Revista de Informática Teórica e Aplicada - RITA - ISSN 2175-2745
Vol. 31, Num. 2 (2024) 120-137

REVIEW

Systematic Literature Review on the Application of Controllers Based on Cellular Automata in Robotic Tasks

Revisão Sistemática da Literatura sobre a Aplicação de Controladores Baseados em Autômatos Celulares em Tarefas Robóticas

Naya Letícia Batista Souza[1], Danielli Araújo Lima[1]*

Abstract: In recent years, robotics has garnered significant attention from researchers, driven by the desire to develop robots capable of undertaking challenging or laborious tasks traditionally performed by humans. Cellular automata (CA) has emerged as an intriguing solution in this realm, albeit with relatively limited exploration in robotics. Nonetheless, its evolution over time is evident through increasing research interest, propelled by its status as an important artificial intelligence technique. The CA operates as an evolutionary system where cells, initially in a defined state, adhere to predefined rules governing interactions with their surroundings. Widely applicable, CA finds utility in simulating natural phenomena, robotic control, and modeling various systems across physical, biological, and sociological domains. This article presents a systematic review of literature on the application of CA in robotics, drawing insights from data generated through the StArt software. Our review, spanning a decade, aimed to identify relevant studies within the extant literature. Following rigorous evaluation, 31 articles were selected, covering themes such as path planning, surveillance, navigation, garbage collection, and foraging. However, our assessment uncovered a notable scarcity of research output in this domain, with only a limited number of authors contributing globally, many of whom are still in early stages of inquiry. Notably, a significant proportion of the selected works originated from Brazilian researchers, underscoring their pioneering contributions to advancing the field.
Keywords: Cellular Automata — Robotics Tasks — Cognitive Control — Artificial Intelligence — Systematic Literature Review — Scientometrics.

Resumo: Nos últimos anos, a robótica tem atraído atenção significativa dos investigadores, impulsionados pelo desejo de desenvolver robôs capazes de realizar tarefas desafiantes ou laboriosas tradicionalmente executadas por humanos. Os autômatos celulares (AC) emergiram como uma solução intrigante neste domínio, embora com exploração relativamente limitada em robótica. No entanto, a sua evolução ao longo do tempo é evidente através do crescente interesse de investigação, impulsionado pelo seu estatuto como uma importante técnica de inteligência artificial. Os ACs operam como um sistema evolutivo onde as células, inicialmente num estado definido, aderem a regras predefinidas que regem as interações com o seu entorno. Amplamente aplicável, o AC encontra utilidade na simulação de fenômenos naturais, controle robótico e modelagem de vários sistemas nos domínios físico, biológico e sociológico. Este artigo apresenta uma revisão sistemática da literatura sobre a aplicação de ACs em robótica, extraindo insights de dados gerados através do software StArt. Nossa revisão, abrangendo uma década, teve como objetivo identificar estudos relevantes na literatura existente. Após avaliação rigorosa, foram selecionados 31 artigos, abrangendo temas como planejamento de trilhas, vigilância, navegação, coleta de lixo e forrageamento. No entanto, a nossa avaliação revelou uma notável escassez de resultados de investigação neste domínio, com apenas um número limitado de autores contribuindo globalmente, muitos dos quais ainda estão em fases iniciais de investigação. Notavelmente, uma proporção significativa dos trabalhos selecionados originou-se de pesquisadores brasileiros, ressaltando suas contribuições pioneiras para o avanço da área.
Palavras-Chave: Autômatos Celulares — Tarefas de Robótica — Controle Cognitivo — Inteligência Artificial — Revisão Sistemática da Literatura — Cienciometria.

[1] *Laboratório de Inteligência Computacional, Robótica e Otimização (LICRO), Instituto Federal de Educação, Ciência e Tecnologia do Triângulo Mineiro (IFTM), Patrocínio, Minas Gerais, Brasil*
*__Corresponding author__: danielli@iftm.edu.br
DOI: https://doi.org/10.22456/2175-2745.140214 • **Received:** 16/05/2024 • **Accepted:** 10/07/2024

1. Introduction

Robotics is the science that studies the technologies used for the creation and construction of robots, which are automatic mechanisms that, in turn, are integrated circuits used to perform human tasks and movements, whether simple or complex [1, 2, 3]. Since the creation of the first mechanical robots, robotics has evolved and today carries out various tasks efficiently and precisely [4, 5, 6]. Increasingly present in human daily life, it can be seen in the industrial, medical, military sectors, and even in simple household tasks. Several studies can be found in which robots perform tasks such as foraging [7], path planning [8], surveillance [9], or even waste collection [10, 11].

We know that robots are divided into hardware, the physical part, and software, the logical part. The software is the set of encoded commands that control the robot, informing it of which tasks or movements should be performed in specific situations. Numerous techniques are used in robotic controllers, including swarm robotics [12], ant colony [13], genetic algorithms [14, 15], Tabu search [11], and cellular automata [16] as the main ones used in studies that provide the framework for this study.

