EÖTVÖS LORÁND UNIVERSITY

FACULTY OF INFORMATICS

DEPT. OF ARTIFICIAL INTELLIGENCE.

Myocardial Perfusion Imaging using Vision Transformers

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Declaration

I hereby declare that this thesis titled "Myocardial Perfusion Imaging with Vision Transformers" and the work presented in it is my own original research. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at Eötvös Loránd University.

- Where I have consulted the published work of others, this is always clearly attributed.

- Where I have quoted from the work of others, the source is always given.

- I have acknowledged all main sources of help.

- This thesis has not been submitted for any other degree or professional qualification.

Signed: Haris Ali

 Date: 13th April, 2025

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Thank you all.

Contents

CONTENTS

Abstract

The manual delineating the left ventricle (LV) in Myocardial Perfusion Imaging (MPI) is one of the most labour-intensive and time consuming tasks in nuclear cardiology and radiology. The outcome of the diagnosis of the MPI is extremely dependent on the accuracyand the consistency of the segmentation of the ventricles, hence the process is done under extreme caution in roder to minimize the risks of any possible error. However, the process of turning this task into an automated one present a number of challenges that need to bbe mitigated. Fist of all, the signal-to-noise ration (SNR) is mostly low and the resolution of the image is limited, complicating the process of detecting the boundaries. Secondly, the high disparity in both the cardiac traces uptake ad the differences in the hardware used for the imaging introduces inconsistencies. Finally, their is a lack of a standardized definition of the shape of the LV and the there is no standard shape that can be traced based purely on image data, which introduces a lot more ambiguity in the task.

This thesis proposes a novel method built to address the limitations mentioned above by using a Transformer-based architecture, integrating statistical shape prior (SSP) technique. This approach is specifically used to mitigate the data-hungry nature of the transformers in case of limited deta. The proposed architecture achieves over 4% improvementover a number of metrics in segmentation and classification against the benchmarked state-of-the-art (SOTA) approaches use for LV segmentation, both on the synthetic data and the real-world clinical scans.

In addition to the improvements in the quantitative metrics, the incorporation of the prior shape information enabled the model to learn insights into the variability and the structural patterns of the LV anatomy in MPI single-photon emission tomography (SPECT) imaging. This deeper understanding of the LV enhances the reliability of the AI-powered automatic segmentation of the LV and also the general comprehension of the morphology of the LV in clinical practice.

Chapter 1

Introduction

Myocardial Perfusion Imaging (MPI) using single-photon emission computed tomography (SPECT) pllays an important role in the process of non-invasive assessment of the coronary artery disease (CAD). Considerig cardiovascular diseases being one of the leading causes of mortality all across the world, the need for an efficient, accurate and accessible tool for diagnosis is at a high demand. MPI SPECT provides critial information about the perfusion status of the heart, which helps in the early detection and planning the treatment wich improves the outcomes of the patients.

Radionuclide MPI under a specific condition, such as stree, is majorly regarded as one of the most effective diagnosis technique, which ia also non-invasive, in order to identify the or detect the coronary artery disease (CAD). Using the application of MPI SPECT, clinicians become equipped to diagnose and detect the functionally relevant coronary stenoses with a relatively high level of specificity This actually enables them to decisions that are informed and possibly the right ones recarding the pathways of the patients' treatment [1]. One of the major strengths of MPI is the adaptability of the technique, as it can incorporate a number of radiopharmaceutical agents, such as 201Tl Chloride, 99mTc Tetrofosmin, and 99mTc Sestamibi, which basically is dependant upon the imaging protocols and imaging needs. The mentioned agents are typicallyy administered intravenously before the image acquisition part, and then the collected image data are later reconstructed using techniques which are dedicatedly designed for cardiac imagery. The last, and possibly the most crucial, stages in the diagnostic process involves the segmentation of the anatomical structures relevant to the diseases and then the reorientation of this segmented volumetric data. This part of the diagnostic is usually performed by trained clinical

professionals in order to ensure precision, better reliability and to mitigate the risks of errors.

