Comparative Analysis between Micro and Macro Agent Evacuation Using PedSim Simulator

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Abstract

Disaster management pertains to coping with disaster, relief and evacuation in the event of a catastrophe. It is of paramount importance as it pertains to the protection of lives and property during the time of calamity. To mitigate the damage of such incidents, simulations are performed in order to formulate an efficient and optimized exit strategy for the people who are struck by such unfortunate incidents and to evacuate them to a safe zone as quickly as possible. The simulation of an evacuation of the participating agents broadly falls under three categories - Macro Agent Simulation, Micro Agent Simulation and/or a combination of Macro-Micro Agent Simulation (grouping according to age, gender, social ties such as family, friendships etc.). Although extensive work has been carried out to simulate disaster scenarios comprising of a massive number of agents with an aggregate set of characteristics (Macro Agent Simulation), very little work has been done so far to simulate realistic social behaviour of agents during a disaster scenario, especially pertaining to micro agent simulations. Realistic human and social behaviour characteristics are possible only through micro agent-based simulations as complex psychological and sociological paradigms can be mapped and hence dynamic real-time strategy decisions can be better understood, especially during a crisis. Through this thesis, I aim to present the simulation and comparison of various micro and macro agent scenarios.

In order to run the aforementioned simulations, an open source microscopic pedestrian simulator - PedSim is used. This tool not only simulates the various complex scenarios. it also provides visual feedback in real time. PedSim is a crowd simulation library capable of analysis of real time pedestrian flow rate. This agent-based model (ABM) tool is a class of computational models for simulating the actions and interactions of autonomous agents (either individual or collective entities such as organizations or groups) with a view to assessing their effects on the system as a whole. It combines elements of game theory, complex systems, emergency, computational

sociology, multi-agent systems, and evolutionary programming. Although there are many proposed agent modelling simulators that are available, many if not most are with commercial license and do not support real time data flow. This tool is also customized and further extended in order to take an optimized routing algorithm for agents. The PedSim simulator is modelled for both indoor and outdoor areas (parking lots, forests etc.). The simulation tool is able to take sensory based data and apply them to the modelling agents/nodes to simulate real/design time analysis. The main advantage of this library is the architecture that enables visibility of users live using tcp/stream-based output through batch processing. The implementation is pure in C++ with minimal external dependencies like Qt Framework. The output of PedSim can be translated using a graphics engine to provide visually appealing realistic render of a walking person. The code is modular, scalable and open source available under GPL license.

The main goal of this thesis is to exhibit an objective performance analysis and a comparison between an existing macro agent simulation algorithm against an optimized algorithm coupled with realistic constraints, testing them against a massively populated macro and micro agent model for real-time dynamic evacuation.

Acknowledgements

I would like to thank the Informatics department for providing all the support and guidance.I would like to thank my parents, without whom my life would not be possible. I would also like to thank my advisor, my dissertation committee, and my research collaborators because every graduate student needs to do so. And finally, I thank the members of the research group, for providing me so many opportunities to learn and grow.

I finally thank the Amrita University and University of L'Aquila for selecting me for the I2Cost Dual Degree program that has catapulted me thus far and is continuing to do so.

To my parents.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

Due to increasing topological changes in urban environment, the human civilization has been subjected to increasing risk of disasters due to natural or artificial, and/or a combination of the two causes, since the better part of the modern era. Hence it has become an ever increasing need to design infrastructure to handle such disasters in the event it may occur. But even more so, the safe evacuation of people and personnel with the premises of the affected infrastructure takes precedence when dealing the necessary mitigation and disaster risk management. The evacuation time of people from a scene of disaster is extremely crucial in the case of an emergency in disaster situation. In order to reduce the time taken for evacuation, better and more robust exit strategy evacuation algorithms are developed which are used to model participating agents for their exit patterns and exit strategies and clock them based on performance, efficiency and practicality. In order to evaluate such parameters, evacuation simulation models have been developed and constantly tested over the years to investigate the emergency egress capabilities of the built environment for a variety of reasons including: difficulty in conducting real evacuation tests (drills); aiding building design and confirming conformity to building regulations; and even determining optimal evacuation routes for the building occupiers [1] [?]. Computational models were first introduced in the early 1980s since the inception of computers. During the 90s, academic researchers aimed to improve these the capabilities of these models in order to optimize and improve the pathfinding performance of the evacuees and their corresponding movements [2]. Over the course of many years, these algorithms have become the industry standard to perform exit evacuation time and performance analysis. The purpose of this thesis is to study the state of the art algorithm and to draw comparisons between micro model agent simulation with respect to its counterpart, the macro model agent simulation.