A highly discussed topic currently, artificial intelligence (AI) has become a major study tool for robotics, as it solves complex tasks by simulating human behavior and reasoning. In this context, robotics and AI are essential in contemporary technological evolution, impacting varied areas of society, from industry to medicine, from education to space exploration [9]. They drive advances by creating autonomous systems that perform some tasks more efficiently than humans can [7]. In industry, they enhance production, minimize errors, and improve safety. In agriculture, they automate harvesting and monitor crops [17]. In health [18] and education services [19], they provide diagnostic, therapeutic, and educational support, enhancing access and quality of care. For space and underwater exploration [20], robots are indispensable for investigating extreme and inaccessible environments, collecting crucial data.

Thus, cellular automata (CA), an AI technique, prove to be interesting for the logical system of controllers. CA are defined as discretized dynamic models in state, space, and time where simple cells, in an initial state [21], interact with their adjacent cells following predefined rules to determine their future state [8]. They are also used in other situations such as simulating natural phenomena and modeling physical [22], biological [23], cryptography [24] and sociological systems [25]. In robotics, they stand out in tasks such as path planning, navigation control and coordination of swarms of robots [9, 26]. CA allow simulations and optimization of complex behaviors in an efficient and scalable way, expanding the capabilities of robotics and AI [26, 21]. They not only complement but also expand the boundaries of science and engineering, offering a flexible and powerful approach to solving a wide range of practical and theoretical challenges.

For a deeper analysis, this article proposes a systematic literature review (SLR) on the use of CA applied to coordinate and controller in robotics. Thus, it was possible to obtain a more analytical view of the topic, generating data and graphics showing the approaches of different authors worldwide on the mentioned topic. This article is structured as follows: section 3.1.1 is presented the paper background. Section 3, subdivided into topics explaining in detail the methodology used to develop the SLR. Section 4 discusses the studies chosen in the extraction stage. And finally, section 5 concludes the article.

2. Theoretical Foundation

This section presents the main definitions of cellular automata and their applications in the field of robotics, which will serve as a guide for a better understanding of this SLR work.

2.1 Cellular Automata

Cellular automata (CA) are computational systems composed of interacting cells, each with a state and governed by predetermined rules. Originally developed as mathematical models to simulate natural systems, CA operate based on local interactions among neighboring cells [13] over time (t steps). The system's evolution depends on transition rules, which can be deterministic or probabilistic [27].

CA can be represented as vectors or matrices and classified by their dimensional organization: one-dimensional (1D) with linear arrangements, two-dimensional (2D) forming grids, or three-dimensional (3D) in cube formations. A notable example is Conway's Game of Life (GL) [27], devised by John Conway in 1970 (Figure 1). GL operates on a grid where cells can be alive (colored) or dead (white), evolving according to specific rules: live cells with too few or too many neighbors perish, and dead cells with precisely three neighbors revive. These rules are applied simultaneously across the grid to generate subsequent generations, showcasing emergent behavior from simple rules [27, 13]. Cellular automata find extensive applications in scientific domains for spatial modeling of complex systems with numerous local interactions and potential for unpredictable outcomes.

2.2 Robotics controller

Robotics and CA intersect in fascinating ways, particularly through the use of 2D-CA grids to control and simulate robotic behavior in complex environments. In robotics, a 2D-CA grid serves as a computational model where each cell represents a discrete area in the robot's environment. These grids are pivotal for simulating and controlling robot movement and decision-making processes.

In a CA-grid used in robotics, several components play crucial roles in shaping how robots navigate and interact within their environment. **Empty cells** designate regions where robots can maneuver without hindrance, providing pathways for efficient movement and exploration [13]. **Occupied cells** are areas occupied by either robots themselves or objects, influencing local interactions and potentially affecting

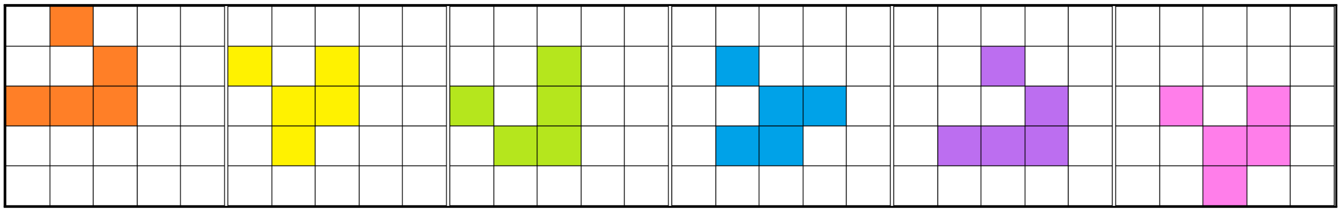

Figure 1. Time evolution by ($t = 6$) steps of the Game of Life, a two-dimensional cellular automaton created by John Conway in 1970.

navigation strategies based on their presence [26]. **Obstacles**, ranging from walls to other physical barriers, are fixed elements within the grid that robots must navigate around. These obstacles come in various forms, differing in size, shape, and density, thereby posing significant challenges for path planning and requiring robots to adapt their routes and behaviors dynamically to avoid collisions and optimize efficiency [9]. Besides that, we can consider **rooms and spaces** that represents various environmental zones, like rooms, corridors, and open areas, present distinct challenges and navigation requirements for robots [6]. **Mapping and exploration** in grids facilitate systematic exploration and mapping tasks, enabling robots to gather comprehensive environmental data [28].

