Large-scale 3D printing with multiple mobile robots for building and construction

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**LARGE-SCALE 3D PRINTING
WITH MULTIPLE MOBILE ROBOTS
FOR BUILDING AND CONSTRUCTION**

**ZHANG XU
SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING
2021**

**LARGE-SCALE 3D PRINTING
WITH MULTIPLE MOBILE ROBOTS
FOR BUILDING AND CONSTRUCTION**

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School of Mechanical and Aerospace Engineering

A thesis submitted to the Nanyang Technological University
in partial fulfilment of the requirement for the degree of
Doctor of Philosophy

2021

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Large-scale 3D Printing with Multiple Mobile Robots for Building and Construction

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Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

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I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

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Authorship Attribution Statement

This thesis contains material from 3 papers published in the following peer-reviewed journals / from papers accepted at conferences in which I am listed as an author.

Chapter 3 is published as Xu Zhang, Mingyang Li, Jian Hui Lim, Yiwei Weng, Yi Wei Daniel Tay, Hung Pham and Quang-Cuong Pham. "Large-scale 3D printing by a team of mobile robots." *Automation in Construction* 95 (2018): 98-106. DOI: 10.1016/j.autcon.2018.08.004.

The contributions of the co-authors are as follows:

- Prof Quang-Cuong Pham provided the initial project direction and edited the manuscript drafts.
- I wrote the manuscript drafts, and prepared all the algorithms and programs.
- Jian Hui Lim and Hung Pham contributed to the robot printing framework.
- Mingyang Li, Yiwei Weng and Yi Wei Daniel Tay prepared concrete materials in the experiment and wrote the material section in the manuscript drafts.

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The contributions of the co-authors are as follows:

- Prof Quang-Cuong Pham provided the initial project direction and edited the manuscript drafts.
- Mehmet Efe Tiryaki worked on the control part of the study and prepared the manuscript drafts.
- I worked on the planning part of the study and wrote the planning section in the manuscript drafts.

Chapter 5 is published as Xu Zhang and Quang-Cuong Pham. "Planning coordinated motions for tethered planar mobile robots." *Robotics and Autonomous Systems* 118 (2019): 189-203. DOI: 10.1016/j.robot.2019.05.008.

The contributions of the co-authors are as follows:

- Prof Quang-Cuong Pham provided the initial project direction and edited the manuscript drafts.
- I prepared the manuscript drafts and performed all the experiments.

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Abstract

With its ever-increasing applications in various industrial fields, additive manufacturing, also known as 3D printing, has been gaining ground in building and construction (B&C) industry in recent years. Compared to traditional construction techniques, 3D printing carries the promise of faster, safer, more customizable, and less labor-intensive operations in multiple segments of the B&C industry. However, scalability is a problem common to existing 3D printing processes, such as the mainstream gantry-based techniques, where the size of the design is strictly constrained by the chamber volume of the 3D printer. This issue is more pronounced in the B&C industry, where it is impractical to have printers that are larger than actual buildings. There is thus a need to develop a novel robotic framework that is practical and is adaptive to large-scale printing applications in B&C industry.

In this thesis, a 3D printing system based on a team of mobile robots is first proposed. Such a system can potentially print single-piece structures of arbitrary sizes, depending on the number of deployed robots. The system is then extended from a stationary-based printing to a *printing-while-moving* paradigm, which further extends its scalability. Next, two problems related to the practical deployment of multi-robot 3D printing are addressed. First, as hoses are indispensable for the 3D printing system to deliver fresh concrete from the mixer to the print nozzle, a method is developed to make sure that they are not entangled when robot printers move around. Second, in many settings, the structures (which possibly have been previously 3D-printed) need to be transported and assembled into other structures (also possibly 3D-printed). Since the structures to be transported and assembled are usually large and heavy, it is important to automate those tasks as well to achieve improved productivity. Thus, an admittance-based control framework is

developed for multiple mobile manipulators to work in cooperation with humans.

The robotic framework and algorithms presented in this thesis have been successfully demonstrated on the hardware system. Compared to other 3D concrete printing techniques, experimental results suggest that the proposed multi-robot printing system offers greater practical scalability, higher time efficiency and better on-site printing capability. On top of these superior characteristics, the system is versatile and highly adaptive to various B&C applications thanks to its modular mobile robotic manipulator configuration.

Contents

1	Introduction	1
1.1	Motivation	1
1.2	Aims and objectives	2
1.3	Contributions	3
1.3.1	Multi-robot printing system	3
1.3.2	Printing-while-moving paradigm	4
1.3.3	Motion planning for multiple tethered mobile robots	4
1.3.4	Collaborative in-situ robotic assembly	5
1.4	Outline of the Thesis	6
2	Literature review	7
2.1	Existing 3D concrete printing systems	7
2.1.1	Gantry-based 3D printing systems	7
2.1.2	Arm-based 3D printing systems	8
2.1.3	Other 3D printing systems	12
2.1.4	Summary	12
2.2	Other applications of robotics in B&C	14
2.2.1	Printing process control	14
2.2.2	Non-3D printing construction robots	15
2.2.3	Summary	19
2.3	Path planning for mobile robots	20
2.3.1	Path planning for tethered robots	20
2.3.2	Path planning for non-tethered mobile robots	22
2.3.3	Summary	23

2.4	Compliant control of cooperating manipulators	23
2.4.1	Compliant control schemes	24
2.4.2	Summary	26
3	Multi-robot printing system	27
3.1	Introduction	27
3.2	Large-scale 3D printing by multiple mobile robots	29
3.2.1	System set-up	29
3.2.2	Pipeline	30
3.2.3	Materials preparation and extrusion methods	31
3.2.4	Robot placement optimization	32
3.2.5	Multi-robot motion planning	35
3.2.6	Actual printing	35
3.3	Results	36
3.3.1	Simulation	36
3.3.2	Execution	37
3.3.3	Printed specimen	39
3.4	Discussion	39
3.5	Conclusion	41
4	Printing-while-moving for large-scale 3D printing	43
4.1	Introduction	43
4.2	System development	45
4.2.1	Mobile printing system	45
4.2.2	Motion planning	45
4.2.3	Localization of the mobile base	48
4.2.4	Motion control for the mobile base	49
4.3	Experiments	50
4.3.1	Accuracy and precision assessment	50
4.3.2	Actual printing	51
4.4	Discussion and conclusion	53
4.4.1	Scalability	53
4.4.2	Improvement in motion planning	54

4.4.3	Other limitations and future work	55
5	Motion planning for multiple tethered mobile robots	57
5.1	Introduction	57
5.1.1	Illustrative example	58
5.1.2	Contributions and organization of the Chapter	62
5.2	Background: non-intersecting target cable configurations and realizability	62
5.2.1	Problem formulation	62
5.2.2	Non-intersecting target cable configurations	63
5.2.3	Realizability of non-intersecting target cable configurations	64
5.3	Algorithm for Straight/Concurrent motion	69
5.3.1	Overview of the algorithm	69
5.3.2	Constructing the Pair Interaction Graph (PIG)	71
5.3.3	Detecting and solving pair deadlocks	73
5.3.4	Constructing the Network Interaction Graph (NIG)	74
5.3.5	Detecting and solving network deadlocks	75
5.3.6	Computing the final motion schedule	78
5.3.7	Complexity of the algorithms	79
5.4	Examples	80
5.4.1	An example from Hert & Lumelsky 1996	80
5.4.2	Hardware experiment	80
5.5	Conclusion	86
5.A	Proofs of the pair interaction propositions	88
5.B	Revising and supplementing Hert and Lumelsky 1997	89
5.B.1	Detecting Route Intersection (revised and supplemented)	90
5.C	Extension to workspace with obstacles	93
6	Collaborative in-situ robotic assembly	97
6.1	Introduction	97
6.2	Background	99
6.2.1	Admittance control	100
6.2.2	Modeling	100

6.3	Methodology	101
6.4	Experiments	102
6.4.1	Experimental setup	102
6.4.2	Experiment 1: Window frame transportation	103
6.4.3	Experiment 2: Window installation	105
6.4.4	Discussion	105
6.5	Conclusion	107
7	Conclusion	109
7.1	Summary	109
7.2	Future work	112

Chapter 1

Introduction

1.1 Motivation

The concept of additive manufacturing, also known as 3D printing, was first brought up in the 1980s. Instead of removing redundant material from a stock in the conventional subtractive machining process, 3D printing creates a three-dimensional product from computer-aided design (CAD) model, usually by sequentially depositing material in a layer-by-layer manner [1]. The 3D printing technology has been evolving rapidly in recent years. There has been widespread adoption of 3D printing in a number of industrial areas, such as manufacturing [2, 3] and medical [4, 5]. The technology offers more than just being economical through minimizing waste incurred in traditional manufacturing techniques; flexibility in product design, significantly shortened lead time, and superior physical properties of final product boost the development of 3D printing application in Building and Construction (B&C) industry.

Recent years have seen rapid developments in 3D printing B&C industry, from the formulation of printable materials [6–8], to the design of new printing systems [9–14], to commercialization [15, 16]. Compared to traditional construction techniques, 3D printing has significant advantages in terms of safer, faster, more customizable, and less labor-intensive operations [17]. However, there are still many challenges present for the technology to be widely adopted in the B&C industry. The primary concern is the limitation on the sizes of the printed structures. As

reviewed in detail in Chapter 2.1, scalability is the major issue common in the existing 3D concrete printing systems, where the size of the design is strictly constrained by the chamber volume of the mainstream gantry-based 3D printer, or by the reach of a stationary robotic arm printer. This issue is more pronounced in the B&C industry, where it is impractical to have printers that are larger than actual buildings. One workaround consists in printing smaller pieces, which can then be assembled on-site. This workaround generates however additional design and process complexities, as well as creates potential weaknesses at the assembly interfaces. While some other printing systems have been put forward trying to tackle this, such as the multi-agent Minibuilders [14] and the mobile based Digital Construction Platform [13], to date they have made little headway towards resolving the scalability problem in concrete 3D printing, due to either material constraints or technical difficulties.

Targeting at overcoming this scalability issue, in this thesis, a novel mobile based multi-robot system is developed, which demonstrates large-scale 3D printing and manipulation capability that are essential for the B&C industry.

1.2 Aims and objectives

The purpose of this thesis is to present a versatile robotic framework that is developed for on-site large-scale 3D printing for the B&C industry.

The main objectives are:

- to review the existing 3D concrete printing techniques and to recognize their various hindrances to large-scale printing.
- to identify the system configuration that is capable of practical large-scale 3D printing and to develop software algorithms for the system to demonstrate the capability.
- to study and propose solutions to some problems that emerge during and after 3D printing, such as robot path planning considering hose for printing material delivery as well as transportation and manipulation of printed specimens. These problems are tightly associated with 3D printing in B&C

industry, and tackling them is important to enhance system competence and to validate the versatility of the proposed system.

1.3 Contributions

There are four major contributions of this thesis. Centering on solving the scalability issue in large-scale 3D printing, contribution 1 and 2 establish overall robot system configuration and printing strategies. In contribution 3 and 4, problems that are closely related to the practical deployment of printing and construction processes are investigated.

1. A robot printing system consisting of a team of mobile robots is proposed. The system can potentially print single-piece structures of arbitrary sizes in a safe, efficient and scalable manner, depending on the number of deployed robots.
2. A *printing-while-moving* paradigm is developed to supplement the proposed multi-robot printing system, which leverages the robot mobility to further extend the scalability of the printing system.
3. Motion planning algorithms are developed for multiple tethered mobile robots so that the mobile printers carrying the material delivery hoses can move to their respective target locations efficiently without tether entanglement.
4. A compliant control framework is developed for multiple mobile manipulators to work in cooperation with humans for object transportation and assembly.

Each of the aforementioned contributions is discussed in more detail in the following sections.

1.3.1 Multi-robot printing system

With a view to overcoming the scalability issue of existing 3D printing techniques, a large-scale printing system comprised of multiple mobile robot printers is proposed. The first contribution of this thesis is a multi-robot printing system that is

capable of on-site printing large structures in a safe, efficient and scalable manner. The system configuration contains several modules: planning of robot placement to optimize workspace, mobile robot navigation and localization to reach target printing location, and planning of manipulator trajectory to deposit material accurately on desired path. The work presents, to the author’s knowledge, the first physical demonstration of large-scale, concurrent, 3D printing of a concrete structure by multiple mobile robots.

1.3.2 Printing-while-moving paradigm

Although the aforementioned multi-robot printing system is able to alleviate the scalability issue, the printing is performed with stationary printers, imposing thereby a limit on the size of structures that can be printed in a single take with fixed number of robotic printers. In this second contribution, the author supplements the proposed multi-robot system with *printing-while-moving* paradigm, which enables printing single-piece structures of arbitrary sizes with a single robot. This development requires solving motion planning, localization, and motion control problems that are specific to mobile 3D printing. The framework is reported to address those problems, and demonstrate, for the first time, a printing-while-moving experiment, wherein a $210\text{ cm} \times 45\text{ cm} \times 10\text{ cm}$ concrete structure is printed by a robot arm that has a reach of 87 cm.

1.3.3 Motion planning for multiple tethered mobile robots

As tethers are indispensable for the 3D printing system to deliver the fresh concrete from the mixer to the print nozzle, it is important to make sure that the cables are not entangled while the robots move to their target positions. It is thus necessary to consider the motion planning problem for multiple tethered mobile robots: how to plan and coordinate the robot motions to realize a given non-intersecting target cable configuration. Four possible modes of motion are identified, depending on whether (i) the robots move in straight lines or following their cable lines; (ii) the robots move sequentially or concurrently. An in-depth analysis of **Straight/Concurrent** is presented, which is the most practically-interesting

mode of motion. In particular, algorithms that (a) detect whether a given target cable configuration is realizable by a **Straight/Concurrent** motion, and (b) return a valid coordinated motion plan are proposed. The algorithms are analyzed in detail and validated in simulations and in a hardware experiment.

1.3.4 Collaborative in-situ robotic assembly

The potential applications of the proposed robotic framework are not limited to printing tasks in the B&C industry. In many settings, the structures (which possibly have been previously 3D-printed) need to be transported and assembled into other structures (also possibly 3D-printed). Since these structures are usually large and heavy, it is important to automate those tasks as well to achieve improved productivity. Thus, as the fourth contribution of the thesis, a compliant control framework is developed for multiple mobile manipulators to work in cooperation with humans, which ensures human safety and avoids damages to the object being handled. Experimental results are provided, where two physical mobile manipulators perform a window transportation and installation task smoothly guided by a human operator. To the author’s knowledge, this is the first demonstration of multiple mobile manipulators working in cooperation with humans on transporting and manipulating a rigid object.

Overall, this thesis presents a radical departure from existing 3D printing techniques, which has demonstrated great potential in advancing concrete 3D printing technology in the B&C industry. Attributed to the multi-robot and mobile-based system configuration, the proposed 3D printing framework brings tangible benefits on practical scalability, time efficiency and on-site printing capability. Apart from these breakthroughs, the system’s modular formulation makes it highly versatile and amenable to various other applications in the B&C industry.

1.4 Outline of the Thesis

The remainder of the thesis is organized as follows. In Chapter 2, the literature of existing 3D printing systems for B&C, path planning problems for tethered robot and compliant control of cooperating manipulators is reviewed. In Chapter 3, the proposed system based on a team of mobile robots is presented in details, and the results of the multi-robot printing experiment are reported. The system is further developed to adopt printing-while-moving paradigm that is detailed in Chapter 4. In Chapter 5, an efficient path planning algorithm for multiple tethered mobile robots is proposed. In Chapter 6, the admittance-based control algorithm for multiple mobile manipulators working in cooperation with humans is presented. Finally, in Chapter 7, the thesis is concluded and some directions for future work are sketched.

Chapter 2

Literature review

2.1 Existing 3D concrete printing systems

There is no single classification standard for 3D concrete printing systems. They can be categorized into powder-based systems and extruded material systems based on the type of material used in the process; or gantry-based systems and robotic arm-based systems according to the system mechanism. In the following sections, a thorough review of the existing 3D concrete printing systems is presented from the perspective of system mechanism.

2.1.1 Gantry-based 3D printing systems

Since applying 3D printing in construction was first proposed in the early 1990s [18], the gantry-based system has been widely adopted in the early stage of 3D concrete printing, and remains a popular technique in the current B&C industry. Such a system uses a gantry to position the print nozzle(s) in XYZ Cartesian coordinates, and its build scale is determined by the enclosed volume of the gantry.

A number of notable methods that use a gantry-based system include Contour Crafting [9, 19–21], Concrete Printing [6, 10, 22, 23] and D-shape [11]. The printing process of Contour Crafting consists of two main phases: extrusion and backfilling. During the extrusion phase, the boundaries of each layer are printed to serve as a mould for the target structure. The extrusion nozzle has two trowels attached to it in order to create a smooth surface finish of the printed specimen. The backfilling

phase begins once the boundary forms are printed. To produce minimal lateral pressure on the form, the concrete is injected to fill the internal volume in several batches, such that the concrete at the lower part of the form hardens to some extent before the next batch of material is poured in [24]. However, the segmented backfilling batches lead to weak bonding strength by making fresh concrete adjoin hardened concrete at the junctions [23].

Similar to but different from Contour Crafting, Concrete Printing is purely an extrusion-based method that is akin to the well-known fused deposition modeling (FDM) in additive manufacturing. The method uses a smaller extrusion nozzle to achieve finer deposition resolution, thus better geometrical control [25]. Since the Concrete Printing system has only one extrusion nozzle, the material deposition is inevitably limited and the aforementioned bonding strength problem is likely to arise, especially for a target structure that has large cross-sectional area.

D-shape is another gantry-based printing method. It uses a binder jetting technique to selectively deposit binders on a powder bed to create a stone-like object. For each layer, the powder material is spread over the bed and flattened to the desired thickness. The binders are then injected at the target locations that need to be solidified. The unbounded powder material remains on the bed as temporary support and is not removed until the whole printing is finished. Instead of having one nozzle to print along the entire printing path, the D-shape printer has an array of nozzles mounted in-line such that only few traverses are required for each layer.

The schematic system set-ups and the printed specimens of Contour Crafting, Concrete Printing and D-shape are presented in Figure 2.1 [23, 26, 27].

2.1.2 Arm-based 3D printing systems

Robotic arm-based systems are relatively new compared to the gantry-based counterparts. A 6-DoF articulated robotic arm offers additional roll, pitch and yaw controls to the end-effector (print nozzle), allowing the print nozzle to perform more articulate print designs, such as printing with the tangential continuity method [12]. The tangential continuity method allows a smoother transition between print layers

(a) Contour Crafting set-up.

(b) The specimen printed by Contour Crafting.

(c) Concrete Printing set-up.

(d) The specimen printed by Concrete Printing.

(e) D-shape set-up.

(f) The specimen printed by D-shape.

Figure 2.1: Schematic set-up and printed specimens of Contour Crafting, Concrete Printing and D-shape [23, 26, 27].

by maintaining a continuous rate of curvature change, giving a more aesthetically pleasing look. The printing system utilizes a 6-axis robotic arm, which is capable of achieving full 3D topologies as opposed to the 2.5D topologies generated by the vertical extrusion using conventional gantry-based systems with Cartesian kinematics. The printing process is illustrated in Figure 2.2 (a).