Realistic simulations involve complex relationships between an individual and the surroundings. Three types of interactions are possible whilst the individual performs complex decision making during an evacuation scenario. Through this thesis I aim to optimize these three types of interactions through various constraints and real time elements. The following encounters may be classified as below [1]:

- People-people interactions - interactions between participating evacuees.
- People-structure interactions- interactions within the enclosed topology.
- People- environment interactions- interactions with quarantined atmosphere (fire, smoke etc.) and possible debris.

During disaster scenarios standard evacuation pathways are often rigid and cannot autonomously provide modification for an exit strategy as the disaster ensues. The evacuees often find themselves in situations that force them to rely on general guidelines about how to react in emergency evacuation [3]. While such dynamic hazards cannot all be dealt with, using the traditional approach, Lujak, M., Billhardt H., Dunkel, J. et al [4] attempts to help the evacuees adapt to the changing topography of the environment due to hazard dynamics by updating a real time monitoring system using an IoT architecture built in place within the premises of the said topology of the building. The above mentioned work uses a combination of IoT devices to sense and identify and provide real-time monitoring for the participating agents. Our work also obtains data from real time sources and then it is simulated with both macro and micro based agent models and then used to analyse and draw conclusions from the resulting data.

The present thesis is a design of a computational software using Agent Based Model (ABMS) to help speedy evacuation in emergency situations. Our software architecture help optimise the navigational flow rate in cases of real-time disaster management. The scenario is that of many victims are struck up in a very large building in the event of an occurrence of a disaster like fire, earthquake, poisonous chemical gas leakage, imminent bomb attack, potential imminent building collapse (similar to that of twin towers of 9/11). As a side benefit the experience acquired gives valuable information in the case of architecture design at the time of building construction itself. By conveying a suggestive path for each individual in the building at the time of disaster, the panic, erratic and groping movements are reduced to minimum helping to achieve a streamlined flow. Bottlenecks in the flow are avoided by redirecting people to alternate paths. The benefit of the overall perspective of the scenario and informed management is instantaneously conveyed to each and every individual in real time. The floor capacities and width of the doors and passageways form part of the constraints in the modelling. This is scalable and generic version.

PedSim is a pedestrian simulator tool designed as a front end to facilitate disaster management scenarios. Disaster management plans are multi-layered and topology specific. Tools catering to disaster management require the users to input topographic information and also provide crowd/agent location information. This aggregate of data is then processed initially to create a layout of the premises. The layout defines several rules and boundary conditions imposing restrictions for the crowd to navigate. Such information can be used to instantly model very specific scenarios such as evacuation of specific floors of a building. Since, PedSim enables input of design specific topology, protocols can be established quickly for speedy evacuation. The second part includes behaviour analysis of crowd during different disaster patterns. The social behaviour of victims in disaster afflicted scenarios have been of keen interest to researchers over the recent years. Disaster affected regions often portray victims who exhibit severe trauma or stress leading to emotional/psychological shut down or present themselves making erratic decisions etc. This tool enables a platform for crowd flow modelling. Erratic movement patterns can be modelled, simulated and visualized to study the impact and speed of evacuation. Such processed information can be used to provide instructions or navigation guidelines for optimal evacuation. PedSim also allows for real time monitoring of crowds providing instant feedback on the visual front end. This enables redirection of crowds for balancing congestion while developing exit strategies. Each exit can also be associated with restrictive exit capacity and corresponding flow rate ensuring crowd balancing. The architectural design of the tool itself takes into account various factors such as streaming and batch processing of time critical data within permissible thresholds.