Efficient and accurate quantitative analysis of the 3D MPI SPECT data is extremely sensitive to a number of factors that are involved in the full end-to-end imaging and reconstruction pipeline. All of these factors together contribute not only to the reliability of the evaluation of the data, but also to the detection of a range of cardiac abnormalities [2]. One important step in this process is the segmentation and reorientation of the LV, which basically refers to the determination of te spatial alignment of the LV and its segmentation based on the anatomical midline. The tasks of both reorientation and the segmentation within MPI SPECT imaging have been acknowledged, for a long time, as one of the central yet difficult challenges. Over the course of years, mutltiple commercial systems have been developed in order to counter these issues, but more often relying on very extensive and curated datasets in order to ensure reliable performance in clinical environments [3], [4], [5].However, the eixisting solutions fall short when they are applied to the newer reconstruction paradigms, especially in the situations where there are only a limited number of labled patients datasets. In order to mitigate these imitations faced by the current solutions and to increase the generalization capabilities of the models under llimited data conditions, approaches incorporating self-supervised learning and few-shot learning have gained popularity. Nevertheless, the effectiveness of these strategies is most of the times overshadowed by the high costs associated with the expert annotations. In addition to this the lack of consensus regarding a standard segmentation protocol also complicate the practical application of the processes.

In the recent years, within the field of MPI SPECT imaging, the adoption of Deep Learning (DL) techniques are looking at a significant revival [6]. This renewal is basically driven in part by the development of the novel radiotracers and also the growing clinical demand to minimize the amount of administered radiation dose and also the image acquisition time of the performed procedures [7]. As a consequence, the modern methods of reconstruction have been focusing on configurations that are based on low photon count data, sparse acquisition views and reduced amount of injected doses [8], [9], [10]. But inspite all that, the advancements do not fully rosolve the challenges which are inherent to the segmentation tasks of MPI SPECT. Despite using state-of-the-art neural network based reconstruction strategies, the segmentation accuracy is still heavily relied on the underlying reconstructed images.

When working with lower-dose inputs, the images mostly lack proper structural clarity, which diminishes the benefits which are offered by the DL based reconstruction methods. Even in situations where the image reconstruction achieves are visual equivalence to a full-dose filtered back projection methods, the issues of low Signal-to-Noise Ratio (SNR), Poisson noise characteristics, and the impact of partial volume effect (PVE) continue to affect the generalization capabilities and hence the reliability of automated segmentation models.

Chapter 2

User documentation

Lorem ipsum dolor sit amet $\mathbb{N}$, consectetur adipiscing elit. Duis nibh leo, dapibus in elementum nec, aliquet id sem. Suspendisse potenti. Nullam sit amet consectetur nibh. Donec scelerisque varius turpis at tincidunt. Cras a diam in mauris viverra vehicula. Vivamus mi odio, fermentum vel arcu efficitur, lacinia viverra nibh. Aliquam aliquam ante mi, vel pretium arcu dapibus eu. Nulla finibus ante vel arcu tincidunt, ut consectetur ligula finibus. Mauris mollis lectus sed ipsum bibendum, ac ultrices erat dictum. Suspendisse faucibus euismod lacinia $\mathbb{Z}$.

2.1 Enumerations and lists

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- Fusce in aliquet neque, in pretium sem.

- Donec tincidunt tellus id lectus pretium fringilla.

- Nunc faucibus, erat pretium tempus tempor, tortor mi fringilla neque, ac congue ex dui vitae mauris.

Donec dapibus sodales ante, at scelerisque nunc laoreet sit amet. Mauris porttitor tincidunt neque, vel ullamcorper neque pulvinar et. Integer eu lorem euismod,

faucibus lectus sed, accumsan felis. Nunc ornare mi at augue vulputate, eu venenatis magna mollis. Nunc sed posuere dui, et varius nulla. Sed mollis nibh augue, eget scelerisque eros ornare nec.

1. Donec pretium et quam a cursus. Ut sollicitudin tempus urna et mollis.

2. Aliquam et aliquam turpis, sed fermentum mauris. Nulla eget ex diam.

3. Donec eget tellus pharetra, semper neque eget, rutrum diam Step.

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Vestibulum venenatis malesuada enim, ac auctor erat vestibulum et. Phasellus id purus a leo suscipit accumsan.