Another remarkable robotic arm-based system is Digital Construction Platform (DCP) developed by a group of researchers at Massachusetts Institute of Technology (MIT) for on-site fabrication (see Figure 2.2 (b) and (c)) [13]. The system consists of two robotic arms combined in a micro-macro manipulator configuration with a reach of more than 10m, mounted on a track driven mobile platform. A laser sensor is attached to the wrist of the small robot and measures the variations in ground height as the large arm performs gross positioning. The small arm is controlled with real-time sensor feedback for fine positioning and oscillation compensation under different environmental conditions. DCP is also equipped with a electrical drive system that is rechargeable through the on-board solar panels, making it self-sufficient and suitable for out-door on-site printing tasks. The capability of the DCP is demonstrated by 3D printing a 14.6-m-diameter, 3.7-m-tall hemispherical open dome with polyurethane foam. It is worth noting that although DCP is outfitted with a mobile platform, the printing is demonstrated from a stationary position. *“Further autonomy and full-body motion planning would require additional sensor feedback”* [13].

Besides the academic advances, arm-based 3D concrete printing system has been developed rapidly in the B&C industry as well in recent years. XtreeE, a 3D concrete printer manufacturing startup founded in 2015, has developed a multi-component printing system attached to the end-effector of a 6-axis robotic arm, as shown in Figure 2.2 (d) [28]. Cybe RC 3Dp [29] is a printer that has a 6 axis robotic arm mounted on caterpillar tracks and is used in 3D printing the R&Drone Laboratory in Dubai(Figure 2.2 (e)) [16]. Similar to the other arm-based printers that are mounted on a mobile platform in the literature, the mobility is only limited to navigation.

System set-ups and printing illustrations of the above mentioned arm-based systems are presented in Figure 2.2.

(a) 3D concrete printing process with robotic arm [12]

(b) Digital Construction Platform (DCP)

(c) DCP printing process

(d) Multi-component printing system developed by XtreeE

(e) Cybe RC 3Dp printing process

Figure 2.2: System set-up and printing process for arm-based printing systems.

2.1.3 Other 3D printing systems

Aside from the before reviewed gantry-based and arm-based mainstreams, the following subsection introduces some other unorthodox yet interesting printing systems.

Minibuilders

Minibuilders [14] presents an alternative approach for 3D concrete printing. The system consists of three small mobile robots. The first robot is equipped with a sensor that follows an initial marked path and builds the concrete foundation. The second robot is placed on the foundation and gripped the foundation with rollers before printing additional layers of concrete, and building up the structure. The last robot uses suction cups and pressurized air to print vertically up the printed structure and reinforced the printed structure which had only horizontal layers. Figure 2.3 presents Minibuilders and its printing process.

Cable-suspended robotic printer

A cable-suspended robotic printer is introduced in [30], which uses a 6-DoF cable-suspended robot for positioning. The printing system uses polyurethane foam as the printing material and a separate material shaving foam as the support. Compared to other existing printing systems, such a system has the advantage of being cheaper, easier to configure and lightweight thus more transportable, however, at the expense of a lower accuracy. Figure 2.4 presents the proposed cable-suspended 3D foam printer that has been used to print a 2.16-m-high statue.

2.1.4 Summary

The most significant limitation of existing printing systems is the scalability issue. Gantry-based system and stationary robotic arm system require a massive external framework to support the single print nozzle in building the structure. While mobile robotic arm system helps extend the printing range, a single print nozzle still hoards the entire print space, limiting the efficiency of the printer. Although a multiple agent system is introduced by *Minibuilders*, their robots require a harden

(a) Three small mobile robots used in Minibuilders.

(b) Print the foundation.

(c) Build up layers.

Figure 2.3: System set-up and printing process of Minibuilders. [14].

structure for climbing and therefore has limited application as it involves waiting for the printed concrete to grant sufficient strength before deployment. The accuracy issue of cable-suspended robotic printer makes it not suitable or robust for full-building-scale printing tasks.

This gap in scalability motivates my research of a multi-robot printing system. The proposed system utilizes multiple mobile robot printers in a multi-agent setting to print their individual portion of a large print structure. They are capable of localization, collision avoidance and efficient coordinated printing through optimal robot placement. The system demonstrates scalability by allowing users to introduce as many robots as needed in a share environment for task completion in a fast and efficient manner.

Figure 2.4: The cable-suspended 3D foam printer proposed in [30].

2.2 Other applications of robotics in B&C

2.2.1 Printing process control

During actual printing experiments, the printing quality could be affected by a number of factors that are unlikely to be accurately and consistently controlled throughout the printing process. Consequently, it is desirable to introduce some feedback control schemes to monitor and regulate the printing process. In [31], a 1D Time of Flight (ToF) distance sensor is attached to the nozzle to measure the distance between the nozzle and the substrate. The distance is monitored and fed back to the system control unit in real time, and the nozzle position is adjusted accordingly to correct the deviation of the actual nozzle height from the intended one, which is typically caused by imperfection in the hardware setup and the material deformation [32]. Figure 2.5 demonstrates tracking of the desired nozzle height with the proposed measurement and feedback system when printing over a non-flat surface that is not predefined. Other than controlling the nozzle height to regulate the printing quality [31], A. Kazemian et al. develop a vision-based system that automatically adjusts the material extrusion rate based on the vision feedback [33]. A camera is attached to the nozzle to capture the top view

of the printed filament. With the proposed vision algorithm, the filament shape is extracted, and the layer width is measured and compared with the desired one to detect over-extrusion or under-extrusion conditions. The material extrusion rate is thus adjusted accordingly to match the desired layer dimensions.

Figure 2.5: Printing over a non-flat surface whose geometry information is not predefined using the real-time nozzle height measurement and feedback control system [31].

2.2.2 Non-3D printing construction robots

Other than 3D concrete printing systems, there are also construction robots developed for tiling, brick-laying and masonry, etc. The following sections present several concerns that appear in the literature. Please refer to [34,35] for some other reviews on automation and robotics in construction.

Robotic tiling

Although automation has been developed for multiple segments of B&C industry, currently the tiling process is still performed manually and is highly dependent on tiler's skills. In order to achieve higher tiling efficiency and accuracy, cut cost and release tilers from the non-ergonomic working conditions, there have been efforts made by researchers to automate this process.

Some works have presented conceptual designs of a dedicated tiling robot [36–39], but none of them have delivered a physical or commercially available tiling

machine. Apostolopoulos et al. discussed possibilities for tiling process automatization, described a potential configuration of the tiling robot and proposed to evaluate tile placement quality base on computer vision [37]. In [36], the author described the concept of the Surface Horizontal Autonomous Multipurpose Interior Robot (SHAMIR), which is designed for horizontal surface treatment, floor covering and some other general assignments. In the author’s later work [38], more detailed development of the floor-tiling module was presented. The system utilizes a six degrees-of-freedom robotic arm, mounted on the wheel carriage, for tile handling. A computer vision-based system was developed for quality assurance.

There are several other developments based on the same setup, a six degrees-of-freedom robotic arm mounted on a wheeled platform, that have presented some demonstrations of the actual tiling process with the hardware system [40,41]. However, at the current stage, mobility of these systems have not been validated. A robot called TAMIR (Technion Autonomous Multipurpose Interior Robot) was designed to perform various interior finishing tasks, including tiling [40]. The major limitation of TAMIR is that there is no real-time quality assurance and control. The tile placement counts on the pre-calibration of the robot position against the working scene, making the system error-prone. A more recent work is the mobile tiling robot developed in [41]. The robot has four point laser sensors equipped on its terminal actuator for position measure. The pose of the actuator is adjusted with reference to the adjacent reference tile based on the sensing information [42]. However, this method requires known relative position between the terminal actuator and the tile to be laid, and good levelness is not guaranteed.

Construction robots by DFAB HOUSE

Among the many other developments of construction robots, there are some remarkable contributions by DFAB HOUSE that are to be highlighted in this section.

DFAB HOUSE is an institution that aims to explore the possibility of applying digital fabrication technologies to B&C industry [43]. An autonomous construction robot named the In situ Fabricator has been designed, which comprises a robotic arm mounted on top of the hydraulically driven tracks [44–46]. The system is designed to be self-contained, with batteries, controllers, sensing and computing

systems integrated on-board. The In situ Fabricator (IF) has been deployed for several construction experiments: brick-laying [44–46] and mesh mould fabrication [46–48].

In [44], an undulating brick wall was constructed with IF in a semi-autonomous manner (see Figure 2.6 (a)). The robot was manually repositioned 14 times during the brick-laying experiment so that it was able to cover the entire work piece. Each time after IF was repositioned, 3D scans of the environment was generated with the laser-range-finder (LRF) mounted on the robotic arm’s end-effector. The robot then localized itself and continued building a patch of the brick wall within its reachability. The wall was successfully constructed with a maximum positioning error of 7 mm over the entire workpiece. In their later work [45], the repositioning and localization process of IF was developed to be autonomous and the capability was demonstrated by the fabrication of a vertical stack of bricks (see Figure 2.6 (b)). A 1.3 m high stack of 26 bricks was successfully built and IF repositioned itself after placing each brick. The maximum brick positioning error is 4.6 mm for the entire stack.

(a) An undulating brick wall constructed semi-autonomously by IF [44].

(b) IF stacking up the bricks [45].

Figure 2.6: The brick-laying and brick-stacking experiments by DFAB HOUSE.

In the mesh mould experiments, IF was equipped with a specially designed end effector, which is able to cut and weld steel wires to additively manufacture a mesh structure [46–48]. The fabricated mesh was then infilled with concrete to form a concrete wall. The mesh served as both a formwork and a reinforcement

structure for the wall. Different from the brick-laying experiments, camera-based sensing was used in the mesh mould experiments instead of the LRF. Two cameras mounted on the base of the robot were used for global localization and a pair of stereo cameras attached to the tool-head were utilized for local detection of the mesh. The global localization system alone provided an accuracy of less than 5 mm, which was not sufficient for the fabrication task. However, with real-time feedback from the coupled local detection system, the contour of the mesh being welded could be determined and compared with the desired CAD design. Any significant error would be compensated by planning the subsequent layers to pull the mesh back. Figure 2.7 presents the metal mesh built by the IF and filled with concrete subsequently.

(a) IF building a doubly curved metal mesh.

(b) Mesh filled with concrete.

Figure 2.7: The mesh mould experiment by DFAB HOUSE [46].

The works mentioned above are very impressive, but the construction applications being demonstrated are all *discrete*. On the contrary, 3D concrete printing is a *continuous* process, which essentially poses more challenges to system control. Unlike in the mesh mould fabrication, where the "pulling back" strategy can be adopted to compensate errors, there is no remedy for 3D concrete printing once an error occurred during printing: an offset of few millimeters in one layer would be fatal and potentially lead to printing failure. The printing accuracy is critical and much more demanding in order to prevent the subsequent layers from falling, which indeed must be improved further to sub-millimeter level.

Teleoperation Robot System

In the literature of construction robotics, tele-robot system is commonly used to remote control a robot to carry out tasks in extreme or hazardous environments that are not suitable for humans [49–54]. Such a system generally consists of two parts: a local master system and a remotely controlled slave robot. On the basis of the sensor feedback information from the slave robot, the human operator sends commands to the local robot, which are forwarded to the remote slave robot.

Many papers aim at developing control strategies to improve the transparency of the system, such that the human operator feels as if he/she is operating the actual remote robot, and the remotely controlled robot could reproduce exactly the same motions as commanded for the local robot [55–61].

Recently, with the development of virtual reality (VR), VR-based techniques are introduced to teleoperation robot systems to improve task efficiency and operation safety [62]. Apart from the force feedback, the working environment is updated in real-time based on image information obtained from the camera in the remote site. Reconstruction of the virtual environment evolves from 2D to 3D, and the operator can better emerge in the environment and perform safer operations.

2.2.3 Summary

From the literature, the configuration of our proposed robotic system, mobile-based robotic manipulators, is recognized to be versatile and can easily be adapted to various other applications in the B&C industry, such as tiling, grinding, welding, manipulation and many more. With that being said, accurate control is a major technical difficulty when employing such a mobile-based robotic system for certain tasks that require high precision or cooperation of multiple parties. This crucial control problem has been considered and addressed in Chapter 4 and Chapter 6, where printing-while-moving paradigm for 3D printing and human-robot cooperative manipulation are discussed. The research presented in this thesis would inspire people to rethink the construction process and it has great potential to boost the B&C industry to the next level of digitalization and automation.

2.3 Path planning for mobile robots

This section reviews path planning methods for tethered mobile robots and other construction mobile robots.

2.3.1 Path planning for tethered robots

As the hose for material delivery is indispensable in 3D concrete printing, it is necessary to investigate on planning algorithms for tethered robots.

Single tethered robot

Study regarding motion planning for a single tethered robot in the literature mainly falls into two topics - shortest path planning as well as coverage and terrain exploration.

Planning the shortest path for a single tethered robot from a starting position to a target position was studied by Xavier [63] and Xu et al. [64]. They use similar methods that triangulate the environment with polygonal obstacles and construct a visibility graph, finally perform an almost-exhaustive enumeration of graph paths in the selected homotopy class. In [65–67], the authors approach the problem by using a notion of homotopy classes of the cables. The difference lies in the way they identify homotopy classes. Igarashi and Stilman [65] uses distance from the initial vertex that solely based on a metric, which would fail to identify that two vertices in the graph represent two different homotopy classes under some situations. To avoid this failure, Kim et al. [66, 67] use a true homotopy invariant (h-signature) to construct a h-augmented graph that explicitly bears the topological information and can produce optimal result based on discretized workspace. Another more recent study [68] is built on work by Kim et al. [66, 67]. They replace the grid-based approach with a visibility-graph based approach and extend the point robot assumption to polygonal (translating) robot.

Planning for tethered robots has also been studied in the context of coverage and extreme terrain exploration. Shnaps and Rimon [69] present an online algorithm in which a tethered robot has to cover an unknown planar environment that contains obstacles and return back to base. Abad-Manterola et al. [70] give a motion planar

for a tethered axel rover on steep terrains whose geometry is known a priori with high precision. Their work is later extended to an online algorithm where the terrain is poorly known prior to the start of the descent [71].

Multiple tethered robots

Cooperative control and manipulation, as well as navigation from respective starting to target positions for each robot are two major streams for multiple tethered robots planning.

With respect to the cooperative control and manipulation, in [72], the authors propose a method that make multiple mobile robots use tools to accomplish tasks, where the cables act as tools connected between the robots. Similarly, in [73], the authors address the cooperative control of two autonomous surface vehicles for oil skimming and cleaning.

Among the related works for multiple tethered robots navigation, Khuller et al. [74] plan for a team of robots having a particular configuration to move from any starting location to any goal destination in a graph-structured space simultaneously.

In some other applications, instead of keeping a particular formation, each of the group of robots needs to navigate to a different location for certain task, where cable entanglement avoidance emerges as a crucial challenge. There are some remarkable works by Hert and Lumelsky in this field of study. In [75,76], to achieve tangle-free planning, robots are prioritized and scheduled to move sequentially in a common planar and spatial environment that is free of obstacles. But the sequential motion of a group of robots is not efficient and the planning may fall in deadlock under certain circumstances. Although in their later work [77] simultaneous motion of the robots is mentioned, the robots still follow the same routes as computed for sequential motion, which implies that deadlock situations happened in sequential motion remain unsolved and certain robots have to move in some unnecessary detour in this case.

Another work by Sinden provides an algorithm for scheduling multiple robots moving simultaneously to avoid tether tangling, but only under some specific system configurations [78].

2.3.2 Path planning for non-tethered mobile robots

This sub-section reviews some studies on path planning for non-tethered robots, in particularly local path planning, in which the mobile robot sense its surrounding obstacles and tries to move towards the target location with limited local knowledge about the environment [79]. This field is important for navigation of the proposed 3D printing system when being deployed to other construction related tasks, such as exploring and construct in unknown or dynamically changing environment. For more thorough reviews on mobile robot navigation in cluttered environment, see [80] for a recent survey. The following reviews several famous local planning algorithms: Potential field method [81,82], Bug algorithm family [83] and Rapidly Exploring Random Trees (RRT) [84].

The potential field method regulate a robot motion in the environment with the artificial potential field that is assigned to each point in the environment. In general, the region around target position has low potential, and the regions around obstacles have high potential. The robot is guided to navigate in the field towards lower potential points and eventually reaches the target position. The method is intuitive and simple, but it is well known to perform poorly in narrow passages and dynamic environment, and the robot is likely to get trapped in local minima. Some vibrations of the basic potential field method have been proposed to improve some of the above mentioned drawbacks [85–88].

Another famous technique for local path planning is the Bug algorithms family, whose termination conditions for unknown environments have been proven. The basic strategy of the algorithms is to guide the robot to move in a straight line from the starting location to target location, until it senses any obstacle in the way. The robot then follows the boundary of the obstacle until the path to the target location is clear again. A collision-free path can thus be generated with the algorithms' boundary-following and motion-to-goal characteristics. However, the Bug algorithms normally are not directly applicable to real-world applications for its three assumptions: i). the robot is a point; ii). the robot has perfect localization ability; iii). the robot has perfect sensors. A number of variations of the Bug algorithms have been implemented. Readers can refer to [83, 89, 90] for

comparisons of their performances.

The RRT technique is relatively new and is gaining popular in many applications for its simplicity and outstanding performance. The method explores the search space by expanding a random tree from the starting node to the target node, connecting nodes whose edges are no longer than the specified length and do not cross obstacles. A node is obtained by the random sampling process and can be at any position that is free of obstacles. More details of the algorithm can be found in a recent review [91].

2.3.3 Summary

In this corresponding work of the thesis, the same problem formulation is adopted as in [75] since it fits well into the 3D concrete printing application, where each mobile robot moves from home station to a target printing position, carrying a hose for material delivery. The core of this research is to plan an optimal final cable configuration given certain criteria (total hose length in our application for less material waste), and examine the realizability of different modes of motion for robots to achieve the planned configuration. It has been demonstrated that the proposed **Straight/Concurrent** motion is the most practically interesting mode, as it is efficient and capable of solving several challenging deadlock situations for other motion modes.

2.4 Compliant control of cooperating manipulators

There are many occasions in B&C industry when large object manipulation and heavy payload transportation are performed that requires corporation of multiple robots. Consider a case where some robots need to transport several 3D printed pieces of a large-scale structure to a target location and assemble them. As the construction site is usually dynamic and unstructured, and the assembly requires highly accurate alignment of workpieces, autonomous robot navigation and precise manipulation would require expensive sensing and computational cost. On the

other hand, the task could be executed by the robot system working in cooperation with a human operator. In such a situation, the manipulated object is expected to interact with the environment. Compliant control of the manipulators is necessary to ensure human safety and avoid damages to the object being handled.

2.4.1 Compliant control schemes

Apart from passive compliance design of the system mechanics, there are two main approaches to solve the interaction control problem in the literature: direct force control and indirect force control, which includes impedance/admittance control [92].

Hybrid force/motion control is a widely adopted direct force control strategy to introduce compliant behaviors to the robotic system [93–97]. It allows simultaneous control of the end-effector motion and contact force in mutually independent subspaces via reasonable decomposition. This method works well for tasks that have explicit model of the interaction, but it is not suitable for situations that require interactions with unknown environments, and a fully compliant behavior is not guaranteed.