My work pertains to application of PedSim on our university building to implement and analyze the impacts of crowd evacuation during a disaster. The university building taken into consideration for our present study is level 3 of building (Coppito 0). The area under consideration is divided into 18 blocks. Each block consists of a set number of cells. Each cell represents a cubicle or a room. There are 26 cubicles/rooms in all. There is also one conference hall and two generic multipurpose areas used for allied purposes. In addition, there are several hallways and pathways for navigation. This area has four key exits distributed across the different boundary walls of the premises. At any given time, each cell hosts atmost twenty agents, reaching a maximum during peak hours of 10am to 2 pm Italy time. The premises often hosts about 100 people. We architected pedestrian flow simulation during a generic disaster which can include earthquake, fire and chemical leakage. The data is used to generate crowd clusters during events other than disasters such as workshops, cafeteria gatherings, conference gatherings etc. Below figure shows a typical population cluster during a conference gathering.

This thesis presents a case study where the Coppito 0 building is simulated during a disaster scenario using grid geometry based navigation algorithm as presented in the An IoT Software Architecture for an Evacuable Building Architecture by H.Muccini et.al [5]. The work also involves in expanding the capabilities of the existing PedSim simulation tool to include the new topology and the also to incorporate the algorithm and also further extended developed from the aforementioned paper and perform a real time analysis between micro and macro agents with the following criteria:

- specifying the cells by social distances
- respecting the area capacity and doors capacities constraints
- setting the speed accordingly for various groups
- simulating social attachment among some agents

As it is evident from the above constraints, the goal of this algorithm and this simulation is to make exit strategies as realistic as possible. By grouping certain agents together for instance, we can achieve realistic movement of participating agents, as in reality, people usually move in groups. families, friends etc. Furthermore, congestion is a big part of the evacuation scenario, as it is congestion that determines how fast or efficient the evacuation of agents occur and also how it would take to move groups of people. With groups of people clumped together, the next most natural constraint would be to assign varying speeds as not all agents and not all groups of agents travel with the same speed across the topology of the building. There is also one other constraint which determines the cell capacity, which determines how spaced out and occupied agents are in a room, a hall or a passageway. This also help determine how many can get through a single doorway in order to transition from one passageway to another. This of course leads to previously mentioned issue of congestion.

All these constraints are hence taken into account as the simulation is performed in order to clock and test for the performance time and efficiency of the algorithm used for micro and macro model simulation.

The structure of the thesis is formulated as follows: chapter 2 provides a detailed literature and background work pertaining to the area of agent based simulation models and exit strategies. Chapter 3 focuses on the implementation details of the algorithm and specific details that are incorporated in order to extend the algorithm in order to adapt it to a more realistic setting and also technical details regarding the PedSim simulation environment. Chapter 4 presents the results of the comparisons of the optimized(realistic) algorithm between the macro and micro agent simulation setting and to chart out the various performance metrics that are obtained. Chapter 5 attempts to draw conclusions based on the obtained performance metrics and also present the future work related to the aforementioned. This thesis also provides a technical appendix for reference for the simulation of various micro and macro agent scenarios within the environment of PedSim.

Chapter 2

Related Work

In this section the background literature and the work related to agent based simulation is dicussed.

2.1 Pre-Modern Disaster Preparedness, Management and Relief Techniques

Although disasters have existed throughout the history of the universe for all living organisms, human beings are perhaps the only one to be affected on a massive scale as a collective group as we are vulnerable and weak compared to other animals that live and co-exist with us. Hence human beings have taken very many steps over the years fortifying and defending ourselves as best as we can through the various buildings and escape routes we design. The early inhabitants of mankind were not idle and did not become easy victims. There is historical evidence that the early man took various measures in order to cope with, reduce and mitigate risks. The mere fact that they chose to inhabit caves are a testament to this theory [6].

