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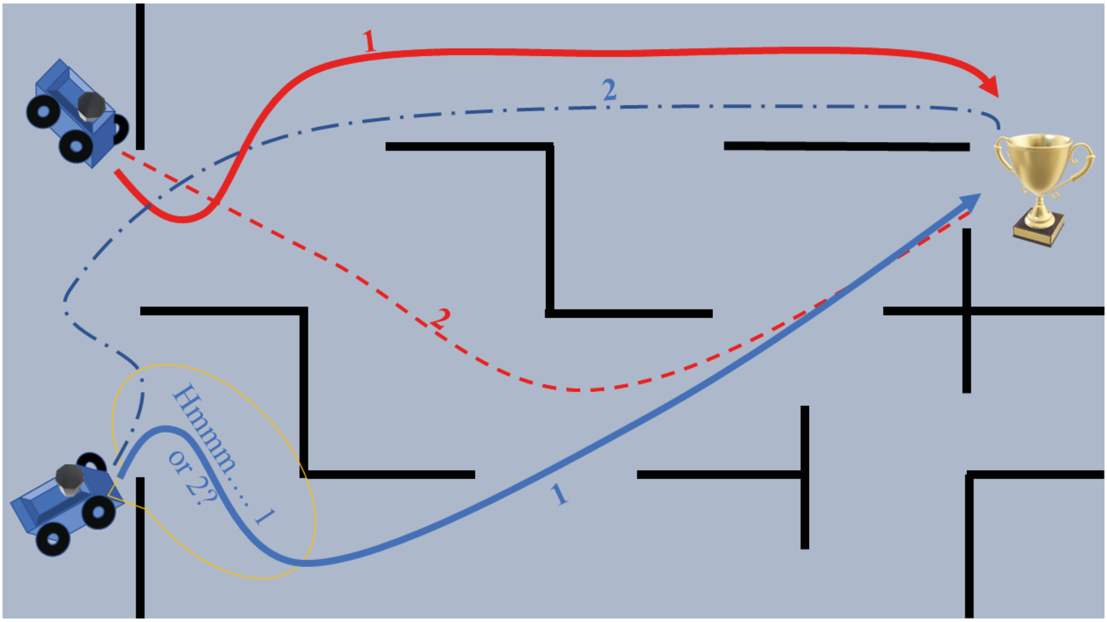
Toward Dependable Multiple Path Planning for Autonomous Robots with Obstacle Avoidance and Congestion Control

Lan Anh Trinh



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Lan Anh Trinh

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School of Innovation, Design and Engineering

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Lan Anh Trinh

Akademisk avhandling

som för avläggande av teknologie doktorsexamen i elektronik vid Akademin för innovation, design och teknik kommer att offentligen försvaras tisdagen den 18 januari 2022, 14.00 i U2-024 and virtually on Zoom/Teams, Mälardalens högskola, Västerås.

Fakultetsopponent: Associate Professor Lucia Pallottino, University of Pisa

MÄLARDALEN UNIVERSITY
SWEDEN

Akademin för innovation, design och teknik

Abstract

Over decades, automatic robots that are pre-programmed to perform repetitive tasks in industrial production has been reaching the cutting edge of technology. There is emerging the next development with autonomous control, where a robot is able to have some levels of its own decision, i.e. self-governing, without direct controls from humans. This brings autonomous robots extensively applicable not only in industry but also in commonly accessible services in our daily life such as self-driving cars, automated health care, or entertainment. Yet, one of the backbone of the robotic system, the navigation and path planning, has to face more and more challenges including unstructured environments, uncertainty of moving objects, coexist with humans, and multiple robotic agents. Aiming toward a dependable, i.e. available, reliable, and safe, path planning system to overcome such challenges, this thesis proposes the development of multiple path planning along with obstacle avoidance and congestion control algorithms. At first, a novel dipole flow field, which is constructed from a flow field to drive robots to their goals and a dipole field to push robots far away from potential collision directions, is proposed. The algorithm is efficient in implementation yet is able to overcome the drawback of conventional field-based approach, which is easily trapped by a local optimisation of energy functions. Secondly, a congestion control mechanism with Petri net is developed to synchronise the movement of robots when they enter in a cross or narrow area. Different Petri nets are evaluated to find the optimal configuration to reduce the traffic jam through possible conflict regions. In the next contribution, the dead- or live-lock problem of a path planning system is addressed. The solution is based on multiple path planning where each robot has alternative paths to the goal. All robots in the same working space communicate with each other to update their locations and paths so that the appropriate configuration can be chosen to avoid potential deadlocks. The algorithm also takes into account the obstacle avoidance so that the robots are able to avoid mutual collisions as well as collisions with unexpected moving objects like humans. Finally, a distributed multiple path planning algorithm is implemented to help the system to deal with some level of failures, which happens when the central controlling system of robots stops working or a part of communication network between the robots is unexpectedly disconnected. The proposed approaches have been evaluated by extensive experiments to show their effectiveness in addressing collisions, congestion, as well as deadlocks. The implementation of the algorithms has been performed on widely accessible platform, robot operating system (ROS) and transferred into real robots.

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To my parents, my husband Thang Nguyen and our lovely kids Khang (Sam) and Lam Anh (Alisa).

Acknowledgments

As time flies, it is being close to the end of my PhD study. Through the PhD life with a lot of pains but also much of happiness, I have gained a lot from the way I have been: research vision, knowledge, practical experiences, patience as well as friendships. The most important word I want to say at this moment is THANK YOU.

I would like to express my thanks to many persons who have directly and indirectly helped me on the path leading to this dissertation. First, I especially express my thanks to my supervisors, Prof. Dr. Mikael Ekström and Dr. Baran Cürüklü, to give me a great chance to experience the most wonderful PhD life at Mälardalen University. I would like to express my sincere gratitude for their valuable supports and advices in both research and life. Thanks to their experience and conversations, I have become more and more open-minded to solve my difficulties. Thanks to their encouragements I did and do overcome all challenges to go through till the end of this PhD study.

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Many next thanks to DPAC leaders who proposed an excellent project so that I have learnt a lots and enjoyed working within the project. I am always thankful to administrative officers who have made all the complicated administrative procedures to become easy and smooth.

Last but yet importantly, I would like to express my utmost appreciation to my family in Vietnam, my husband, my lovely son Sam and my little newborn daughter Alisa. I am truly indebted to them for their unconditional supports, endless love, and encouragement. They are always beside me, and available whenever I feel down and need someone to share the burden of stress. They are the ones whom I want to care about most, the persons whom I want to bring all happiness to. I would like to dedicate this thesis to them whom I love most in my life.

Lan Anh Trinh
Västerås, December, 2021

Sammanfattning

Under årtionden har automatiska robotar som är förprogrammerade för att utföra repetitiva uppgifter i industriell produktion nått framkant inom teknik. Det kommer nästa utveckling med autonom kontroll, där en robot kan ha vissa nivåer av sitt eget beslut, det vill säga självstyrande, utan direkta kontroller från människor. Detta ger autonoma robotar i stor utsträckning tillämpliga inte bara inom industrin utan ocksåi vanligt tillgängliga tjänster i vårt dagliga liv, till exempel självkörande bilar, automatiserad sjukvård eller underhållning. Ändåmåste en av ryggraden i robotsystemet, navigering och vägplanering, möta allt fler utmaningar, inklusive ostrukturerade miljöer, osäkerhet kring rörliga föremål, samexistera med människor och flera robotagenter. Syftet med ett pålitligt, dvs tillgängligt, tillförlitligt och säkert, vägplaneringssystem för att övervinna sådana utmaningar, föreslår denna avhandling att utveckla flervägsplanering tillsammans med algoritmer för att undvika hinder och överbelastning. Till en början föreslås ett nytt dipolflödesfält, som är konstruerat från ett flödesfält för att driva robotar till sina mål och ett dipolfält för att skjuta robotar långt bort från potentiella kollisionsriktningar. Algoritmen är effektiv vid implementering men kan övervinna nackdelen med konventionellt fältbaserat tillvägagångssätt, som lätt fångas av en lokal optimering av energifunktioner. För det andra utvecklas en mekanism för överbelastningskontroll med Petri net för att synkronisera rörelser hos robotar när de kommer in i ett kors eller smalt område. Olika Petrinät utvärderas för att hitta den optimala konfigurationen för att minska trafikstockningen genom möjliga konfliktregioner. I nästa bidrag åtgärdas problemet med död- eller livlåsning av ett vägplaneringssystem. Lösningen baseras påmultipelvägsplanering där varje robot har alternativa vägar till målet. Alla robotar i samma arbetsutrymme kommunicerar med varandra för att uppdatera sina platser och vägar såatt lämplig konfiguration kan väljas för att undvika potentiella dödlägen. Algoritmen tar ocksåhänsyn till hinderundvikande såatt robotarna kan undvika inbördes kollisioner såväl som kollisioner med oväntade rörliga föremål som människor. Slutligen implementeras en decentraliserat algoritm för multipla banplanering för att hjälpa systemet att hantera vissa nivåer av fel, vilket händer när det centrala styrsystemet för robotar slutar fungera eller en del av kommunikationsnätverket mellan robotarna oväntat kopplas bort. De föreslagna tillvägagångssätten har utvärderats genom omfattande experiment för att visa deras effektivitet för att hantera kollisioner, trängsel och blockeringar. Implementeringen av algoritmerna har utförts påallmänt tillgänglig plattform, robotoperativsystem (ROS) och överförts till riktiga robotar.

