INSTITUTO TECNOLÓGICO DE AERONÁUTICA

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MULTI-AGENT GRAPH EXPLORATION WITHOUT COMMUNICATION

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MULTI-AGENT GRAPH EXPLORATION WITHOUT COMMUNICATION

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*"If I have seen farther than others,
it is because I stood on the shoulders of giants."*
— Sir Isaac Newton

Resumo

Aqui começa o resumo do referido trabalho. Não tenho a menor idéia do que colocar aqui. Sendo assim, vou inventar. Lá vai: Este trabalho apresenta uma metodologia de controle de posição das juntas passivas de um manipulador subatuado de uma maneira subótima. O termo subatuado se refere ao fato de que nem todas as juntas ou graus de liberdade do sistema são equipados com atuadores, o que ocorre na prática devido a falhas ou como resultado de projeto. As juntas passivas de manipuladores desse tipo são indiretamente controladas pelo movimento das juntas ativas usando as características de acoplamento da dinâmica de manipuladores. A utilização de redundância de atuação das juntas ativas permite a minimização de alguns critérios, como consumo de energia, por exemplo. Apesar da estrutura cinemática de manipuladores subatuados ser idêntica a do totalmente atuado, em geral suas caraterísticas dinâmicas diferem devido a presença de juntas passivas. Assim, apresentamos a modelagem dinâmica de um manipulador subatuado e o conceito de índice de acoplamento. Este índice é utilizado na sequência de controle ótimo do manipulador. A hipótese de que o número de juntas ativas seja maior que o número de passivas ($n_a > n_p$) permite o controle ótimo das juntas passivas, uma vez que na etapa de controle destas há mais entradas (torques nos atuadores das juntas ativas), que elementos a controlar (posição das juntas passivas).

Abstract

Well, the book is on the table. This work presents a control methodologie for the position of the passive joints of an underactuated manipulator in a suboptimal way. The term underactuated refers to the fact that not all the joints or degrees of freedom of the system are equipped with actuators, which occurs in practice due to failures or as design result. The passive joints of manipulators like this are indirectly controlled by the motion of the active joints using the dynamic coupling characteristics. The utilization of actuation redundancy of the active joints allows the minimization of some criteria, like energy consumption, for example. Although the kinematic structure of an underactuated manipulator is identical to that of a similar fully actuated one, in general their dynamic characteristics are different due to the presence of passive joints. Thus, we present the dynamic modelling of an underactuated manipulator and the concept of coulpling index. This index is used in the sequence of the optimal control of the manipulator.

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List of Abbreviations and Acronyms

CTq	computed torque
DC	direct current
EAR	Equação Algébrica de Riccati
GDL	graus de liberdade
ISR	interrupção de serviço e rotina
LMI	linear matrices inequalities
MIMO	multiple input multiple output
PD	proporcional derivativo
PID	proporcional integrativo derivativo
PTP	point to point
UARMII	Underactuated Robot Manipulator II
VSC	variable structure control

List of Symbols

a	Distância
$\mathbf{a}$	Vetor de distâncias
$\mathbf{e}_j$	Vetor unitário de dimensão n e com o j-ésimo componente igual a 1
$\mathbf{K}$	Matriz de rigidez
m_1	Massa do cumpim
δ_{k-k_f}	Delta de Kronecker no instante k_f

Contents

1 Introduction

This graduation work aims to discuss the main maze exploration algorithms and then propose a method where multi-agents must find the maze solution without any type of communication, only working with probability distributions to guide their behaviors. The main challenge of this research is to find a distributed exploration approach with total communication restriction since an agent's partial knowledge cannot be shared with another agent and, at the same time, a single agent must avoid repeating a branch of another agent. The proposed maze structure abstraction is a traditional regular grid that can be generalized into graphs.

This report is the initial part of the bachelor's thesis, and this chapter intends to introduce the general concept of the related thesis and present the motivation (Section 1.1), the related work (Section 1.2), and the main definitions about maze-solving algorithms (Section 1.3).

