Bachelor Thesis

Motion Planning for Reconfigurable Magnetic Modular Cubes in the 2-Dimensional Special Euclidean Group

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Statement of Originality

This thesis has been performed independently with the support of my supervisor/s. To the best of the author's knowledge, this thesis contains no material previously published or written by another person except where due reference is made in the text.

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Aufgabenstellung / Task Description

Deutsch: Um spezifische Aufgaben besser zu bewältigen, lassen sich modulare, rekonfigurierbare Roboter zu größeren Strukturen zusammensetzen und wieder auseinandernehmen. Magnetic-modular-cubes sind skalierbare Einheiten, bei welchen Permanentmagneten in einen würfelförmigen Körper eingebettet sind. Diese Einheiten zählen als rekonfigurierbare Roboter, obwohl sie selber keine Logik oder Stromversorgung beinhalten. Stattdessen lassen sich diese durch ein externes, gleichmäßiges und sich zeitlich änderndes Magnetfeld steuern. Durch diese Steuerung können die magnetic-cubes auf der Stelle gedreht oder durch pivot-walking nach rechts und links bewegt werden. Obwohl sich das Magnetfeld auf alle Einheiten gleichermaßen auswirkt, kann durch Kollision mit der Arbeitsflächenbegrenzung eine Änderung der Anordnung bewirkt werden. Befinden sich zwei magnetic-cubes nah genug beieinander können sich diese durch die Permanentmagneten miteinander verbinden und so Polyominos als größere Strukturen aufbauen, welche auf die gleiche Weise wie einzelne cubes gesteuert werden können. Frühere Arbeiten betrachteten das "tilt-model", bei welchem sich Strukturen jeder Größe mit gleicher Geschwindigkeit in ganzzahligen Schritten und mit ausschließen 90° Drehungen bewegen lassen.

Herr Keunes Aufgabe in dieser Bachelorarbeit ist es, einen motion-planner für die beschriebenen magnetic-cubes zu entwerfen, welcher mit beliebigen Positionen und Rotationen umgehen kann. Dabei ist es erforderlich, eine Simulationsumgebung zu schaffen, welche das Verhalten der magnetic-cubes repliziert. Es soll ein lokaler motion-planner entwickelt werden, um zwei Polyominos an gewünschten Kanten zu verbinden. Dieser local-planner soll Heuristiken und optimale Bewegungsabläufe mit möglichst wenig Schritten realisieren. Ebenfalls soll dieser global eingesetzt werden, um Bewegungsabläufe zu finden, die gewünschte Polyominos aus einer zufällig gegebenen Startkonfiguration erzeugen. Ein interessantes Ergebnis wird es sein, zu sehen, wie gut Probleminstanzen dieser Art in der Realität gelöst werden können und welche Parameter die gravierendsten Auswirkungen auf die Schwierigkeit von motion-planning Problemen haben.

English: Reconfigurable modular robots can dynamically assemble/disassemble to better accomplish a desired task. Magnetic modular cubes are scalable modular subunits with embedded permanent magnets in a 3D-printed cubic body. These cubes can act as reconfigurable modular robots, even though they contain no power, actuation or computing. Instead, these cubes can be wirelessly controlled by an external, uniform, time-varying magnetic field. This control allows the cubes to spin in place or pivot walk to the left or right direction. Although the applied magnetic field is the same for each magnetic modular cube, collisions with workspace boundaries can be used to rearrange the cubes. Moreover, the cubes magnetically self-assemble when brought in close proximity of another cube, and form polyominoes, which can be controlled the same way as single cubes. Related work has considered the "tilt model," where similar cubes and polyominoes move between integer positions, all move at the same speed, and only rotate by 90 degree steps.

In his thesis, Mr. Keune's task is to design a motion planner for magnetic cubes that can assume arbitrary positions and orientations in the workspace. This requires designing a simulation environment that replicates the behavior of magnetic cubes. He will design local planners for moving two polyominoes to assemble at desired faces. Designing the local planner includes heuristics and computing optimal motion plans that minimize the number of steps. The local planner will be used to search for global planning sequences to generate desired polyominoes from a given starting configuration. One exciting outcome will be studying how well instances can be solved in practice and analyzing which parameters have the most significant effect on the difficulty of the motion planning problem.

Abstract

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Contents

1 Introduction

Self-assembling modular parts forming bigger structures is a well-known concept in nature and most functionalities of living organisms follow this principle [5]. DNA for example has the ability to self-replicate by using differently shaped proteins, that combine themselves in various ways. If you zoom out, these cells can by combined to assemble things like tissue, organs and even whole organisms. Complex structures can be assembled and disassembled depending on the task they should accomplish during a given point in time. Using self-reconfiguring robot swarms in such a way, has promising applications in the future. Biomedical applications could be targeted drug delivery or drug screening [15], or a robot swarm could be used for milliscale and microscale manufacturing [12].