Besides that, we have to consider rules to collision avoidance rules, which are pivotal for the safe and efficient operation of robots within dynamic environments. **Local sensing** enables robots to perceive neighboring cells using onboard sensors, determining whether they are empty, occupied by other robots or objects, or obstructed by obstacles. When faced with potential collisions, robots initiate [29, 8]. **Avoidance maneuvers** based on predefined rules. These maneuvers can include selecting alternative paths, adjusting their speed, or even halting altogether to prevent collisions and ensure safe navigation. The effectiveness of these rules lies in their **dynamic adaptation** capability [30], which allows robots to respond in real-time to changes in their surroundings. Whether it's the sudden movement of another robot or the introduction of new obstacles into the environment, these adaptive rules enhance the robot's ability to navigate efficiently and avoid accidents in crowded and ever-changing spaces [31].

The integration of 2D-CA grids empowers robotics with advanced control and navigation capabilities, enhancing autonomy and operational efficiency across diverse applications. Path planning benefits from efficient route optimization, navigating from start to destination while considering obstacles to minimize travel time [9]. In swarm robotics, multiple robots coordinate seamlessly using CA rules, facilitating collaborative tasks such as exploration and surveillance with synchronized movements. For monitoring and surveillance, robots adeptly navigate complex environments, ensuring thorough coverage and adeptly avoiding obstacles. By simulating real-world environments and implementing robust collision avoidance strategies, the incorporation of 2D cellular automata grids significantly expands the capabilities of robots [32]. This approach not only enhances operational efficiency but also broadens the applicability of robotics across industries, including manufacturing, logistics, healthcare, and space exploration.

3. Methodology

Systematic Literature Review (SLR) is a scientific investigation in which an experimental study of literature retrieval and critical analysis is conducted. In this type of investigation, the objective is to collect, gather, and critically analyze the methodology used in primary studies on a particular topic, so that they meet some predefined requirements, thus being able to synthesize the results obtained. Similarity, scientometrics refers to the quantitative analysis and evaluation of scientific research and its impact, often involving bibliometric and citation analysis techniques.

The SLR developed in this study was based on a systematic literature review presented in [33], in addition to the use of StArt Tool, developed by Software Engineering Research Laboratory (LaPES), belonging to the Computing Department at the Federal University of São Carlos (DC/UFSCar) [34]. The SLR was divided into three stages: (1) planning, (2) execution, and (3) summarization, which are further divided into eight sub-stages, as represented in the diagram in Figure 2.

3.1 Planning

The planning stage is subdivided into protocol and database definition. The protocol is created manually and contains the predefinitions for the selection of studies in the SLR, thus becoming the database used for the research. The database definition occurs after the automated extraction of articles found in the chosen web repositories, which comply with the search protocol.

3.1.1 Protocol

The first planning stage consists of elaborating the research protocol to be used for the SLR. The first step was to define a search string, used to relate articles from web repositories with the keywords "cellular automata" and "robotics", as well as variations of these two terms. In the end, the defined string was "(cellular Automata `OR` cellular automaton `OR` lattice automata `OR` lattice gas) `AND` (robots `OR` robotics `OR` robot `OR` swarm `OR` multiagent)", range from 2012 to 2022, spanning the last 10 years.

Also in this stage, four research questions (RQs) are proposed to guide the development of the SLR, listed below. To