Abstract

Over decades, automatic robots that are pre-programmed to perform repetitive tasks in industrial production has been reaching the cutting edge of technology. There is emerging the next development with autonomous control, where a robot is able to have some levels of its own decision, i.e. self-governing, without direct controls from humans. This brings autonomous robots extensively applicable not only in industry but also in commonly accessible services in our daily life such as self-driving cars, automated health care, or entertainment. Yet, one of the backbone of the robotic system, the navigation and path planning, has to face more and more challenges including unstructured environments, uncertainty of moving objects, coexist with humans, and multiple robotic agents. Aiming toward a dependable, i.e. available, reliable, and safe, path planning system to overcome such challenges, this thesis proposes the development of multiple path planning along with obstacle avoidance and congestion control algorithms. At first, a novel dipole flow field, which is constructed from a flow field to drive robots to their goals and a dipole field to push robots far away from potential collision directions, is proposed. The algorithm is efficient in implementation yet is able to overcome the drawback of conventional field-based approach, which is easily trapped by a local optimisation of energy functions. Secondly, a congestion control mechanism with Petri net is developed to synchronise the movement of robots when they enter in a cross or narrow area. Different Petri nets are evaluated to find the optimal configuration to reduce the traffic jam through possible conflict regions. In the next contribution, the dead- or live-lock problem of a path planning system is addressed. The solution is based on multiple path planning where each robot has alternative paths to the goal. All robots in the same working space communicate with each other to update their locations and paths so that the appropriate configuration can be chosen to avoid potential deadlocks. The algorithm also takes into account the obstacle avoidance so that the robots are able to avoid mutual collisions as well as collisions with unexpected moving objects like humans. Finally, a decentralised multiple path planning algorithm is implemented to help the system to deal with some level of failures, which happens when the central controlling system of robots stops working or a part of communication network between the robots is unexpectedly disconnected. The proposed approaches have been evaluated by extensive experiments to show their effectiveness in addressing collisions, congestion, as well as deadlocks. The implementation of the algorithms has been performed on widely accessible platform, robot operating system (ROS) and transferred into real robots.

List of Publications

Papers Included in the Doctoral Thesis[1]

Paper A Toward Shared Working Space of Human and Robotics Agents Through Dipole Flow Field for Dependable Path Planning
Authors: Lan Anh Trinh, Mikael Ekström, Baran Cürüklü
Status: Published in Frontiers in Neurorobotics, volume 12, 2018.

Paper B Dependable Navigation for Multiple Autonomous Robots with Petri Nets Based Congestion Control and Dynamic Obstacle Avoidance
Authors: Lan Anh Trinh, Mikael Ekström, Baran Cürüklü
Status: Submitted to Journal of Intelligent and Robotic Systems, Springer, 2021. Minor revision.

Paper C Multi-Path Planning for Autonomous Navigation of Multiple Robots in a Shared Workspace with Humans
Authors: Lan Anh Trinh, Mikael Ekström, Baran Cürüklü
Status: Published in The 6th IEEE International Conference on Control, Automation, and Robotics, 2020.

Paper D Decentralised Multi-Robot Path Planning with Obstacle Avoidance and Congestion Control Constraints

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[1] The included papers have been reformatted to comply with the thesis layout

Authors: Lan Anh Trinh, Mikael Ekström, Baran Cürüklü
Status: Submitted to IEEE Access.

Additional Peer-Reviewed Publications, not Included in the Doctoral Thesis

- ”Fault Tolerant Analysis for Dependable Autonomous Agents Using Colored Time Petri Nets”. Lan Anh Trinh, Baran Cürüklü, Mikael Ekström. The 9th International Conference on Agents and Artificial Intelligence, ICAART 2017.

- ”Dipole Flow Field for Dependable Path Planning of Multiple Agents”. Lan Anh Trinh, Mikael Ekström, Baran Cürüklü. Workshop on Shared Autonomoy, IEEE/RSJ International Conference on Intelligent Robots and Systems, 2017.

- ”Failure Analysis for Adaptive Autonomous Agents using Petri Nets”. Mirgita Frasheri, Lan Anh Trinh, Baran Cürüklü, Mikael Ekström. The 11th International Workshop on Multi-Agent Systems and Simulation (MAS&S’17).

- ”Dependability for Autonomous Control with a Probability Approach”. Lan Anh Trinh, Baran Cürüklü, Mikael Ekström. Newsletter in ERCIM News 109, Autonomous Vehicles.

- ”Petri Net Based Navigation Planning with Dipole Field and Dynamic Window Approach for Collision Avoidance”. Lan Anh Trinh, Mikael Ekström, Baran Cürüklü. Published at 6th International Conference on Control, Decision and Information Technologies, 2019.

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I

Thesis

Chapter 1

Introduction

There has been an undeniable inclination of the revolution in robotics and autonomous control over the last decade. The trend has started since the new definition of Industry 4.0 [1] based on the foundations of robotics, Internet of thing (IoT), wireless communication, and artificial intelligence was introduced. Furthermore, the pandemic with Covid-19 increases the needs of autonomous robots and virtual communications to reduce direct contacts among humans. So far, numerous intelligent robotic systems have been developed to support humans in a variety of tasks in both daily life such as healthcare services, smart home, autonomous driving, as well as industrial environments such as warehouse systems, cargo robots, or robotics hands. Generally, an autonomous system primarily composes of four specific yet interconnected components in which they are integrated and influenced by the design of the system architecture varying for different applications, i.e., (i) sensors and sensor fusion, (ii) modelling and control, (iii) map building and path planning, and (iv) decision making and autonomy.

Obviously, artificial intelligence is now a crucial part of an autonomous robot system to help it to deal with decision making without receiving direct commands from humans in some extends. To fulfil the mission, particularly for autonomous mobile robots, path planning and navigation is one of the core components, which needs to be efficiently designed for the controlling system of robots. There are certain issues (Figure 1.1) related to solving the path planning problem, including how to generate a natural move, i.e the moving trajectory of the robot is smooth and has few turns; multiple robotic agents, i.e how the robot can coordinate with others to avoid mutual collisions; environment uncertainty where the robot needs to handle unpredictable moving objects such as humans; deadlocks in which the robot is able to avoid/escape a loop trajectory to approach its defined goal; lastly, efficiency means that the robot is able to choose the most optimal path to accomplish its navigation tasks with minimal energy consumption.

Whatever solution is used to address any of those issues, the main aim has led to the development of a dependable, i.e, availability, reliable, and safe, algorithm for a navigation system [2, 3]. Hitherto, dependability has been well studied in the literature to introduce a pathway to understand faults and to proactively prevent them to happen inside and outside a system. Targeting toward a dependable path planning algorithm makes it more widely acceptable for both daily life and industry applications. To reach there, first the analysis of what are the root that could cause the failures of a path planning algorithm is performed. The assumption is that the robot is equipped with sufficient hardware and software to know the relative location of the robot with respect to others and to destination. The robot must have the map of environment and sensors to be able to detect surrounding obstacles. Finally, it is able to communicate wirelessly to share information among each others in the same working space. Those requirements are kinds of standard in robotics where all functions now are easily reachable by just using embedded devices and computational board. Back to the main focuses of this study, the first question is how to ensure efficiency of the path planning algorithm. The answer to this question relates to the amount of energy spent by a robot for a moving task. It is obvious that routing a robot through a zigzag path is not optimal as the activity of slowing down the robot and speeding it up again usually consumes energy unnecessar-

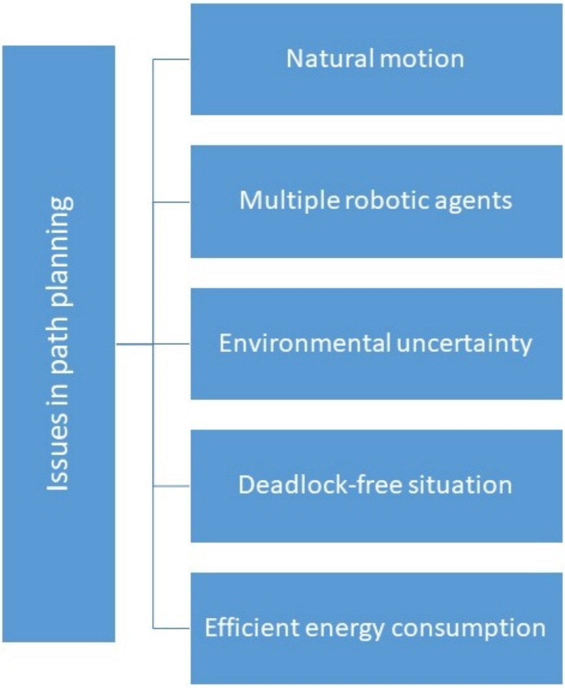

Figure 1.1: Certain issues in navigation and path planning.

ily. Thus, smoothening the path plays an important role here to address such a problem. Second, the path planning algorithm needs to be reliable to correctly drive each robot to its goal. The continuity of the service is also important to make it always available to the robot system. However, a robot while trying to avoid moving obstacles and other robots could face live- or dead-locks which make it no longer be able to move. The problem happens if the robot thinks a single global path to the goal and only takes into account the local information in a short range to decide the next move. Planning multiple paths and utilising global information shared by all robots in the working space are the key to help robot to predict and avoid the congestion region. Finally, it is critical to have a safe path planning algorithm to ensure no mutual collisions among robots and collisions between robots and humans. This is to avoid any fatal consequence on humans, a robot itself, and surrounding environments.