Differently from the hybrid force/motion control method that controls the force and position explicitly, impedance/admittance control enforces dynamical relationships between the manipulator position/velocity and the external forces, making the control strategy perform superiorly when the robot is either in free space, or in contact with unknown environments. Considerable effort has been made in this field for cooperative manipulators. Note that in the robot control literature, impedance control and admittance control essentially refer to the same control scheme used for different robot mechanics. In [98], the authors proposed a centralized control method for the object-environment interaction, where a desired impedance is enforced at the manipulated object. Impedance control policy that regulates the internal stresses on the object has also been investigated [99]. Motion of each manipulator is coupled with the internal forces on the manipulated object by the controller, and each manipulator is given the corresponding impedance. Later in [100], a distributed impedance approach was presented. Instead of object

level control, end-effector level impedance control was developed, where each co-operating manipulator is controlled independently. More recently, an integrated impedance control scheme has been proposed to handle both external interaction with the environment and internal stresses on the object [101]. A centralized control strategy is applied to enforce compliance at the object level for object-environment interactions, and its decentralized counterpart is applied at the end-effector level to avoid undesired forces on the manipulated object due to the manipulators-object interactions. In [102], the developments of impedance control have been further extended to mobile manipulators. The authors identified the cooperation imperfection caused by the kinematic errors due to uncertainties in the system model, and applied impedance-based control strategy to restrain the internal stresses on the manipulated object. In addition to the aforementioned impedance control methods for symmetric manipulation tasks, [103] is a piece of interesting work that considers dual-arm robots performing asymmetric bimanual tasks, where relative impedance control was proposed based on the relative Jacobian concept.

There have been some studies pertaining to impedance control schemes for robots working with humans. An impedance-based control algorithm for multiple manipulators handling a single object in cooperation with humans was proposed in [104, 105]. The authors implemented the impedance control scheme on a dual-arm mobile robot in their later work [106, 107]. Motion dynamics of the mobile platform and that of dual-arm manipulator was decoupled.

Some researches were inspired by the impedance modulation strategies of humans and have touched on human intention retrieval during the human-robot co-operation. Ikeura et al. proposed a variable damping control method based on impedance characteristics of human-human interaction and the control parameters are tuned according to the inferred human intentions [108, 109]. Similar topics have also been studied in [110], and the authors proposed to use differentiation of the force to sense the human intention in [111]. In [112], the variable damping control method is further developed for redundant robot system. In a recent paper [113], a kinematic control strategy was proposed for a dual-arm robot working with humans for object transportation. Human intention was retrieved by visual monitoring the operator's contact with different pre-defined interaction points.

2.4.2 Summary

In Chapter 6 of this thesis, admittance control of a robot system that consists of two (potentially more) mobile manipulators working in cooperation with humans is proposed. Compared to the multi-arm mobile system setups in the literature, which normally comprises either multiple manipulators with stationary base or dual-arm manipulators mounted on a single mobile platform, our swarm setup with modular mobile manipulator is more versatile and is capable of covering a broader task spectrum. The work explores the potential of applying the admittance control strategy to mobile-based industrial manipulators and discusses the possibility of utilizing the system redundancy to incorporate other functions into the control framework such as manipulability maximization and obstacle avoidance.

Chapter 3

Multi-robot printing system

3.1 Introduction

Compared to traditional construction techniques, 3D printing carries the promise of faster, safer, more customizable, and less labor-intensive operations in multiple segments of the Building and Construction (B&C) industry [17].

A major hurdle to the widespread adoption of 3D printing in B&C is the limitation on the sizes of the printed structures. As reviewed in detail in Chapter 2, most existing 3D printing systems for B&C are based on a gantry, which can only print structures whose sizes are at most as large as that of the gantry itself. Some arm-based systems have been demonstrated, but the sizes of the printed structures in this case are limited by the reach of the robotic arm. One workaround consists in printing smaller pieces, which can then be assembled together. This workaround generates however additional design and process complexities, as well as creates potential weaknesses at the assembly interfaces [114–117].

To overcome this scalability issue, a 3D printing system based on a team of multiple mobile robots is proposed in this work. Such a system can potentially print single-piece structures of arbitrary sizes, depending on the number of deployed robots. It is demonstrated, for the first time to the author’s knowledge, the actual printing of a single-piece concrete structure by two mobile robots operating concurrently (see Figure 3.1 and video at https://youtu.be/p_jcG25tUoo). The size of structure is 1.86 m $\times$ 0.46 m $\times$ 0.13 m (length, width, height), which is larger

than the reach of each robot arm taken separately (1.74 m), highlighting the need for multi-robot deployment. Note that concurrent printing is important to guarantee good bonding properties at the junctions: sequential printing would lead to fresh concrete adjoining hardened concrete at the junctions, weakening thereby the bonding strength [7, 118].

Figure 3.1: Concurrent printing of a large, single-piece, concrete structure by two mobile robot printers. See the full video of the experiment at https://youtu.be/p_jcG25tUoo.

Concurrent 3D printing by multiple mobile robots is difficult for several reasons. First, the robot motions must be carefully planned and coordinated to optimize material delivery while avoiding mutual collisions. Second, robot localization must be highly precise to ensure that the pieces printed by different robots are perfectly aligned. Finally, the mixing and pumping systems of the robots must be coordinated to deliver materials in a synchronized manner.

The remainder of this chapter is organized as follows. In Section 3.2, the system based on a team of mobile robots is presented in detail. In Section 3.3, the results of the multi-robot printing experiment are reported. In Section 3.4, the advantages and limitations of the proposed system are discussed. Finally, the work is concluded in Section 3.5.

3.2 Large-scale 3D printing by multiple mobile robots

3.2.1 System set-up

Each mobile robot printer in our set-up consists of a holonomic mobile platform, a 6-axis robotic arm, a stereo camera and a pump as shown in Figure 3.2. The robotic arm is mounted on the holonomic mobile platform and is equipped with a print nozzle. The robotic arm has a reach of 0.9 m with a repeatability of 0.02 mm. The holonomic mobile platform is equipped with sensors for localization and odometry, which includes wheel encoders, inertial measurement unit (IMU) and a 2D laser scanner. Localization is performed using on-board sensors, the stereo camera and some ArUco markers [119] placed on the platform. The markers have a black border for fast tracking and an inner binary matrix which determines its identifier, preventing feature mismatch. The pump system is responsible for delivering cementitious material to the print nozzle for selectively concrete deposition to build up the final print structure.

Figure 3.2: System set-up for one robot printer (Stereo camera is placed out of the scene).

3.2.2 Pipeline

The printing pipeline is illustrate in Figure 3.3.

Figure 3.3: Printing pipeline.

Firstly, for a given 3D CAD model, it was sliced into thin, closely packed paths in a layer wise fashion. The coordinates and normal of the path were extracted as way points for the robotic arm. Using the geometry information of each layer, the multi-robot placement situation was formulated as an optimization problem, which was solved for finding feasible and reasonable pose for each corresponding robotic manipulator. A feasible solution is defined if a robot is its placement can deposit material accurately onto the desired print path without self-collision or exceeding its joint limit, while a reasonable solution is defined if the robot is able avoid potential failure points if there is a better solution. The algorithm for multi-robot placement optimization will be illustrated in Section 3.2.4.

Secondly, with the construction environment and robot placement, the mobile robots would navigate to their respective target position accurately and without collision. In this phase, an environment map is generated with the on-board sensors and feasible paths are planned for navigation. When the mobile robots are in

proximity to their target position, they are guided to their final position, using the stereo cameras. This methodology will be explained in Section 3.2.4.

Subsequently, the nozzle trajectory is planned so that it can extrude cementitious material accurately onto the required path in a time-coordinated manner in order to avoid collision with the environment, the printed structure and the other robot printers. This trajectory planning phase is done in parallel while the robot printer is navigating its environment. The nozzle trajectory planner takes into account the individual sub-workspace of each robot and the coordinates and normal of the way points generated in the first module, while correcting for minor error in the mobile platform localization. The algorithm for the multi-robot motion will be discussed in Section 3.2.5.

Finally, with the robot printers in their respective position, the printing process will begin.

3.2.3 Materials preparation and extrusion methods

The cementitious materials were designed to meet rheological requirements (yield stress and viscosity) for printing, and this was reflected by pumpability during the material delivery phase and buildability during the extrusion phase. Two separate materials were chosen to demonstrate the adaptability of the system towards multi-material printing. One material consist of ordinary concrete with its mix design shown in Table 3.1, and the other material is a fibre reinforced concrete mix design [120] and shown in Table 3.2.

Table 3.1: Mixture proportion for robot printer 1 (kg/m^3)

Materials	Cement (OPC, ASTM Type 1)	Fly ash (Class F)	Silica fume (Undensified, Elkem)	River Sand	Water
Proportion	613.7	287.7	57.5	767.2	402.8

A Hobart mixer X200L was used in mixing. Factors such as mixing time, speed and temperature are known to affect the cement’s rheological properties, hence, mixing procedures were kept constant to the procedures developed by Weng et al [121]. After the cementitious material is mixed, it is filled in the hopper of

Table 3.2: Mixture proportion for robot printer 2 (kg/m^3)

Materials	OPC	Sand	Water	Fly ash	Silica fume	Superplasticizer
Proportion	575.7	590	330.3	575.7	863.40	1.4

Note: All ingredients contents are expressed as weight proportion of cement content

the pump. During printing, the Rotor/Stator pump will deliver the cementitious material through a 5 m long 2.54 mm diameter hose pipe at a speed of 650 rpm. The print nozzle extrudes the cementitious material in a controlled fashion by the robotic arm in a layer wise manner to build up the printed structure. The print nozzle tip used in the experiment has a tapered outlet of 10 mm diameter. The choice of a round nozzle also eases the orientation constraint on the nozzle allowing a wider pose solution to be found, which translates to a bigger printing volume by the robot printer.

3.2.4 Robot placement optimization

In literature, there are multiple studies on collision avoidance for multiple robots working in a shared workspace [122–124] or optimal robot placement given a prescribed task [125,126] but not the combination of two situations which is required in our multi-robot printing system. The multiple robotic printers have to cover the complete work piece in a collision-free environment yet no overlap of their individual workspace is allowed. A previous work of our group [127] formulated this situation as an optimization problem that tries to minimize the length of work piece that is not able to be covered. However, just satisfying workspace coverage might result in some robot configurations that would cause potential planning problems. In this work, the algorithm is further improved by introducing a score scheme for robot configuration considering its kinematic reachability.

The kinematic reachability of a point in the robot workspace is given by the number of possible robot configurations which realize this point. A kinematic reachability database for one robot printer was generated prior to printing (See Figure 3.4).

Kinematic reachability was then normalized to the interval from 0 to 1 and

Figure 3.4: Kinematic Reachability of a robot printer. The colours represent different levels of kinematic reachability: green and orange denoting the highest and lowest levels respectively.

was incorporated to an optimization program to find the optimal robot placement. In general, let N denote the number of robot printers, the optimization objective function is given by

$$\arg \min_{\mathbf{x}_1, \dots, \mathbf{x}_N \in \text{SE}(2)} - \sum_{i=1}^N \mathcal{S}(\mathbf{x}_i) + \mathcal{C}(\mathbf{x}_1, \dots, \mathbf{x}_N) \quad (3.1)$$

where $\mathbf{x}_i$ is the pose of the i -th robot printer, $\mathcal{S}(\mathbf{x}_i)$ evaluates the total reachability of the i -th robot printer regarding the target object, $\mathcal{C}(\mathbf{x}_1, \dots, \mathbf{x}_N)$ is the cost of collision between the robots, which is assigned to 0 if the system is collision-free and a large value if collisions exist.

Robot localization

Among the myriad of SLAM algorithms, GMapping [128] has been adopted for map construction because of its high efficiency and accuracy. Figure 3.5a shows a map of our lab constructed with the sensors on board of the platform using GMapping. Before the printing started, one mobile robot was driven around the printing site to construct the map. The constructed map was then used in adaptive Monte Carlo localization (AMCL) [129] for robot localization during the printing task.

In Figure 3.5b the rainbow color thin lines were from the sensor data, while the

Figure 3.5: Map construction and robot printer localization.

blue regions are places considered occupied on the occupancy grid map. It showed the situation that the mobile robot succeeded in localizing itself in the map using AMCL algorithm, with the sensor observations fitting the given map well.

With the SLAM and AMCL algorithms, mobile platforms are able to localize themselves in a rough-scale and navigate in the environment at a low cost. However, this is far from the precision required for them to print concurrently on one work piece. Hence, vision control was switched to when the platform is near to the target printing site for higher accuracy. ArUco markers were attached on the mobile platforms and stereo cameras were installed around the construction site, providing easy and unique features for the camera to identify and avoid feature mislabels when using nature features in the environment. Upon observation of the markers, relative pose between the camera and the detected marker is calculated, and the robot can localize its position unambiguously.

3.2.5 Multi-robot motion planning

Motion planning is required in the stage of multiple mobile platforms navigation and nozzle trajectory planning. In this work decoupled planning approach is used since it is generally faster.

A path for each robot is first computed independently, then a coordination diagram is used to plan collision-free trajectories for each robot along its path. The second step can be thought of as a re-timing process, which is analogical to finding a path from $(0, 0, \dots, 0)$ to $(l_1, l_2, \dots, l_n)$ of a virtual cube with perpendicular axes representing trajectories of the robots. Each point inside the cube corresponds to one combination of robot configurations at particular time instance.

The above stated trajectory planning is a naive process which assumes perfect execution of the trajectory. However, for platform navigation the uncertainty can be significant due to the slippery of the wheels and imperfect condition of the floor, especially for construction environment. Therefore, to avoid collision of the mobile platforms and to navigate to the goal positions accurately, the platforms broadcast their locations at certain frequency for collision checking, and the trajectory is re-planned upon update of new data.

3.2.6 Actual printing

The author used Ubuntu operating system for system integration [130], ROS for device control, message-passing between processes and package management [131], and OpenRAVE for planning and collision checking [132].

Prior to printing, a kinematic reachability database of the robot printers was generated. Subsequently, a map of the printing site was constructed with GMapping by moving a robot printer around the printing site. Stereo cameras were also set up around the site.

By slicing a 3D model of the target object, the waypoints, each consists of XYZ coordinates and a normal vector, were generated. This can be carried out using common slicing programs for 3D printing.

Next, taking as inputs the target printing pattern, the robot printers' models and their kinematic reachability databases, the algorithm in Section 3.2.4 was used

to compute the desired placement of the robot printers.

Subsequent to robot placement optimization, trajectories for the print nozzles are planned in OpenRAVE so that they can deliver material accurately on the desired paths without causing collisions with printed parts and other robot printers. Concurrently, the mobile printers plan their trajectories from home station to target printing positions using the map of the printing site constructed in earlier stage.

Upon completion of the planning, mobile printers navigate towards their target printing locations, using AMCL algorithm to track the mobile printers. In an effort to increase the robot localization accuracy, when the printers are within a pre-defined proximity to their target position, they will switch to vision-feedback control using the stereo cameras to track the ArUco markers placed on the mobile platforms. On reaching their target locations, the printers start to print on the work piece concurrently following the planned paths. The planned paths may be re-planned at this stage to compensate for any minor error in platform localization as discussed in Section 3.2.2.

Upon completion of printing, the robot printers will return to their home station, using the same navigation strategies when moving to the printing location. In the entire process, the robot printers will broadcast their status for collision checking, and also to synchronize the printing with the pumping system.

3.3 Results

Results of both simulation and demonstration on actual robotic system are presented in this section.

3.3.1 Simulation

In the simulation as shown in Figure 3.6, two robot printers were required to build a large-scale structure whose size is $1.86\text{ m} \times 0.46\text{ m} \times 0.13\text{ m}$ (length, width, height), which is beyond the printing volume of one single robot printer.

The structure was designed with the purpose of demonstrating the proposed system's capability of extending single printer's printing scalability. For that reason,

the size of the structure was chosen to best fit each robot's maximum reachability: if the structure grows higher, it has to be narrower (Refer to Figure 3.4). For more intuitive presentation of large-scale printing without having to print slanted walls, the pattern to be printed was designed to be wide and relatively short.

Figure 3.6: Simulation of multi-robot printing process.

It took 23.8 s to plan for mobile platform navigation from home station to target printing locations, and 25.2 s from printing location back to home station. Planning of trajectories for the print nozzles to print 12 layers of the target structure took 11.0 s.

3.3.2 Execution

The simulation in Section 3.3.1 has been implemented on actual robotic system with the proposed printing pipeline. Figure 3.7 presents an ordered sequence of intermediate steps during the printing process¹.

Given target printing location and printing pattern, placement of robot printers and their corresponding printing paths were simulated. The two robot printers navigated from home station to their respective printing locations. Subsequently they started printing concurrently on the large structure in a coordinated fashion without collision. Upon completion of the print, the robot printers return to the home station.

¹Timings taken from the supplement video material: 10 s to move to printing position, 470 s for printing (7 min 50 s), 10 s to move back to home station.

Figure 3.7: Snapshots taken during the actual printing process. See the full video of the experiment at https://youtu.be/p_jcG25tUoo. A. Robot printers at home station; B. Navigating towards target locations; C. Reaching target locations; D. Starting printing; E. Printing in progress; F. Building up layers; G. Finishing printing; H. Robotic manipulators back to standby pose; I. Navigating back; J. Reaching home station.

3.3.3 Printed specimen

The printed structure was $1.86\text{ m} \times 0.46\text{ m} \times 0.13\text{ m}$ (length, width, height). The specimen was covered by a plastic sheet to simulate field conditions for ambient curing. After 10 days of curing, it could be turned over, as shown in Figure 3.8.

Figure 3.8: Printed specimen after 10 days of curing.

The mechanical properties of the 3D printed concrete with each of the two materials can be found in [8] and [120]. Regarding the junctions, tests were not performed (since this would involve cutting the specimen), but noted that the bonding strength was high enough to easily support the specimen's own weight when it was placed on its side (Figure 3.8B). Informal visual and stress inspections suggested that the bonding was strong. Extensive and quantitative tests will be performed as part of the future work.

3.4 Discussion

The printing demonstration in Section 3.3.2 serves as a proof of concept for the multi mobile robot printing system for printing concrete structure in an efficient and scalable manner. The printed design was chosen to incorporate complex curves and internal void that would be challenging to build using traditional construction methods. The size of the printed design was also chosen to extend beyond the workspace of a single robot printer, requiring the concurrent printing by multiple robots.

As the proposed system has the attribute of arm-based system, mobile platform and swarm printing, its major advantages over gantry-based system, stationary printer and single printer are discussed here.

1. *Advantages over gantry-based system:*

Robotic arm printers benefits from the greater flexibility of having full 6 degrees of freedom as compared to 3 or 4 degrees of freedom in the conventional gantry system. This extra articulation allows the robotic arm printer to print complex curved parts using the tangential continuity method [12]. This results in a smoother transition between print layers by maintaining a continuous rate of curvature change, hence giving a more aesthetically pleasing look.

2. *Advantages over stationary printer:*

The mobile platform of our robot printer extends the reachability of the printer, by allowing the printer to print beyond the fixed environment it will otherwise be confined to when stationary. By printing large structures in a single attempt on site, it removes the need for transportation of printed parts to site. This in turns reduces manpower requirements in the 3D concrete printing and promotes increasing automation in construction.

3. *Advantages over single printer:*

It can be easily seen that swarm printing afford greater scalability and efficiency as compared to a single printer. With the decoupling of printer system from print material, it allows flexibility for users in selection of materials for different applications such as printing a load bearing structural wall to wall fillers. As proof of concept, our demonstration has intentionally used two different materials in showing its non reliance on material type, as mentioned in Section 3.2.3.

However, there are also challenges for the system to work robustly for application in B&C industry. A major technical difficulty would be accurate localization of the robot printer under different terrain conditions. When the terrain is bumpy

and dusty, which is common to a construction site, the mobility scheme for the mobile printer plays a vital role in the printing system. As Mecanum wheel designs for holonomic mobiles can perform poorly on rough terrains [133], it would be necessary to investigate alternative wheel schemes to enhance the robustness of the printing, such as differential tank drive.

Besides the wheel investigation, statistic evaluation of the proposed method is also important future work. Mechanical tests on the printed specimen was not planned in this work for the following reasons.