1.1 Motivation

Graph exploration has been the target of studies since Leonhard Euler proved that Seven Bridges of Königsberg (SHIELDS, 2012) has no solution. It has been researched not only in academia but also in the industry due to several practical applications, like airline scheduling, planning path on maps, search engine algorithms, social media marketing, Internet routing protocols, and robotics.

Specifically in robotics, graph exploration can be used to explore a maze with a single agent through a bunch of traditional algorithms: random mouse, wall follower, Trémaux, etc (SADIK et al., 2010). And it can be useful to guide many real-life problems such as search in nuclear plant disasters, burning buildings, and extraterrestrial environments. In these previous examples, the multi-agent exploration is more interesting than the single-agent approach since it can speed up the exploration. Recent studies have explored multi-agent maze-solving algorithms as seen in the Multi-Agent Maze Exploration paper (KIVELEVITCH; COHEN, 2010), where authors proposed a Tarry's algorithm generalization. It is important to emphasize that maze-solving algorithms consider that the structure is unknown, and then traditional search algorithms, such as Dijkstra and A*, cannot be used to solve the maze.

Traditional multi-agent maze exploration approaches is based on internal communication between agents, where each agent knows about visited cells by another agent. It avoids a second exploration in a useless path and thus it decreases computational costs. However, there are some real situations where communication is limited or impossible, such as deep sea exploration, search in large wall structures, or search with low energy-based autonomous agents.

However, the incommunicable approach between agents have not been concretely found in the literature despite it may have real applications and may guide search plans in real-world problems. In order to explore it, this work presents some ways to achieve the solution of a maze based on agents without communication, that might be generalized to graph exploration algorithms.

1.2 Related work

Multi-agent cooperative system approaches are common in literature, especially when it comes from robotics researches. In the context of communicable agents, mainly in robotics, this chapter presents some related works.

Matarić (1995) established common properties across different scenarios of mobile multi-agent interactions, such as dispersion - “the ability of a group of agents to spread out in order to establish and maintain some minimum interagent distance” -, aggregation - “the ability of a group of agents to gather in order to establish and maintain some maximum interagent distance” -, homing - “the ability of an agent to find a particular region or location” -, etc. The author proposes a synthetic structure in order to abstract different types of interagent basis behaviors.

Burgard et al. (2005) pointed out that an exploration group of robots takes several advantages over single agent exploration, despite a coordinating group might introduce redundancy. The authors present an algorithm to efficiently explore an environment by mobile and autonomous robots within a communication range.

Sadik et al. (2010) presents, as seen in the title of the paper, a comprehensive and comparative study of maze-solving algorithms techniques by implementing graph theory. The research is delimited in the “Micromouse competition” context, which is a famous maze competition that has been performed worldwide since late 1970s. The authors compared maze-solving methods based on graph theory algorithms, such as DFS (Depth First Search) and BFS (Breath First Search) flood-fill, to common algorithms in the

"Micromouse" context, such as Wall Follower. They concluded that, despite graph theory algorithms demands higher computational complexity, they are more proficient compared to non-graph theory methods.

Based around maze-solving algorithms, Kivelevitch & Cohen (2010) proposed a generalization of Tarry's algorithm, but the new approach is that all visited cells of the maze are known by each agent, since each agent shares its knowledge with all the others. In that sense, each one holds an dynamic map of the maze excluding redundant information, allowing information sharing. The authors presents in the article the performance of the proposed solution, where a group of virtual coordinate agents is required to find the goal without an a-priori knowledge of the maze, so-called "maze exploration".

Beisel (2014), similarly to aforementioned, worked in simulation and mathematical analysis for strategies related to cooperative autonomous robots, that can share messages with each other. The author concluded that a cooperative approach might result in significant performance improvements.

1.3 Definitions

Mainly considering these previous references, this chapter intends to define common terms about maze-solving algorithms, graph theory, and mathematical tools that were useful to abstract the proposed solution. Furthermore, it intends to clarify the approach domain of this work.