With regards to above analyses, the main contribution of this thesis is to develop a dependable path planning algorithm for a system of multiple robots by focusing on collision avoidance, congestion control, and centralised as well as decentralised multiple path planning. The work has started with the introduction of an effective path planning frame work based on dipole flow field, which includes the static flow field to drive the robot to its goal and the dipole field for obstacle avoidance. The proposed algorithm has low computational complexity yet is effective to mitigate the local optimisation of conventional field-based approach. The path driven by the flow field is suitable to plan dynamic motions of mobile robots and has been proved with real implementation. Continuously, the obstacle avoidance is advanced into the next level with congestion control. The basic idea is that routing too many robots into a same place could lead to a congestion that robots must go around and around to avoid collisions. Sometimes, they block each other inside a narrow area. A Petri net, an efficient tool to solve resource conflict for a dependable system, has been utilised in this work to synchronise the movements of multiple robots through a region or a cross. An optimisation problem is formulated to model the traffic of multiple robots where its solution returns the most suitable Petri network to control robots' movements. Finally, in order to tolerate up to some level of failures of a navigation system, a centralised as well as decentralised framework with multiple path planning is proposed. Each robot will has several possible paths to the goal which can be the shortest path found by conventional searching algorithms or any longer path but to provide alternative selection for a robot. The robots communicate with each other to negotiate the moving paths so that they are able to proactively avoid the conflicts that may cause a potential deadlocks in future. The obstacle avoidance is also taken into account to help robots to avoid collisions with any moving obstacles on the moving way. In overall, the summary of the dependable multiple path planning system proposed in this thesis is depicted in Figure 1.2.

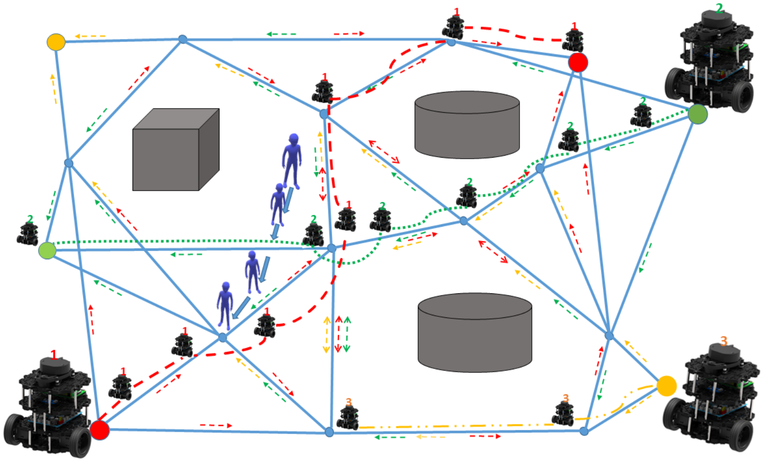

Figure 1.2: Overview of the proposed path planning algorithms. The multiple potential paths of three robots (marked with red, green, and yellow colours) to move from one vertex of the graph to other are described by dash arrows. The actual moving trajectories are chosen to minimise the conflicts and collisions and expressed by bold lines without arrows.

Thesis Overview

This thesis is divided into two main parts.

- The first part of the doctoral thesis is organised as follows. Chapter 2 presents the basic foundation of the research work, including the definition of dependability, and the key features of dependable path planning. Chapter 3 summarises the state-of-the art techniques for dependable path planning for autonomous robots, congestion control and multiple path planning. Chapter 4 presents the pathway to conduct this research work from initialise the target of the research to define the research questions, and hypotheses. Continuously, Chapter 5 summarises the major contributions of this work and Chapter 6 concludes the thesis with some discussions on the development of path planning algorithms at present and in future.

- The second part of this thesis is a collection of four articles (paper A-D) presenting the main contributions of the thesis in details.

Chapter 2

Dependable Path Planning

This chapter provides the backgrounds of dependability and the proposal of a dependable path planning system. The chapter is divided into three main sections. As first, the general definition of dependability and its role in the autonomous system are introduced in Section 2.1. Correspondingly, the overview of how those dependable properties are applied in the path planning algorithm is described on Section 2.2. Finally, the implementation for dependable path planning with the uses of multiple paths, obstacle avoidance and congestion control is introduced in Section 2.3.

2.1 Dependability and Autonomous Robots

Recently, autonomous robots are being widely used in numerous areas in which the robot either collaborates with other robots and humans to complete a task or even performs the task alone. For those robots to be able to work with humans, safety is the most important factors to avoid possessing any dangers. For those robots operating by themselves, they must be able to handle failures without a humans assistant. The above issues raise new research challenges in robotics, the dependability of robotic systems. Although the implementation of a dependable system increases the cost in the short-term, it gains the sustainability of the system over long-term runs.

Originally, dependability is defined by Avižienis et al. [2] as the ability to provide services that can be trusted. Basically, to assess the dependability of the system, five main attributes *availability, reliability, safety, integrity*, and *maintainability* are introduced including as given in Table 2.1.

Table 2.1: Dependable properties.

Availability	Be available or ready to provide services at any time
Reliability	Continuously provide of correct services within a period of time
Safety	Avoid any fatal consequence on operators, other robots, and environments
Integrity	Avoid improper system changes, like unauthorised access, or modification of program
Maintainability	Support the processes of modifications and repairs

In overall, the autonomous robotic system must be able to recognise, work with, and adapt to humans and other robots' behaviours in a possibly unstructured and unknown environment. These possess challenges corresponding to different aspects to implement the dependability of an autonomous system such as:

- *Learning and adaption*: Adaption of robots to unknown conditions in new environments with limited learnt knowledge.
- *Modelling, analysis, and simulation*: Development of a model simulation to analyse and verify the dependability of robot systems.
- *Control and planning*: Robot control under some levels of uncertainty and co-operation with other robots.
- *Perception*: Perception of environments in hazardous and complex situation.

- *Human-robot interaction*: Collaboration and interaction between humans and robots.

This thesis mainly addresses the challenges related to the **navigation control and planning** of autonomous systems and focuses on the three main properties including **availability**, **reliability**, and **safety**.

In order to implement the dependable properties [2, 3], threats are defined to understand any factor which affects system dependability. In overall, threats include failures, errors, and faults. The failure happens when the provided service is deviated from the correct service due to an an error. As the cause of the error is fault, fault is considered as the root of every failure happening both inside and outside of the system. Therefore, in order to enhance system dependability, the system must be prevented from faults with the introduction of means. There are four certain means including fault prevention, fault removal, fault forecasting, and fault tolerance. Fault prevention requires the use of appropriate development methodologies, standard implementation techniques, and good practices to design the system; Fault removal utilises verification tools through a log-file to identify, diagnose, and remove faults; Fault forecasting estimates the possible incidence and what can be the consequence of faults with safety or risk analysis; Finally, fault tolerance is implemented with redundant hardware or software to provide recovery mechanisms once a system fails to complete its task. The last mean is usually applied during the operations of a system.

The taxonomy showing the relationship between dependability and its components is given in Figure 2.1.

2.2 Dependable Path Planning

Path planning, basically, is defined as finding a sequence of points to construct a free collision way for a robot to reach a desired goal. In general, the path planning system is divided into global path planning and local path planning and. The global path planning system of the robot perceives information on the

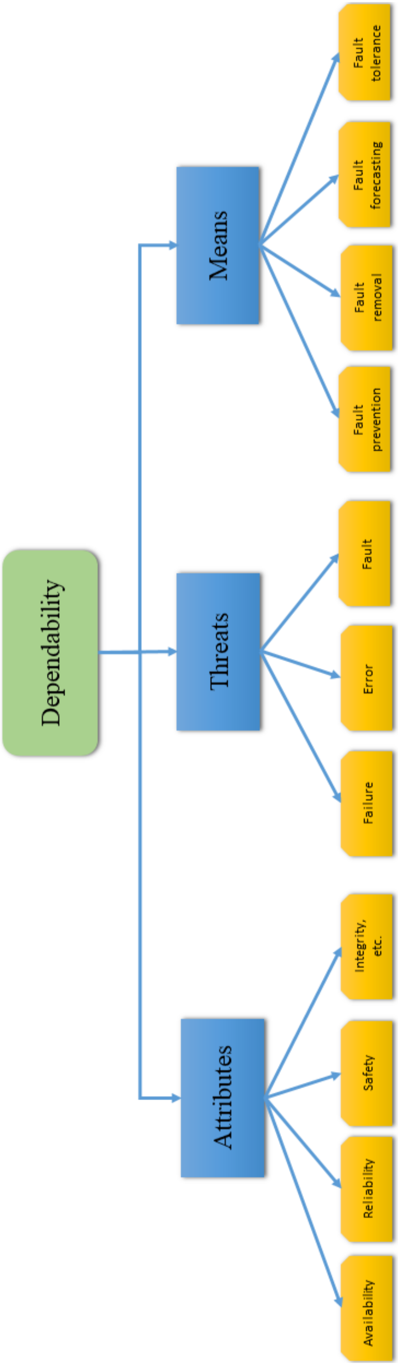

Figure 2.1: Dependability taxonomy.

surrounding environment to generate a route from a starting point to a predefined goal. Meanwhile, the local path planning controls movement of the robot along the global path to avoid collision with all the obstacles within a local area. Conventionally, the global path planning mainly applies for static environment, i.e., the presence of other moving objects such as other robots and human is not taken into account when the global path is established. There are numerous algorithms used for global path planning, however the graph/map/-grid search-based algorithms are the most popular techniques for searching in a map. For the local path planning where the robot has to deal with both following the global path and collision avoidance.