Designing robots at these small scales faces challenging problems. Equipping each robot with its own sensors, actuation-system, connection-system and power supply seem very infeasible, in terms of the sheer size and power-limitations [16]. Therefore, the use of external global control, effecting every robot uniformly, is a promising solution [16]. Using robots with embedded permanent magnets, has all the desired effects. Robots can be controlled by an external magnetic field and also connect to each other without any internal power supply and for sensing an external camera can be used [13].

One example for magnetically controlled robots are the magnetic modular cubes by Bhattacharjee et al. [4], which are the subjects of this thesis. We will develop a simulation that simulates the behavior of magnetic modular cubes, without assuming discrete movement or limiting rotations to a certain amount. The simulation will be used for developing closed-loop planing algorithms, which provide a control sequence to assemble desired target shapes. For that it is necessary to develop a local planner that is able to connect structures at desired faces. We will look at the difficulties and problems that occur, when working with magnetic modular cubes in the 2-dimensional special euclidean group $SE(2)$, the space of rigid movements in a 2-dimensional plane.

1.1 Related Work

Continues motion planning is a crucial subject in the field of robotics. The goal is to find a path from the initial state of a robot to a desired goal state, by performing actions which the robot is capable of. For that it is necessary to avoid collision with static obstacles and with other robots. The state of the system is also called a configuration. All possible configurations one or multiple robots can be in is defined as the configuration-space. The dimension of the configuration-space gains rapidly in complexity by increasing the number of robots and possible actions. It is difficult to engineer algorithms that explore these huge configuration-spaces and provide a sequence of actions that lead to the goal configuration, or report failure, if the goal is not reachable. A lot of research was done on motion planning and the textbooks [6] and [10] offer a great overview and also explain a lot of important concepts in detail.

When working with configuration-spaces that are uncountable infinite, like the special Euclidean group, one of these concepts is sample-based motion planning. By taking samples, you can reduce the configuration space to a finite object, but you might lose possible solutions. Algorithms like that are not complete anymore, but by using a good sampling technique you can get arbitrarily close to any point, and therefore these algorithms can be called resolution complete. Ways of sampling include random sampling or using a grid with a resolution that is dynamically adjustable. After sampling, conventional discrete planning algorithms can be applied [6].

One state-of-the-art sampling-based approach are algorithms that use rapidly-exploring random trees (RRT). This method tries to grow a tree-shaped graph in the configuration space by moving into the direction of randomly chosen samples from already explored configuration. That way the space gets explored uniformly without being too fixated on the goal configuration [7, 8].

When working with multiple robots, the interaction of robots with each other becomes important. One interesting idea is that single robots can connect to form bigger structures. This is referred to as self-assembly and E. Winfree [17] proposed the abstract Tile Assembly Model (aTAM) in the context of assembling DNA. In this model, particles can have different sets of glues and connect according to certain rules regarding the glue type. However, he considers this process as nondeterministic, so there is no exact instruction on how to assemble a desired structure.

One model more related to the magnetic modular cubes used in this thesis is the Tilt model from Becker et al. [1]. In the Tilt model, all tiles move into one of the cardinal directions until hitting an obstacle. Different variations of the model include moving everything only one step, or the maximally possible amount. It offers a solution when robots are controlled uniformly by external global control inputs. In this paper it is shown that transforming one configuration into another, known as the reconfiguration-problem, is NP-hard. Following work [2] also proves that finding an optimal control sequence, minimizing the number of actions, for the configuration-problem is PSPACE-complete. Furthermore, research is done on designing environments in which the Tilt model can be used to accomplish certain tasks. In particular, Becker et al. [2] create connected logic gates that can evaluate logical expressions.

More on the side of self-assembly, in [3] the construction of desired shapes using the tilt model is researched. It presents a method that can determine a building sequence for a polyomino by adding one tile at a time, considering the rules of Tilt. Which is also examined are ways of modifying the environment to create factories that construct shapes in a pipeline by repeating the same global control inputs. Shapes can be constructed more efficiently by combining multi-tiled shapes to an even bigger structure. One article considering the construction with so called sub-assemblies is proposed by A. Schmidt [14].

Most recently, Bhattacharjee et al. [4] developed the magnetic modular cubes. These robots contain embedded permanent magnets and have no computation or power supply. Instead, they are controlled by an external time-varying magnetic field and are able to perform various actions. Most importantly, they can rotate in place or use a technique called pivot walking to move either left or right. The magnets also act as glues and allow the cubes to perform self-assembly. Although it is theoretically possible to assemble 3-dimensional structures, most research was done by only connecting cubes in two dimensions. Since all cubes are the same size, the assembled 2-dimensional shapes can be represented as polyominoes. An enumeration was done on the amount of possible polyominoes that can be created by cubes with different magnet configurations [9].