1.3.1 Graph

In the context of computer science, a graph is a abstract data type that can be represented topologically as a interconnected node network. Several computational problems are discussed in terms of graphs.

It is worth to mention that there is a subdomain of graph data type called tree. A tree is also a abstract data type, which can be represented topologically as a hierarchical structure of nodes. In fact, a tree is a subset of graph theory, therefore a tree is a graph under a different perspective. In Section 2.1, a tree topology perspective of a maze will be explored.

1.3.2 Maze

This report define a maze at the same perspective presented in Kivelevitch & Cohen (2010). A maze is a n-dimensional gridded space of any size, usually rectangular. The gridded space is composed by a set of cells, while a cell is the elementary item of a maze, defined as a delimited n-dimensional space. Cells might be connected or not connected to another adjacent cell, separated by a "wall" in the latter case. Without losing generality, as will be presented in Section 2.1, this work considered a maze, for simulation purposes, as a two-dimensional gridded space composed by two-dimensional bounded cells.

Thus, from the above definition, a graph or a tree are good candidates to abstract a maze, which might be described as a interrelated nodes (cells) network.

1.3.3 Agent

As defined in Kivelevitch & Cohen (2010), an agent is an autonomous entity that can traverse the maze obeying the interrelation of the cells.

In a maze context, a multi-agent approach describes the coordinating behavior of several autonomous agents.

1.3.4 Maze-solving algorithms

A maze has a goal to be achieved, which is usually a single marked cell or a path for an agent to exit the maze. Since the last century, many scholars have been studied algorithms to solve the maze computationally, and the proposed solutions are so-called "maze-solving algorithms".

1.3.5 Mixed Radix

Mixed radix is a numerical representation that does not rely on standard positional numeral systems. In a traditional numerical system, there is not a base variation through the numbers, nevertheless, in a mixed radix representation, a number is represented by a sequence of numerals in different bases, where each numeral is a multiple of the previous numerical sequence, however relied on a different base.

For example, Arndt (2011) establishes a arithmetical method to manipulate a specific subset of mixed radix numbers. The mixed radix representation $A = [a_0, a_1, a_2, ..., a_{n-1}]$ of a number x with respect to a radix vector $M = [m_0, m_1, m_2, ..., m_{n-1}]$ is given by:

$$x = \sum_{k=0}^{n-1} a_k \prod_{j=0}^{k-1} m_j \qquad (1.1)$$

where $0 \leq a_j < m_j$ (and $0 \leq x < \prod_{j=0}^{n-1} m_j$, so that n digits suffice). In a traditional positional numerical system, the vector M is like $M = [r, r, r, ..., r]$, and then the relation is simply given by:

$$x = \sum_{k=0}^{n-1} a_k r^k \tag{1.2}$$

Despite the aforementioned representation, this work presents a slightly different approach in Section 2.2.

2 Models

2.1 Maze from a graph topology perspective

For simulation purposes, this work modeled a maze under an interrelated cells perspective, where each cell is a square with its edges composed by a wall or not. If there is a wall, an agent cannot traverse the maze across the related edge. On the other hand, if there is not a wall, an agent has a free way to traverse the maze through the related edge. It is worth to mention that, if an edge has a wall, the edge of the adjacent corresponding cell also has necessarily a wall.

The maze has a goal that is a single marked cell, and an agent inside the maze aims to find the marked cell, traversing the maze cell by cell. This agent is an autonomous entity that follows a specific algorithm according the current explored path and its programmed initial rules. So that it doesn't go through the same path more than one time, it stores the visited cells. Thus, every time the agent find a branched cell (a cell with at least one edge without a wall), it ignores the already visited branches by itself, and, if there is not a candidate to be a possible branch, the agent go back to the previous visited cell. Furthermore, specifically to this research, differently from some approaches presented in Beisel (2014), Burgard et al. (2005), and Kivelevitch & Cohen (2010), there is no intercommunication between agents in a multi-agent situation to solve the maze.

