



DEGREE PROJECT IN TECHNOLOGY,
SECOND CYCLE, 30 CREDITS
STOCKHOLM, SWEDEN 2022

Template

KTH Thesis Report

Max Schaufelberger

Author

Max Schaufelberger <maxscha@kth.se>
School of Engineering Sciences
KTH Royal Institute of Technology

Place for Project

Stockholm, Sweden
Ottignies-Louvain-la-Neuve, Belgium

Examiner

Prof. Olof Runborg
Department of Numerical Analysis
KTH Royal Institute of Technology
Stockholm, Sweden

Supervisor

Prof. Elias Jarlebring
Department of Numerical Analysis
KTH Royal Institute of Technology
Stockholm, Sweden

Supervisor

Arvind Kumar
Division of Computational Science and Technology
KTH Royal Institute of Technology
Stockholm, Sweden

Supervisor

Frédéric Crevecoeur
Institute of Information and Communication Technologies, Electronics and Applied
Mathematics
UCLouvain Catholic University of Louvain
Louvain-la-Neuve, Belgium

Abstract

This is a template for writing thesis reports for the ICT school at KTH. I do not own any of the images provided in the template and this can only be used to submit thesis work for KTH.

The report needs to be compiled using XeLaTeX as different fonts are needed for the project to look like the original report. You might have to change this manually in overleaf.

This template
was created by Hannes Rabo <hannes.rabo@gmail.com or hrabo@kth.se> from the template provided by KTH. You can send me an email if you need help in making it work for you.

Write an abstract. Introduce the subject area for the project and describe the problems that are solved and described in the thesis. Present how the problems have been solved, methods used and present results for the project. Use probably one sentence for each chapter in the final report.

The presentation of the results should be the main part of the abstract. Use about 1/2 A4-page. English abstract

Keywords

Template, Thesis, Keywords ...

Abstract

Svenskt abstract Svensk version av abstract – samma titel på svenska som på engelska.

Skriv samma abstract på svenska. Introducera ämnet för projektet och beskriv problemen som löses i materialet. Presentera

Nyckelord

Kandidat examensarbete, ...

Acknowledgements

Write a short acknowledgements. Don't forget to give some credit to the examiner and supervisor.

Acronyms

NN	Neural Network
ANN	Artificial Neural Network
SNN	Spiking neural network
IF	Integrate and Fire
LIF	Leaky-integrate-and-fire
HH	Hodgkin–Huxley

Contents

1	Introduction	1
1.1	Background	4
1.2	Problem	5
1.3	Purpose	5
1.4	Goal	5
1.5	Benefits, Ethics and Sustainability	6
1.6	Methodology	6
1.7	Stakeholders	7
1.8	Delimitations	7
1.9	Outline	7
2	<Theoretical Background>	8
2.1	Use headings to break the text	8
2.2	Related Work	8
2.3	Dynamic systems	9
2.4	Neuron model	9
2.4.1	Biological Neuron model	9
2.4.2	"IF and LIF"	10
2.4.3	Izhikevich Neuron	11
2.5	Neural Networks	12
2.5.1	Biological Neural Network	12
2.5.2	Artificial Neural Networks	12
2.5.3	Spiking Neural Networks	12
2.5.4	Poisson-Networks	12
2.5.5	Liquid state machines	12
2.5.6	GLM	12

2.5.7	Balanced Networks	12
2.5.8	Learning: SGD and STDP	12
3	<Engineering-related content, Methodologies and Methods>	14
3.1	Engineering-related and scientific content:	14
4	<The work>	16
4.1	Creating the SNN	16
4.2	Creating the NN	16
4.3	Creating the regular Controller	16
5	<Result>	17
6	<Conclusions>	18
6.1	Discussion	18
6.1.1	Future Work	18
6.1.2	Final Words	18
	References	20

Chapter 1

Introduction

Provide a general introduction to the area for the degree project. Use references!

Link things together with references. This is a reference to a section: 1.1.