In this thesis, a dependable path planning algorithm is proposed with the aim to cope with both global and local range and to avoid both static and uncertain dynamic obstacles like humans. As aforementioned, three main dependable attributes are focused including availability, reliability, and safety. Given the robot an interval time to finish a navigation mission, those three attributes are expressed as following:

- Availability: The availability is measured by the continuity of the path planning algorithm. Therefore, the availability of the navigation system is measured by the probability that the system is functioning correctly at an instance time.

- Reliability: This attribute presents the continuity of correct services. This means the path planning algorithm is expected to operate without interruption. Thus, the reliability in the given interval time of the navigation system is measured by the probability that the robot is still running under the control navigation system without any failures.

- Safety: This attribute is assessed by the ability that the navigation system can avoid any catastrophic consequences on the users, other robots and the environments. This means during the given interval time for the robot to complete the navigation task, the navigation system enables the robot to avoid all obstacles including moving objects such as humans to reduce the danger to the environment, also the robot is less interrupted while operating.

To aim toward a dependable path planning algorithm, at first, it needs to be ensured to be implemented on a good platform with ready functions of coding standardisation, unit-testing, building system, documentation, etc. By choosing the well developed open-source framework ROS [4], and adapting its path for implementation, the necessary tools for the first two means, fault prevention and fault removals, are basically realised in thesis. This thesis mainly concentrates on the development at algorithm levels to address the fault prediction and fault tolerance. They are expanded into specific aims for a the path planning algorithm. First, the algorithm is able to drive all robotic agents to reach their goals with optimal paths correctly. Here, the optimal path is defined as a path with a minimum cost calculated based on one or some the elements including the total length of the path, the energy used by a robot to complete the path, the complexity of the terrain over the path, etc. Second, for safety reasons the robot needs to avoid collisions with other robots and humans in its working space. Lastly, the robots are also required to complete the moving tasks. This means that if the robots are not able to reach the goals or take a long time to do so, it is considered that the robots are in the deadlock situation and failed to complete a path planning task. It is obviously that should potential failures of a path planning algorithm be proactively located, they can be mitigated. The congestion control is developed in this thesis as a new mechanism to reduce traffic in congestion areas, so that several robots are not routed into a same narrow place, which possibly leads to a deadlock. Meanwhile, during operations of robots, fault tolerance enhances the system ability to handle with failures by using backup solution. Adapting fault tolerance into a path planning algorithm, this thesis proposes the uses of multiple path planning to allow each robot to have several options to reach to its goal and the communication of all robots in their work space to find optimal path assignments. The overall dependable path planning approaches presented in this thesis include obstacle avoidance, congestion control, and multiple paths.

2.3 Dependability with Obstacle Avoidance, Congestion Control, and Multiple Path

In summary, the conventional global path planning provides the basic dependable properties of a navigation system with the function to drive a robot to a goal within the map of static objects. Obstacle avoidance enhances all safety, availability and reliability by avoiding the collisions with moving obstacles that can lead to the stop of navigation services. The congestion control and multiple path drive the robots to less crowded and less risky areas, thus indirectly help to improve all three dependable properties. Finally the extra implementation of the system with decentralised manner reduces the dependency of robots to one central node to enhance the availability and reliability in general. The dependable attributes are mapped into different component of path planning algorithms in Table 2.2.

Table 2.2: Dependability attribute map.

Attribute	Obstacle avoidance	Congestion control	Multiple path	Decentralised manner
Availability	✓	✓	✓	✓
Reliability	✓	✓	✓	✓
Safety	✓	✓	✓	

Chapter 3

Related Works

As aforementioned, the requirements that an autonomous navigation system needs to be dependable, i.e. safe, available, and reliable, are becoming more and more important. This chapter provides overall literature of related researches. The dependability for autonomous robots is surveyed in Section 3.1 while the introduction of path planning algorithms is given in 3.2. Continuously, other works about obstacle avoidance are surveyed in Section 3.3, and about congestion control and multiple path planning are given in Section 3.4 respectively.

3.1 Dependability and Autonomous Robots

Over decades, separate dependable attributes of an autonomous system have been developed. For example, an intelligent home care robot, Care-O-bot, was introduced by Birgit et.al [5] for elderly people assistance. The robot was mounted with extensive sensors to detect motion, and also to prevent accidents caused by a person hitting the robot with different levels of safety. Meanwhile, a dependable platform has been concerned in industrial robots to create collaborating working environment between human and robot in manufacturing factories. For instance, ABB has been working on an open robotics platform [6] with analysis tools in order to monitor and find the failure robot causes with a testing procedure. Close to the works presented in this thesis, there has been a rise on the development of self-driving cars from big companies like Tesla, Google, Uber, or Volvo. To minimise the risks of causing accidents to human, autonomous cars would have to tested to be driven in different environments like city traffic, busy highways, etc. to demonstrate a safe and reliable self-driving system [7, 8].

Regarding definition from software perspective, the dependability of a system is evaluated by attributes including availability, reliability, safety, integrity, and maintainability [9]. The dependability of a system can be assessed by one, several, or all attributes mentioned above. The researches on dependability have shown that faults are the roots of failures occurring inside or outside of autonomous system. Thus, different means are developed to prevent faults and enhance the tolerance of a system to failures. Fault prevention focuses the use of appropriate tools. This can be accomplished by good implementation techniques, good tools, and the component-based designed of a system such as LAAS [10], RAX [11] or standardised middleware like robot operating system (ROS) [4], OROCOS [12], etc. Fault removal deals with identifying, diagnosing, and removing faults. Fault identifying is performed with verification tools including dynamic verification (run test to find faults through log-file and analysis) [13] and static verification [14] (system analysis, model checking, etc.). Besides, during the operation stage, all failures must be logged for the maintenance cycle. Fault forecasting deals with the prediction of the potential future incidence and its consequence. If the robot system is described by unified modelling language (UML) [15], then the safety analysis is studied with Hazard and Operability Studies (HAZOP) [16] or Fault Tree Analysis (FTA) [17]. Other common approaches are Bayesian network and Petri net (PN). Finally, fault tolerance is implemented by using redundant hardware and software [18, 19, 20].

3.2 Global Path Planning

First of all, conventional algorithms about path planning are introduced in this section. Many of them have focused on searching to find a path from a source to a destination in static map without considering moving obstacles. One of the most conventional yet still effective approaches for the navigation of an agent in a large map is related to Dijkstra-based algorithm [21], its extension of A* searching algorithm [22, 23], and incremental search [24]. In details, the A* algorithm improves the Dijkstra's algorithm by approximating the cost-to-go function with heuristics to reduce the expansive of the searching tree to the goal. Meanwhile, incremental search algorithms seek for the shortest paths by utilising the results of similar searches to make the search faster, instead of solving each search problem separately. By applying incremental search on top of the A*, Koenig et al. [25] developed lifelong planning A* (LPA*) as an initial variant of A*, in order to address path planning for dynamic graphs where edge costs are updated. In the D* algorithm [26], incremental search is applied to repeatedly update the shortest paths between the current position of a robot and a goal, during the travelling of robots to approach to the goal. Koenig and Likhachev [27] improved the D* by LPA* to have D*-Lite and alternatively Sun et al. [28] developed dynamic fringe saving A* to reuse the OPEN and CLOSED lists from previous A* searches.

Although different variants of A* are able to address a graph change due to the moving of a robot to a new vertex, or the incremental updates of edge costs, there are lacking particular versions of A* to deal with moving obstacles. One of the approaches have been developed by Hu and Brady [29] was to model the uncertainties of mobile obstacles using probability map. However, the complexity of path planning significantly increases when the cost of the edges on the graph are presented by random variables. Therefore, the most common solution is to keep a robot moving on global path but the obstacle avoidance is handled separately.