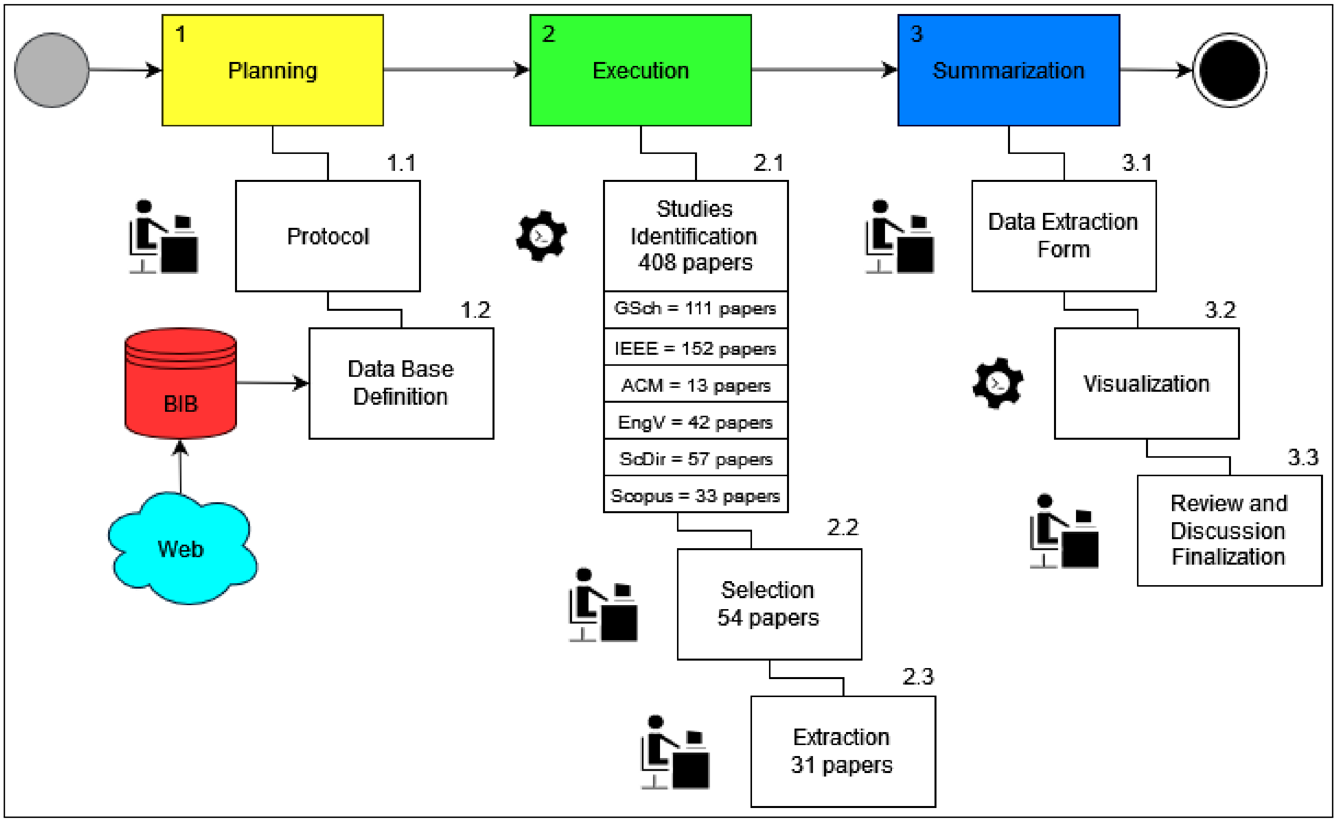

Figure 2. Diagram representing the process of conducting the SLR in this study. The stages where a user appears alongside were developed manually, while the stages with a gear were developed automatically by software.

answer them, it was necessary to execute data mining methods and select, from the entire database, only the articles that truly fit the theme:

RQa Does the work deal with a controller, coordination or cognitive control for robots?

RQb If so, how do they complement or highlight the area of controller and coordination in robotics?

RQc What is the objective of the work or what task does it solve?

RQd What can we infer when we relate the works?

Furthermore, a data extraction form was created considering: (1) the study's objective, (2) the defined testing environments, (3) the techniques or algorithms used, (4) quantity of robots = {single robot or team of robots}, (5) how the experiments were defined, (6) the investigated robotic task, (7) type of analysis = {quantitative, qualitative, or mixed methods}, (8) publication year, (9) nationality of the authors, and (10) where the study was published = {journal or conference}. This form was used in the data summarization stage.

3.1.2 Database Definition

The first step in defining the database used in the SLR was to decide which web repositories to use. Understanding that the topic encompasses the field of engineering and computer science, the chosen repositories were Google Scholar (GS), IEEE, Engineering Village (EV), ACM, Scopus, and Science Direct. It is in these repositories that the search string is used since it allows filtering only articles that meet its conditions. It is worth noting that the search method used was TAK (title, abstract, and keywords), meaning that the conditions of the string are searched only in these sections.

It is at this stage that inclusion (I) and exclusion (E) criteria are defined, which are the necessary requirements to analyze whether an article will be accepted or rejected. The inclusion (I) criteria were: (a) study suitable for the topic, (b) study in English, (c) simulated or practical study, (d) study reviewed and published in a journal or conference, (e) study with one robot or a team of robots, (f) study published in the last ten years, 2012-2022. For the exclusion (E) criteria, we have: (a) gray literature, (b) short papers, (c) unavailable papers, (d) study not suitable for the topic, and (e) duplicate study.

3.2 Execution

The execution stage is subdivided into three different substages. The first is the identification of articles. The second stage consists of selecting the studies that meet the inclusion and exclusion criteria, analyzing only general information of the article. The last stage is the complete reading of the selected articles for the extraction stage, analyzing the inclusion and exclusion criteria in detail.

3.2.1 Identified Studies

When uploading the Bibtex (`.bib`) files from each repository to the StArt software, it was verified if there were duplicate articles. This verification was done individually for each of the six repositories, meaning that at this stage, there was still no data cross-referencing to see the possibility of duplicate articles between the repositories.

From Figure 3, we can see that Google Scholar found 111 studies (27%), IEEE found 152 (37%), Science Direct found 57 (14%), Engineering Village found 42 (10%), Scopus found 33 (8%), and ACM found 13 (3%). In the end, totaling 408

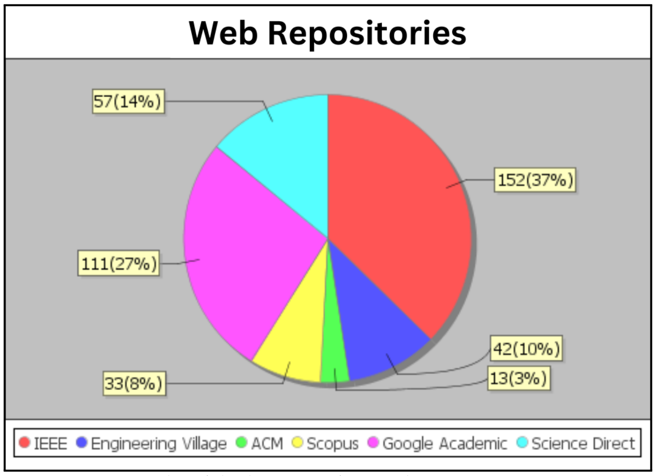

Figure 3. Graph with the quantity and percentage relationship of studies found in each repository.

studies that matched the search string and therefore passed to the SLR selection stage.