Given that an agent ignores visited cells, there is one important point related to this work: if there is only one path to the goal from the agent's initial cell, it is valid to consider a maze as a tree. However, if there is more than one path to the goal from the agent's initial cell, the maze cannot be considered as a tree, but it might be considered as a graph.

Muhammad (2021)

imagem de um agente percorrendo o labirinto

2.2 Mixed radix representation of the agent path

3 Results

RESULTS

4 Next steps

NEXT STEPS

Bibliography

Arndt, J. (2011). **Mixed radix numbers.** In: Matters Computational. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-14764-7$_9$

Beisel, B. W. (2014). **Distributed Maze Solving By Cooperative Robotic Platforms.** University of Maryland, Department of Electrical and Computer Engineering.

Burgard, W., Moors, M., Stachniss, C., Schneider, F. E. (2005). **Coordinated multi-robot exploration.** IEEE Transactions on Robotics, 21(3), 376-386. doi:10.1109/tro.2004.839232

Cormen, Thomas H., Leiserson, Charles E., Rivest, Ronald L. and Stein, Clifford. **Introduction to Algorithms.** 4th : The MIT Press, 2022.

Kivelevitch, Elad & Cohen, Kelly. (2010). **Multi-Agent Maze Exploration.** Journal of Aerospace Computing Information and Communication. 7. 391-405. 10.2514/1.46304.

Matarić, M. J. (1995). **Designing and Understanding Adaptive Group Behavior.** Adaptive Behavior, 4(1), 51-80. doi:10.1177/105971239500400104

Muhammad Ahsan Naeem. **pyamaze**. GitHub, 2021. Available at: <https://www.github.com/MAN1986/pyamaze>. Accessed on: June 6, 2023.

Sadik, A. M. J., Dhali, M. A., Farid, H. M. A. B., Rashid, T. U., Syeed, A. (2010). **A Comprehensive and Comparative Study of Maze-Solving Techniques by Implementing Graph Theory.** 2010 International Conference on Artificial Intelligence and Computational Intelligence. doi:10.1109/aici.2010.18.

Shields, R. (2012). **Cultural Topology: The Seven Bridges of Konigsburg, 1736.** Theory, Culture & Society, 29(4-5), 43-57. doi:10.1177/0263276412451161.

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11. RESUMO:

Aqui começa o resumo do referido trabalho. Não tenho a menor idéia do que colocar aqui. Sendo assim, vou inventar. Lá vai: Este trabalho apresenta uma metodologia de controle de posição das juntas passivas de um manipulador subatuado de uma maneira subótima. O termo subatuado se refere ao fato de que nem todas as juntas ou graus de liberdade do sistema são equipados com atuadores, o que ocorre na prática devido a falhas ou como resultado de projeto. As juntas passivas de manipuladores desse tipo são indiretamente controladas pelo movimento das juntas ativas usando as características de acoplamento da dinâmica de manipuladores. A utilização de redundância de atuação das juntas ativas permite a minimização de alguns critérios, como consumo de energia, por exemplo. Apesar da estrutura cinemática de manipuladores subatuados ser idêntica a do totalmente atuado, em geral suas caraterísticas dinâmicas diferem devido a presença de juntas passivas. Assim, apresentamos a modelagem dinâmica de um manipulador subatuado e o conceito de índice de acoplamento. Este índice é utilizado na sequência de controle ótimo do manipulador. A hipótese de que o número de juntas ativas seja maior que o número de passivas ($n_a > n_p$) permite o controle ótimo das juntas passivas, uma vez que na etapa de controle destas há mais entradas (torques nos atuadores das juntas ativas), que elementos a controlar (posição das juntas passivas).

12. GRAU DE SIGILO:

(**X**) **OSTENSIVO** ( ) **RESERVADO** ( ) **SECRETO**