Orci varius natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Nullam interdum rhoncus nisl, vel pharetra arcu euismod sagittis. Vestibulum ac turpis auctor, viverra turpis at, tempus tellus.

Morbi dignissim erat ut rutrum aliquet. Nulla eu rutrum urna. Integer non urna at mauris scelerisque rutrum sed non turpis.

2.1.1 Lists with narrow spacing inbetween items

Phasellus ultricies, sapien sit amet ultricies placerat, velit purus viverra ligula, id consequat ipsum odio imperdiet enim:

1. Maecenas eget lobortis leo.
2. Donec eget libero enim.
3. In eu eros a eros lacinia maximus ullamcorper eget augue.

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[1]Phasellus faucibus varius purus, nec tristique enim porta vitae.

In quis turpis metus. Proin maximus nibh et massa eleifend, a feugiat augue porta. Sed eget est purus. Duis in placerat leo. Donec pharetra eros nec enim convallis:

- Pellentesque odio lacus.

- Maximus ut nisl auctor.

- Sagittis vulputate lorem.

Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Sed lorem libero, dignissim vitae gravida a, ornare vitae est.

Cras maximus massa commodo pellentesque viverra.

Morbi sit amet ante risus. Aliquam nec sollicitudin mauris

Ut aliquam rhoncus sapien luctus viverra arcu iaculis posuere

2.2 Images and figures

Aliquam vehicula luctus mi a pretium. Nulla quam neque, maximus nec velit in, aliquam mollis tortor. Aliquam erat volutpat. Curabitur vitae laoreet turpis. Integer id diam ligula. Nulla sodales purus id mi consequat, eu venenatis odio pharetra. Cras a arcu quam. Suspendisse augue risus, pulvinar a turpis et, commodo aliquet turpis. Nulla aliquam scelerisque mi eget pharetra. Mauris sed posuere elit, ac lobortis metus. Proin lacinia sit amet diam sed auctor. Nam viverra orci id sapien sollicitudin, a aliquam lacus suscipit
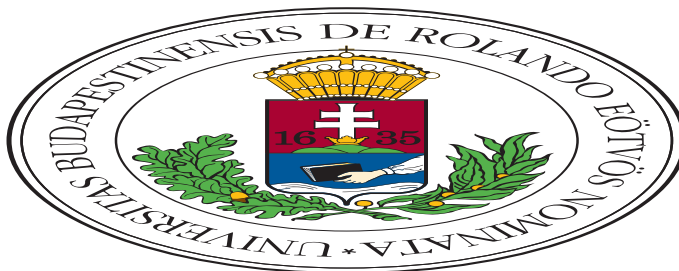
Figure 2.1: Quisque ac tincidunt leo

2.2.1 Framing figures

Ut aliquet nec neque eget fermentum. Cras volutpat tellus sed placerat elementum. Quisque neque dui, consectetur nec finibus eget, blandit id purus. Nam eget ipsum non nunc placerat interdum.

Figure 2.2: Quisque ac tincidunt leo

2.2.2 Subfigures

In non ipsum fermentum urna feugiat rutrum a at odio. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Nulla tincidunt mattis nisl id suscipit. Sed bibendum ac felis sed volutpat. Nam pharetra nisi nec facilisis faucibus. Aenean tristique nec libero non commodo. Nulla egestas laoreet tempus. Nunc eu aliquet nulla, quis vehicula dui. Proin ac risus sodales, gravida nisi vitae, efficitur neque

(a) Vestibulum quis mattis urna

(b) Donec hendrerit quis dui sit amet venenatis

Figure 2.3: Aenean porttitor mi volutpat massa gravida

Nam et nunc eget elit tincidunt sollicitudin. Quisque ligula ipsum, tempor vitae tortor ut, commodo rhoncus diam. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Phasellus vehicula quam dui, eu convallis metus porta ac.

2.3 Tables

Nam magna ex, euismod nec interdum sed, sagittis nec leo. Nam blandit massa bibendum mattis tristique. Phasellus tortor ligula, sodales a consectetur vitae, placerat vitae dolor. Aenean consequat in quam ac mollis.