3.3 Obstacle Avoidance

The limitation of global path planning to deal with dynamic moving obstacles is addressed by obstacle avoidance, which is considered as path planning within a local range. Conventionally, a field-based approach is of the way to combine the global path planing with obstacle avoidance. The solution is usually constructed by the combinations of two fields including a repulsive field to push a robot away from the obstacles, and an attractive one to pull the robot towards the goal. The Voronoi diagram was proposed by Ok et al. [30] to partition the working space into regions which are close to static obstacles. Correspondingly, the repulsive field was built along with the attractive field to route a robot to it goal. Meanwhile, the physics model of heat flow was used by Wang and Chirikjian [31] and Golan et al. [32] where obstacles were presented by hot obstacles and the goal was the cold one. Solving partial differential equations of heat exchanges among objects has revealed a way to drive a robot to a goal without colliding with obstacles. Obviously, the biggest limitation of using the field-based approach is the trap into local optimum due to the cancellation of repulsive and attractive field. In consequence, a robot stops moving at local optimal point where no forces are generated. Attempts have been introduced to reduce the local convergence with extra elements. For instance, García-Delgado et al. [33] customised the repulsive field with regards to the angle between an attractive force to an obstacle. The basic idea is to mitigate the cancellation of the two opposite attractive and repulsive forces once present. Unfortunately, velocity is one of the key factor to avoid collision with moving obstacles but it has not been utilised effectively in most of field-based approaches.

So far, there has been another direction to use velocity constraints to seek for a collision free path. Particularly, by knowing the current location of robots and their moving directions with velocities, the collision regions are defined in velocity space (VO). Owen and Montano [34, 35] extended this definition of VOs into the obstacle avoidance of robots. Similarly, Damas and Santos-

Victor [36] developed the forbidden velocity zones with the bounds on robots' velocity so that a robot adjusts its moving speed accordingly to avoid obstacles. In addition, other extensions of VOs have been investigated such as the integration with acceleration in the works presented by Berg et al. [37, 38] and by Wilkie et al. [39], or the consideration of different robot shapes tackled by Lee et al. [40]. However, the complexity of the VO-based approach increases significantly once static obstacles are included. In particular, each static obstacle is presented by a VO where its shape needs to be taken into account with representation as a polygon or a similar kind of complex geometric object. Using velocity control sometimes results in oscillatory motion once robots come back to the preferred path after escaping from a collision area. Finally, a fast collision avoidance is necessary under urgent situations, for example, when a human approaches closely to the robot.

In order to address the above mentioned issues, in this thesis, a new obstacle avoidance with dipole flow field has been proposed. Obviously, the lacking of a mechanism to drive a robot to follow the global path to the destination could lead to a trap by a local optimum. The dipole flow field integrates the global path planning into the navigation field to address such an issue. For global planning, the method applies any-angle path planning algorithm of Theta* [41] to generate smooth paths with few turns, from a starting point to a goal for a pool of agents. Although different A* variants of any-angle path planning have been proposed, such as A* post smoothing, block A* [42] and field D* [43], the Theta* is able to provide the optimal path with effective implementation once compared with others [44]. As the computations of the Theta* algorithm is costly, the a static flow field along the planned path is defined to pull the robot back to the continue reaching to the goal if the robot has a small deviation from the planned path. Meanwhile, the dipole field is developed to help robots avoid collision with others and humans the shared working space. So far, conventional field-based methods generate pushing forces with respect to the location of robots. In this thesis, the moving directions and velocity amplitudes of robots are taken into account in dipole field to push robots far away from prospective collision area. Last yet importantly, the proposed dipole flow field is simple but effective to provide a quick response of a robot to sudden events like the appearance of an unexpected moving obstacles in a very close distance.

In overall, different obstacle avoidance mechanisms help to gain the dependability of a navigation system to mitigate the effects from external factors like moving obstacles on its performance. Continuously, the availability and reliability of a navigation system is improved further with proactive manner using congestion control as presented in the following section.

3.4 Congestion Control and Multiple Path Planning

As mentioned in the previous chapter, fault tolerance is one of key mean to implement dependable system with redundancy. However, the redundancy is also needed to be combine with an analysis method to proactively predict what could wrongly happens to the system. Therefore, congestion control is combined in this work to help the system to analyse surrounding environments and make a right decision.

Commonly, the term of congestion control has been widely applied in transportation to avoid traffic jams [45]. To take advantage of this into robotics, it has been used to monitor and control the moves of the swarm robots [46]. In order to extend the definition of congestion controls in path planning, in this work, PN has been utilised to organise the path planning tasks of multiple robotic agents solve conflicts and collisions among them. The PN framework is chosen because it provides solution for fault analysis and fault prevention in both development and operational stages of a system. Related works of PN with dependability are found in [47, 48, 49], PN for system modelling and analysis in [50, 51, 52, 53, 54], PN with collaborative robots in [52, 55, 56, 57], PN to design and implement robots in [58, 57, 59, 53], PN and fault tolerance in

[49, 60, 15], and PN with ROS in [61].

Aforementioned, the main aim of this thesis is to develop a dependable navigation system for multiple autonomous robots. To avoid congestion leading to deadlock situation where the robot is blocked by human or other robots to reach the goal. Besides, to make the navigation system more dependable, i.e., fault-tolerant system, a proactive multiple path planning algorithm is proposed in which the autonomous robots are equipped with multiple global paths to the goal. Multiple robots are able to communicate to exchange information about the planned paths and negotiate to find the optimal paths for all robots in a global scale.

For the graph-based solutions, the robots move on a connected graph from a vertex to its neighbours in one time step to reach their goals. A conflict happens when two robots occupying on a single vertex at the same time and the main aim of the path planning is to find a conflict-free solution satisfied by all robots. An extra cost function, namely sum-of-cost, like the total maximum time for all robots to reach their goals (or the sum of all path cost) is introduced as an optimal condition for the search. As the problem is shown to be non-deterministic polynomial-time (NP) hard [62], numerous approaches have chosen to seek for a close optimal solution to reduce processing time. A*-based optimal search finds a non-conflict solution among all combinations of assigning *k*-agent into the graph. To avoid the exponential grows of the state-space with respect to the number of agents, different methods have been applied, e.g. independence detection (ID) [63] to include robots only when necessary or operator decomposition (OD) [63] to treat a move as an operator to control a single robot at a time. Alternative to A*, the increasing cost tree search (ICTS) [64] proposed two-layers including high-level and low-level searching where the lower is used as a goal test of the higher. Another solution different from A*, conflict based search (CBS) is introduced by Sharon et al. [65]. In CBS, the agents are constrained by a triple of parameters including agent, occupying vertex, and time step. It means that the agent at the particular time step is refused to occupy an occupied vertex. The path is found only if all agent's constraints are satisfied. The searching is completed when the paths for every agents are resolved.

Beside above solutions, there have been suboptimal solutions for multiple agent path planning. For instance, hierarchical cooperative A* (HCA*) [66] introduced a reservation table which is used to store the path assigned into an agent. The other agents according to their priority in the group search for their paths not registered in the reservation table and update the table accordingly after the paths are found. In an improved version of HCA* like Windowed-HCA* (WHCA*) [66], the reservation table is only applied for a limited time slot, i.e., window, when the other agents are rejected to reserve to the table. Later, in the work of Bnaya and Felner [67], a dynamic window focused around conflicts and agents likely to be involved to a conflict are prioritised to be processed next. In overall, the heuristic search A* and its variants are still costly computational solutions.

There have been researches developed to reduce the running time of the search-based algorithms with rule-based algorithms. Specific rules are defined for the movement of the agents to reduce searching time. Yet, the resulted paths from the rule-based algorithms are not always optimal. Alternatively, in the work of Yu and Lavalle [68], the path planning problem for multiple agents is modeled as a network flow and the collision-free paths are found by the integer linear programming (ILP) solver.

Most of conventional works on multiple path planning are based on an assumption of a working environment without the presence of human. Due to the safety reasons, the operation of robot will be terminated when a human enters the working zones or crosses the moving trajectories of robot. In this thesis work, a new method of multiple path planning is proposed to consider the human and other uncontrolled moving objects as factors into the path planning problem. This help to enhance autonomous functions of robot navigation to allow more flexibility of robots to continue working even with the presence of other robots in unfamiliar environment.

Chapter 4

Research Overview

The research presented in this thesis has been divided into four main stages (Figure 4.1) which reflect the step-by-step evolution to build up the whole system.

In the beginning of research, the investigation on a dependable path planning algorithm was conducted. The details of dependability properties and their roles in autonomous control system have been reviewed in comprehensive surveys, which result in the research of using Petri net to analyse the failures happened inside a system of multiple robotic agents. The study was presented in a conference paper (ICCART, 2017). Based on that, the dependable properties suitable for a navigation system are selected where a dependable, i.e., safe, reliable and available, path planning algorithm is proposed based on a novel dipole flow field which consists of a static flow field and a dynamic dipole field. The static flow field is to drive the robotic agents to the goals with less requirements to update the global path, meanwhile the dipole field plays an important role to prevent collision with other agents and moving obstacles appearing in the working space. The idea was initially presented in a workshop paper, later extended into a full paper [Paper A]. After the principle of the algorithm is evaluated through extensive experiments, its implementation on the middle-ware ROS framework has been performed to transfer from theory into a practical system. Eventually, the implementation was done on Husqvanar Research Platform within the scope of UNICORN master project.