3.2.2 Selection

After all 408 studies were identified, the selection stage was executed with the aim of refining the articles to be accepted and then proceeding to the extraction stage. In the selection stage, only general information of the study is read, such as title, abstract, publication date, authors, and keywords, providing some refinement to the articles. In this stage, which presents its results in Figure 4, 54 articles (13%) were ac-

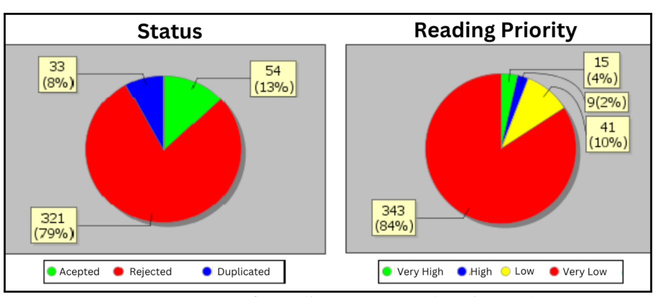

Figure 4. Percentage of studies accepted, rejected or duplicated in the selection stage. Followed by reading priority in the selection stage, defined manually for each study.

cepted based on the inclusion criteria, 321 (79%) articles were rejected based on the exclusion criteria, and another 33 articles were evaluated as duplicated, meaning they were also not accepted in the extraction stage.

The degree of reading priority is manually inserted data, which can be classified as `Very High`, `High`, `Low`, and `Very Low`. All 321 rejected articles were declared with `Very Low` priority, as they did not meet the inclusion criteria. Other articles that were initially accepted, upon further analysis, were deemed rejected in the extraction stage, changing their reading priority to `Very Low`, so they were then considered among the 343 articles (84%). The remaining articles were classified into the other priority levels, according to what was possible to analyze in the selection stage, and passed to the extraction stage.

3.2.3 Extraction

After the selection stage, only 54 studies were selected for the extraction stage. In this stage, the entire article is read, allowing for a detailed analysis of the study's methodology. This stage represents the highest degree of refinement for the SLR, in which only studies that truly meet the inclusion criteria remain.

Figure 5 presents the same graphs as the selection stage, following the same reasoning but with the data from the extraction stage. From the graphs, we conclude that 31 arti-

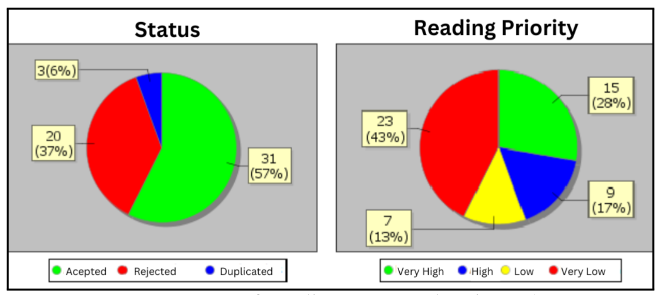

Figure 5. Percentage of studies accepted, rejected or duplicated in the extraction stage. Followed by reading priority in the extraction stage, defined manually for each study.

cles (57%) were accepted based on the inclusion criteria, 321 (20%) articles were rejected based on the exclusion criteria, and 3 articles were evaluated as duplicates.

These 31 accepted articles were used for the summarization stage of the SLR, with 8 articles found in IEEE, 19 in Google Scholar, 1 in Science Direct, and 3 duplicates found in both IEEE and Google Scholar repositories. This analysis of duplication from one repository to another was only done in the extraction stage, when there were fewer studies to be analyzed. The Venn diagram, Figure 6, illustrates these findings.

3.3 Summarization

The summarization stage is divided into three sub-stages: data extraction form, visualization, and, finally, review and final

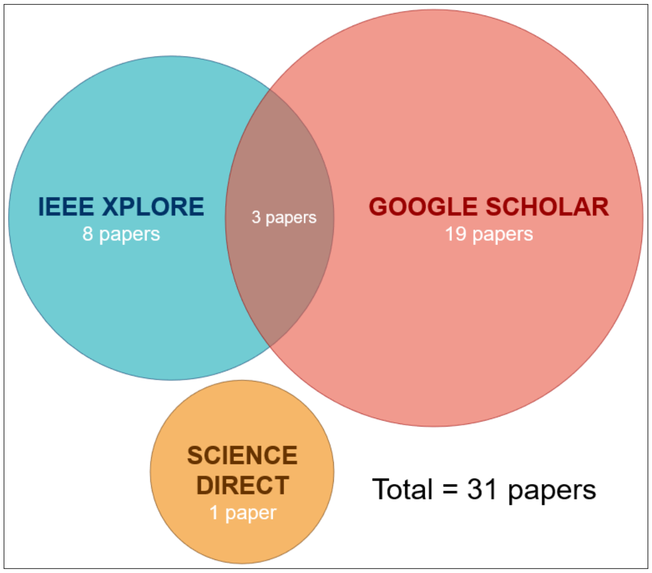

Figure 6. Venn diagram for the extraction stage.

discussion. This stage is the synthesis of the collected data, presenting them in a visual and practical manner.

