful83** ). Then do a `\printbibliography` just before the `refsection` ends.

*This is the Third Chapter*

[You can have chapters that were published as part of your thesis. The text style of the body should be single column, as it was submitted to the publisher, not formatted as the publisher did.]

*This is the Fourth Chapter*

*This is the Fifth Chapter*

*This is the Sixth Chapter*

*This is the Seventh Chapter*

*This is the Eighth Chapter*

*Questionnaire*

*Consent Form*

# INDEX

[1]Endnotes are notes that you can use to explain text in a document.

# POCKET MATERIAL: MAP OF CASE STUDY SOLAR SYSTEMS