The ancient man also used other natural techniques for disaster preparedness. One of the prominent ones include the observation of animals since they are very perceptive to natural disasters, animal behavior can and has been used for the better part of the millenia to predict the onset of a natural disaster such as floods, earthquakes etc. One of the earliest works to be done in this field involves in the observation of the behavior of fish, specifically the catfish, as they were found to exhibit a definitive behavior in advance of the occurence of an earthquake [7]. Other experiments and observations pertaining to such natural responses include the obeservation of ground electric field effects on behavior of Albino rats, Mongolian gerbils (sand rats), hair-footed Djungarian hamsters, guinea pigs, and red sparrows [8]. A summary of such animal behavior and work is presented by Neeti Bhargava et. al. [9].

To combat various natural disasters that affect us, mankind has tried for over a millenia to improve and adapt buildings, and entire cities to cope during the time of a catatrosphe. There are two broad categories to the mitigation of these disasters that have been long employed [10]:

- structural based mitigation
- non-structural based mitigation

Since my work pertains to indoor simulation and evacuation management, the discussion for non-structural mitigation forms here is considered unnecessary and beyond the scope of this thesis. Structural mitigation involves the presence of a building or a man-made mechanical or technological adaptations performed to reduce hazards and mitigate risks. The following sub-section expands more on the more modern techniques that have been developed over the course of the modern era and their implications. Although better and state of the art systems have been developed over the years, these systems have complications of their own. Failure of the perfect working of an evacuation system leads to the possible death of all the agents who are in need of evacuation.

2.2 Routing Algorithms and IoT Based Evacuation Management

Routing algorithms and maze solving algorithms have especially been applied to the structural domains for the real time analysis of shortest paths and obstacle avoidance by both machine and human agents since the time the earliest shortest paths algorithms were developed. The development of the shortest path algorithm by Dijkstra in 1956, especially has seen a plethora of applications in various fields. As one can guess most of its applications have been catered to graph based problems and obstacle avoidance. Shortest paths exit strategy formation approach is a good way to analyse a safe egress as it provides obstacle avoidance as well. How can it successfully be applied to a real disaster scenario? Before the advancements were made to IoT based infrastructure, maze solving algorithms were used to successfully analyze a safe egress.

IoT and computation systems have brough about a tremendous potential to perceive the environment and then form the necessary strategies that are required to safely escort the human agents to a safe exit point during the time of disaster. Modern evacuation systems have sensors in place to allow for better perception of the world during a disaster scenario. For instance the work by Kobes et al. determined that during fire related disaster scenarios, 56.3% of the participating agents were able to determine the exit points based on the exit signs when there was no smoke present whilst 81.8% was able to identify exit points only based on the exit signs when their vision was imparied due to smoke [11]. Based on such data for instance, it greatly enhances our need to analyse the fastest and shortest egress path so that all human agents in the vicinity can get to the exit points. The shortest path algorithm - Dijkstra's algorithm is currently used as a great tool to provide the shortest exit points as it is demonstrated in the work by Jehyun Cho [12]. His research pertains to the dynamic analysis of a shortest path algorithm based on information obtained from the sensors and the smart infrastructure.

In order to address the issue of agent(s) and infrastructure mapping during a disaster event, state of the art sensors are placed all through the infrastructure in order to perceive the environment and the surrounding structures in order to analyze a safe egress. Motion detectors for instance are used to understand how many people are still trapped inside the building during a catastrophe. One example of using IoT technologies is proposed by Prasad Annadata et al. using multiple WIFI channels and the aforementioned motion detectors [13]. Based on the statistics gathered heuristic solutions are proposed in order to detect the number of personnel inside the infrastructure as well as perceive the environment.

Although the proposed methods and techniques are helpful in determining the shortest path to an exit point, they rarely can be used in a realistic scenario due to its simplistic nature. A real world scenario is more complex due the social dynamics of people. Such complexities are better understood while simulating agents in real and static simulations and then performing an analysis based on the observed stats. Such is what I hope to achieve through this thesis.