Phasellus tortor	Aenean consequat
Sed malesuada	Aliquam aliquam velit in convallis ultrices.
Purus sagittis	Quisque lobortis eros vitae urna lacinia euismod.
Pellentesque	Curabitur ac lacus pellentesque, eleifend sem ut, placerat enim. Ut auctor tempor odio ut dapibus.

Table 2.1: Maecenas tincidunt non justo quis accumsan

2.3.1 Multi rows and multi columns

Mauris a dapibus lectus. Vestibulum commodo nibh ante, ut maximus magna eleifend vel. Integer vehicula elit non lacus lacinia, vitae porttitor dolor ultrices. Vivamus gravida faucibus efficitur. Ut non erat quis arcu vehicula lacinia. Nulla felis mauris, laoreet sed malesuada in, euismod et lacus. Aenean at finibus ipsum. Pellentesque dignissim elit sit amet lacus congue vulputate.

Quisque	Suspendisse		Aliquam		Vivamus	
	Proin	Nunc	Proin	Nunc	Proin	Nunc
Leo	2,80 MB	100%	232 KB	8,09%	248 KB	8,64%
Vel	9,60 MB	100%	564 KB	5,74%	292 KB	2,97%
Auge	78,2 MB	100%	52,3 MB	66,88%	3,22 MB	4,12%

Table 2.2: Vivamus ac arcu fringilla, fermentum neque sed, interdum erat. Mauris bibendum mauris vitae enim mollis, et eleifend turpis aliquet.

2.3.2 Long tables over multiple pages

Nunc porta placerat leo, sit amet porttitor dui porta molestie. Aliquam at fermentum mi. Maecenas vitae lorem at leo tincidunt volutpat at nec tortor. Vivamus semper lacus eu diam laoreet congue. Vivamus in ipsum risus. Nulla ullamcorper finibus mauris non aliquet. Vivamus elementum rhoncus ex ut porttitor.

Praesent aliquam mauris enim	
Suspendisse potenti	*Lorem ipsum dolor sit amet*
Praesent	Nulla ultrices et libero sit amet fringilla. Nunc scelerisque ante tempus sapien placerat convallis.
Luctus	Integer hendrerit erat massa, non hendrerit risus convallis at. Curabitur ultrices, justo in imperdiet condimentum, neque tortor luctus enim, luctus posuere massa erat vitae nibh.
Egestas	Duis fermentum feugiat augue in blandit. Mauris a tempor felis. Pellentesque ultricies tristique dignissim. Pellentesque aliquam semper tristique. Nam nec egestas dolor. Vestibulum id elit quis enim fringilla tempor eu a mauris. Aliquam vitae lacus tellus. Phasellus mauris lectus, aliquam id leo eget, auctor dapibus magna. Fusce lacinia felis ac elit luctus luctus.
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Pellentesque	Donec felis nibh, imperdiet a arcu non, vehicula gravida nibh. Quisque interdum sapien eu massa commodo, ac elementum felis faucibus.
Molestie	Cras ullamcorper tellus et auctor ultricies. Maecenas tincidunt euismod lectus nec venenatis. Suspendisse potenti. Pellentesque pretium nunc ut euismod cursus. Nam venenatis condimentum quam. Curabitur suscipit efficitur aliquet. Interdum et malesuada fames ac ante ipsum primis in faucibus.

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Vivamus semper	In purus purus, faucibus eu libero vulputate, tristique sodales nunc. Nulla ut gravida dolor. Fusce vel pellentesque mi, vel efficitur eros. Nunc vitae elit tellus. Sed vestibulum auctor consequat.
Condimentum	Nulla scelerisque, leo et facilisis pretium, risus enim cursus turpis, eu suscipit ipsum ipsum in mauris. Praesent eget pulvinar ipsum, suscipit interdum nunc. Nam varius massa ut justo ullamcorper sollicitudin. Vivamus facilisis suscipit neque, eu fermentum risus. Ut at mi mauris.