Relying on a single path could lead to deadlock or congestion when multiple robotic agents are routed into a narrow area. Therefore, in the second stage, a proactive multiple path planning algorithm has been proposed to avoid deadlock situations with congestion control. In this work, the global paths of the robots are formed as a graph of a Petri net network. The movement of the robot along its global path is synchronised into the movement of a token in the network. Moreover, a communication channel is also established to help the agents to share their information of positions and velocities to each other. Hence, the control place, i.e., the place where the potential congestion happens, in the Petri net of the agents is estimated, so that the agent can predict when the congestion happens before hand. Thank to the integration with the dipole field, the agents are able to avoid collision at the control place of the Petri net. The result of the work initially is presented in a conference paper published at CODIT, 2019. Later, the proposed algorithm is extended into a full paper [Paper B]. In this paper, each robot is equipped with different paths from starting point to its goal. The travelling time of all trajectories of the robots are analysed by analysing the Petri net. The most optimal configuration of paths for the robots is chosen which is based on the criteria for congestion avoidance.

Finally, an optimisation problem for multiple path planning has been proposed to optimise the paths for all the robots with obstacle avoidance constraints. The evaluation of the proposed method is presented in [Paper C]. As the above proposed multiple path planning has been evaluated in a centralised manner, the interrupt of the centre node could cause the system failures. A decentralised approach is proposed to cope with such a problem, making the robotic agent less dependent on each other, aiming at a self-governing system. The result has been condensed in a journal paper [Paper D] with the implementation on Turble bot 3 to evaluate the presented method.

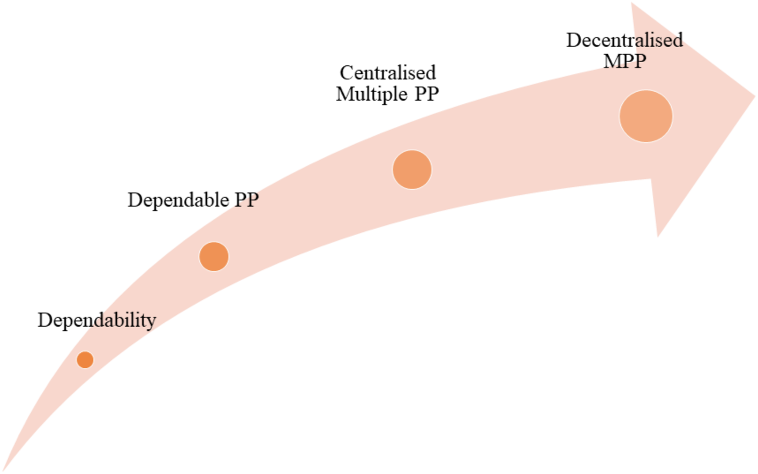

Figure 4.1: Comprehensive research flow.

4.1 Research Methodology

The path way to conduct research presented in this thesis follows inductive reasoning methodology. First of all, the overall objectives of the research are defined. With regards to the goals, the comprehensive literature review of previous works related to the research topics are studied. The research questions are defined based on the analyses of pros and cons of different approaches and of the missing pieces to be solved to achieve the main goals. Continuously, the hypotheses are stated to define what are expected to be evaluated with the ideas/algorithms proposed by the researches. In the next steps, the new ideas are invented and deployed to answer research questions. The experiments are performed to test the developed algorithms with regards to the defined hypotheses. Once the cycle of researches is finished, the limitations of the works are evaluated again to formulate the next iteration of researches. The research progress is therefore performed a step-by-step to build up the complete solution.

Along the pathway to conduct my research with inductive methodology, I always present the ideas of new theory in conferences to get comments from research communities to improve the contents of the work. Once the preliminary results are evaluated, the complete studies with more expensive experiments are performed to report the results into a journal before the next iteration of my research is circulated. In the implementation pathway, after a successful test in a comprehensive simulation, i.e. Gazebo, the real implementation is transformed into a real robot. The robotic platform, i.e. ROS, is chosen in both simulated and real environment to reduce the implementation efforts. My research strategy is summarised in Figure 4.2.

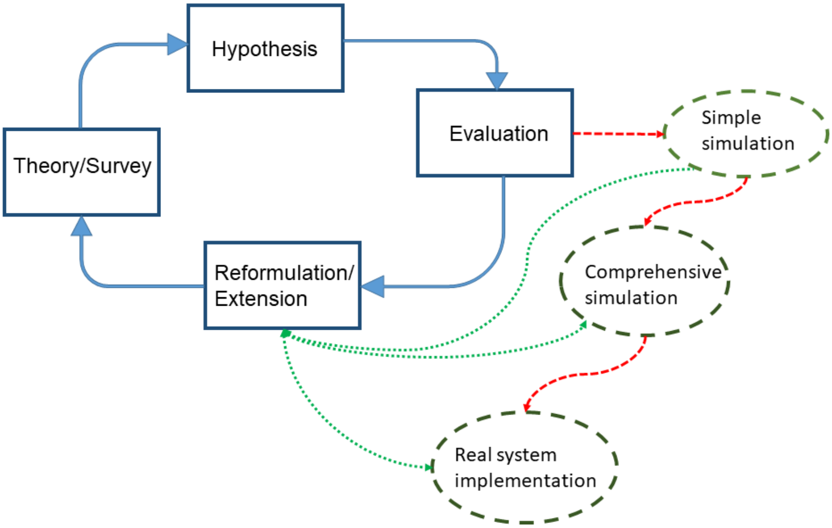

Figure 4.2: Research methodology.

4.2 Research Goals

In overall, the goal of the research works presented in this thesis is to develop a dependable path planning system for multiple robots to navigate them to reach the goals, assuming that the robots coexist with users/operators on the same working space. With regards to availability, reliability, and safety as the main dependable properties, the aims consist of driving all robots to the goals correctly, minimising the possibility and factors that could cause the stopping of the services like the live- and dead-locks, and finally, avoiding collisions among robots and between robots and humans. The hypothesis are defined at each step of my research accordingly.

4.2.1 Research questions

In the initial phases of this research, the research questions mainly focus on how to define the dependability of an autonomous system and then how to develop a dependable path planning for multiple robots system. Continuously, the ideas of obstacle avoidance, congestion control, and multiple path planning have been formulated. At every stages, the research questions (RQs) are raised accordingly:

1. RQ1: *How to define a dependable path planning framework for multiple robotic agents working in a sharing environment with human subjects ?*

   The answers to this question help to define the basics of a dependable system to extend them into path planning algorithms. This includes the theory of dependability, the means to implement a dependable system, the essential components of a path planning system, and the effects of multiple humans and robots on the sharing space into the design of path planning system.

2. RQ2: *How to develop a path planning algorithm to provide safe and reliable moving paths for multiple robots?*

RQ2 is a follow up of RQ1 to deploy dependability properties on a path planning algorithm. The questions are put in a context where humans and robots are living together and safety is a critical factor needs to be ensure to no serious collisions between them. It is noted that the positions of human subjects are estimated from the observation of sensors, thus some levels of uncertainty should exist. The complexity of environment is also taken into account to reach a robust solution that is not limited to a restricted area. Effectiveness on energy consumption is an extra factor to be considered in a path planning algorithm to target sustainable and environmental friendly solutions for long-term uses.

3. RQ3: *How to avoid a deadlock situation through multiple path planning and congestion control?*

   The aim of this question to enhance a path planning algorithm with fault tolerance. This means if a robotic agent fails to do a moving task to the target (deadlock situation), there should be a backup plan for it to recover its navigation activities. The question are to how to formulate the multiple path planning and how to use congestion control to help a group of robotic agents to proactively synchronise their movements through a cross intersection to avoid congestion.

4. RQ4: *How to integrate the proposed path planning algorithm on real robots? What case studies with real autonomous robots can be used to test the whole system?*

   Many challenges related to a realistic environment need to be concerned. They include how to choose a right framework to utilise existing developed solutions, how to detect and monitor the moving trajectories of humans and other objects, how to build a map and localise the robot in there, how to develop a communication method to share information among robots etc.