1. The materials used by the two printers were intentionally chosen to be different in order to demonstrate the proposed method's non-reliance on material type, making the printed specimen unconventional for mechanical testing.
2. The demonstration was meant to serve as a proof of concept of multi-robot large-scale printing in an efficient and scalable manner, and feasibility of robotic techniques was the main focus.

Nevertheless, the bonding strength at the junction was shown to be fairly strong from informal stress inspections. To produce sound evaluation of the proposed method from the perspective of mechanical property, different bonding strategies at the interface are to be explored. Extensive tests and analysis need to be carried out to compare various printing strategies as well as other modular structure assembly techniques. As this thesis focuses on robotic solutions to large-scale 3D printing, the aforementioned evaluation has been further discussed in Chapter 7 as suggested future work.

3.5 Conclusion

In this chapter, a multi-robot printing system that is capable of on-site printing large structures in a safe, efficient and scalable manner has been demonstrated. The system configuration contains several modules: planning of robot placement to optimize workspace, mobile robot navigation and localization to reach target printing location, and planning of manipulator trajectory to deposit material accurately on desired path.

Both simulation and demonstration on actual robotic system were presented: two mobile robot printers work concurrently on one structure whose size is twice the printing volume of one single printer.

Comparing to existing 3D cementitious material printing techniques, experimental results suggest that the proposed system is superior in its greater practical scalability and higher time efficiency due to the employment of multiple robot printers, as well as better on-site printing capability credited with mobility of the system. These advantages make the proposed system promising to be scaled up for on-site large-scale printing applications in B&C industry. Furthermore, using a fleet of mobile robots for construction could have an extreme potential in other non-conventional aspects. One such application is to allow automated construction in hard-to-reach, remote areas, such as underground caves, the Moon or Mars [134], to which it is inconvenient or even impossible to bring other kinds of machine required for existing cementitious material printing methods.

Chapter 4

Printing-while-moving for large-scale 3D printing

4.1 Introduction

In Chapter 3, a multi-robot mobile printing system has been proposed to alleviate the scalability issue that is common to existing concrete 3D printing techniques. However, the printing at this stage can only be executed when the printer is stationary, which still places limitations on the size of structures that can be printed by a single robot *in a single take*. Note that “single take” is critical to ensure good structural properties: a sequence of printing-upon-arrival moves would lead to fresh concrete adjoining hardened concrete at the junctions, weakening thereby the bonding strength [7, 118, 135].

In this chapter, a 3D printing system that implements printing-while-moving paradigm is proposed. This paradigm enables printing single-piece structures of arbitrary sizes with a single mobile robot printer and in a single take. It is demonstrated in this work, *for the first time*, the actual printing of a single-piece concrete structure by a mobile robot printer. The size of the structure is 210 cm $\times$ 45 cm $\times$ 10 cm (length, width, height), which is larger than the reach of the robot arm (87 cm).

Achieving printing-while-moving requires addressing several challenges. The motions of the robot manipulator and the mobile platform must be carefully

Figure 4.1: The mobile robotic 3D printing system presented in this work. A video of the printing experiment is available at <https://youtu.be/ZIbY00iTFwY>.

planned and coordinated. In addition, precise robot localization and feedback motion control are necessary to ensure that the nozzle deposits concrete at the right place and with the right speed. This is particularly important in the layer-by-layer process at hand: nozzle position offsets of more than 1 cm between two consecutive layers can cause the structure to collapse.

The remainder of this chapter is organized as follows. In Section 4.2, the proposed mobile printing system is presented in detail. In Section 4.3, results of the accuracy and precision assessment, as well as the actual printing experiment, are reported. Section 4.4 is conclude by discussing the limitations of the current system and sketch some directions for future work.

4.2 System development

4.2.1 Mobile printing system

The hardware setup is mostly the same as in the previous chapter 3, to which the reader is referred for more details. Briefly, the system comprises: a holonomic mobile base (Clearpath Ridgeback), a 6-DoF industrial robot manipulator (Denso VS-087) mounted on top of the mobile base, a nozzle mounted on the manipulator flange and connected to a pump through a hose (Figure 4.2, **Top**).

The main difference with chapter 3 is that the stereo camera (Microsoft Kinect for Xbox One) is mounted on the back of the mobile base, instead of being stationary. Conversely, the Aruco markers [136] of size $12\text{ cm} \times 12\text{ cm}$ are placed on the ground, instead of being placed on the robot as in [135]. This change enables the localization system to be continuously effective in a larger area.

During execution, while the mobile base runs with its own battery, the robot arm's power is supplied externally. Image processing, sensor fusion and motion planning are performed on an off-board computer.

The pipeline of the process is depicted in Figure 4.2, **Bottom**. From the 3D model of the desired object, the coordinated motions of the mobile base and the robot arm in order to print the object layer by layer (Motion planning) is planned offline. Next, the planned motions on the actual platform are executed. During execution, the position of the mobile base is monitored in real-time (Localization), and feedback control is exercised to track the planned motions as close as possible (Motion control). The following sections detail these processes.

4.2.2 Motion planning

Compared to standard motion planning for a 6-DoF manipulator to cover a large workspace (see e.g. [137]), the present motion planning problem involves two additional difficulties

- The continuous printing process precludes switching between different Inverse Kinematics (IK) classes [138];

Figure 4.2: **Top:** Hardware setup, comprising: holonomic mobile base, 6-DoF robot manipulator, camera, markers, pump, print nozzle. **Bottom:** Pipeline of the printing process. Block “a” is the closed-loop position controller of the robot arm, while block “b” is the closed-loop position controller of the mobile base.

- The mobile base adds three extra (redundant) DoFs, as well as additional collision possibilities (between the robot and the base, or between the base and the printed specimen).

To address these issues, the following simplified approach is taken:

1. Prescribe a motion for the base, which avoids collision with the to-be-printed specimen and takes into account the manipulator reachability (Figure 4.3);
2. Synchronize the base motion with the nozzle motion (which follows the design of the specimen and has constant speed in order to deliver the printing materials at a constant rate);
3. Given the base motion and the nozzle motion, compute the joint trajectories for the manipulator by differential IK (see e.g. [138]).

Figure 4.3: Motion planning for the mobile base. Red: the nozzle path to print the specimen of Figure 4.1. Cyan: the path prescribed for the mobile base. The dashed black line depicts the synchronization of the two paths at the start of the printing.

Note that this approach is not optimal and is not guaranteed to always work. For instance, the differential IK of step 3 might not find any continuous motion for the manipulator, given the prescribed base and nozzle motions [138]. Developing a more principled planning algorithm for mobile 3D printing is part of the future work, which is sketched in the discussion in Section 4.4.

4.2.3 Localization of the mobile base

As stated in the Introduction, the accurate control of the mobile base trajectory is crucial for printing quality. Note that, because the accuracy of the industrial robot arm is significantly higher than that of the mobile base, it is assumed that the former is 100% accurate.

An essential component in trajectory control is localization (or pose estimation), i.e. knowing accurately where the mobile base is at any given time instant. Since the built-in localization module of the mobile base has substantial drift over time, a vision-based scheme is used: several fiducial Aruco markers are placed on the ground, and when marker i is seen by the on-board camera, the position of the mobile base can be estimated by

$${}_{\mathcal{W}}\mathbf{T}_i^{\mathcal{B}} = {}_{\mathcal{W}}\mathbf{T}_i^{\mathcal{M}} {}_{\mathcal{M}}\mathbf{T}_i^{\mathcal{C}} \mathbf{T}^{\mathcal{B}}, \text{ where}$$

- ${}_{\mathcal{W}}\mathbf{T}_i^{\mathcal{B}}$ is the estimated homogeneous transformation of the Base w.r.t. the World frame;
- ${}_{\mathcal{W}}\mathbf{T}_i^{\mathcal{M}}$ is the (known) transformation of Marker i w.r.t. the World frame;
- ${}_{\mathcal{M}}\mathbf{T}_i^{\mathcal{C}}$ is the transformation of the Camera w.r.t. the marker (computed in real-time by the Aruco module [136]);
- ${}_c\mathbf{T}^{\mathcal{B}}$ is the (known) transformation of the Base w.r.t. the Camera.

From the transformation ${}_{\mathcal{W}}\mathbf{T}_i^{\mathcal{B}}$, one can obtain the estimated position and orientation of the mobile base $\mathbf{x}_i^e \in \text{SE}(2)$. Next, to compensate for the delay associated with image processing (which could be as long as 50 ms), the estimated position and orientation are propagated using the controls that were sent during the delay period by

$$\mathbf{x}_{i,k}^p = \mathbf{x}_{i,k-N}^e + \Delta \sum_{j=k-N}^{k-1} \mathbf{u}_j,$$

where $\mathbf{x}_{i,k}^p$ is the propagated estimation at time instant k , Δ is the control time step, N is the number of control time steps that have passed during the delay, $\mathbf{u}_j := [v_j^x, v_j^y, \omega_j]$ is the control input at time step j . Grouping together all the markers

that are visible to the camera at time step k , one finally obtain the measurement

$$\check{\mathbf{x}}_k := [\mathbf{x}_{1,k}^p, \dots, \mathbf{x}_{M,k}^p],$$

where M is the number of visible markers at time step k . Note that at least one marker is visible at any time instant.

Finally, the measurements are fused with the controls using an Extended Kalman Filter

- State prediction: $\mathbf{x}_{k+1} = \mathbf{x}_k + \Delta \mathbf{u}_k + \mathbf{w}_k^1$;
- Measurement: $\mathbf{z}_k = \check{\mathbf{x}}_k + \mathbf{w}_k^2$,

where $\mathbf{w}_k^1 \sim \mathcal{N}(\mathbf{0}, \mathbf{Q})$ and $\mathbf{w}_k^2 \sim \mathcal{N}(\mathbf{0}, \text{diag}(\mathbf{R}, \dots, \mathbf{R}))$ are respectively the prediction noise and the measurement noise at step k . The values of the weight matrices $\mathbf{Q}$ and $\mathbf{R}$ were chosen following a calibration process.

4.2.4 Motion control for the mobile base

There are two important design objectives in the control of the mobile base: (i) track the desired trajectory accurately; (ii) obey the velocity constraints for safe autonomous operation. In order to address these objectives, a Model Predictive Controller (MPC) is implemented. Note that the control inputs $\mathbf{u}_k := [v_k^x, v_k^y, \omega_k]$ are calculated in the world frame.

The discrete dynamics of the mobile base for a horizon of N steps is given by

$$\mathbf{X}_{k+1} = \underbrace{\begin{bmatrix} \mathbf{A} \\ \vdots \\ \vdots \\ \mathbf{A}^N \end{bmatrix}}_{\mathbf{S}^x} \mathbf{x}_k + \underbrace{\begin{bmatrix} \mathbf{B} & 0 & \dots & 0 \\ \mathbf{AB} & \mathbf{B} & \dots & 0 \\ \vdots & \ddots & \ddots & 0 \\ \mathbf{A}^N \mathbf{B} & \dots & \mathbf{AB} & \mathbf{B} \end{bmatrix}}_{\mathbf{S}^u} \mathbf{U}_k,$$

where $\mathbf{A} := \mathbb{I}_{3 \times 3}$, $\mathbf{B} := \Delta \mathbb{I}_{3 \times 3}$, $\mathbf{X}_{k+1} := [\mathbf{x}_{k+1}, \dots, \mathbf{x}_{k+N}] \in \mathbb{R}^{3N}$, and $\mathbf{U}_k := [\mathbf{u}_k, \dots, \mathbf{u}_{k+N-1}] \in \mathbb{R}^{3N}$.

Next, consider the errors

$$\begin{aligned} \tilde{\mathbf{x}}_{k+i} &:= \mathbf{x}_{k+i} - \mathbf{x}_{k+i}^d, \\ \tilde{\mathbf{u}}_{k+i} &:= \mathbf{u}_{k+i} - \mathbf{u}_{k+i}^d, \end{aligned}$$

where the superscript d indicates the desired trajectory and the nominal inputs. Note that $\mathbf{u}_{k+i}^d$ is zero in our case. The error dynamics can then be written as

$$\tilde{\mathbf{X}}_{k+1} = \mathbf{S}^x \mathbf{x}_k + \mathbf{S}^u \mathbf{U}_k - \bar{\mathbf{A}} \mathbf{X}_{k+1}^d,$$

where $\bar{\mathbf{A}} := \text{diag}(\mathbf{A}, \dots, \mathbf{A}) \in \mathbb{R}^{3 \times N}$, $\mathbf{X}_{k+1}^d := [\mathbf{x}_{k+1}^d, \dots, \mathbf{x}_{k+N}^d] \in \mathbb{R}^{3N}$.

The control inputs for horizon N are calculated with the following quadratic optimization

$$\begin{aligned} J^*(\mathbf{x}_k) = \min_{\mathbf{U}} \quad & \mathbf{U}^T \mathbf{H} \mathbf{U} + 2\mathbf{q}^T \mathbf{U} \\ \text{s.t.} \quad & \mathbf{G} \mathbf{U} \leq \mathbf{w} + \mathbf{E} \mathbf{x}_k + \mathbf{E}^d \mathbf{X}_{k+1}^d, \\ & \mathbf{H} = (\mathbf{S}^u)^T \bar{\mathbf{Q}}^c \mathbf{S}^u + \bar{\mathbf{R}}^c, \\ & \mathbf{q} = (\mathbf{x}_k^T (\mathbf{S}^x)^T - (\mathbf{X}_{k+1}^d)^T \bar{\mathbf{A}}^T) \bar{\mathbf{Q}}^c \mathbf{S}^u. \end{aligned}$$

where $\bar{\mathbf{Q}}^c := \text{diag}(\mathbf{Q}^c, \dots, \mathbf{Q}^c)$ and $\bar{\mathbf{R}}^c := \text{diag}(\mathbf{R}^c, \dots, \mathbf{R}^c)$ are block-diagonal weight matrices. The matrices $\mathbf{G}$, $\mathbf{w}$, $\mathbf{E}$ and $\mathbf{E}^d$ encode input and state constraints, see e.g. [139] for details.

4.3 Experiments

4.3.1 Accuracy and precision assessment

Optitrack, a Motion Capture system, with 6 cameras, was used to provide an independent measurement. Markers were placed on the nozzle and the mobile base and capture their motions during an air printing session. Figure 4.4 shows the marker trajectories for 15 laps. Since the industrial robot arm has superior accuracy when compared to base motion, the accuracy and precision evaluation was focused on the mobile base motion.

Before assessing the *accuracy* of the system (how close the printed shape is to the desired shape), its *precision* (how repeatable the system is) was first evaluated, which is critical in the layer-by-layer material deposition process.

Consider a segment parallel to the X-axis (segments A and C in Figure 4.4). All the data points $(x_i, y_i)_{i \in [1, N]}$ corresponding to this segment across the 15 laps

were collected. A line $y = ax + b$ was then fit to those data points. The precision was then quantified by the maximum and the mean error

$$e_{\max} := \max_i |y_i - (ax_i + b)|$$

$$e_{\text{mean}} := \sqrt{\frac{1}{N} \sum_i (y_i - (ax_i + b))^2}$$

For segments that are parallel to the Y-axis (segments B and D), we swapped the roles of x and y . Given the above definitions, the maximum and mean errors across the four linear segments of base motion were respectively 9.9 mm and 2.2 mm. Overall, the precision of our base motion, 2.2 mm, is under the required precision to build up the layers of cement.

Figure 4.4: Accuracy and precision assessment using an external Motion Capture (Mocap) system. Black: nozzle trajectory across 15 laps as measured by Mocap. Blue: mobile base trajectory across 15 laps as measured by Mocap. Dashed green: straight lines fitted upon the blue lines. Red: desired trajectory for the base. The difference between the blue and dashed green lines reflects the precision, while the difference between the red and dashed green lines reflects the accuracy of our system.

4.3.2 Actual printing

The mobile printing system was tested in the laboratory environment. To demonstrate the printing-while-moving concept, 3D slicer was not focused on and a thin

walled structure has been chosen. The structure to be printed is shown in Figure 4.3 and has size a $210\text{ cm} \times 45\text{ cm} \times 10\text{ cm}$, which is significantly larger than the reach of the robot arm (87 cm). A nozzle of diameter 1 cm and a nozzle speed of 10 cm/s were used. The cement was prepared as in the previous work of our group [135, 140].

Figure 4.5: Snapshots of the actual printing experiment. A video of the experiment is available at <https://youtu.be/ZIbY00iTFwY>.

Figure 4.6: Printed specimen after three days of curing.

10 layers of the structure was printed in 9 min 16 s. A video of the experiment is available at <https://youtu.be/ZIbY00iTFwY>. Snapshots of the printing session are shown in Figure 4.5. After three days of curing, the structure was hard enough to be flipped and put on its side, as shown in Figure 4.6. As mentioned previously,

the precision of our trajectory tracking enabled to obtain a surface finish similar to the specimen obtained by fixed-based printing [135].

4.4 Discussion and conclusion

A printing-while-moving approach for large scale in-situ concrete robotic 3D printing is presented. The proposed mobile printing system is able to print single-piece concrete structures that are larger than the robot reach, in a single take – “single take” being critical to ensuring good structural properties. It was demonstrated, for the first time, a printing-while-moving experiment wherein a $210\text{ cm} \times 45\text{ cm} \times 10\text{ cm}$ concrete structure was printed by a robot arm that has a reach of 87 cm.

4.4.1 Scalability

The printing-while-moving scheme therefore significantly enlarges the size of single-piece structures that a single robot can print, as shown in Figure 4.7.

There still exist a number of limitations. First, the length of hose for supplying the printing material is limited by the pressure of the pump used in the system. For instance, according to our experimental experiences with 24.5 mm diameter pipe, 10 mm nozzle diameter and 650 rpm pumping speed, 5 m hose length is the upper limit without experiencing major clogging problem. The workspace limit for maximum hose length is shown in Figure 4.7(b) with the red dashed line.

Second, the hose motion obstructs some region in the printing area, shown in Figure 4.7(b). It is possible to enlarge the workspace but, with a stationary pump configuration, some of the workspace is sacrificed for the hose motion. Nevertheless, quite complex structures can possibly be built from inside of the printing area as in Figure 4.7(b) or from outside of the printing area.

Finally, maintaining the precision of the printer requires that at least one marker be visible at any time instant (Sec. 4.2.3). Hence, to scale up, markers need to be distributed around the workspace as shown in Figure 4.7(b). Furthermore, since the hose might obstruct some of the markers, one might need to ensure that more than one marker is visible at any time instant.

Figure 4.7: Figure (a) shows the printable area (blue) with a stationary base (labeled R). Figure (b) shows the widest possible printable area using a given number and configuration of markers (labeled M). One robot is shown at different locations during printing, the gray thick lines show the corresponding hose configuration, the black dashed line shows the mobile base path. The red dash line shows the range limit due to the hose length. Red area is obstructed by the hose motion.

4.4.2 Improvement in motion planning

As mentioned in Section 4.2.2, our current motion planning method is not guaranteed to always work: there might not exist any continuous motion for the manipulator, given the prescribed base and nozzle motions [138]. In addition to this “completeness” issue, it was observed during the experiment that sharp turns at the corners affected the precision of the system in several manners. First, they cause vibrations of the camera, which affects the vision-based localization as discussed previously. Second, they cause vibrations of the nozzle, affecting the material deposition. Third, the step-like control inputs are difficult to track accurately by the physical system, causing large tracking errors at the corners (see Figure 4.4).