Existing literature on surveying personnel and the surrounding infrastructure for assistance based support for immediate first responders include the work the done by Palmieri et al., who proposes a hybrid cloud architecture to manage and store the necessary required resources to command and control activities during emergencies [14]. However the work done by H. Muccini et al. [5] aims to improve this work by adapting geolocation of first responders to track people during a disaster for evacuation. Furthermore W.Choi et al. [15] proposes to model building evacuation by dynamic flow maximization and by considering variable capacities on some arcs as a function of flows in incident arcs. For the purposes of modeling our topology we have used a similar arc based geometry for determining the topological capacity of a particular cell into which the entire infrastructure is divided into. Chen et al. [16] in addition to the above, proposes a flow control algorithm that calculates evacuation paths depending on building plan and total number of evacuees. Computation in this case aims at minimizing total evacuation time and assigning an optimal number of evacuees to each evacuation path. However [5] provides a robust solution by architecting an IoT system to monitor and update dynamically the topology of the environment.

Another important aspect that remains unaddressed is that in real disaster scenarios, over crowding and congestion of certain pathways and exit points are bound to occur frequently. The issue of congestion is serious and perilous and is arguably pointed out by a case study performed by John El Khoury [17] and analyses the dangers due to high traffic intensity during a disaster event. Although the analysis is performed on a wide scale city range, the implications of congestion and other such constraints are just a applicant to a much smaller scale infrastructure. To dynamically reallocate personnel to routes that are not just shortest paths but optimal paths is what we try to achieve through these simulations and added constraints. The work done by Antoine Desmet et al. [18] addresses the congestion issue by a "self adaptation" algorithm much inspired by the computer network routing algorithm - The Cognitive Packet routing algorithm by E. Gelenbe [19]. A robust evacuation with optimized routing solution proposed by H.Muccini et al. [5] are as follows:

- Optimal solutions that can be continuously updated, so evacuation guidelines can be adjusted according to visitors position that evolve over time.
- Paths that become suddenly unfeasible can automatically be discarded by the system.
- The model can be incorporated into a mobile app supporting emergency units to evacuate closed or open spaces.

The aforementioned algorithm is still incomplete as dynamic and realistic constraints are yet to be added. The constraints are 4 fold as mentioned in the introduction section. Over the course of chapter 3, the details of the algorithm is explained and how these constraints provide an even more optimized route since it considers congestion, grouping, varying age and speeds in addition.

2.3 Simulation Tools and Conditions

Chapter 3

Usage

To start, in your main .tex file, use this class as your main documentclass instead of 'report' or 'book'. For example:

$$\backslash documentclass[12pt, lot, lof]\{puthesis\}$$

In this example, we setup our document to use the PU Thesis style, with 12pt font for body text, and to include a List of Tables and List of Figures in the front matter. You could instead set an 11 point or 10 point font by changing the first option. You can also add 'los' to include a list of symbols.

To use single spacing, add the option 'singlespace'. This is a special option for the `puthesis` documentclass, which sets single spacing for both the front matter and for the document itself. Additional parameters should be set in your main .tex file, and are described in detail in Section 3.1.

The template itself declares two other options, to be set immediately after the `documentclass` command. First is 'printmode', declared with the command:

$$\backslash newcommand\{\backslash printmode\}\{\}$$

This command, used later in the thesis.tex file, turns off the `hyperref` package and all internal links in the PDF file. This removes any colored links and highlighting that would not be appropriate in a printed and bound thesis. Instead the `url` package is loaded, so that

url commands in your document will continue to work and urls will break properly across multiple lines.

When ‘printmode’ is not specified, the hyperref package is included. It creates colored links for citations, footnotes, and internal references, which can be used to navigate the PDF document more easily. It also adds bookmarks to the PDF file, mirroring the table of contents. By default, it is set to use colored links. For the PDF file that you will submit electronically to ProQuest, this may not be desirable since some copies may be printed, while others will be used electronically. Thus another option, ‘proquestmode’, is defined that keeps hyperref but disables colored links:

$$\backslash newcommand\{\backslash proquestmode\}\{\}$$

This mode has no effect when used in combination with ‘printmode’.

3.1 Options

In this section, we describe the options you can set when using this thesis class.

Table 3.1: List of options for the puthesis document class and template

Option	**Description**
12pt	Specify the font size for body text as a parameter to `documentclass`. The Mudd Library requirements [**?**] state that 12pt is preferred for serif fonts (e.g., Times New Roman) and 10pt for sans-serif fonts (e.g., Arial).
letterpaper	If your document is coming out in a4paper, your LaTeX defaults may be wrong. Set this option as a parameter to `documentclass` to have the correct 8.5”x11” paper size.
lot	Set this option as a parameter to `documentclass` to insert a List of Tables after the Table of Contents.