3.3.1 Data Extraction Form

The data extraction form created in the protocol, presented in section 3.1.1, was used to create the graph in Figure 7. However, of the ten questions that were to be answered during the extraction stage, only three of them were closed-ended questions, with the other seven being open for description. Therefore, the questions analyzed in the graph were: (4) quantity of robots = single robot or team of robots, (7) type of analysis = quantitative, qualitative, or mixed methods, and (10) where the study was published = journal or conference.Venn diagram for the extraction stage.

In Figure 7, the green squares represent all 31 articles accepted in the extraction stage, while the green, red, and blue circles represent the characteristics that each article could have according to the form. The article published by [6] is highlighted in red in the figure. From the graph, we can understand that it is an article of quantitative analysis, published in a conference, and that it used a single robot to perform its task. In the case of mixed methods articles, both options are selected, appearing in shades of orange.

3.3.2 Visualization

The visualization sub-stage presents two complementary graphs, built with the data generated by the inclusion and exclusion criteria. These graphs consider only the articles that passed to the extraction stage, as represented in Figure 7.

The first graph shows the quantity of articles that fit into each inclusion criterion. It is worth noting that articles cannot meet all eight inclusion criteria. For example, we can mention the quantity of robots to perform the proposed task in the article, meaning either a single robot or a team of robots was used. On the other hand, the second graph shows the quantity of articles that fit into each exclusion criterion. In this graph, each of the rejected articles fits into only one exclusion criterion.

From Figure 8, we see that all 31 articles fit the theme, were written in English, were peer-reviewed and published in a journal or conference, and were published in the last ten years. However, of these 31 articles, 24 were simulated studies and 7 were practical studies. Additionally, 10 articles used a single robot, and 21 articles used a team of robots.

In turn, articles could be rejected based on five different criteria. From Figure 9, we see that of the 23 rejected articles, 8 articles were rejected because they were short papers, another 8 were rejected because they did not fit the theme, 3 articles were unavailable for reading, 3 were rejected because they were studies duplicates in the repositories and 1 article was rejected for being gray literature.

3.3.3 Final review

To conclude the review, in Figure 10, we have a word cloud graph with the names of the authors of the 31 articles accepted in the extraction stage. From the graph we noticed that some names appeared more frequently, having greater visibility on the graph. This means that some authors were authors of more than one of the 31 articles, such as: GMB Oliveira, DA Lima, Liu and Wang. The word cloud graph is also featuring the names of the authors associated with these articles, offering insight into the distribution and prominence of contributing researchers. Similarly, Figure 11 showcases a word cloud graph illustrating the titles of the accepted articles, highlighting the recurring themes and topics addressed within the literature, such as, cellular automata, model, optimization, particle, swarm and robot. Moving on, Figure 12 presents a word cloud graph representing the abstracts of the selected articles, providing a condensed overview of the research findings and methodologies. The most frequent abstract words are: CA, model, proposed, algorithm, method, simulation results, and robot. Finally, Figure 13 depicts a word cloud graph containing the keywords associated with the accepted articles, offering a glimpse into the primary focus areas and subject matter explored across the literature. The most frequent paper keywords are: CA, robots, particle swarm optimization, computational modeling, mathematical model, biological system, and genetic algorithms (GA).

The world map, shown in Figure 14, contains the number of articles, among the 31 accepted, by country. It is possible to analyze that the country with the highest number of published articles is Brazil, with 23 articles. Followed by Scotland with 6 articles, Portugal and Pakistan with 2 articles each. Lastly, Iran, Indonesia, United States, China, Costa Rica and Slovakia with 1 article each. An important point about this map is that among the 31 articles, 6 of the authors were not all Brazilian, resulting in 39 and not 31 markings in the countries on the map.

Figure 15 shows the publications trends of our research after extraction step and also the distribution of publications by year demonstrates varying levels of activity within the specified timeframe: 2012 to 2022. The trend indicates vari-