4.2.2 Hypothesis

At the beginning of this research, the basic framework for a planning algorithm is investigated along with the new navigation method for multiple robots. Aiming at the simple yet effective method to drive the robots to goals safely, the dipole flow field is invented. An any-angle-path planning with Theta* algorithm is employed to initialise the paths from a starting point to a goal for a set of robots. To deal with the movements of the robots, a static flow field along the configured path is defined. This field is used by the robots to navigate and reach their goals even if the planned trajectories are changed. In parallel, a dipole field is calculated to avoid the collision of robots with others and human subjects. In this approach, each robot is assumed to be a source of a magnetic dipole field in which the magnetic moment is aligned with the moving direction of the robot. The magnetic dipole-dipole interactions between these robots generate repulsive forces to help them to avoid collision. Note that the collision happens if the distance between a robot and the target is smaller than predefined thresholds. The first hypothesis is stated to evaluate the proposed path planning approach as follows:

Hypothesis 1: *Using the path planning algorithm as the combination of the dipole field and flow field, it is possible to correctly drive a robot to its desired goals and avoid the collisions of the robot with humans, other robots and obstacles on the moving way.*

Conventionally, path planning algorithms have addressed the navigation problem for multiple robots with a single path planning. Relying on a single global path planning could lead to a deadlock situation where a robot takes a very long time to reach a goal or even is not able to do so. This happens in the case of multiple robots moving in a narrow area. Since the local path planning to avoid obstacle only takes into account the collision of other robots in the vicinity, a robot must turn back to the predefined path to reach a goal. However, if two robots are routed through a very narrow area, like a corridor, and enter it through two opposite sites, robots may face a deadlock situation where they repeat the same moving trajectories through that area again and again without finding the path to the goal. Considering human as a big obstacle due to safety reason could block a robot to enter a small way to follow its global path. Therefore, it is important for a robot to prepare different solutions to reach a goal and the robot needs to proactively switch between solutions whenever necessary to avoid dead lock situation. With regards to the studies about PN and the new path planning algorithm with dipole field, the research in this proposal is continued with the uses of PN for congestion control. Obviously, the navigation of several robots into one narrow area may make them to block each other and harder to find the way out from the area or to take longer time to reach their goals. To address the congestion of routing multiple robots into one place, a group of robots should find effective routes to avoid conflicts with each other. As PN is an effective tool in dependable autonomous control to resolve conflicting problems, it is able to apply PN to plan the paths of multiple robots with a delay to avoid routing many robots into a same place so that the robot may not need to turn around with longer paths to approach to their goals.

The next hypothesis to be tested is formulated as:

Hypothesis 2: *Using multiple path planning with PN to synchronise the movements of robots to cross through an intersection or narow region, it is able to avoid the deadlock situation or the livelock situation, i.e. agents "dance" back and forth when directly opposing each other.*

The multiple path planning using PN to resolve traffic jams of multiple robots is centralised, meaning that if the central controlling node is offline, the whole system stops working. In order to enhance the fault tolerance, it is important to decouple the centralised system to reduce the dependency on the communication network and on a single node to remain operations. The work has started with the introduction of an optimisation framework to integrate both controlling congestion of multiple robots and avoiding collisions. The former involves discrete variables while the other is the continuous optimisation problem. Their combination forms the mixed-integer quadratic programming (MIQP) problem where its solution on embedded devices have been introduced recently, making the solution widely available for mobile robots. As solving the navigation in a centralised manner poses a risk as aforementioned, the distributed algorithms is investigated to solve the MIQP problem. The hypothesis is stated as:

Hypothesis 3: *The MIQP optimisation problem to address multiple path planning with congestion control and obstacle avoidance can be solved in the decentralised manner.*

Chapter 5

Thesis Results

5.1 Contributions and Results

The works done by the thesis have led to five main contributions to the researches of dependable path planning. First, the general theory about dependability has been investigated to find the fundamental properties and means to achieve a dependable path planning algorithm. Thereafter, a new path planning algorithm with dipole flow field has been developed. Third, a new application of PN on path planning algorithm to avoid congestion has been proposed. The fourth contribution is multiple path planning with its role to improve a dependable path planning with fault tolerance. Finally, the basic ideas of the thesis have been implemented in ROS to be applicable in real robots and practical application. The combination of different approaches presented in this thesis reveals the implementation of three layer protections for a robot at different ranges (Figure 5.1).

Dependable properties of a path planning algorithm For a path planning algorithm, it is crucial to enhance three dependable properties including reliability, availability, and safety. Both reliability and availability are assessed by the correctness of the path planning algorithm, i.e. robots are precisely

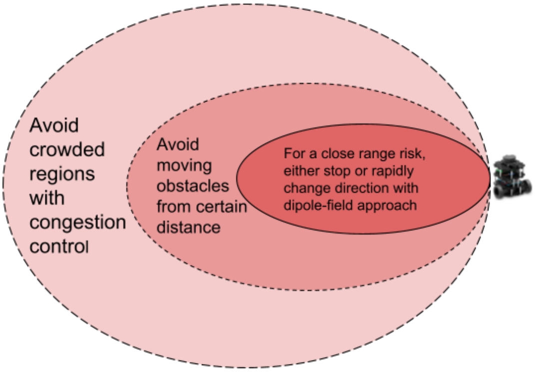

Figure 5.1: Multiple layers proposed to enhance path planning dependability.

navigated to the defined goal. Also they are shown by the continuity of path planning services, e.g. not facing a dead-lock situation so that the robots are no longer to be able to operate. Meanwhile, safety is realised by protecting robots free from collisions with any static and moving obstacles.

Dipole flow field A new path planning algorithm with dipole flow field has been developed. The algorithm is able to process path planning with a fast and effective algorithm by developing a navigation field so that the movements of agents are just simply controlled by the forces generated from the field. The attractive forces that drive the agents toward their desired goals are created by a static flow field. Simultaneously, the repulsive forces that prevent agent-agent and human-agent collisions are generated by a magnetic field of dipoles. The combination of the static flow field and dipole field forms a force to determine the moving directions of the agents at a specific time instance. The simulation results showed that the static flow field safely navigated the autonomous agents to their goals, meanwhile the dipole filed is effective in avoiding collisions. However, routing several robots into a narrow area, e.g., a corridor, might lead to a dead-live lock situation where robots try to avoid collisions with each other but not able to escape from the trapped region. One solution to address this problem is locating potential areas that have high possibility to cause traffic jams and controlling the movements of robots through that area with the following contribution.

Congestion control with PN The application of PN is utilised to control the movement of the robots when they are routed through a cross or a narrow area. The cross/intersection regions of the moving paths are considered as a conflict resource so that a PN is an appropriate approach to avoid traffic congestion among robot. A PN is applied to control the movements of robots at every intersection by organising one by one passing through a cross. Those PN analyses and controls are available with robots when they are able to communicate and share information with each other. For humans and other moving objects, the previous work with dipole field is integrated with dynamic window approach is implemented based on the local planning of the system to help robots to avoid collisions. By regarding the velocity and direction of such dynamic obstacles as a source of a virtual magnetic dipole moments, the dipole-dipole interaction between the moving objects will generate repulsive forces to prevent collisions. Analyses and experiments demonstrated with the Gazebo simulator have revealed that the PN control is able to synchronise the movements of multiple robots passing through the intersection, which helps to shorten the travelling paths of the robots. Meanwhile, the dipole field implemented on DWA is able to advance the local path planning with an ability to avoid moving humans and other robots in the shared work-space.

Multiple path planning in both centralised and decentralised manner The next contribution is the proposed multiple path planning and its role to improve dependable path planning with fault tolerance. Relying on a single global path planning could lead to a dead - or live lock situation which happens when multiple robots moving in a narrow area and they repeat the same moving trajectories through that area again and again without finding the path to the goal. Thanks to the use of multi-paths, or back-up planned paths, the robot is able to switch to another planned path when the currently planned path could lead to blocking. This helps to improve the availability of the system with the ability to provide correct services by proactively preventing the situation when the system fails to complete their planning tasks. The proposed multiple path planning is combined with obstacle avoidance in a unique optimisation framework. The solution for the problem is developed and presented both centralised and decentralised manner.

Implementation on ROS Lastly, one of the crucial contributions of this thesis work is the attempt to transfer the developed framework into the middleware, Robotic Operation System, which can be effectively implemented on real robots. Most of the thesis's experiments and evaluations are implemented on ROS and tested with Gazebo simulator. A basic part of the dependable path planning which is Theta* combined with dipole field, is implemented on a real HRP robot, showing that the implementation works well on a real robotic system and helps the robots avoid both static and dynamic obstacles including moving humans.

5.2 Summary of Papers

The contributions and results are detailed in four articles (Papers A-D) that are summarised as follows.

Paper A This paper presents the basic framework for dependable path planning for multiple robotic agents (or agents in short) with a field-based approach. The main navigation aim is to drive an agent to the goal with a shortest path and to avoid collisions with other agents and moving obstacles, e.g. humans. The definition of dipole flow field is proposed with the combination of static flow field and dipole field. For the static flow field, the Theta* is applied to initialise a single path from a starting point to a desired goal for each autonomous agent. Thereafter, a static flow field is configured along the found path to navigate the agents back to their planned routes if they are deviated from the path due to the meeting with static or dynamic obstacles. To deal with collisions that may happen among moving agents, a novel dipole field is introduced. The field generates dipole forces between two moving agents (presented as two dipole magnets) approaching to each other to push them far away to avoid collision. The combination of these two fields results in a safe path planning algorithm for controlling autonomous agents to reach to their goals. Several scenarios are used to evaluate the effectiveness of the proposed approach. For a static flow field, one hundred trials of experiments have been performed to evaluate this field to drive a single agent from a start to a goal in a $50m \times 50m$ map with static obstacles. Experimental results have shown that the agent is able to move to its goals in a binary map of static obstacles with a small number of re-initialising the global path using the Theta* algorithm. The dipole field is evaluated with the simple crossing scenario of two agents moving toward each other in different orientations in an empty map. The dipole force helps them to avoid collisions yet keep them in smooth moving trajectories to their goals. With the combined dipole-flow field, the robotic agents are well routed to their destinations, while possible collisions with other agents and human are taken into account to protect them and environments from damages caused by a hit and to ensure safety to operating users. In conclusion, the basic dependable properties of completing navigation tasks to the goal and of protecting agents free from collisions have been realised with an simple yet effective approach with dipole-flow field.