(Continued on next page)

Table 3.1: (continued)

Option	**Description**
lof	Set this option as a parameter to `documentclass` to insert a List of Figures after the Table of Contents and the List of Figures.
los	Set this option as a parameter to `documentclass` to insert a List of Symbols after the Table of Contents and the other lists.
singlespace	Set this option as a parameter to `documentclass` to single space your document. Double spacing is the default otherwise, and is required for the electronic copy you submit to ProQuest. Single spacing is permitted for the printed and bound copies for Mudd Library.
draft	Set this option as a parameter to `documentclass` to have LaTeXmark sections of your document that have formatting errors (e.g., overfull hboxes).
$\backslash newcommand$ $\{\backslash printmode\}\{\}$	Insert this command after the `documentclass` command to turn off the hyperref package to produce a PDF suitable for printing.
$\backslash newcommand$ $\{\backslash proquestmode\}\{\}$	Insert this command after the `documentclass` command to turn off the 'colorlinks' option to the hyperref package. Links in the pdf document will then be outlined in color instead of having the text itself be colored. This is more suitable when the PDF may be viewed online or printed by the reader.
$\backslash makefrontmatter$	Insert this command after the $\backslash begin\{document\}$ command, but before including your chapters to insert the Table of Contents and other front matter.
$\backslash title$	Set the title of your dissertation. Used on the title page and in the PDF properties.
$\backslash submitted$	Set the submission date of your dissertation. Used on the title page. This should be the month and year when your degree will be conferred, generally only January, April, June, September, or November. Check the Mudd Library rules [?] for the appropriate deadlines.
$\backslash copyrightyear$	Set the submission year of your dissertation. Used on the copyright page.
$\backslash author$	Your full name. Used on the title page, copyright page, and the PDF properties.

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Table 3.1: (continued)

Option	**Description**
$\backslash adviser$	Your adviser's full name. Used on the title page.
$\backslash departmentprefix$	The wording that precedes your department or program name. Used on the title page. The default is "Department of", since most people list their department and can leave this out (e.g., Department of Electrical Engineering), however if yours is a program, set $\backslash departmentprefix\{Programin\}$
$\backslash department$	The name of your department or program. Used on the title page.
$\backslash renewcommand$ $\{\backslash maketitlepage\}\{\}$	Disable the insertion of the title page in the front matter. This is useful for early drafts of your dissertation.
$\backslash renewcommand*$ $\{\backslash makecopyrightpage\}\{\}$	Disable the insertion of the copyright page in the front matter. This is useful for early drafts of your dissertation.
$\backslash renewcommand*$ $\{\backslash makeabstract\}\{\}$	Disable the insertion of the abstract in the front matter. This is useful for early drafts of your dissertation.

I've seen other people print their dissertations using $\backslash pagestyle\{headings\}$, which places running headings on the top of each page with the chapter number, chapter name, and page number. This documentclass is not currently compatible with this option – the margins are setup to be correct with page numbers in the footer, placing them 3/4" from the edge of the paper, as required. If you wish to use headings, you will need to adjust the margins accordingly.

Chapter 4

Conclusion

In this work, we explain how to use the puthesis.cls class file and the accompanying template.

4.1 Future Work

Future work should include options in the template for a masters thesis or an undergraduate senior thesis. It should also support running headings in the headers using the 'headings' pagestyle. The print mode and proquest mode included in the template might also be candidates to include in the class itself.

Appendix A

Implementation Details

Appendices are just chapters, included after the *appendix* command.

A.1 Switching Formats

When switching `printmode` on and off (see Section 3.1), you may need to delete the output .aux files to get the document code to compile correctly. This is because the hyperref package is switched off for `printmode`, but this package inserts extra tags into the contents lines in the auxiliary files for PDF links, and these can cause errors when the package is not used.