The human brain is comprised of more than 80 billion neurons. Each of these neurons can have thousands of connections to other neurons.. Between these connection, information travels as electrical impulses that interact with the neurons own polarity. With the careful arrangement the human brain is capable of vastly different and complex things. Tasks that are still next to impossible to recreate on machines and algorithms. Moreover many tasks lack the human speed, precision, flexibility or a combination of them.

Spiking neural networks mimic the inner workings of the brain. They are often dubbed the third generation of Neural Networks (NNs). On the contrary the more traditional

Human brain amazing

We struggle to make to replicate at the computer level with algorithms

Neural network a way to imitate the brain and its inner workings.

Neural networks have shown and proven performance in certain areas

They lack in some others

Therefore considerable research went into it

Now we have spiking neural networks, that imitate the brain even more

We hope that with that we have even better performance

Neuro stuff
very rapid
development
tremendous
progress, m
things are
successful v
NNs. Then
list fields th
work well.
E.g pattern
recognition
bioinformat
neuroscienc
With spikin
neural netw
they are be
the state of
art feedforv
networks b
the gap is
closing. Th
are already
fields where
they are ex

From very biological to very abstract there have been many proposals

Cost performance trade off.

Spiking networks have gained similar or exceeding performance compared to the artificial one in some areas-> refs

Key advantage is in the temporal dimensional gain.

One field they are suited well is the control of dynamic systems

In this thesis we use a spiking neural network to control a linear dynamic system

The usual way to simulate biological dynamic systems is using LQG control -> ref

I believe because of the energy minimization

So we can compare them with usual NN and control in terms of performance... i guess

We start by giving an intro into spiking neural networks

Then spiking neural networks for dynamic systems

After control theory with SNN and maybe regular LQG control

Lately the learnign of SNNs for the control of dynamic system

Further work:

Maybe learning methods to control nonlinear dynamic systems

Maybe we can even do the adversarial attack to try to screw with the network.

Implement this on neuromorphic hardware

Problem:

Problem is that it is unnatural for classic NN to use temporal data.

They usually quantize it and make a big input layer -> ref

There are recurrent networks but ... they need to have smth bad as well

The LQG control is also not great for some reason I need to find

There are many spiking network archetypes like poisson and GLm and balanced

Also problem is that for some spiking networks learning rules could be hard to come by.

There are many prospects though as for example->refs

Also usually learning rules smth of an inverse and that the brain does not have or do I believe arvind said

Method:

We use a SNN to control any arbitrary DS

Balanced networks show some key motives seen in the brain like poisson distribution and smth else ->ref

The SNN is to be trained with a STDP rule

Then compared to optimal weights

Then investigated about robustness and other things as many before

One part of robustness is trying to get the most essential nodes of the snn to function well.

, Then we have the potential to find a classic nn and train it with that ???

With that out of the way we can compare the performance of all the methods.

Then we could study the usability for biological interpretation.

Maybe even train time over performance or smth whatever

Goal:

The goal is to have a performant SNN that can be taught to control any linear system with robustness for nodes and weights degrading.

It should be as good as a conventional NN or LQG controller.

It should be trained using a method that can resemble the way our brain learns.

Should be minimal (aka no poisson), so fast and small

It should be general, so any system can be trained on

It should converge, but for the Balanced it has already been proven if I am not mistaken-> check and ref

Work:

Explain the controller method aka what the math of the controller

In method explain the balanced and the derivation

In work summarize the implementation

Same for the conventional NN

Summarize the training method

Explain and derive the training method in method

Results:

To everthign mentioned in method for performance and so on

Answer the questions of the problem!!!!

1.1 Background

Present the background for the area. Give the context by explaining the parts that are needed to understand the degree project and thesis. (Still, keep in mind that this is an introductory part, which does not require too detailed description).

Use references¹

Detailed description of the area should be moved to Chapter 2, where detailed information about background is given together with related work.

This background presents background to writing a report in latex.

Example citation [**Jones2017**] or for two authors: [**Jones2017, Liu2017**]

Look at sample table 1.1.1 for a table sample.

Table 1.1.1: Sample table. Make sure the column with adds up to 0.94 for a nice look.