To address the above mentioned issues, the following planning pipeline can be considered in the future:

1. Generate an initial base path by translating the printing pattern by d_{opt} , where d_{opt} corresponds to the manipulator pose that is the furthest away

from the boundary of its IK class when the nozzle is on the print path, taking also into account collision avoidance with the to-be-printed specimen. This base path is guaranteed to work, as the arm would simply need to keep a fixed configuration during the printing of a given layer, and to make a small motion to lift the nozzle by one layer thickness after each layer;

2. Smooth the base path (e.g. using splines). Since the smoothed path is close to the initial path, there will exist IK configurations in the same IK class to track the print path;
3. Iteratively deform the base path (e.g. to reduce its footprint, to improve smoothness) while checking at every deformation step that there exists continuous IK solutions for arm motions to track the print path.

Our future work will consider refining and implementing this motion planning pipeline.

4.4.3 Other limitations and future work

Localization errors may come from several sources: (i) errors in the positions of the fiducial markers with respect to each other and with respect to the world frame; (ii) vibrations of the camera during the movements of the mobile base. Source (i) mainly affects the accuracy, and can be mitigated by careful calibration. Source (ii) can have a very large effect on the precision, and can be mitigated by installing proper vibration isolators for the camera or by implementing smoother base motions as discussed previously. More generally, one can also integrate other sensors, such as IMU or laser scanners, or implement more sophisticated localization algorithms (e.g. based on particle filters), to improve localization.

Finally, the unevenness of the ground affects the quality of the printing in two ways. First, at locations where the ground level rises significantly, the extruded cement is squeezed more and spreads laterally, resulting in a thinner layer in vertical direction. Second, ground height variations also amplify the vibrations of the mobile base. Again, those issues can be mitigated by mechanical vibration isolation or by active disturbance rejection with the robotic arm.

Besides addressing the current limitations, there are also many exciting avenues for further development. For example, the multi-robot version of the presented concept can dramatically increase productivity, but is intrinsically more challenging. It requires for instance a motion planning algorithm that can plan optimal mobile base trajectories considering multiple printing paths, multi-robot collision avoidance, and material supply hoses.

Chapter 5

Motion planning for multiple tethered mobile robots

5.1 Introduction

In many applications, tethers are used to provide power and resources to robots or used as a communication link [135, 141, 142], especially in extreme environments, such as in underwater, disaster recovery and rescue [143–145]. While tethering helps in communication and resource delivery, it also poses challenges to robot control and planning. The limited-length cable restricts the mobile robot to the workspace around its home station. In addition, due to the presence of obstacles and cables, certain positions can be reached by robot only under specific robot cable configurations. Under many circumstances, multiple tethered robots have to cooperate and work together in a shared workspace [135, 143, 144, 146], which introduces more constraints to the planning and control problems. More specifically, in the large-scale, multi-robot 3D printing system [135], the tethers are indispensable to deliver the fresh concrete from the mixer to the print nozzle. Consider also the cable-cable interaction and robot-cable interaction when multiple tethered robots are deployed for terrain and harsh environment exploration [143, 144, 146]. It is important to make sure that the cables are not entangled while the robots move to their target positions, considering the above mentioned interactions and obstacle avoidance. Here multiple tethered planar (point) mobile robots sharing a common

workspace is considered. Each robot is attached to a fixed base by a flexible cable, which is kept taut at all times. The cable can be pushed by other robots, and can bend around other robots or obstacles. The assumptions are consistent with the requirements of the tethers in many practical applications, such as the material-delivery tethers in the concrete 3D printing system [135], or in terrain explorer system [146]. Previous work has studied the problem of detecting whether a target cable configuration is intersecting (or entangled) [147]. Here, we investigate the *motion planning* problem to *realize* a given non-intersecting target cable configuration. More precisely, we study four possible modes of motion – **Straight/Sequential** and **Straight/Concurrent**, **Bent/Sequential**, **Bent/Concurrent**, depending on whether (i) the robots move in straight lines or following their cable lines; (ii) the robots move sequentially or concurrently.

5.1.1 Illustrative example

To illustrate some of the difficulties, consider a scenario with three tethered robots as in Figure 5.1: each robot r_i ($i = 1, 2, 3$) tethered to its starting base S_i must navigate from S_i to its target position T_i . The target cable configuration as shown in solid lines has to be achieved upon arrival of all robots.

In **Bent/Sequential** mode, the target cable configuration can be achieved, for example, in the order: r_1 , r_2 and r_3 . Since the cables are kept taut at all times, when r_1 first moves along $S_1 - T_2 - T_1$, its cable C_1 retracts to the straight-line segment S_1T_1 when it reaches T_1 . Then r_2 moves along $S_2 - T_3 - T_2$, pushing cable C_1 to the layout $S_1T_2T_1$ as it reaches T_2 , and C_2 retracts to S_2T_2 . Finally r_3 moves along $S_3 - T_1 - T_3$ and pushes cable C_2 to the layout $S_2T_3T_2$. Since r_1 has already arrived at T_1 , cable C_3 will bend around it and remain at its final layout as $S_3T_1T_3$. The target cable configuration is thus achieved (see Figure 5.2(a)). Note that the configuration can also be achieved by **Bent/Concurrent** mode where the robots move simultaneously following their cable lines.

However, simply following robots' cable lines is not the most desirable motion scheme. Compared to **Bent** motion, **Straight**-line robot motion offers the following benefits:

Figure 5.1: An example of coordinated motion planning problem for three tethered mobile robots. (a) Each robot r_i ($i = 1, 2, 3$) must move from its starting position S_i towards its target position T_i , while being tethered to S_i . The desired configuration of the cables at the end of the motions are depicted in solid lines. This chapter proposes an algorithm to plan simultaneous, straight-line, motions of the robots to realize the desired cable configuration. We show in particular that the motion priority at the intersection points A, B, C is critical. (b) Hardware implementation of the coordinated motion. See full video of the experiment at <https://youtu.be/mFR72jbCT38>.

Figure 5.2: An example of planning for a target cable configuration by different modes of robot motion. (a) **Bent/Sequential** mode. The target cable configuration can be achieved when robots move in the order: r_1 , r_2 and r_3 . Dotted cable lines retract to solid ones since the cables are kept taut at all times. (b) **Straight/Sequential** mode. The target cable configuration *CANNOT* be achieved by this mode of motion. The example shows how the final result deviates from the target cable configuration. (c) **Straight/Concurrent** mode. The target cable configuration can be achieved when robots move along the (S_i, T_i) straight-line segments at the same velocity.

- 1) Straight-line robot motion reduce traveling distance, which in turn improves time and energy efficiency. Take the two target cable configurations provided in this chapter for example. To achieve the target cable configuration in Figure 5.1 and Figure 5.7(a), straight-line robot motion saves respectively 30% and 20% of the traveling distance compared to robot motion that follows cable lines.
- 2) It is well-known that in robot localization, rotational and curved translational motions induce larger estimation errors than straight motions, in relation to both Inertial Measurement Unit (IMU) and odometry [148]. Thus, by using the **Straight** mode, one can significantly reduce localization errors;
- 3) Working environment safety could be enhanced as straight-line robot motion is more predictable for the workers who need to collaborate or work in the same environment with the robots;

The first benefit motivates the work by Hert and Lumelsky [75], where an algorithm is proposed for robots to achieve a given target cable configuration by **Straight/Sequential** motion. **Straight/Sequential** mode improves the efficiency at the sacrifice of realizability, which is illustrated in Figure 5.2(b). Suppose the robots move in the order of r_1 , r_2 and r_3 along $S_1 - T_1$, $S_2 - T_2$ and $S_3 - T_3$ respectively. Upon arrival of r_1 at T_1 and r_2 at T_2 , the same cable configuration can be obtained as under **Bent/Sequential** motion, but after that, r_3 must push C_2 in order to navigate to T_3 , which violates the target cable configuration, resulting in a deadlock. In their later work [77], **Straight/Concurrent** mode is considered, but the concurrent motions are not leveraged to solve deadlocks. Yet, considering again the example of Figure 5.1, concurrency can be leveraged to solve the deadlock as follows: r_1 , r_2 and r_3 move along their (S_i, T_i) straight-line segments at the same velocity (see Figure 5.2(c)). By doing so, they will indeed pass respectively points A , B and C at the same time, which in turn satisfies the requirement that r_1 passes A before r_2 does, r_2 passes B before r_3 does, and r_3 passes C before r_1 does. The general algorithm to produce such a schedule is one of the main contributions of the present Chapter in this thesis.

5.1.2 Contributions and organization of the Chapter

Our contribution in this work is three-fold. First, the realizability of a target cable configuration is systematically examined by the above mentioned four modes of motion. A further analysis of **Straight/Concurrent** motion is then presented, which is the most practically-relevant mode. Second, algorithms are proposed to detect whether a given target cable configuration is realizable by **Straight/Concurrent** motion. Third, our algorithms return a valid coordinated motion plan if there exists a solution. In addition, some corrections to the algorithms presented in [147] are provided to detect whether a cable configuration is intersecting.

The remainder of this chapter is organized as follows. In Section 5.2, the author introduce the background on non-intersecting cable configurations, formulate the planning problem for multiple tethered robots, and survey the realizability of cable configurations by the four modes of motion. In Section 5.3, the planning algorithms for **Straight/Concurrent** robot motion are presented in detail. In Section 5.4, experimental results are reported in simulation and in hardware. Finally, the work is concluded in Section 5.5.

5.2 Background: non-intersecting target cable configurations and realizability

5.2.1 Problem formulation

Consider n point robots on a planar workspace $\mathbf{W}$. Each robot r_i , $i = 1, \dots, n$, must navigate from its starting position S_i to its target position T_i , while being attached to S_i by a flexible cable. The cables are assumed to remain on the ground and to be taut at all times; they can bend around other robots, and be pushed by other robots.

Definition 1 (Cable line, cable configuration). *Because of the assumption that the cables are taut and can only bend around point robots, the cable of any robot at any time instant is a polygonal chain, which we call the robot's cable line. The final (target) cable line of a robot is the (desired) state of the robot's cable line after all*

robots have reached their target positions.

A cable configuration *consists of the cable lines of all robots at a given time instant*. A final (target) cable configuration *is the (desired) cable configuration after all robots have reached their targets*.

Cable polygon in the following definition was originally defined as *retraction polygon* in [75].

Definition 2 (Cable polygon). *The cable polygon Π_i of a given robot r_i is formed by closing the robot's target cable line with the straight-line segment (S_i, T_i) joining the robot's starting and target positions.*

Two important assumptions are now introduced.

Assumption 1 (Starting positions and cable polygons). *The starting position S_i of a robot r_i does not belong to any cable polygon Π_j , $j \neq i$.*

Assumption 1 fully covers the hypotheses of previous works [75, 76], which assume that $\mathbf{W}$ is a convex polygon and that all starting positions lay on the boundary of $\mathbf{W}$. The extension to more general cases with obstacles present in the environment is discussed in 5.C.

Assumption 2 (No self loop). *When a target cable line contains repeated waypoints, we say that it contains self loops (see Figure 5.3(a)) We assume that there is no self loop in any target cable line.*

self loops are obviously redundant and there is always a better solution. An example is presented in Figure 5.3: The target cable configuration in Figure 5.3(a) is valid in the sense that no cable tangle happens, but it is highly inefficient and can be replaced with an alternative simple cable layout as shown in Figure 5.3(b).

5.2.2 Non-intersecting target cable configurations

We say that a cable configuration is *non intersecting* if no pair of cable lines in that configuration intersect each other. In [147], the problem of finding non-intersecting target cable configurations is formulated as a graph problem. $G = \{V, E\}$ contains

Figure 5.3: An example of cable self loop and its alternative simple layout.

all starting points $\{S_1, \dots, S_n\}$ and target points $\{T_1, \dots, T_n\}$ in its node set V , and all edges in the form of (S_i, T_j) in its edge set E . Finding non-intersecting target cable configuration is now equivalent to finding a set of consecutive edges from S_i to T_i for each robot r_i while observing cable property. An algorithm using exhaustive search method with pruning is suggested to identify and eliminate every route intersection case, producing all possible non-intersecting cable configurations. Regarding the cable intersection detection algorithm, readers may refer to [147] for more details. Note however that the algorithm would fail under certain circumstances. The failure cases are discussed and corrections are provided in 5.B.

5.2.3 Realizability of non-intersecting target cable configurations

The realizability of a given non-intersecting target cable configuration is now studied (in the following text the term “non-intersecting” shall be omitted when there is no possible confusion).

There are four reasonable modes of motion: **Bent/Sequential**, **Bent/Concurrent**, **Straight/Sequential** and **Straight/Concurrent**. **Straight** and **Bent** refer to the route that the robots have to follow during the navigation: **Straight** denotes that the robots moves in straight lines from their starting positions directly towards target positions, while **Bent** indicates that the robots follow their target cable lines. Meanwhile, **Sequential** and **Concurrent** refer to the schedule of the robot motion: **Sequential** indicates that the robots are

prioritized and they have to move towards their target positions one at a time, while **Concurrent** denotes that the robots move to target positions simultaneously. The solution spaces of these different modes of motion is shown in Figure 5.4, and a thorough analysis is presented in the following sections.

Figure 5.4: Solution spaces of the different modes of motion (**Bent**, **Straight/Concurrent**, **Straight/Sequential**).

Realizability by **Bent/Sequential**

It is proved in [75] that: “*If each robot moves along its target cable line, the final cable configuration will be the same as the target cable configuration.*” Note that the proof is non-trivial because of the assumption that the cables remain taut at all time. A robot’s cable line will thus deform and auto-retract to maintain tautness if the robots that cause bends in its target cable line are not yet in position.

Realizability by **Bent/Concurrent**

It is straightforward to infer that **Bent/Sequential** could be regarded as an extreme case of **Bent/Concurrent**. Since **Bent/Sequential** mode of motion is proved to be able to achieve any feasible target cable configuration, it follows that **Bent/Concurrent** can produce a solution for any feasible target cable configuration as well.

The most efficient motion for this mode would be “just move”, which means that the robots move along their target cable lines at the same time. When robot

r_i passes point T_j on its target cable line, if T_j has already been occupied by robot r_j , cable C_i wraps r_j from the desired direction; if r_j has not reached T_j yet, C_i will be retracted and will be pushed by r_j later from the correct side (see Figure 5.5).

Figure 5.5: An illustration of realizability by **Bent/Concurrent**. When r_1 passes T_2 : (a) r_2 has reached T_2 . C_1 wraps around r_2 at T_2 ; (b) r_2 has not reached T_2 yet. C_1 retracts to the dotted line and is pushed by r_2 at P during r_2 's navigation later.

Compared to **Bent/Sequential** motion, **Bent/Concurrent** requires less execution time as robots do not need to wait and move one by one. However, restricting the robots to move along their target cable lines is still a waste of time and energy. The most efficient motion scheme would be straight-line motion for robots to navigate from starting to target positions.

Realizability by Straight/Sequential

In [75], Hert and Lumelsky provide an algorithm where robots are prioritized and scheduled to move sequentially in a straight line as much as possible. In this case, “each robot must move before any robot its cable line bends around has moved” [75]. With this observation, a directed graph can be constructed: each vertex in the graph represents a robot, and a directed edge from v_i to v_j implies that robot r_i must move before r_j . The order of robot motions can then be determined by extracting at each step the root node of the graph, which corresponds to the robot that does not have to wait for any other robots. In the event of loop occurrence in the graph, the robot motion falls in deadlock situation. As an illustration,

Figure 5.6 is the directed graph constructed from Figure 5.1. Since cable C_1 , C_2 and C_3 have to wrap around robot r_2 , r_3 and r_1 at their target positions respectively, a loop is formed in the directed graph, and no root node can be extracted in this case. Therefore, there is no feasible solution for the target cable configuration by **Straight/Sequential** motion, leading to a deadlock situation.

Figure 5.6: The corresponding directed graph [75] for the target cable configuration in Figure 5.1. A directed loop implies that it is a deadlock situation for **Straight/Sequential** motion.

This approach is intuitive, but it fails to detect all possible deadlocks. Consider the scenario depicted in Figure 5.7(a), which is a deadlock situation for **Straight/Sequential** motion. However, with its corresponding directed graph as shown in Figure 5.7(c), the robots' motion order is extracted, and eventually leads to a wrong final cable configuration as shown in Figure 5.7(b) [75].

A later work by Hert and Lumelsky [77] supplements the previous algorithm. In addition to the previous rule, they consider each pair of robots r_i and r_j that satisfies the following constraints:

1. there is no directed edge between v_i and v_j in the directed graph;
2. the straight-line paths of r_i and r_j cross each other.

Then an edge from v_i to v_j is added to the graph if T_j is in the cable polygon of r_i , and vice versa. This supplemented constraint plays an important role in deadlock detection. Recall the target cable configuration in Figure 5.7(a). With this supplemented constraint, an edge from v_4 to v_1 should be added to Figure 5.7(c), forming a directed loop $v_1 - v_5 - v_4 - v_1$, which reveals the deadlock nature of the target cable configuration by **Straight/Sequential** motion. However, this algorithm is

Figure 5.7: An example of deadlock detection failure for **Straight/Sequential** motion with the algorithm proposed in [75].

still not complete in detecting all possible deadlock situations. It fails to include the case when straight-line paths of robots do not cross each other, but their target points are in each other's cable polygon. This case is a deadlock situation for **Straight** mode, and is illustrated in Figure 5.9(e, f). It is defined as *pair deadlock*, and the conception is detailed in Section 5.3.2.

Realizability by Straight/Concurrent

Straight/Sequential motion improves the efficiency compared to the **Bent** modes due to its shorter paths, yet it is a waste of time if the target cable configuration can be achieved by concurrent robot motion.

It is not difficult to infer that the solution space of **Straight/Concurrent**

mode covers that of **Straight/Sequential** mode. In other words, target cable configurations that can be achieved by **Straight/Sequential** motion can also be achieved by **Straight/Concurrent** motion, with a more efficient solution; deadlock conditions for **Straight/Concurrent** motion must also be deadlock conditions for **Straight/Sequential** motion.

Although in [77], the simultaneous motion of robots is discussed, it is not leveraged to solve deadlocks. Take Figure 5.7(a) as an example. As an output from their algorithm, the target cable configuration is a deadlock situation, and the path for r_4 is $S_4 - T_1 - T_4$. However, this target cable configuration is shown to be realizable by **Straight/Concurrent** motion with the algorithms that are present in the next section.

Summary

In this chapter, the author proposes algorithms that (a) detect whether a given target cable configuration can be achieved by **Straight/Concurrent** motion, and (b) return a valid coordinated motion plan, if applies. When there is no feasible solution, some robots will be selected to move along their target cable lines to maintain the correctness of the final cable configuration.

5.3 Algorithm for Straight/Concurrent motion

5.3.1 Overview of the algorithm

The flow of the algorithm is as follows (see Figure 5.8): given an input target cable configuration,

1. construct the Pair Interaction Graph (PIG), which encodes the interactions between pair of robots based on their cable polygons;
2. detect *pair deadlocks* in the PIG, and solve them (prune the PIG) by assigning one robot of each pair deadlock to follow its target cable line;

Figure 5.8: Flow of the algorithm.

3. from the pruned PIG, construct the Network Interaction Graph (NIG), which encodes the network interactions induced by the pair interactions, taking into account the intersections of robot paths;
4. detect *network deadlocks* in the NIG, and solve them (prune the NIG) by assigning one robot involved in each network deadlock to follow its cable line;
5. from the pruned NIG, compute the final motion schedule.

The different steps of the algorithm are detailed in the following sections.