A.2 Long Tables

Long tables span multiple pages. By default they are treated like body text, but we want them to be single spaced all the time. The class therefore defines a new command, *tablespacing*, that is placed before a long table to switch to single spacing when the rest of the document is in double spacing mode. Another command, *bodyspacing*, is placed after the long table to switch back to double spacing. Normal tables using `tabular` automatically use single spacing and do not require the extra commands.

When the documentclass is defined with the 'singlespace' option, these commands are automatically adjusted to stay in single spacing after the long table.

Make sure there is always at least one blank line after the *bodyspacing* command before the end of the file.

Some times long tables do not format correctly on the first pass. If the column widths are wrong, try running the LaTeXcompiler one or two extra times to allow it to better calculate the column widths.

If you want your long table to break pages at a specific point, you can insert the command *pagebreak*[4], to tell LaTeXthat it really should put a page break there. *pagebreak*[2] gives it a hint that this is a good place for a page break, if needed. If there's a row that really should not be broken across a page, use *, which will usually prevent a pagebreak.

A.3 Booktabs

The booktabs package is included to print nicer tables. See the package documentation [**?**] for more details and motivation. Generally, all vertical lines are removed from the tables for a better visual appearance (so don't put them in), and better spacing and line thicknesses are used for the horizontal rules. The rules are defined as *toprule* at the top of the table, *midrule* in between the heading and the body of the table (or between sections of the table), and *bottomrule* at the end of the table. *cmidrule* can be used with the appropriate options to have a rule that spans only certain columns of the table.

A.4 Bibliography and Footnotes

The bibliography and any footnotes can also be single spaced, even for the electronic copy. The template is already setup to do this.

Bibliography entries go in the .bib file. As usual, be sure to compile the LaTeXcode, then run BibTeX, and then run LaTeXagain.

To cite websites and other electronically accessed materials, you can use the '@electronic' type of BibTeX entry, and use the 'howpublished' field to include the URL of the source material.

The formatting of bibliography entries will be done automatically. Usually the titles are changed to have only the first word capitalized. If you'd prefer to have your original formatting preserved, place the title in an extra set of curly braces, i.e., "title = {{My title has an AcroNyM that should stay unchanged}},".

A.5 Figures and Tables

The captions of figures and tables take an optional parameter in square brackets, specifying the caption text to be used in the Table of Contents. The regular caption in curly braces is used for the table itself.

Generally captions for tables are placed above the table, while captions for figures are placed below the figure.

Appendix B

Printing and Binding

B.1 Printing

For the library copies of your dissertation, you must use archival quality printing and binding. This means acid-free paper, containing at least 25% cotton fiber. Triangle Repocenter on Nassau Street in Princeton offers both 25% cotton paper and 100% cotton paper. Most people choose the 25% cotton paper, and this is generally recommended by the binders. The 100% copy paper is somewhat thicker and the extra expense is unnecessary.

Triangle offers online submission of your printing and binding order at: `http://triangleprinceton.com/collegiatebinding/thesis/`. If you request binding from them, they will deliver the paper copies to Smith-Shattuck Bookbinding for you and allow you to pick up the completed copies at their store on Nassau Street. The whole process takes 2-3 business days, but check with them in advance during the busy thesis-printing season in April and May.

Currently, your printed and bound dissertation copies can be single spaced. Only the electronic copy submitted to ProQuest must be double spaced. All copies must be printed single-sided, with specific margins.

B.2 Binding

An archival-quality sewn binding is required for the library copies of your dissertation. Smith-Shattuck Bookbinding is highly recommended, and is used by most students. Triangle Repocenter will send your copies there for you, greatly simplifying the process, but you can call Smith-Shattuck with special requests.

The "library standard" sewn binding is sufficient for the copies to be sent to Mudd Library. It uses a black buckram cloth cover, which is the most popular option. For extra copies for yourself and your family members, you can choose "buckram roundback binding", which adds decorative lines on the spine, and printing of the title and author on the front cover. For a small additional fee, you can include the Princeton University shield on the front cover and a ribbon bookmark. Leather covers are also available. See Smith-Shattuck's website for more details at: `http://www.thesisbookbinding.com/`.