SAMPLE	TABLE
One	Stuff 1
Two	Stuff 2
Three	Stuff 3

Boxes can be used to organize content

Development environment for prototype

Operating systems

computer: Linux - kernel 4.18.5-arch1-1-ARCH

android phone: 8.1.0

Build tools

exp (build tool): version 55.0.4

...

¹You can also add footnotes if you want to clarify the content on the same page.

1.2 Problem

NN have excelled at many fields

Fields where they are not fit

aka temporal data

They have ways to compromise on that

-> reference

Spiking nn inherently temporal

more natural choice

However they also have problems

like the following::: reference!!

1.3 Purpose

The purpose of the degree project/thesis is the purpose of the written material, i.e., the thesis. The thesis presents the work / discusses / illustrates and so on.

It is not “The project is about” even though this can be included in the purpose. If so, state the purpose of the project after purpose of the thesis).

Probably delete as a own paragraph but mention smth like that.

1.4 Goal

The goal means the goal of the degree project. Present following: the goal(s), deliverables and results of the project.

Goal is to write a SNN that can deliver good performance in solving a task that sucks with a conventional NN. We test the performance of a SNN and a conventional NN for linear dynamic systems.

The performance of of the SNN should be close to equal to conventional control schemes and better than conventional NNs.

Ideally the SNN has desired features like small number of spikes, precision, learning, poisson distribution etc. more find references.

Ideally we stress the network by removing many neurons and see the performance. maybe to recreate the performance of the one paper..

Potentially find the optimal minimal network in the network. The paper dass der Typ aus louvain vorgestellt hat.

1.5 Benefits, Ethics and Sustainability

Describe who will benefit from the degree project, the ethical issues (what ethical problems can arise) and the sustainability aspects of the project.

Use references!

1.6 Methodology

Introduce, theoretically, the methodologies and methods that can be used in a project and, then, select and introduce the methodologies and methods that are used in the degree project. Must be described on the level that is enough to understand the contents of the thesis.

Use references!

Preferably, the philosophical assumptions, research methods, and research approaches are presented here. Write quantitative / qualitative, deductive / inductive / abductive. Start with theory about methods, choose the methods that are used in the thesis and apply.

Detailed description of these methodologies and methods should be presented in Chapter 3. In chapter 3, the focus could be research strategies, data collection, data analysis, and quality assurance.

We build a SNN for a control problem and check it for performance as mentioned above. In addition we design a conventional controller and compare the result. IF we have the time for it we put a conventional NN to it too. We see the performance compared to the others and look at the specs we mentioned above. The SNN is trained by learning using STDP rule. We can compare the learned weights with the optimal weights when we have our own optimal controller/ we simulate our trajectory. For our approach we use a balanced spiking network.

1.7 Stakeholders

Present the stakeholders for the degree project.

1.8 Delimitations

Explain the delimitations. These are all the things that could affect the study if they were examined and included in the degree project. Use references!

1.9 Outline

In text, describe what is presented in Chapters 2 and forward. Exclude the first chapter and references as well as appendix.

Chapter 2

<Theoretical Background>

In this chapter, a detailed description about background of the degree project is presented together with related work. Discuss what is found useful and what is less useful. Use valid arguments.

Explain what and how prior work / prior research will be applied on or used in the degree project /work (described in this thesis). Explain why and what is not used in the degree project and give valid reasons for rejecting the work/research.

Use references!

2.1 Use headings to break the text

Do not use subtitles after each other without text in between the sections.

2.2 Related Work

You should probably keep a heading about the related work here even though the entire chapter basically only contains related work.

Here just what has been done for each of the headlines

Previous efforts were already made to control dynamic systems with Spiking neural networks (SNNs).

List here also efforts with other concepts apart from Balanced Networks

Neural networks in general spiking neural networks and their differences and what they are better for. neuron models, iwazishi neuron and maybe one more mein neuron model und warum ich es ausgewaelt habe: einfach zu implementieren. Bereits fuer dynamische systeme verwendet, Nachteile dieses modells. Vlt vergleich mit einem anderen modell. Ganz kurzer ausflug in die regelung von dynamischen systemen.