5.3.2 Constructing the Pair Interaction Graph (PIG)

The elementary interactions that occur between a pair of robots is first considered. Those interactions are determined by the position of one robot's target with respect to the other robot's cable polygon (recall from Assumption 1 that a robot's starting position is always outside other robots' cable polygons). Given a pair of robots (r_i, r_j) , there are thus four types of pair interactions: (1) $T_i \notin \Pi_j, T_j \notin \Pi_i$ [Figure 5.9(a)]; (2) $T_i \in \Pi_j, T_j \notin \Pi_i$ [Figure 5.9(c)]; (3) $T_i \notin \Pi_j, T_j \in \Pi_i$; (4) $T_i \in \Pi_j, T_j \in \Pi_i$ [Figure 5.9(e)]. Note that types 2 and 3 are symmetrical and will be treated together.

Figure 5.9: Pair robot interactions are determined by the position of targets with respect to cable polygons. Left (a, c, e): cable polygons for type (1), (2-3), and (4) respectively. Right (b, d, f): retracted cable polygons after removing robots that are not involved in the pair interaction.

Since we are interested in pair interactions, it is supposed that the other robots are temporarily removed from the problem (multi-robot interactions will be ad-

dressed in Section 5.3.4). As a result, the cable polygons are *retracted* as in Figure 5.9(b, d, f). Note that the retraction process does not affect the interaction types just described.

The following propositions establish the motion priorities induced by each type of pair interactions.

Proposition 1. *If $T_i \notin \Pi_j$ and $T_j \notin \Pi_i$, then there are no priority induced by the pair interaction.*

Proof. It is proven in 5.A that, in this case, the two segments (S_i, T_i) and (S_j, T_j) do not intersect. Thus, the retracted cable polygons are reduced to two independent segments [Figure 5.9(b)], inducing no motion priority between r_i and r_j . $\square$

Proposition 2. *If $T_i \in \Pi_j$ and $T_j \notin \Pi_i$, then, with P denoting the intersection point between (S_i, T_i) and (S_j, T_j) , r_j must pass P before r_i does.*

Proof. It is proven in 5.A that, in this case, the two segments (S_i, T_i) and (S_j, T_j) must intersect, at a point P . One can then see that r_i must pass P before r_j does. Figure 5.9(d) illustrates this statement: the motion paths (S_1, T_1) and (S_2, T_2) intersect at P and $T_2 \in \Pi_1$. Clearly, r_1 must pass P before r_2 does, so that r_2 can “push” the cable line of r_1 . $\square$

Proposition 3. *If $T_i \in \Pi_j$ and $T_j \in \Pi_i$, then there is a deadlock, which we call a pair deadlock. One of the two robots must diverge from the straight line motion.*

Proof. It is proven in 5.A that, in this case, the two segments (S_i, T_i) and (S_j, T_j) do not intersect. This case implies a deadlock situation, which we call *pair deadlock*, as illustrated in Figure 5.9(f). The motion paths (S_1, T_1) and (S_2, T_2) do not intersect, but $T_1 \in \Pi_2$ and $T_2 \in \Pi_1$. When r_1 and r_2 move along their motion paths, the final cable configuration will be two independent segments (S_1, T_1) and (S_2, T_2) , which are different from their retracted polygons as shown in Figure 5.9(f). In this case, r_1 (r_2) has to diverge from the straight line motion and move around T_2 (T_1) in order to push $\mathcal{C}_2$ ($\mathcal{C}_1$) to the desired target cable configuration. $\square$

Based on the above propositions, Algorithm 1 can be formulated to encode pair interactions. The algorithm constructs a directed graph, termed the Pair

Interaction Graph (PIG), whose vertices represent the robots, and whose edges encode motion priority relationships: (1) if there is a unidirectional edge pointing from vertex v_i to vertex v_j , then robot r_i must pass the intersection point before r_j ; (2) if there is a bidirectional edge between vertex v_i and vertex v_j , then there is a pair deadlock.

Algorithm 1 Constructing the Pair Interaction Graph

Input: Target cable configuration

Output: Pair Interaction Graph (PIG)

```

1: for  $i = 1 : n$  do
2:   Add a vertex  $v_i$  for each robot  $r_i$ 
3: end for
4: for  $i = 1 : n - 1$  do
5:   for  $j = i + 1 : n$  do
6:     if  $(S_i, T_i)$  and  $(S_j, T_j)$  intersect at  $P$  then
7:       if  $T_i \in \Pi_j$  then
8:         Add an edge from  $v_j$  to  $v_i$ , labeled  $\{v_j \xrightarrow{P} v_i\}$ 
9:       else
10:        Add an edge from  $v_i$  to  $v_j$ , labeled  $\{v_i \xrightarrow{P} v_j\}$ 
11:      end if
12:    else if  $T_i \in \Pi_j$  and  $T_j \in \Pi_i$  then
13:      Add a bi-directed edge between  $v_i$  and  $v_j$ 
14:    end if
15:  end for
16: end for

```

5.3.3 Detecting and solving pair deadlocks

When a pair deadlock occurs, one of the two robots must diverge from the straight line motion. Consider the deadlock case of Figure 5.9(f): the deadlock can be solved by (i) one robot, say r_1 , moves in a straight line from S_1 to T_1 ; (ii) the other robot, r_2 , follows its target cable line (start from S_2 , wrap around T_1 , then go to

T_2). Although motion paths other than the robot target cable line are possible in stage (ii), we shall not consider them to avoid too much complexity.

Accordingly, the following steps are proposed to address pair deadlocks:

1. Detect all pair deadlocks (by finding all bi-directional edges in the PIG), and put the robots involved in those deadlocks into a list $\tilde{L}$;
2. Iteratively extract one robot, say r_i , from $\tilde{L}$; put it in a list L^* ; remove r_i completely from the problem; update accordingly the PIG and $\tilde{L}$; repeat until $\tilde{L}$ is empty.

At the end of this algorithm, one has a list L^* of robots that will be forced to follow their target cable lines after all other robots have moved, and a PIG that no longer contains pair deadlocks (pruned PIG).

In step 2, there are diverse methods to choose which robot to remove first from the problem. One can for instance choose the robot that is involved in the largest number of pair deadlocks, or the one whose target cable line generates the largest detour as compared to the straight line.

5.3.4 Constructing the Network Interaction Graph (NIG)

We have seen in Section 5.3.2 that pair interactions of type 1 do not induce priority, while pair interactions of type 4 induce deadlock situations, which are subsequently solved by forcing one of the robots of the pairs to follow its target cable line. As also discussed, pair interactions of types 2 and 3 give rise to priority relationships between the two robots of the pair at their intersection point. These relationships can in turn lead to *network* interactions if some robots are simultaneously involved in more than one pair interactions.

To illustrate, consider the scenario depicted in Figure 5.10(a). The pair interactions give rise to the PIG of Figure 5.10(c), which includes a circular priority chain. Yet, this situation is not deadlocked, since the following coordinated motion leads to the correct target cable configuration: r_1 , r_2 and r_3 move along their (S_i, T_i) motion paths at the same velocity. By doing so, they will indeed pass respectively points A , B and C at the same time, which in turn satisfies the requirement that

r_1 passes A before r_2 does, r_2 passes B before r_3 does, and r_3 passes C before r_1 does.

Consider now the scenario depicted in Figure 5.10(b). The pair interactions give rise to the same PIG of Figure 5.10(c). However, one can see that the situation is deadlocked. The intersection points between each pair of robots have different relative positions along robots' (S_i, T_i) motion paths now: C is closer to S_1 than A , A is closer to S_2 than B , and B is closer to S_3 than C . Indeed, the constraint imposed by the three directed edges in PIG (see Figure 5.10(c)) implies that r_1 passes C before r_2 passes A , r_2 passes A before r_3 passes B , and r_3 passes B before r_1 passes C . It is thus clear that the situation is deadlocked.

It appears from the two scenarios discussed above that correctly handling network interactions requires taking into account, not only the priority relationship between the robots at their intersection points, but also the *relative arrangement of those intersection points*. To encode this information, the author proposes to construct the Network Interaction Graph (NIG) whose vertices are the *events* “robot r_i passes intersection point P ”, denoted (r_i, P) , and whose directed edges encode the temporal relationships among the events, as follows [see Figure 5.10(d, e) for illustrations]:

1. For each robot r_i of the PIG, add to the NIG a chain $\mathcal{K}_i$: $(r_i, S_i) \rightarrow (r_i, P_1) \rightarrow \dots \rightarrow (r_i, P_m) \rightarrow (r_i, T_i)$, where $P_1, \dots, P_m$ are the ordered intersection points along the segment (S_i, T_i) ;
2. For each edge $\{v_i \xrightarrow{P} v_j\}$ of the PIG, add to the NIG a directed edge from (r_i, P) (in $\mathcal{K}_i$) to (r_j, P) (in $\mathcal{K}_j$).

5.3.5 Detecting and solving network deadlocks

The author can now state and prove the following proposition.

Proposition 4. *If the NIG contains a directed cycle, then there exists a network deadlock.*

Proof. Note that an edge $(r_i, P) \rightarrow (r_i, P')$ added in step 1 of the algorithm to construct the NIG (intra-chain edge) encodes the requirement that robot r_i must

(c) Pair interaction graph (same for both configurations).

Figure 5.10: Network interactions are determined, not only by the priority relationship between the robots at their intersection point, but also by the relative arrangement of the intersection points.

pass point P before point P' . This relationship is noted $(r_i, P) < (r_i, P')$.

An edge $(r_i, P) \rightarrow (r_j, P)$ added in step 2 (inter-chain edge) encodes the requirement that robot r_i must pass point P before robot r_j passes P . This relationship is noted $(r_i, P) < (r_j, P)$.

Observe that the relationship “ $<$ ” just defined, by its temporal nature, is a strict order relationship in the set of events, i.e. it verifies the irreflexivity, antisymmetry, and transitivity properties.

Consider now a directed cycle in the NIG. Such a cycle induces a cycle for the strict order relationship “ $<$ ”, which is clearly not satisfiable. Therefore, there exists at least one priority requirement that cannot be satisfied in the cycle, i.e. a deadlock situation. $\square$

When there is a network deadlock, one of the involved robots has to diverge from the straight-line motion, similarly to the pair deadlock case. Accordingly, the following steps are proposed to address network deadlocks:

1. Detect all network deadlocks (by finding all directed cycles in the NIG), and put the robots involved in those deadlocks into a list $\tilde{L}$;
2. Iteratively extract one robot, say r_i , from $\tilde{L}$; put it in the list L^* (the same as used previously for solving pair deadlocks); remove r_i completely from the problem; update accordingly the NIG and $\tilde{L}$; repeat until $\tilde{L}$ is empty.

At the end of this algorithm, one has a list L^* of robots that will be forced to follow their target cable lines after all other robots have moved, and a NIG that no longer contains network deadlocks (pruned NIG).

Similarly to the case of pair deadlocks, there are diverse methods, in step 2, to choose which robot to remove first from the problem. One can for instance choose the robot that is involved in the largest number of network deadlocks, or the one whose target cable line generates the largest detour as compared to the straight line.

5.3.6 Computing the final motion schedule

When the motion of a pair of robots is coordinated at the intersection point of their (S, T) motion paths, we could either make the lower priority robot wait until the higher priority robot passes the point, or adjust the speed of the robots to produce continuous motions. In this work, the waiting scheme is adopted for illustration. A coordinated motion plan with shortest traveling time is generated if the target cable configuration can be achieved by **Straight/Concurrent** robot motion.

In the following procedures, (r_i, P^-) and (r_i, P^+) denote the predecessor and successor of (r_i, P) on the chain $\mathcal{K}_i$ respectively. $\mathcal{T}_i$ represents the time-line for robot r_i , and $T_{i,P}$ is the time-stamp on $\mathcal{T}_i$, upon which robot r_i starts to navigate from (r_i, P) to (r_i, P^+) . Weight $w_{i,P}$ of node (r_i, P) indicates the amount of time that r_i takes to travel from (r_i, P^-) to (r_i, P) .

From the NIG (which we suppose does not contain any cycle), a coordinated motion schedule can be extracted for the robots to achieve the target cable configuration as follows:

1. For each chain $\mathcal{K}_i$ of the NIG, $i = 1, \dots, n$, calculate and assign the weight to every node (weight is 0 for (r_i, S_i));
2. Initialize time-line $\mathcal{T}_i$ for each robot r_i , $i = 1, \dots, n$;
3. For the root node (r_i, R) in $\mathcal{K}_i$, $i = 1, \dots, n$,
 - (a). If there is no incoming inter-chain edge from any $\mathcal{K}_j$, $i \neq j$, append traveling time $w_{i,R}$ to $\mathcal{T}_i$, and remove (r_i, R) from the NIG;
 - (b). If there is an incoming inter-chain edge from an already removed node (r_j, P) in $\mathcal{K}_j$, $w_{i,R}$ must be appended to $\mathcal{T}_i$ at a time-stamp that is *no earlier than* $T_{j,P}$ ¹, after which (r_i, R) and this incoming inter-chain edge are removed from the NIG;
4. Repeat step 3 until there is only the node T_i left in each chain $\mathcal{K}_i$, $i = 1, \dots, n$ of the NIG;

¹Here the author use a relaxed chronological order *no earlier than* for a directed inter-chain edge from (r_j, P) in $\mathcal{K}_j$ to (r_i, R) in $\mathcal{K}_i$ in order to exempt r_i from the unnecessary waiting time for the whole duration $w_{j,P}$.

5. Make robots in L^* move along their target cable lines after all other robots have reached their target positions.

A detailed example is presented in Section 5.4.

5.3.7 Complexity of the algorithms

The complexity of the algorithms just presented is now analyzed as a function of the number n of robots. Note first that, for each robot r_i , the number of vertices (and edges) of its cable polygon Π_i is $O(n)$ since it is bounded by the total number of robots (the cables can only wrap around other robots).

Pair Interaction Graph

To construct the PIG, the step with the highest complexity is to check whether $T_i \in \Pi_j$ for all pairs (i, j) . The test $T_i \in \Pi_j$ has a linear complexity in the number of edges of Π_j , which is $O(n)$. Thus, the construction of the PIG has a complexity of $O(n^3)$.

Detecting pair deadlocks involves finding all bi-directional edges in the PIG and can therefore be done in $O(n^2)$.

There are potentially $O(n)$ deadlocked robots. For a deadlocked robot, say robot r_i , one needs to remove it and update the PIG accordingly, which can be done in $O(n^2)$. Thus, pruning the PIG can be done in $O(n^3)$.

Network Interaction Graph

To construct the NIG, the main step is to compute, for each robot r_i , the intersections of (S_i, T_i) with all the (S_j, T_j) and order those intersections along (S_i, T_i) . This can be done in $O(n^2 \log(n))$.

Detecting network deadlocks involves checking whether the NIG has a cycle, which can be done in $O(n^2)$ (topological sort). Pruning the NIG can be done in $O(n^3)$.

Motion schedule

The algorithm for scheduling the robot motions is linear in the number of nodes of the NIG and is therefore $O(n^2)$.

From the above analysis, the worst time-complexity of the full pipeline is $O(n^3)$.

5.4 Examples

5.4.1 An example from Hert & Lumelsky 1996

In this section, the proposed algorithms are validated with the example previously shown in Figure 5.7(a), which is a deadlock situation for **Straight/Sequential** motion. It is shown that the target cable configuration can be achieved by **Straight/Concurrent** motion and r_4 does not need to take a detour as in the output of the algorithm in [77].

The intermediate stages of achieving the target cable configuration with our proposed algorithms are shown in Figure 5.11. In addition, a step-wise illustration of motion scheduling is presented in Figure 5.12.

To avoid the wrong final cable configuration as shown in Figure 5.7(b), r_4 must pass A before r_1 does. It is not possible in **Straight/Sequential** motion, since r_1 has to reach its target position before r_4 does. However, moving in **Straight/Concurrent** motion following the local navigation priority as indicated in Figure 5.11(d), which contains no directed cycle, the target cable configuration can be achieved successfully.

5.4.2 Hardware experiment

The proposed algorithms are validated in a hardware experiment. The large-scale, multi-robot 3D printing system previously developed by Chapter 3 is considered. The tethers are indispensable here to deliver the fresh concrete from the mixer to the print nozzle. The size of each mobile robot is $960 \times 793 \times 296$ mm. Each cable is 10 m in length and has a bend radius of 110 mm. The coordinated motion plan of Figure 5.1 was implemented. (S_i, T_i) segment for each robot was 7 m. The maximal

(a) The given target cable configuration. (b) (S, T) straight-line segments of the robots with labels for intersection points.

(c) Pair interaction graph.

(d) Network interaction graph.

Figure 5.11: The proposed algorithms are validated with a deadlocked target cable configuration for **Straight/Sequential** motion.

(a) Initialized time-lines for the robots.

(b) The weighted NIG.

(c) Schedule step 1.

(d) Updated NIG after step 1.

(e) Schedule step 2.

(f) Updated NIG after step 2.

(g) Schedule step 3.

(h) Updated NIG after step 3.

Figure 5.12: Motion schedule generation for target cable configuration in Figure 5.7(a).

Figure 5.12: Motion schedule generation for target cable configuration in Figure 5.7(a).(cont.)

velocity of each robots was 0.6 m/s. To achieve the target cable configuration, at each intersection point, the robots must follow the motion priority as indicated in the NIG (see Figure 5.10(d)).

Figure 5.13 shows snapshots of the coordinated motions when the robots respected the calculated motion priority. The mobile robots moved in **Straight/Concurrent** mode: they were commanded to move simultaneously along their (S_i, T_i) straight-line segments. It is worthy of mention that at 14s in the video of the experiment, r_2 stopped and waited until r_1 passed point A , after which r_2 passed A and proceeded towards T_2 . This movement reflects the motion priority of r_1 and r_2 at point A : r_1 must pass A before r_2 does. Although the robots were not strictly points, and that the tethers were not perfectly flexible, the target cable configuration could be achieved as the robot motions respected the calculated priorities at the intersection points. The result was evaluated purely based on positions of the robots, without taking their orientations into account.

Figure 5.13: Snapshots of the coordinated motions that achieve the desired target cable configuration. See the full video of the experiment at <https://youtu.be/mFR72jbCT38>. A. Tethered robots at starting positions; B. Navigating towards target locations in concurrent straight-line motion; C. Passing intersection points with calculated priority; D. Pushing other robot's cable during navigation; E. Navigation in progress; F. Achieving final (target) cable configuration.

By contrast, Figure 5.14 shows snapshots of a second run, where the robots did not respect the calculated priorities at the intersection points. For better illustration of motion order at each intersection point, the robots were commanded to move in **Straight/Sequential** mode in the order of r_1 , r_2 and r_3 (see Figure 5.2(b)). Therefore, r_1 already reached T_1 before r_3 started to move (see Figure 5.14D), which violated the motion priority at point C : r_3 must pass C before r_1 does. When r_3 navigated towards T_3 , it had to push C_1 from C all the way to T_3 , resulting in a

wrong final cable configuration as shown in Figure 5.14F. Due to the limitation in tether length and the elastic property of the tethers, r_1 was dragged back when C_1 was pushed forward by r_3 , and r_3 failed to reach its target position.

Figure 5.14: Snapshots of the motions that fail to achieve the desired target cable configuration. See second part of the video <https://youtu.be/mFR72jbCT38>. A. Tethered robots at starting positions; B. Robot r_1 passing A before r_2 as calculated; C. Robot r_2 passing B before r_3 as calculated; D. Robot r_3 pushing r_1 's cable from the wrong side as the motion order of r_1 and r_3 at C is wrong; E. Robot r_3 continuing its navigation; F. Resulting in wrong final cable configuration.

A comparison of the total travel distance and the travel time for the above mentioned two hardware implementations is provided in Table 5.1. Data for Bent/Concurrent and Bent/Sequential modes was also computed for system-

atical comparison.