Paper B In this paper, the next direction to enhance the dependability of a path planning system is investigated with the uses of Petri net (PN) for congestion analysis and movement control. Obviously, the indirect reason behind the failures of a path planning algorithm for multi-robots links to a traffic jam at a narrow area or at a crossing place. To tackle this problem, in a transportation system, the controls at each intersection, like the uses of traffic light or the moving in a queue at round-about, have been well implemented. This paper adapts those mechanisms for multiple robots to analyse and control their movements using a PN. For each robot, several paths to the goal are created and shared among robots. A central node collects information of global paths and construct an map of intersections where each of them are crossed by at least two paths. Correspondingly, the PN is built where each robot is modelled by a token while the control place is defined a critical resource. The PN control the robot movement by allowing only a limited number of robots passing through the intersection. Other control places are also formulated at a narrow area to determine a maximum number of robot simultaneously going through it.

The whole proposed algorithm is divided into two main stages. In the first stage, the simulation of firing a token through the PN analyses how the movements of the robots look like with a specific configuration of a global path. All combinations of multi-paths assigned to robots are evaluated to find the optimal configuration of the global path for each robot. Once the global path is decided, in the second stage, the PN is utilised to synchronise the movement of a robot through the intersection in first-in-first-out manner with a link of a robot to a token in PN. The PN is mainly applied to help robots avoid mutual collisions with each other. For humans and unexpected moving obstacles, the dipole field is integrated to prevent collisions by repulsive forces generated by moving objects modelled as dipole magnets. The whole framework is implemented on an common and open platform ROS with possibility to be applicable on real robots. Analyses and experiments are demonstrated with an extensive simulator to evaluate the effectiveness of the proposed approach.

Paper C Continuously, this paper presents a simplified version of congestion control for multiple path planing. As aforementioned, a single path planning may lead to a deadlock when a robot fails to continue its moving plan. The deadlock can happen when two or more robots occupy a same place at an instance of time and the obstacle avoidance in a local range is insufficient to drive robot to another way to escape from the deadlock. Multiple-path planning plays an important key to overcome this limitation. The missing question to solve the puzzle is to how to find the right path among multiple choices to go. Therefore, this paper formulates the multiple path planning with obstacle avoidance as an optimisation framework where the cost function is the summation of the path length and the minimal change in velocity and direction. The obstacle avoidance is presented by a constraint in a velocity obstacle space to select a moving direction not collide with other incoming robots. The congestion constraint is to prevent more robots moving through a narrow area. The optimisation problem is solved in a centralised manner with IBM CPLEX. Once the right path and velocity are found, they configure the moving plan of the robots with the ROS platform. The simulated experiment is conducted with three HRP robots which travel from one side of the map to the opposite one and through a narrow corridor. The starting and goal are randomly placed. The experiment has shown that the proposed optimisation has reduced the number of deadlocks and collisions, compared with conventional dynamic window approach (DWA) [69] and DWA+VO.

Paper D This paper presents a decentralised framework to tackle the path planning algorithms for multiple robots. The path planning is stated as an optimisation problem to find the optimal path to a goal for every robots in the working space to minimise or maximise a cost function. At first, the solution requires the needs of constructing multiple paths for each robot to address the situation that two or more robots occupy a same location or a same moving way at an instance of time. Correspondingly, the check of where or when a collision happens is performed to provide the constraints for the optimisation problem to avoid the conflicts. However, it is hard to determine the exact constraints of the meeting time of robots under uncontrolled environments with randomly moving obstacles and humans as the robot has to adapt its speed and moving directions to avoid them. The paper therefore proposes soft constraints which, instead of finding a conflict-free, attempt to reduce the congestion on the moving way of robots. The congestion constraints are estimated by the number of crosses or narrow areas on a specific path. By avoiding the path with heavy traffic jams, the robots proactively avoid the possibility of congestion, which could lead to a collision or a dead-locks to prevent them reaching their goals.

As allowing a change of several robots meeting each other, the obstacle avoidance is required in this situation. Several constraints are integrated into an optimisation problem with a quadratic utilisation function including an object function to minimise the travelling path and a regularisation term to make the moving path to become smooth. In overall, the whole problem is formed as a mixed integer quadratic programming (MIQP) with the integer variables to select a suitable path for each robot. The problem is NP-hard in general where its complexity grows with respect to the number of robots. Therefore, the problem is solved faster by sharing their computational resources to search for the solution of the problem. This is also to enhance the reliability of the system to reduce all dependency on one central node. The optimisation at a local robot is performed with OSQP, a light and efficient solver designed for mobile robot. The algorithms are implemented on ROS and evaluated with simulations on Turtlebot 3.

Chapter 6

Conclusions and Future Works

6.1 General Conclusions

Undoubtedly, navigation is considered as the one of the core components of an autonomous robot system. Starting from a simply requirement of routing a robot to a defined goal, nowadays the path planning problem has become increasingly challenging due to new requirements of an autonomous robot to cooperate with others and even humans to perform a task. In consequence, there have been raising questions to achieve a dependable path planning system, leading to the researches done in this thesis to find the answers for those questions. At first, a board research about dependability and its role in autonomous control has been conducted. Corresponding, three main dependable properties including reliability, availability, and safety for a path planning algorithm have been focused within the scope of this thesis. To aim at a dependable path planning system, the roots to affect those dependable properties are caused by a fault, which could happen due to operator's errors, unexpected events from surrounding environments, or even wrong designs. To reach an acceptable level of dependability, different means have been used as the tools to improve the dependability of a system including fault prevention, fault removal, fault forecasting, and fault tolerance. From above information, the pathway towards the dependable path planning algorithm has been established to drive the researches in the rest of this work. The thesis begins with the development of a safe, reliable, and effective path planning algorithm for a group of robotic agents that share their working space with humans based on a novel dipole flow field including static flow field and dynamic dipole field. The results show that the static flow field is able to drive agents to the goals with a small number of requirements to update the path of agents. Meanwhile, the dipole field plays an important role to prevent collisions. The combination of these two fields results in a safe path planning algorithm to drive agents to their desired goals. Continuously, a fault analysis with a group of multiple robots working together to complete a shared task has been investigated using PN. Consequently, PN is applied to manage the path planning tasks of multiple robots to reduce congestion. The research of this work is continued with multiple path planning with an aim to help multiple robots to avoid the deadlock situation to ensure the availability and reliability of the path planning services. Last yet importantly, it is crucial for a dependable system to always have a reserved solution even with redundancy to avoid the completely failed of the whole system. The final attempt of this thesis work has solved the puzzle of how to bring the implementation of the whole system in a decentralised manner. The key dependable properties including reliability, availability, and safety are evaluated through extensive simulations with Gazebo. The implementation of the proposed algorithm has been transferred into ROS platform to be used in real robots. In overall, the works presented in this thesis have established a pathway and achieved important improvements to approach toward a dependable path planning system.

6.2 Future Works

Research directions have been planned for future works as follows.

Implementation on more real robots/Large scale evaluation In this thesis, the design for the dependable path planning algorithm and the theoretical analysis are developed with ROS and evaluated through Gazebo simulation. The algorithm is initially implemented on ROS-based robots, e.g. HRP. In the next stage, the implementations on other robots as well as more real world scenarios will be planned to show the effectiveness of the proposed method. Furthermore, a large scale evaluation of hundred of robots will be planned with the uses of a powerful computer for simulation.

Diverse fault tolerance and congestion control mechanisms Currently, alternative paths to the goal have been established to provide a backup path if the robot no longer follows the current path. The works can be improved by utilising different algorithms to generate global paths, like RRT-based algorithms [70] to provide more variations of the routes to the goal. A hardware solution for fault tolerance will be also considered. Meanwhile congestion control should focus more on potential areas with high probability of traffic jams instead of applying control on every intersections to reduce complexity of the system.

Hierarchy path planning The complexity of the mixed integer optimisation grows exponentially with respect to the number of discrete variables including in the problem. Therefore, the divide-and-conquer mechanism is the key to tackle the complex path planning problem involving a large number of robots in a big terrain. Robots close together in a configuration space are grouped into clusters and consequently the path planning problem is divided into the local navigation within a cluster and the global navigation among clusters through inter-connections.

Machine learning in path planning Lastly, learning techniques, such as deep reinforcement learning [71], can be investigated to make path planning decisions more accurate and fast by learning experiences from collected data.

Besides, once the system is distributed, finding the right decision will be a heavy task for each independent robot. The path planning task can be mitigated by searching information for learning/collecting data. In another aspect, applying learning methods for data fusion from extensive sensors could also help to fully perceive surrounding environment to achieve a higher level of dependable path planning for a multiple robot system.

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