What is a neural network? -> not here ref a paper. kurze erkl'ung in der einfuehrung in der einfuehrung vlt auch hodgekin huxley erwaehen :)

2.3 Dynamic systems

2.4 Neuron model

2.4.1 Biological Neuron model

The most biologically accurate model of neuron spiking is the Hodgkin–Huxley (HH) model. The HH-model considers the neuron with its ion channels. The membrane acts as a capacitance and the travelling ions in each ion channel contribute a current to the overall membrane potential. These ion gates are voltage dependent and are defined positive in direction out of the cell.

A particular ion channel for ion X can be modelled as

$$I_X = g_X \cdot (V - V_X) \quad (2.1)$$

These currents are summed summed for the different ion channels in question, most commonly for Sodium, Potassium and a leak current. In reality there are a plethora of different channels and channel properties¹. The V_X are the equilibrium potentials for each of the channels and can be computed using the Nernst equation [5].

$$C \frac{dV}{dt} = g_{Na} \cdot (V - V_{Na}) + g_K \cdot (V - V_K) + g_l \cdot (V - V_l) \quad (2.2)$$

Add a
reference to
monograph

To model the voltage dependency of the ion channels, the conductances are described with gating variables, usually called n , h and g for Na-Activation, Na-Inactivation and K-activation respectively. One gating variable is set between $[0, 1]$ and models the permeability of said gate. Multiple gates are used to fit to each ion channel in order

¹See `channelpedia.epfl.ch` for an extensive list

to match experimental data and the model behaviour.

Gates have first order dynamics of the form

$$\frac{dn}{dt} = \alpha_n(1 - n) - \beta_n n \quad (2.3)$$

for e.g the n gate. The other gates' dynamics are analogous. The functions α and β are voltage but not time dependent. The discussion of initial values as well as functions for α_p, β_p $p = (n, h, m)$ can be found in [2] or [5]. The gates for each ion channel's conductance are found to be

$$\begin{aligned} g_{Na} &= \bar{g}_{Na} n^4 \\ g_K &= \bar{g}_K m^3 h \end{aligned} \quad (2.4)$$

and give form to the final model

$$\begin{aligned} C \frac{dV}{dt} &= I(t) - \bar{g}_{Na} n^4 (V - V_{Na}) - \bar{g}_K m^3 h (V - V_K) - g_L (V - V_L) \\ \frac{dn}{dt} &= (1 - n) \alpha_n(V) - \beta_n n(V) \\ \frac{dm}{dt} &= (1 - m) \alpha_m(V) - \beta_m m(V) \\ \frac{dh}{dt} &= (1 - h) \alpha_h(V) - \beta_h h(V) \end{aligned} \quad (2.5)$$

We did not define a gate for the leak term as it is assumed constant.

2.4.2 "IF and LIF"

In contrast of the HH model in eq. (2.5), the simplest models of neurons are the Integrate and Fire (IF) and Leaky-integrate-and-fire (LIF) models.

IF Neurons IF Neurons, as the name implies, integrate the incoming current over time.

$$\frac{dV(t)}{dt} = \frac{1}{C} I(t) \quad (2.6)$$

The membrane voltage is governed by the incoming current spikes of connected neurons and the membrane capacitance. The neuron potential does not change without a change of input current and thus presents as a perfect integrator of the input.

LIF Neurons In contrast to that the LIF neuron contains a leak term on the RHS which brings the voltage back to its resting potential over time. The model can be expressed as

$$\tau \frac{dV(t)}{dt} = -(V(t) - E_r) + RI(t), \quad (2.7)$$

where $\tau = RC$ is the time constant the composed of the membrane resistance R and the membrane capacitance C and the resting potential E_r . In the absence of input $I(t)$ the voltage settles on the membrane potential E_r .

The input $I(t)$ encapsulates external inputs as well as a sum of Dirac functions indicating a spiking neuron

$$I(t) = \sum_k \delta(t - t^k) \quad (2.8)$$

and t_k being the time of the k -th spike. When the membrane voltage exceeds the threshold potential \bar{v} , a spike is sent out by the neuron and the voltage sets back to its reset voltage v_{res} .