Table 2.3: Praesent ullamcorper consequat tellus ut eleifend

Chapter 3

Developer documentation

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Duis nibh leo, dapibus in elementum nec, aliquet id sem. Suspendisse potenti. Nullam sit amet consectetur nibh. Donec scelerisque varius turpis at tincidunt.

3.1 Theorem-like environments

Definition 1. Mauris tristique sollicitudin ultrices. Etiam tristique quam sit amet metus dictum imperdiet. Nunc id lorem sed nisl pulvinar aliquet vitae quis arcu. Morbi iaculis eleifend porttitor.

Maecenas rutrum eros sem, pharetra interdum nulla porttitor sit amet. In vitae viverra ante. Maecenas sit amet placerat orci, sed tincidunt velit. Vivamus mattis, enim vel suscipit elementum, quam odio venenatis elit, et mollis nulla nunc a risus. Praesent purus magna, tristique sed lacus sit amet, convallis malesuada magna. Phasellus faucibus varius purus, nec tristique enim porta vitae.

Theorem 1. *Nulla finibus ante vel arcu tincidunt, ut consectetur ligula finibus. Mauris mollis lectus sed ipsum bibendum, ac ultrices erat dictum. Suspendisse faucibus euismod lacinia. Etiam vel odio ante.*

Proof. Etiam pulvinar nibh quis massa auctor congue. Pellentesque quis odio vitae sapien molestie vestibulum sit amet et quam. Pellentesque vel dui eget enim hendrerit finibus at sit amet libero. Quisque sollicitudin ultrices enim, nec porta magna imperdiet vitae. Cras condimentum nunc dui. □

Donec dapibus sodales ante, at scelerisque nunc laoreet sit amet. Mauris porttitor tincidunt neque, vel ullamcorper neque pulvinar et. Integer eu lorem euismod, faucibus lectus sed, accumsan felis.

Remark. Nunc ornare mi at augue vulputate, eu venenatis magna mollis. Nunc sed posuere dui, et varius nulla. Sed mollis nibh augue, eget scelerisque eros ornare nec. Praesent porta, metus eget eleifend consequat, eros ligula eleifend ex, a pellentesque mi est vitae urna. Vivamus turpis nunc, iaculis non leo eget, mattis vulputate tellus.

Fusce in aliquet neque, in pretium sem. Donec tincidunt tellus id lectus pretium fringilla. Nunc faucibus, erat pretium tempus tempor, tortor mi fringilla neque, ac congue ex dui vitae mauris. Donec pretium et quam a cursus.

Note. Aliquam vehicula luctus mi a pretium. Nulla quam neque, maximus nec velit in, aliquam mollis tortor. Aliquam erat volutpat. Curabitur vitae laoreet turpis. Integer id diam ligula.

Ut sollicitudin tempus urna et mollis. Aliquam et aliquam turpis, sed fermentum mauris. Nulla eget ex diam. Donec eget tellus pharetra, semper neque eget, rutrum diam.

3.1.1   Equations, formulas

Duis suscipit ipsum nec urna blandit, $2 + 2 = 4$ pellentesque vehicula quam fringilla. Vivamus euismod, lectus sit amet euismod viverra, dolor metus consequat sapien, ut hendrerit nisl nulla id nisi. Nam in leo eu quam sollicitudin semper a quis velit.

$$a^2 + b^2 = c^2$$

Phasellus mollis, elit sed convallis feugiat, dolor quam dapibus nibh, suscipit consectetur lacus risus quis sem. Vivamus scelerisque porta odio, vitae euismod dolor accumsan ut.