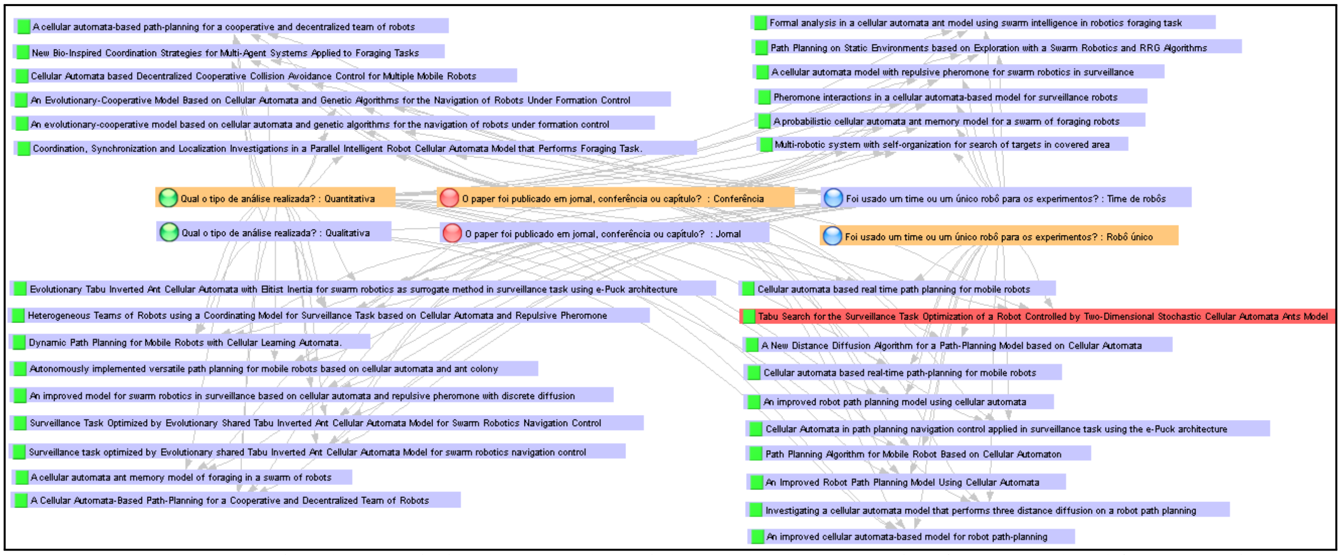

Figure 7. Graph representing the association between the article and the data extraction form completed for each article accepted in the extraction stage.

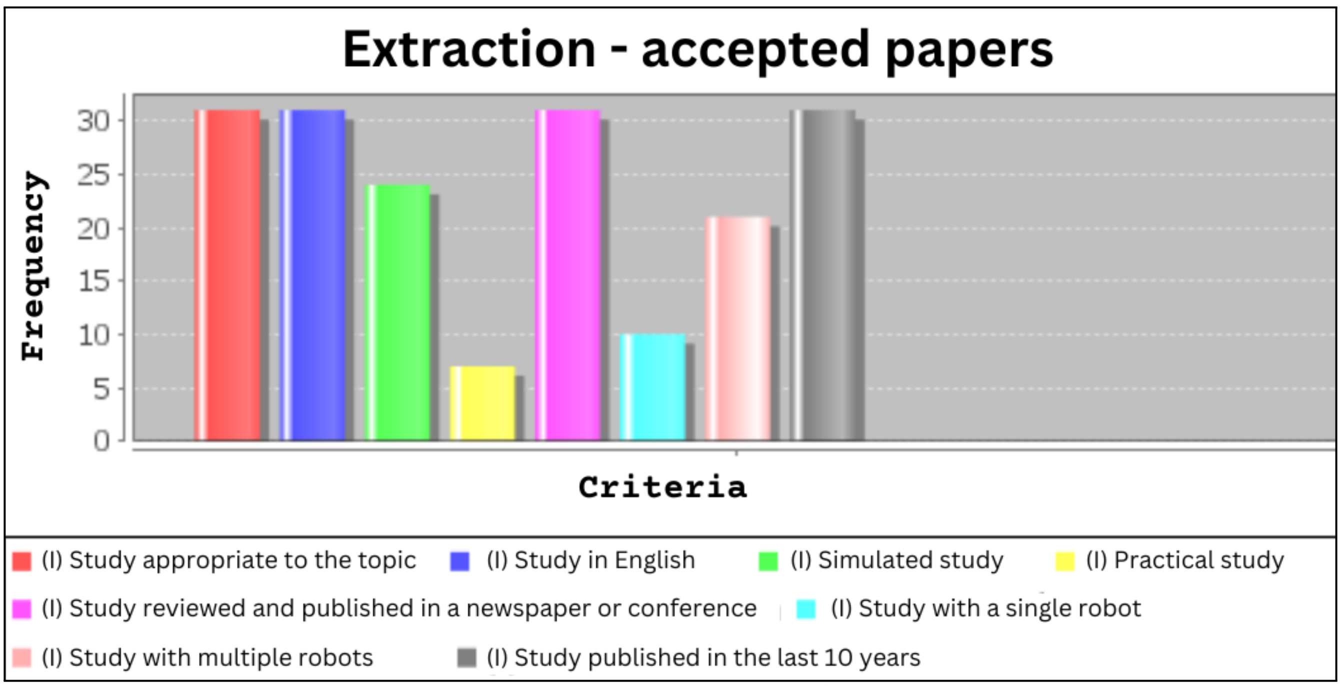

Figure 8. Histogram with the number of articles that fit each inclusion criteria.

ability in publication frequency over the years. In 2012, two publications were recorded, while 2013 saw no publications. However, in 2014, there was a notable increase with four publications. The number fluctuated over the subsequent years, reaching a peak of five publications in both 2019 and 2022. The data suggests varying levels of research activity and interest in the topic over the analyzed period. Together, these visualizations offer a comprehensive overview of the key components and themes present within the body of literature under investigation.