This is not correct. For weights, but the same thing only when there are more than one neuron

2.4.3 Izhikevich Neuron

While the above models deliver a useful and cheap simplification, they lack in accuracy. The Izhikevich model [4] of the neuron tries to be the of both worlds in terms of efficiency and accuracy. It is comprised of 2D ODEs with the membrane potential v as

$$\begin{aligned} \frac{dv}{dt} &= 0.04v^2 + 5v + 140 - u + I(t) \\ \frac{du}{dt} &= a(bv - u). \end{aligned} \quad (2.9)$$

With the chosen factors, the neuron experiences a spike when $u \geq 30\text{mV}$, in which case the neuron resets to

$$\begin{aligned} u &\leftarrow u + d \\ v &\leftarrow c \end{aligned} \quad (2.10)$$

The parameters describe a scale of recovery, b sensitivity, c the reset potential of v and d the reset of variable u . Depending on these parameters one can achieve different behaviours of the neuron e.g. regular spiking, fast spiking and low threshold spiking to name a few [4].

Maybe shift explanation which could be extended on

2.5 Neural Networks

2.5.1 Biological Neural Network

2.5.2 Artificial Neural Networks

2.5.3 Spiking Neural Networks

A spiking Neural network is one step closer to a biologic representation of a brain. Instead of conveying information using a gradient in conventional NNs, information is propagated using discrete spikes of excitation, similar to biological neurons. Hereby one can distinguish between several ideas of implementation.

2.5.4 Poisson-Networks

2.5.5 Liquid state machines

2.5.6 GLM

2.5.7 Balanced Networks

Balanced networks differ from the previous approaches that they closely track excitation an inhibition. The derivation of its behaviour is adopted from [1] and [3].

We s

2.5.8 Learning: SGD and STDP

Key to give any NN the ability to solve a task, it is integral to learn/train the network. The adaption of synapse weights is necessary to accomplish any functionality based on the underlying data[6]. There are various ways to train a network. The most fundamental distinction can be made between supervised, unsupervised and reinforcement learning rules. One needs to remember that Artificial Neural Networks (ANNs) and SNNs require completely different learning algorithms because of their different transport of information.

For a review

Supervised Learning methods

Gradient based methods require differentiability and therefore continuity, thus are only applicable for ANNs.

Explain gradient methods. The derivative of the weights and biases is used for the derivative of the cost function. Efficient methods for building the derivative exists. With reference!

Unsupervised Learning methods

STDP

Reinforcement learning

Here explain the concepts for each of the NNs

Give references for the STDP variances

Chapter 3

<Engineering-related content, Methodologies and Methods>

Describe the engineering-related contents (preferably with models) and the research methodology and methods that are used in the degree project.

Most likely it generally describes the method used in each step to make sure that you can answer the research question.

3.1 Engineering-related and scientific content:

Applying engineering related and scientific skills; modelling, analysing, developing, and evaluating engineering-related and scientific content; correct choice of methods based on problem formulation; consciousness of aspects relating to society and ethics (if applicable).

As mentioned earlier, give a theoretical description of methodologies and methods and how these are applied in the degree project.

was ist meine research question?

zusammensetzung von den beiden systeme: dynamisches system und neuronales netz. mehr oder weniger die herleitung kopieren aus dem paper. Dann mit learning von den gewichten.

Here I describe what how it needs to be done. So this is the place for the derivation The concept and the process whatever that means Later there comes the how I implemented

it. Here is what we needs to be implemented.

Here very detailed explanation of the Balanced network for this problem

Very detailed way for the regular NN for this problem Basics of the controller design used in this comparison aka LQG controller

Method of learning the weights for the SNN Method of comparison

Chapter 4

<The work>

Describe the degree project. What did you actually do? This is the practical description of how the method was applied.

4.1 Creating the SNN

How do we make the SNN Matlab Balanced spiking network (say why to use that) maybe pseudo code Ideally some theorem (convergence???) Simulation? nein kommt in den naechsten part

4.2 Creating the NN

4.3 Creating the regular Controller

Chapter 5

<Result>

Describe the results of the degree project.

