Bachelor Thesis

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

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February 28, 2023

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.

Braunschweig, February 28, 2023

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 die kinetischen und dynamischen Eigenschaften 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 kinematics and dynamics 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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1 Introduction

Motivation, applications...

1.1 Related Work

Motion planning is a crucial subject in the field of robotics. The goal is to change the initial state of a robot to a desired goal state, by performing actions which the robot is capable of. The state of the system is also called a configuration and all possible configurations a robot 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 static obstacles. It becomes necessary to avoid collision between those. It is difficult to engineer algorithms that explore these huge configuration-spaces and provide a sequence of actions to perform to reach the goal configuration or report failure, if the configuration is not reachable. A lot of research was done on motion planning and the textbooks [4] and [7] offer a great overview and also explain a lot of important concepts in detail.

One of these concepts is sample-based motion planing. When working with configuration spaces that are uncountable infinite, like the special euclidean group, it is not only impossible to cover the howl space, it is also unclear how to traverse it. 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 [4].

One state of the art sample-based approach are algorithms that use rapidly-exploring random trees (RRT). This method tries to move into the direction of a randomly chosen sample from the nearest already explored configuration, that way the space gets explored uniformly without being too fixated on the goal configuration [5, 6].

When working with multiple robots, the question of how these interact with each other comes to mind. One interesting idea is that single robots can connect to form bigger structures. This is referred to as self-assembly and E. Winfree [9] 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 here used magnetic modular cubes is the Tilt model from Becker et al. [1]. In the Tilt model, all tiles move either one step or the maximum amount, until hitting an obstacle, into one of the cardinal directions. 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 configuration-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. create logic gates that can be connected and 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. Ways of modifying the environment to create factories, that are able to construct shapes in a pipeline by repeating the same global control sequence, are also examined. Shapes can not only be constructed by adding one tile at a time. Two multi-tiled shapes can connect to an even bigger structure. One article considering the construction with so called sub-assemblies is proposed by A. Schmidt [8].

1.2 Contribution

2 Preliminaries

2.1 Metrics

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