By limiting the controls to only 90 degree turns and assuming a uniform pivot walking distance for all structures per step, magnetic modular cubes follow rules similar to the Tilt model. Following these limitations, a simple discrete motion planer was developed, that explores a finite configuration-space and lists all the possible polyominoes that can be created from an initial configuration [4]. One interesting paper from Blumenberg et al. [11] explores the assembly of polyominoes in arbitrary environments, when cubes obey the tilt model. He provides different algorithmic approaches using various distance heuristics and even a solution making use of RRTs. For that he follows the rules of Tilt in a discrete setting.

1.2 Contribution

2 Preliminaries

Bibliography

[1] A. Becker, E. D. Demaine, S. P. Fekete, G. Habibi, and J. McLurkin. Reconfiguring massive particle swarms with limited, global control. In P. Flocchini, J. Gao, E. Kranakis, and F. Meyer auf der Heide, editors, *Algorithms for Sensor Systems*, pages 51–66, Berlin, Heidelberg, 2014. Springer Berlin Heidelberg.

[2] A. Becker, E. D. Demaine, S. P. Fekete, and J. McLurkin. Particle computation: Designing worlds to control robot swarms with only global signals. In *2014 IEEE International Conference on Robotics and Automation (ICRA)*, pages 6751–6756, 2014.

[3] A. T. Becker, S. P. Fekete, P. Keldenich, D. Krupke, C. Rieck, C. Scheffer, and A. Schmidt. Tilt assembly: Algorithms for micro-factories that build objects with uniform external forces. *Algorithmica*, 82(2):165–187, Feb 2020.

[4] A. Bhattacharjee, Y. Lu, A. T. Becker, and M. Kim. Magnetically controlled modular cubes with reconfigurable self-assembly and disassembly. *IEEE Transactions on Robotics*, 38(3):1793–1805, 2022.

[5] J. Bishop, S. Burden, E. Klavins, R. Kreisberg, W. Malone, N. Napp, and T. Nguyen. Programmable parts: A demonstration of the grammatical approach to self-organization. In *2005 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 3684–3691. IEEE, 2005.

[6] S. M. LaValle. *Planning Algorithms*. Cambridge University Press, Cambridge, U.K., 2006. Available at http://planning.cs.uiuc.edu/.

[7] S. M. LaValle et al. Rapidly-exploring random trees: A new tool for path planning. 1998.

[8] S. M. LaValle and J. J. Kuffner. Rapidly-exploring random trees: Progress and prospects: Steven m. lavalle, iowa state university, a james j. kuffner, jr., university of tokyo, tokyo, japan. *Algorithmic and computational robotics*, pages 303–307, 2001.

[9] Y. Lu, A. Bhattacharjee, D. Biediger, M. Kim, and A. T. Becker. Enumeration of polyominoes and polycubes composed of magnetic cubes. In *2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 6977–6982, 2021.

[10] A. Mueller. Modern robotics: Mechanics, planning, and control [bookshelf]. *IEEE Control Systems Magazine*, 39(6):100–102, 2019.

[11] A. T. B. Patrick Blumenberg, Arne Schmidt. Computing motion plans for assembling particles with global control. In *Under Review*. IEEE, 2023.

[12] R. Pelrine, A. Wong-Foy, A. Hsu, and B. McCoy. Self-assembly of milli-scale robotic manipulators: A path to highly adaptive, robust automation systems. In *2016 International Conference on Manipulation, Automation and Robotics at Small Scales (MARSS)*, pages 1–6. IEEE, 2016.

[13] W. Saab, P. Racioppo, and P. Ben-Tzvi. A review of coupling mechanism designs for modular reconfigurable robots. *Robotica*, 37(2):378–403, 2019.

[14] A. Schmidt, S. Manzoor, L. Huang, A. T. Becker, and S. P. Fekete. Efficient parallel self-assembly under uniform control inputs. *IEEE Robotics and Automation Letters*, 3(4):3521–3528, 2018.

[15] M. Sitti, H. Ceylan, W. Hu, J. Giltinan, M. Turan, S. Yim, and E. Diller. Biomedical applications of untethered mobile milli/microrobots. *Proceedings of the IEEE*, 103(2):205–224, 2015.

[16] P. J. White and M. Yim. Scalable modular self-reconfigurable robots using external actuation. In *2007 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 2773–2778. IEEE, 2007.

[17] E. Winfree. *Algorithmic self-assembly of DNA*. California Institute of Technology, 1998.