Chapter 6

<Conclusions>

Describe the conclusions (reflect on the whole introduction given in Chapter 1).

Discuss the positive effects and the drawbacks.

Describe the evaluation of the results of the degree project.

Describe valid future work.

The sections below are optional but could be added here.

6.1 Discussion

6.1.1 Future Work

6.1.2 Final Words

Todo list

■ Neuro stuff, very rapid development, tremendous progress, many things are successful with NNs. Then list fields that work well. E.g pattern recognition, bioinformatics, neuroscience. With spiking neural networks they are behind the state of the art feedforward networks but the gap is closing. There are already fields where they are excel compared over normal NN.	1
■ Maybe put some exact numbers here and a source	1
■ Sounds vague	1
■ List here also efforts with other concepts apart from Balanced Networks . . .	8
■ Add a reference to a monography.	9
■ This is not truly correct. Forgot weights, but at the same time only when there are more than 1 neuron	11
■ Maybe shitty explanation, which could be extended on.	11
■ Make clear distinction between forward nns and ann. Bcs apparently they are not the same!	12
■ Put this reference in and say its is copied partly from them	12
■ Explain gradient methods. The derivative of the weights and biases is used for the derivative of the cost function. Efficient methods for building the derivative exists. With reference!	13

If you are using mendeley to manage references, you might have to export them manually in the end as the automatic ways removes the "date accessed" field

Bibliography

- [1] Boerlin, Martin, Machens, Christian K. **and** Denève, Sophie. “Predictive Coding of Dynamical Variables in Balanced Spiking Networks”. **in:** *PLOS Computational Biology* 9.11 (14 **november** 2013). Publisher: Public Library of Science, e1003258. ISSN: 1553-7358. DOI: 10 . 1371 / journal . pcbi . 1003258. URL: <https://journals.plos.org/ploscompbiol/article?id=10.1371/journal.pcbi.1003258> (**urlseen** 20/09/2022).
- [2] Hodgkin, A. L. **and** Huxley, A. F. “A quantitative description of membrane current and its application to conduction and excitation in nerve”. **in:** *The Journal of Physiology* 117.4 (1952). _eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1113/jphysiol.1952.sp004764>, **pages** 500–544. ISSN: 1469-7793. DOI: 10 . 1113 / jphysiol . 1952 . sp004764. URL: <https://onlinelibrary.wiley.com/doi/abs/10.1113/jphysiol.1952.sp004764> (**urlseen** 21/09/2022).
- [3] Huang, Fuqiang, Riehl, James **and** Ching, ShiNung. “Optimizing the dynamics of spiking networks for decoding and control”. **in:** *2017 American Control Conference (ACC)*. 2017 American Control Conference (ACC). ISSN: 2378-5861. **may** 2017, **pages** 2792–2798. DOI: 10 . 23919/ACC.2017.7963374.
- [4] Izhikevich, E.M. “Simple model of spiking neurons”. **in:** *IEEE Transactions on Neural Networks* 14.6 (**november** 2003). Conference Name: IEEE Transactions on Neural Networks, **pages** 1569–1572. ISSN: 1941-0093. DOI: 10 . 1109 / TNN . 2003 . 820440.
- [5] Johnston, Daniel **and** Wu, Samuel Miao-sin. *Foundations of cellular neurophysiology*. Cambridge, Mass: MIT Press, 1995. 676 **pagetotals**. ISBN: 978-0-262-10053-3.

- [6] Zheng, Shengjie, Qian, Lang, Li, Pingsheng, He, Chenggang, Qin, Xiaoqin **and** Li, Xiaojian. “An Introductory Review of Spiking Neural Network and Artificial Neural Network: From Biological Intelligence to Artificial Intelligence”. **in:** *arXiv:2204.07519 [cs]* (09 **april** 2022). arXiv: 2204.07519. URL: <http://arxiv.org/abs/2204.07519> (**urlseen** 20/09/2022).

Appendix - Contents

A First Appendix	24
B Second Appendix	25

Appendix A

First Appendix

This is only slightly related to the rest of the report

Appendix B

Second Appendix

this is the information