Table 5.1: Comparison of travel distance and travel time for different motion modes.

Motion mode	Straight/ Concurrent	Straight/ Sequential	Bent/ Concurrent ²	Bent/ Sequential ²
Total travel distance (m)	21	21	30	30
Travel time (s)	14	40	20	60

5.5 Conclusion

The motion planning problem for multiple tethered planar (point) mobile robots has been considered in this work. Motion planning algorithms have been presented for the robots to achieve a given target cable configuration by straight-line and concurrent (**Straight/Concurrent**) motions. The algorithms (i) identify whether the target cable configuration was deadlocked; (ii) return a valid coordinated motion plan accordingly. The correctness of the algorithms was proved in the process of algorithm development, and the worst time-complexity of the full pipeline was shown to be $O(n^3)$.

The proposed algorithms have been validated in both simulations and hardware experiments: it was shown that, using the proposed algorithms, the tethered robots could achieve a target cable configuration that involved a deadlock situation for **Straight/Sequential** motions, and that could not be solved by algorithms previously proposed in the literature.

During the hardware demonstration, it was found that for some applications, it could be challenging to design a tether management mechanism to keep the tether taut and retractable. In addition, robot size and geometry need to be taken into account during motion planning, especially for the purpose of collision avoidance. Our future work will consider integrating tether stiffness property and robot model into the proposed algorithms.

²Note that **Bent/Concurrent** and **Bent/Sequential** modes were not implemented in hardware experiment. The data was computed based on the robot velocity and tether length.

While this work mainly focuses on mathematical algorithms and proof, it provides algorithmic foundations to real-time implementation. The following takes as an example concrete 3D printing with the multi-robot system proposed in Chapter 3, and discusses some typical aspects that need to be considered for real-world applications, including robot localization, obstacle detection, and cable intersection detection. When mobile printers navigate in the construction site, which is normally cluttered with obstacles, it is essential for the robots to be aware of surrounding obstacles and localize themselves in the environment. For this purpose, SLAM and AMCL algorithms are commonly used as described in Chapter 3.2.4. In terms of path planning, extension of the proposed algorithm to workspace with stationary obstacles is included in Appendix 5.C, but to effectively deal with moving obstacles for tethered robot planning is difficult. Although the proposed algorithms can be adapted to handle moving obstacles by scanning the environment and re-planning at constant time intervals, the obstacles are easily trapped by the cables and the robots may need excessive movements to break deadlocks. In the concrete 3D printing example, and many other applications, it is reasonable to assume that the only moving obstacles in the environment are human beings, and they will not be trapped as they can step over the cables. In this case, if humans block certain robots' movements, the robots can simply wait for the humans to walk away and then proceed. As long as the robots observe motion order as planned at their paths' intersection points, the target cable configuration will be reached. In addition to obstacle detection, it is also helpful to be able to monitor and detect cable intersections. One possible approach is to use a camera to capture the robot and cable configuration in the construction site, and detect cable intersection with vision techniques. In the concrete 3D printing application, it could be inferred passively from the Barometer on the pump, as hose intersection could cause material jam, and in turn increases the pressure reading.

Appendix 5.A Proofs of the pair interaction propositions

A topological lemma is first needed, which is also used in Jordan's proof of the Jordan curve theorem (see Lemma 1 of [149]).

Lemma 1. *Consider a polygon Π , a point S in the exterior of Π , and a continuous path starting from S and ending at T . Then T is in the interior of Π if and only if $\mathcal{P}$ intersects the boundary of Π an odd number of times.*

The following propositions can now be proved, which are required by the pair interaction propositions of Section 5.3.2.

Proposition 5. *Assume that $S_i, T_i \notin \Pi_j$ and $S_j, T_j \notin \Pi_i$, then the two segments (S_i, T_i) and (S_j, T_j) do not intersect.*

Proof. Assume by contradiction that (S_i, T_i) and (S_j, T_j) intersect at a point P . Consider the cable line $\mathcal{C}_j$ of robot r_j . By lemma 1, $\mathcal{C}_j$ will intersect the boundary of Π_i an even number of times. Since $\mathcal{C}_j$ has zero intersection with $\mathcal{C}_i$ (cable lines are non intersecting), $\mathcal{C}_j$ must intersect (S_i, T_i) an even number of times. Since (S_i, T_i) already intersects (S_j, T_j) at one point P , the total number of intersections between (S_i, T_i) and the boundary of Π_j is odd. By lemma 1, either S_i or T_i must therefore be in the interior of Π_j , which raises a contradiction. $\square$

Proposition 6. *Assume that $S_i \notin \Pi_j$, $S_j \notin \Pi_i$, $T_i \in \Pi_j$, $T_j \notin \Pi_i$, then the two segments (S_i, T_i) and (S_j, T_j) must intersect.*

Proof. Assume by contradiction that (S_i, T_i) and (S_j, T_j) do not intersect. By lemma 1, $\mathcal{C}_i$ will intersect boundary of Π_j for odd number of times. Since $\mathcal{C}_i$ does not intersect $\mathcal{C}_j$ under the problem formulation, $\mathcal{C}_i$ must intersect (S_j, T_j) for odd number of times. The assumption that (S_i, T_i) and (S_j, T_j) do not intersect then implies that (S_j, T_j) intersects Π_i for odd number of times. Therefore either S_j or T_j has to be in the interior of Π_i , which raises a contradiction. $\square$

Proposition 7. *Assume that $S_i \notin \Pi_j$, $S_j \notin \Pi_i$, $T_i \in \Pi_j$, $T_j \in \Pi_i$, then the two segments (S_i, T_i) and (S_j, T_j) do not intersect.*

Proof. Assume by contradiction that (S_i, T_i) and (S_j, T_j) intersects at a point P . By lemma 1, (S_i, T_i) will intersect boundary of Π_j for odd number of times, and $\mathcal{C}_j$ will intersect boundary of Π_i for odd number of times. Since (S_i, T_i) and (S_j, T_j) intersects at P , (S_i, T_i) will intersect $\mathcal{C}_j$ for even number of times. Therefore $\mathcal{C}_j$ will intersect $\mathcal{C}_i$ for odd number of times, which raises a contradiction as cable lines are non intersecting. $\square$

Appendix 5.B Revising and supplementing Hert and Lumelsky 1997

In this section, route intersection detection algorithms for case 1(b) and 2(b) of the paper [147] are supplemented and revised. Some background terms are first introduced here.

A *cable route* ($\mathcal{R}$) for robot r_i through graph G is defined as the set of adjacent edges leading from S_i to some node. Without loss of generality, it is assumed that no three consecutive nodes from a single route are collinear. Therefore, any two adjacent edges in a route form two distinct angles, one convex ($< \pi$) and the other concave ($> \pi$).

To find a feasible target cable configuration from G , the most fundamental task is to identify whether there is any route intersection in a given cable configuration. As discussed in [147], there are five different ways $\mathcal{R}_A$ and $\mathcal{R}_B$ can meet at a node T_k , considering the relative placement of edges from $\mathcal{R}_A$ and $\mathcal{R}_B$:

1. T_k is the last node of one of the routes, say $\mathcal{R}_A$. $\mathcal{R}_A$ has one edge incident to T_k and $\mathcal{R}_B$ has two. The routes meet in one of the following two ways:
 - (a) $\mathcal{R}_A$ and $\mathcal{R}_B$ do not share an edge incident to T_k ;
 - (b) $\mathcal{R}_A$ and $\mathcal{R}_B$ do share an edge incident to T_k .
2. T_k is not the last node of either of the routes. Each route has two edges incident to T_k . There are three cases as the following:
 - (a) $\mathcal{R}_A$ and $\mathcal{R}_B$ share no edge incident to T_k ;

- (b) $\mathcal{R}_A$ and $\mathcal{R}_B$ share one edge incident to T_k ;
- (c) $\mathcal{R}_A$ and $\mathcal{R}_B$ share both edges incident to T_k .

Route intersection may occur in cases from 1(a) to 2(b), but can be avoided in case 2(c). Besides the above possible intersections, there is one more case where two routes do not intersect at certain node, instead, they intersect in their interiors. Readers may refer to [147] for more details on the cable intersection detection algorithm, but the algorithm for case 1(b) is not complete, and that for case 2(b) needs revision. In the following section, the revised and supplemented algorithms are provided.

5.B.1 Detecting Route Intersection (revised and supplemented)

Case 1(b)

Case 1(b): Suppose $\mathcal{R}_A$ and $\mathcal{R}_B$ have one or more edges in common, and one of them is the last edge for $\mathcal{R}_A$. T_l is the goal node of $\mathcal{R}_A$.

In [147], the authors conclude this case as the following:

Let e_{a1} and e_{b1} be the two edges from $\mathcal{R}_A$ and $\mathcal{R}_B$, immediately before this common set of edges. Let e_{b2} be the edge from $\mathcal{R}_B$ immediately after the common set of edges. Let e_{fc} be the first edge shared by $\mathcal{R}_A$ and $\mathcal{R}_B$, and e_{lc} the last edge shared by $\mathcal{R}_A$ and $\mathcal{R}_B$.

Lemma 2 $\mathcal{R}_A$ and $\mathcal{R}_B$ intersect at T_l if and only if e_{a1} is contained in the clockwise (counterclockwise) angle from edge e_{b1} to e_{fc} and the clockwise (counterclockwise) angle from e_{lc} to e_{b2} is $> \pi$.

However, the above statement and Lemma 2 are capable of intersection detection for case 1(b) only if edge e_{b1} exists. Considering the situation where $\mathcal{R}_A$ and $\mathcal{R}_B$ are developed from different directions and T_k is the target position of $\mathcal{R}_B$, the case has to be reformulated as in Figure 5.16 and Lemma 2s.

Lemma 2s If edge e_{b1} does not exist, and node T_k is goal node of $\mathcal{R}_B$. $\mathcal{R}_A$ and $\mathcal{R}_B$ intersect at T_k if and only if clockwise (counterclockwise) angle from e_{a1} to e_{fc}

Figure 5.15: Case 1(b). $\mathcal{R}_A$ and $\mathcal{R}_B$ intersect at T_l . (The figure is taken from [147] Figure 11.)

Figure 5.16: Case 1(b) supplement. Edge e_{b1} does not exist, meaning node T_k is goal node of $\mathcal{R}_B$. $\mathcal{R}_A$ and $\mathcal{R}_B$ intersect at T_l .

is $> \pi$ and the clockwise (counterclockwise) angle from e_{lc} to e_{b2} is $> \pi$.

Case 2(b)

Case 2(b): Suppose $\mathcal{R}_A$ and $\mathcal{R}_B$ meet at node T_k , and each route has two edges incident to T_k . They share one of the edges. Let $\mathcal{R}_A$ be the route currently in construction and $\mathcal{R}_B$ be a previously constructed route.

In [147], this case is concluded as the following:

The edges and nodes labeling follow the convention in case 1(b), and an edge e_{a2} of $\mathcal{R}_A$ is added immediately after the common set of edges. An illustration is shown in Figure 5.17. Assume that the edge e_{b2} is in the counterclockwise angle from e_{a2} to e_{lc} . Then Lemma 4 is used to determine intersection.

Figure 5.17: Case 2(b). In both (a) and (b) $\mathcal{R}_A$ and $\mathcal{R}_B$ intersect at node T_k . (The figure is taken from [147] Figure 14.)

Lemma 4 $\mathcal{R}_A$ and $\mathcal{R}_B$ intersect at T_k if and only if (a) e_{b1} is contained in the concave angle between e_{a1} and e_{fc} and e_{a1} is contained in the concave angle between e_{b1} and e_{fc} or (b) e_{b1} is contained in the clockwise angle from e_{fc} to e_{a1} .

However, the algorithm is redundant for option (a) in Lemma 4. Since the cable configuration is constructed in a depth-first manner, there is no need to proceed further if intersection has already been detected. Hence, it can be re-formulated as in Figure 5.18.

In addition, option (b) in Lemma 4 only satisfy the situation when edge e_{b2} exists (recall the discussion for case 1(b)). When T_l is the goal node for $\mathcal{R}_B$, meaning there is no edge e_{b2} , Lemma 4(b) has to be revised. The revised version of Lemma 4 is presented below.

Figure 5.18: Revised Case 2(b) for Lemma 4(a).

Lemma 4r $\mathcal{R}_A$ and $\mathcal{R}_B$ intersect at T_k if and only if (a) e_{b1} is contained in the concave angle between e_{a1} and e_{fc} and e_{a1} is contained in the concave angle between e_{b1} and e_{fc} ; or (b1) e_{b1} is contained in the clockwise (counterclockwise) angle from e_{fc} to e_{a1} and edge e_{b2} is in the counterclockwise (clockwise) angle from e_{a2} to e_{lc} ; or (b2) e_{b1} is contained in the clockwise (counterclockwise) angle from e_{fc} to e_{a1} and counterclockwise (clockwise) angle from e_{a2} to e_{lc} is $< \pi$ when T_l is the goal node for $\mathcal{R}_B$.

Appendix 5.C Extension to workspace with obstacles

An obstacle interferes in robot's motion only when the whole piece or part of it is in the robot's cable polygon. An example is given in Figure 5.19.

In Figure 5.19(a), the obstacle is located in the exterior of a robot's cable polygon. Although cable line C_1 wraps around the obstacle at point O in the target cable configuration, r_1 and r_2 can still move along their (S, T) straight-line path to achieve the target cable configuration as long as r_1 passes point P before r_2 does, which behaves the same as the case without obstacles. By contrast, robot's path needs to be modified when the obstacle is (partially) in the interior of the robot's cable polygon. As depicted in Figure 5.19(b, c), to achieve the target cable configuration, the shortest path for r_1 is $S_1 - O' - P' - T_1$, and r_1 must pass P' earlier than r_2 .

The proposed algorithms for **Straight/Concurrent** motion can be adapted easily to the situation where there are obstacles in the workspace. The only mod-

(a) The obstacle is out of Π_1 and Π_2 . The target cable configuration can be achieved by straight-line robot motion as long as r_1 passes point P before r_2 does.

(b) The obstacle is in Π_1 . The target cable configuration cannot be achieved if r_1 moves along (S_1, T_1) .

(c) The shortest paths for the robots for the case in (b). To achieve the target cable configuration, r_1 has to move along $S_1 - O' - P' - T_1$ and passes P' before r_2 does.

Figure 5.19: Interference in robot's motion from the obstacle that is located in and out of robot's retraction polygon.

ification is the robots' paths. Recall that the motivation to adopt straight-line motion is that it is the shortest path for a robot to reach its target position. When there are obstacles in the workspace, the shortest path of a robot is no longer its (S, T) straight-line segment, but its retracted cable line after all other robots are removed from the environment. The algorithms for **Straight/Concurrent** motion still hold for workspace with obstacles with the updated shortest paths. An example is presented in Figure 5.20.

Figure 5.20: An implementation of the proposed algorithms for the case where the workspace contains obstacles.

Chapter 6

Collaborative in-situ robotic assembly

6.1 Introduction

With the advances in recent technology, robots have been used extensively in a variety of industrial applications, such as object manipulation [150], 3D printing [135, 151] and payload transportation. When manipulating large and heavy objects, cooperation of multiple robot manipulators is necessary due to the limited capability of a single manipulator, and a mobile base could further enlarge the potential task scope by extending robot workspace.

Nowadays, however, most of these industrial robots are isolated from humans and are programmed to perform some repetitive tasks. The constraints impose significant limits on the full capability of robots that could have been utilized. Consider a common scenario in concrete 3D printing, where several pieces of a large-scale structure printed off-site are to be transported and assembled on-site. Automation of the process is desired to ease human burden in such kind of hard-labor work. However, as the construction site is usually dynamic and unstructured, and the assembly requires highly accurate alignment of workpieces, autonomous robot navigation and precise manipulation would require expensive sensing and computational cost. On the other hand, the task could be executed with much lesser effort by a robot system under the guidance of a human operator (see Figure 6.1).

Figure 6.1: An example of two mobile manipulators transporting a large object under the guidance of a human operator. See full video of the experiment at <https://youtu.be/jJ-wx9kvfus>.

This work aims at developing a compliant behavior of the robot system when working in cooperation with humans, which ensures human safety while avoids damage to the object being handled. In particular, the work focuses on a robot system with two mobile manipulators. This chapter presents the preliminary stage of the work, where the author targets at exploring the feasibility of applying admittance control on multiple mobile position-controlled industrial robots with minimum external sensing, and testing the robustness of the control in an imperfect environment. Actual experiments have been conducted where two mobile manipulators assist a human operator on successfully transporting and installing a window frame to a 3D printed wall.

The remainder of this chapter is organized as follows. In Section 6.2, the background on admittance control is introduced, and the control problem for dual-arm mobile robot system is formulated. In Section 6.3, the algorithms for admittance control of the dual-arm mobile robot system are presented in detail. Section 6.4 presents experimental results of applying the control strategy on a hardware robot system: mobile manipulators working in cooperation with a human operator to transport an aluminium window frame and install it in the concrete 3D printed wall. Finally, the work is concluded and some directions for future research are sketched in Section 6.5.

6.2 Background

Before admittance control and the dynamics of the object are introduced, the notation to be used throughout this chapter is given in Table 6.1. All terms are expressed in the world base frame Σ otherwise specified.

Table 6.1: Notation

Symbol	Size	Description
$k = 1, 2$	scalar	index of each mobile manipulator
Σ_e	N.A.	frame attached to the object
$\mathbf{p}_e$	3×1	position vector of Σ_e
$\mathbf{r}_k$	3×1	virtual stick [152], from the k th end effector to a point on the object
$\mathbf{w}_e$	3×1	angular velocity of Σ_e
$\mathbf{v}_e$	3×1	linear velocity of Σ_e
$\mathbf{R}_e$	3×3	rotation matrix of Σ_e
$\mathbf{J}(\cdot)$	6×6	Jacobian matrix
$\mathbf{J}_e$	3×3	object's inertia tensor
$\mathbf{g}_e$	6×1	gravitational forces on the object
$\mathbf{q}_k$	6×1	joint value
$\mathbf{f}_e$	3×1	external force acting on the object
$\boldsymbol{\mu}_e$	3×1	external moments acting on the object
m_e	scalar	object mass
$\mathbf{I}$	3×3	identity matrix
$\mathbf{O}$	3×3	null matrix
$\mathbf{S}(\cdot)$	N.A.	skew-symmetric matrix operator performing cross product

6.2.1 Admittance control

For a simple second-order admittance, admittance controller of a general object enforces the following relationship

$$\mathbf{M}_o(\dot{\mathbf{v}}_d - \dot{\mathbf{v}}) + \mathbf{D}(\mathbf{v}_d - \mathbf{v}) + \mathbf{K}(\mathbf{x}_d - \mathbf{x}) = \mathbf{h}_e \quad (6.1)$$

where $\mathbf{M}_o = \begin{bmatrix} m_o \mathbf{I} & \mathbf{O} \\ \mathbf{O} & \mathbf{J}_o \end{bmatrix}$ is the object mass matrix: m_o is the mass of the object, and $\mathbf{J}_o$ is its inertia tensor; $\mathbf{D}$ and $\mathbf{K}$ are damping and stiffness factor matrices. The subscript d represents that the quantity is in the *desired* frame. $\mathbf{h}_e = [\mathbf{f}_e^T \quad \boldsymbol{\mu}_e^T]^T$ is the external wrench.

6.2.2 Modeling

Consider a robot system of two mobile manipulators, grasping a rigid object tightly (see Figure 6.2). Each mobile manipulator comprises one 6-DoF robotic arm mounted atop a holonomic mobile platform, with a wrist-mounted Force/Torque sensor and a gripper as the end effector.