In mathematica, identitatem Euleri (equation est scriptor vti etiam notum) sit aequalitatem Equation.:

$$e^{i \times \pi} + 1 = 0 \tag{3.1}$$

Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia curae; Nullam pulvinar purus at pharetra elementum. Aequationes adsignans aequa-

tionis signum:

$$A = \frac{\pi r^2}{2} \tag{3.2}$$
$$= \frac{1}{2}\pi r^2 \tag{3.3}$$

Proin tempor risus a efficitur condimentum. Cras lobortis ligula non sollicitudin euismod. Fusce non pellentesque nibh, non elementum tellus. Omissa numeratione aliquarum aequationum:

$$f(u) = \sum_{j=1}^{n} x_j f(u_j)$$
$$= \sum_{j=1}^{n} x_j \sum_{i=1}^{m} a_{ij} v_i$$
$$= \sum_{j=1}^{n} \sum_{i=1}^{m} a_{ij} x_j v_i \tag{3.4}$$

3.2 Source code samples

Nulla sodales purus id mi consequat, eu venenatis odio pharetra. Cras a arcu quam. Suspendisse augue risus, pulvinar a turpis et, commodo aliquet turpis. Nulla aliquam scelerisque mi eget pharetra. Mauris sed posuere elit, ac lobortis metus. Proin lacinia sit amet diam sed auctor. Nam viverra orci id sapien sollicitudin, a aliquam lacus suscipit. Quisque ac tincidunt leo.

```cpp
#include <stdio>

int main()
{
  int c;
  std::cout << "Hello World!" << std::endl;

  std::cout << "Press any key to exit." << std::endl;
  std::cin >> c;

  return 0;
}
```

Code 3.1: Hello World in C++

```csharp
1  using System;
2  namespace HelloWorld
3  {
4    class Hello
5    {
6      static void Main()
7      {
8        Console.WriteLine("Hello World!");
9
10       Console.WriteLine("Press any key to exit.");
11       Console.ReadKey();
12     }
13   }
14 }
```

Code 3.2: Hello World in C#

3.2.1 Algorithms

A general Interval Branch and Bound algorithm is shown in Algorithm. An appropriate selection rule is applied in. Source of example: Acta Cybernetica (this is a hyperlink).

Algorithm 1 A general interval B&B algorithm

Funct IBB(S, f)

1: Set the working list $\mathcal{L}_W := \{S\}$ and the final list $\mathcal{L}_Q := \{\}$
2: **while** ($\mathcal{L}_W \neq \emptyset$) **do**
3:     Select an interval X from $\mathcal{L}_W$ ▷ Selection rule
4:     Compute $lbf(X)$ ▷ Bounding rule
5:     **if** X cannot be eliminated **then**   ▷ Elimination rule
6:         Divide X into X^j, $j = 1, \ldots, p$, subintervals   ▷ Division rule
7:         **for** $j = 1, \ldots, p$ **do**
8:             **if** X^j satisfies the termination criterion **then**   ▷ Termination rule
9:                Store X^j in $\mathcal{L}_W$
10:             **else**
11:                Store X^j in $\mathcal{L}_W$
12:             **end if**
13:         **end for**
14:     **end if**
15: **end while**
16: **return** $\mathcal{L}_Q$

Chapter 4

Conclusion

Lorem ipsum dolor sit amet, consectetur adipiscing elit. In eu egestas mauris. Quisque nisl elit, varius in erat eu, dictum commodo lorem. Sed commodo libero et sem laoreet consectetur. Fusce ligula arcu, vestibulum et sodales vel, venenatis at velit. Aliquam erat volutpat. Proin condimentum accumsan velit id hendrerit. Cras egestas arcu quis felis placerat, ut sodales velit malesuada. Maecenas et turpis eu turpis placerat euismod. Maecenas a urna viverra, scelerisque nibh ut, malesuada ex.

Aliquam suscipit dignissim tempor. Praesent tortor libero, feugiat et tellus porttitor, malesuada eleifend felis. Orci varius natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Nullam eleifend imperdiet lorem, sit amet imperdiet metus pellentesque vitae. Donec nec ligula urna. Aliquam bibendum tempor diam, sed lacinia eros dapibus id. Donec sed vehicula turpis. Aliquam hendrerit sed nulla vitae convallis. Etiam libero quam, pharetra ac est nec, sodales placerat augue. Praesent eu consequat purus.

Acknowledgements

In case your thesis received financial support from a project or the university, it is usually required to indicate the proper attribution in the thesis itself. Special thanks can also be expressed towards teachers, fellow students and colleagues who helped you in the process of creating your thesis.

Appendix A

Simulation results

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List of Figures

List of Tables

List of Algorithms

List of Codes