Figure 6.2: System setup for the mobile manipulators.

The object's equation of motion expressed in Σ_e is

$$\mathbf{M}_e \dot{\mathbf{v}}_e + \mathbf{C}(\mathbf{v}_e) \mathbf{v}_e + \mathbf{g}_e = \mathbf{h}_e \quad (6.2)$$

where

$\mathbf{M}_e$ is the object mass matrix;

$$\mathbf{C}(\mathbf{v}_e) = \begin{bmatrix} m_e \mathbf{S}(\mathbf{w}_e) & \mathbf{O} \\ \mathbf{O} & \mathbf{S}(\mathbf{w}_e) \mathbf{J}_e \end{bmatrix};$$

$\mathbf{h}_e = [\mathbf{f}_e^T \ \boldsymbol{\mu}_e^T]^T$ is the external wrench exerted on the object. Therefore the mapping between the contact wrench $\mathbf{h}$ measured by the wrist Force/Torque sensors and the external wrench experienced by the object is given by

$$\mathbf{h}_e = \begin{bmatrix} \mathbf{I} & \mathbf{O} & \mathbf{I} & \mathbf{O} \\ \mathbf{S}(\mathbf{r}_1) & \mathbf{I} & \mathbf{S}(\mathbf{r}_2) & \mathbf{I} \end{bmatrix} \begin{bmatrix} \mathbf{h}_1 \\ \mathbf{h}_2 \end{bmatrix} = \mathbf{W} \mathbf{h} \quad (6.3)$$

where $\mathbf{W}$ is the grasp matrix.

6.3 Methodology

For simplicity, it is assumed that the apparent admittance acts at the center of the object, which can be easily transferred to any other location of the object if necessary.

A pipeline of the admittance control scheme is presented in Figure 6.3. Please refer to [101] for stability proof of the admittance control strategy and gain settings in several scenarios, where the stiffness parameters are tuned to ensure a compliant behavior, and the damping parameters are chosen for a well-damped behavior.

Figure 6.3: Pipeline of the object admittance control scheme.

$\mathcal{T}_{ed}$ is the desired object trajectory; $\mathcal{T}_{ec}$ is the compliant object trajectory with admittance characteristics when the object is exposed to external interruptions; $\mathcal{T}_k$ is the mobile manipulator trajectory calculated from $\mathcal{T}_{ec}$ based on the kinematic

relationships. The inverse kinematics for each mobile manipulator is formulated as a convex optimization problem and solved with quadratic programming

$$\begin{aligned}
\dot{\mathbf{q}}_t^* &= \arg \min_{\dot{\mathbf{q}}_t} \frac{1}{2} \dot{\mathbf{q}}_t^T \mathbf{Q} \dot{\mathbf{q}}_t \\
\text{subject to} \quad & \mathbf{J}(\mathbf{q}_{t-1}) \dot{\mathbf{q}}_t = \dot{\mathbf{p}}, \\
& \dot{\mathbf{q}}^{min} \leq \dot{\mathbf{q}}_t \leq \dot{\mathbf{q}}^{max}.
\end{aligned} \tag{6.4}$$

where $\mathbf{Q} = \begin{bmatrix} \mathbf{Q}_{arm} & \mathbf{O} \\ \mathbf{O} & \mathbf{Q}_{base} \end{bmatrix}$ is a diagonal weighting matrix comprised of the weighting matrix of the arm and that of the mobile base, and $\mathbf{J}(\cdot)$ is the Jacobian matrix for the mobile manipulator. Since the accuracy of the mobile base is considerably lower than that of the industrial robot arm, it is desirable to reduce the base movement whenever possible. Therefore, the weighting matrices for the arm and the base are chosen such that $\|\mathbf{Q}_{arm}\| < \|\mathbf{Q}_{base}\|$.

Given the desired object trajectory, corresponding compliant variables can be computed from the admittance relationship introduced in Section 6.2.1 and the dynamics of the object given in Section 6.2.2 [92]. Since the object is rigid and the grasp is tight, with the known kinematic relationships between the manipulators and the object, final joint variables of the manipulators can be calculated and fed to the robot controllers.

6.4 Experiments

6.4.1 Experimental setup

Actual experiments, where two mobile manipulators transport and install an aluminium window frame in a 3D printed concrete wall under the guidance of a human operator, were conducted to demonstrate the capability of the proposed control scheme. The robot system setup is described in Section 6.2.2: each 6-axis Denso VS-087 robot position-controlled at 125 Hz is mounted atop a Clearpath Ridgeback holonomic mobile base running at 30 Hz; a 2-fingered gripper is equipped with a wrist-attached ATI Force/Torque sensor running at 125 Hz. A Ubuntu 16.04

computer is used as the controller, and ROS multimaster_fkie [153] is adopted to manage the overall network communication. The aluminium window frame being handled is $80\text{ cm} \times 50\text{ cm} \times 2\text{ cm}$ in size, and 2.04 kg in weight. The window opening was concrete 3D printed with a clearance of about 1 cm.

In both experiments, the admittance controller was decoupled in Cartesian space and translation-only object motion was considered.

Note that at the current stage, where solely external interaction is considered, the control strategy can be applied to the system equipped with only one Force/-Torque sensor. The experiment demonstrated in this section was performed with one Force/Torque sensor mounted at the left robot's wrist.

6.4.2 Experiment 1: Window frame transportation

- 1) *Task description:* During the transportation process, the mobile manipulators carrying the window frame followed the guidance of the human operator and navigated to the target installation location. The window frame was carried forward in X direction for around 1 m, and brought up to a comfortable interaction height for the operator in Z direction, while the frame displacement in Y direction was constrained to be 0.
- 2) *Results:* Figure 6.4 (a)-(e) presents a series of screenshots of the transportation task. Force measurement and object displacement during the transportation process are shown in Figure 6.4 (f). The object's weight was compensated in z-force reading.

During **Lifting** phase ($t = 0 - 8\text{ s}$), the operator exerted large force in +Z direction to lift up the window frame to the height that is convenient for interaction. Subsequently in **Pulling** phase ($t = 8 - 35\text{ s}$), the force in +X direction dominated and the frame was pulled towards the target position. During **Transition** phase from $t = 35\text{ s}$ to $t = 45\text{ s}$, the operator released the window frame and changed interaction position from Figure 6.4 (c) to (d) in order to bring the frame closer to the wall. The frame was pushed forward during **Pushing** phase until it reached the target position and was released from $t = 45\text{ s}$ onwards. The controller yields a stable behavior and the overall

(a) Mobile manipulators carry the window frame at the initial position.

(b) The human operator starts to interact with the object.

(c) Cooperative transportation towards the target position.

(d) Human operator changes interaction strategy to adjust the object position.

(e) Reaching the target position.

(f) Force measurement and object displacement during transportation.

Figure 6.4: Window frame transportation by mobile manipulators under the guidance of a human operator.

interaction process was steady.

One can observe minor position error in Y direction over the course of the transportation (less than 2 cm). Besides the intrinsic error of the mobile base odometry data, the major cause for this error is the misalignment in initial robot pose setting, especially the rotation offset of the platforms around Z direction, which could lead to magnified error over a long traveling distance.

6.4.3 Experiment 2: Window installation

- 1) *Task description:* During the installation process, the controller was switched to fixed-base mode, in which mobile base movement was disabled and the manipulators worked locally in cooperation with the human operator to ensure precise and safe installation of the window frame into the concrete wall. Admittance control was implemented in all X, Y and Z directions. Due to high contact stiffness of the concrete installation environment, greater damping coefficient was chosen to enhance stability.
- 2) *Results:* Figure 6.5 (a)-(d) presents a series of screenshots of the installation task. Force measurement and object displacement during the installation process are shown in Figure 6.4 (e). The object's weight was compensated in z-force reading, and the initial object x-, y- and z-position were reset to 0 in installation phase for better visualization.

The frame was brought closer to the window opening and ready for installation during **Adjusting position** phase. **Installing** phase started from $t = 10\text{ s}$, when the operator guided manipulators to insert the frame into the opening. At $t = 22\text{ s}$, the frame was successfully installed and the operator stopped interaction.

6.4.4 Discussion

The experimental results demonstrate the capability of the proposed admittance control architecture being applied to tasks that involve interaction with the environment and cooperation of robots and human operators. The system is stable when

(a) Mobile manipulators carry the window frame at the ready position.

(b) The human operator starts to guide the installation of the window frame.

(c) The human operator assists the manipulators to install the window frame.

(d) The window frame is successfully installed.

(e) Force measurement and object displacement during installation.

Figure 6.5: Window frame installation by mobile manipulators under the guidance of a human operator.

interacting with human and in contact with environment that has high stiffness.

However, parameters need to be tuned for different interaction environments. Using parameters tuned for hard environment, larger efforts are required from the human operator and robot reaction might be sluggish when interacting with softer environment. On the other hand, using parameters tuned for soft environment might cause the controller to lose stability when interacting with harder environment.

From the system setup and algorithm implementation perspective, position error in Y direction during the transportation experiment reflects the necessity of accurate pose calibration of the multiple mobile manipulators. A system accuracy verification mechanism could be designed by commanding the robot to touch certain points of a fixture, and only calibrate the system when the error is out of the allowable range. Moreover, since motion feedback of each mobile platform was purely from its odometry, the accumulated drift error could be significant over a long traveling distance, especially in a dusty construction environment, leading to large internal stress on the manipulated object and potentially causing instability. To improve mobile base localization, the vision techniques that have been introduced in Chapter 3 and Chapter 4 could be integrated. Another option is to mount one more Force/Torque sensor, so that internal admittance control could be developed. The robot motion deviation could be inferred from the stress on the manipulated object, and could be compensated by manipulator or platform motions.

6.5 Conclusion

In this chapter, object-level admittance control has been applied to a robot system comprising two mobile manipulators. The inverse kinematics for each mobile manipulator has been formulated as a convex optimization problem and solved with quadratic programming (QP). Human-robot cooperative window frame transportation and installation tasks have been conducted to demonstrate the capability of the control strategy, which to the author's knowledge, is the first successful demonstration of a practical application that presents interaction of multiple mobile robots

with both humans and the environment.

Looking forward from the current development, there are several interesting aspects to be studied in the future. The primary target would be to improve the control stability for tasks that involve a wide range of material stiffness, and the recently developed Convex Controller Synthesis is promising given its superior performance as demonstrated in [154] and [155]. Apart from external admittance control, internal admittance control could also be considered to avoid excessive stress on the manipulated object. Redundancy of the system could be exploited and integrated into the control framework to improve system performance, such as obstacle avoidance, manipulability maximization and so on. Costs for the mobile-based multi-robot system could be expensive if it is only applied to the stand-alone object transportation and manipulation application. However, such a compact modular-configurable robot system can be employed for many tasks in multiple sections in the Building and Construction industry, such as 3D printing, robotic tiling, wall spraying and painting, and many more. Therefore the system is economically beneficial given its general applicability. This is even more significant when considering outer space exploration, in which a huge amount of resources would be demanded if we need to transport different types of machines for different tasks.

Chapter 7

Conclusion

7.1 Summary

Considered to be cheaper, less labor-intensive, more efficient and more environmental-friendly compared to conventional construction methods, 3D concrete printing has been gaining ground in B&C industry in recent years. A wealth of achievements have been published academically or released commercially, and some have received widespread media attention. Despite these welcoming accomplishments, to date there has not been any mature technique that could practically print a full-sized large-scale building, not to mention any system that is able to demonstrate a fully automated construction pipeline, including printing, spraying, plumbing, tiling, and others. Targeting at resolving these challenges, this thesis has presented a large-scale 3D printing framework with four main contributions. The first one is the proposal of a multi-robot printing system that is capable of on-site printing large structures in a safe, efficient and scalable manner. The second one supplements the proposed multi-robot printing system with the proposed *printing-while-moving* paradigm by leveraging the mobility of the printers. Having established the structure of the printing system, the following two studies that are closely associated with the printing and construction process in practice are presented. As the third contribution, motion planning algorithms for tethered mobile robots have been developed so that the robots carrying the material delivery hoses can move to their respective target locations efficiently while avoiding tether

entanglement. For the forth contribution, admittance control of multiple mobile manipulators working in cooperation with humans has been investigated. All of the aforementioned contributions have been successfully validated with hardware experiments.

Looking closely at the road-map of the development of 3D concrete printing techniques, although gantry-based printer is still in the majority, one can observe the trend of adopting articulated arm based robot in the printing system, which brings more flexibility and enables full 3D printing profile. However, none of the works has touched on the essence of the scalability problem, which remains a major hurdle to the widespread adoption of 3D printing in B&C. It should be well recognized that purely mechanically enlarging the printer to increase the printing volume is dead-end. With a view to overcoming the scalability issue, the multi-robot printing system presented in Chapter 3 enlightens a new direction of large-scale 3D concrete printing. Each robot printer is comprised of a 6-DoF robot arm mounted on top of a mobile platform. The proposed system configuration contains several modules: planning of robot placement to optimize workspace, mobile robot navigation and localization to reach target printing location, and planning of manipulator trajectory to deposit material accurately on desired path. Given the successful proof-of-concept demonstration of two mobile robot printers working concurrently on one structure whose size is twice the printing volume of one single printer, such a system can potentially print single-piece structures of *arbitrary sizes*, depending on the number of deployed robots.

Some works have touched on incorporating mobility into the printing systems to extend the printing range [13,29], but the literature has stuck only at an infant stage where the printing is performed with a stationary base and the mobile platform serves mainly as a transportation vehicle for the printer. The major obstacle that impedes the progress would be accurate printing control while the printer is moving. The motions of the robot manipulator and the mobile platform must be carefully planned and coordinated. In addition, precise robot localization and feedback motion control are necessary to ensure that the nozzle deposits concrete at the right place and with the right speed, such that the layer-by-layer built-up structure would not collapse due to nozzle position offsets. These challenges have been addressed

in Chapter 4, where the *printing-while-moving* paradigm has been realized in a demonstration of the actual printing of a single-piece concrete structure by a mobile robot printer, for the first time in the literature. The size of the structure is 210 cm $\times$ 45 cm $\times$ 10 cm (length, width, height), which is larger than the reach of the robot arm (87 cm).

In applications like concrete 3D printing, hoses are indispensable to deliver material from the mixer to the print nozzle during the printing process. It is crucial to make sure that the target printing plan is feasible (not deadlocked) provided limited hose lengths, and avoid hose entanglement in order to ensure smooth printing when the printers move around. In Chapter 5, the motion planning problem for multiple tethered planar (point) mobile robots has been considered. Motion planning algorithms for the robots to achieve a given target cable configuration by straight-line and concurrent (**Straight/Concurrent**) motions have been presented. The algorithms (i) identify whether the target cable configuration was deadlocked; (ii) return a valid coordinated motion plan accordingly. The proposed algorithms have been validated in both simulations and hardware experiments: it was shown that, using the proposed algorithms, the tethered robots could achieve a target cable configuration that involved a deadlock situation for **Straight/Sequential** motions, and that could not be solved by algorithms previously proposed in the literature.

There are many occasions in B&C industry when large object manipulation and heavy payload transportation are performed that requires corporation of multiple robots. A demonstration has been provided in Chapter 6 where two mobile manipulators smoothly transport and install an aluminium window frame into a 3D printed concrete wall under the guidance of a human operator. Admittance control of multiple mobile manipulators has been implemented so as to avoid damage to the manipulated object when interacting with the environment and ensure human safety when working with the robots.

In the era of the fourth industrial revolution, known as Industry 4.0, 3D concrete printing has been considered as a key driver towards the digitalization of B&C industry [25]. The 3D printing framework presented in this thesis could advance and foster adaptable and versatile building strategies in the emerging field of applying

concrete 3D printing technology in B&C industry. Comparing to existing 3D concrete printing techniques, experimental results suggest that the proposed system is superior in its greater practical scalability and higher time efficiency due to the employment of multiple robot printers, as well as better on-site printing capability credited with mobility of the system. These advantages make the proposed system promising to be scaled up for on-site large-scale printing applications in B&C industry. Another striking benefit of the proposed printing system is the system configuration. From the literature, the configuration of our proposed robotic system – mobile-based robotic manipulators, is proved to be versatile and can easily be adapted to various applications in B&C industry, such as tiling, grinding, welding, manipulation and many more. Indeed, we have seen in Chapter 6 about the object manipulation and transportation with the proposed system. Furthermore, using a fleet of mobile robots for construction could have an extreme potential in other non-conventional aspects. One such application is to allow automated construction in hard-to-reach, remote areas, such as underground caves, the Moon or Mars [134], to which it is inconvenient or even impossible to bring other kinds of machine required for existing concrete printing methods.

7.2 Future work

Moving forward from the proposed system, there are still a number of challenges along the way towards complete automation of 3D printing in B&C industry. Some interesting and important directions for future research are sketched in this section.

In this thesis, to expedite development iteration and verify the concept of mobile-based multi-robot printing system, all the studies are based on immediately available resources in the author’s research lab, for example, the planar mobile platforms, 6-DoF position-controlled robots, 2-fingered grippers and one Force/-Torque sensor. While some exciting proof-of-concept demonstrations have been successfully presented, experiments at the current stage are conducted in the lab environment. The mechanisms of some hardware components need further revision when being commercialized and deployed in the construction site, and wheel design of the mobile platform is a major one. The traditional Mecanum wheels of

the current printer platform are not designed for rough or soft deformable terrains, which are common in the construction environment. Many interesting mechanisms of mobile robots have been proposed for these terrain conditions, including wheeled [133, 156, 157], tracked [158, 159], rover [160–162] and so on, each with its own control method and characteristics. Investigation on a wheel and chassis design that can support heavy load, be easily controlled, and navigate across challenging terrains is an important branch of the future work road map. Another useful addition to the printing system is the lifting mechanism. Printing scalability in x and y directions has been addressed by the proposed multi-robot mobile printers, but the maximal printing height is still constrained by the limited reach of the robot arm. This can be solved by integrating a lifting platform to the system, which coupled with a large robot arm is sufficient in printing practically high structure. Modifications are to be made to certain blocks of the proposed algorithms to adapt to different system configurations. However, the overall framework presented in this thesis is not heavily reliant on the hardware structure, and can hold as long as the system is fundamentally multi-robot mobile based printers.

With the successful experimental demonstration of the proposed multi-robot printing system and printing-while-moving paradigm, an immediate future plan could be to integrate the overall system to boost automation to a greater extent. On account of the integration of *printing-on-arrival* and *printing-while-moving*, study can be carried out to investigate trade-off between workspace size covered by each single mobile robot printer and inter-layer strength of 3D printed concrete. In addition, bonding strategies at the interface of two separate concrete prints would be carried out to identify the optimal method of joining, which could be face-to-face joint or finger joints. Such methods would seek to reduce the degree of material overlapping that could adversely affect part appearance while maximizing interface area for stronger bond.

A technical concern of the proposed system is the complexity in coordinating such a fleet of mobile robots. Although the thesis has demonstrated that this difficulty can be significantly mitigated by utilizing standard robotic techniques, distributed system control is worthy of exploring. Comparing to the centralized control of the multi-robot system, a distributed one is potentially more robust and

error-resilient. Some impressive examples of decentralized multi-agent system for automated construction have been presented in [163, 164], where complex structures have been built by robots coordinating their activity via the shared environment using only local sensing. Such a system control scheme could be extremely useful, especially in the aforementioned scenarios like construction on the Moon or Mars [134], where supervision of the construction is expensive or impossible. Harsher challenges are to be expected when generalizing the distributed control strategies to concrete 3D printing tasks, as the continuous printing process essentially poses more constraints than the discrete construction tasks.

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