The Figure 16 highlights the distribution of publications across different tasks. Among these tasks, path planning (PP) emerges as the most prominent, with 13 publications dedicated to this area. Following closely, surveillance (SV) and foraging (FG) tasks garnered substantial attention, with 11 and 5 publications respectively. Additionally, there were singular publications addressing navigation (NA) and garbage collection (GC) tasks, indicating a diverse range of applications within the field. This distribution underscores the significance of path planning in robotics research, alongside the growing interest in surveillance and foraging tasks.

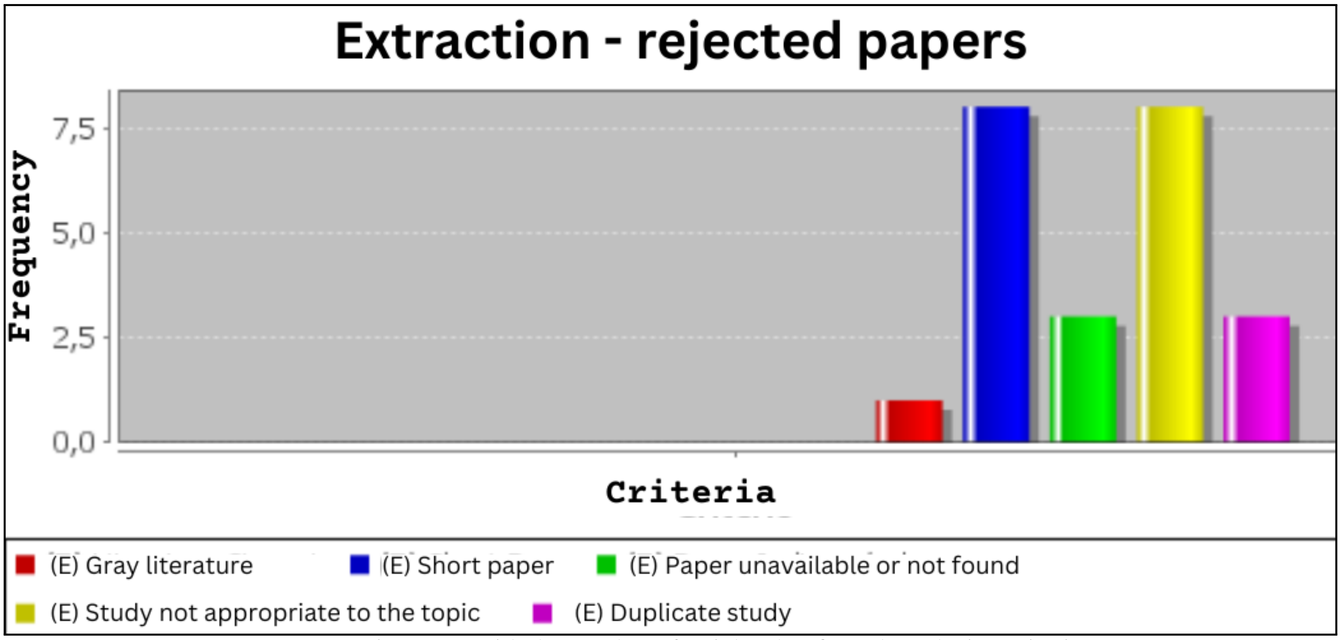

Figure 9. Histogram with the number of articles that fit each exclusion criteria.

Figure 10. Word cloud graph with the names of the authors of the 31 articles accepted for extraction.

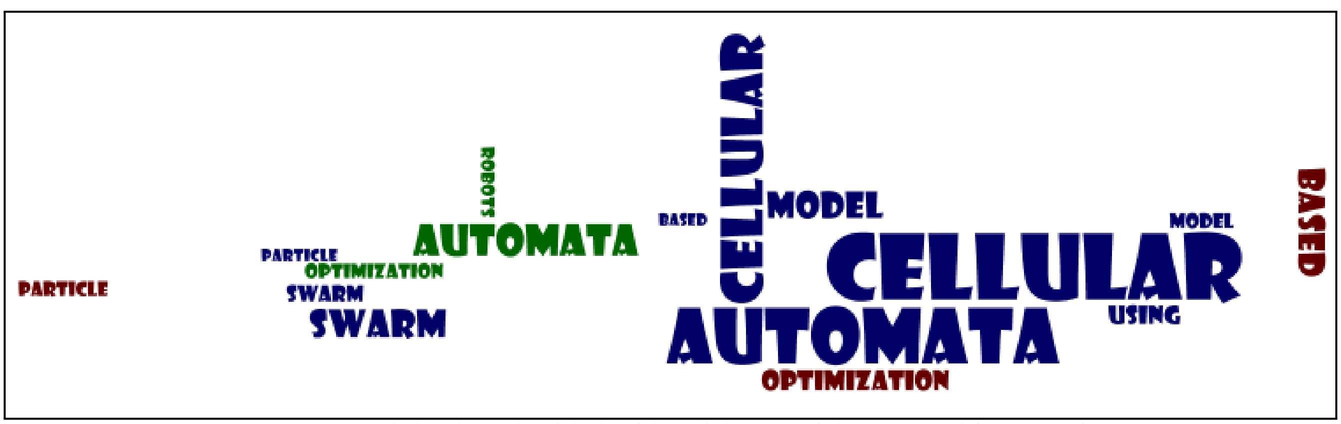

Figure 11. Word cloud graph with the titles of the 31 articles accepted for extraction.

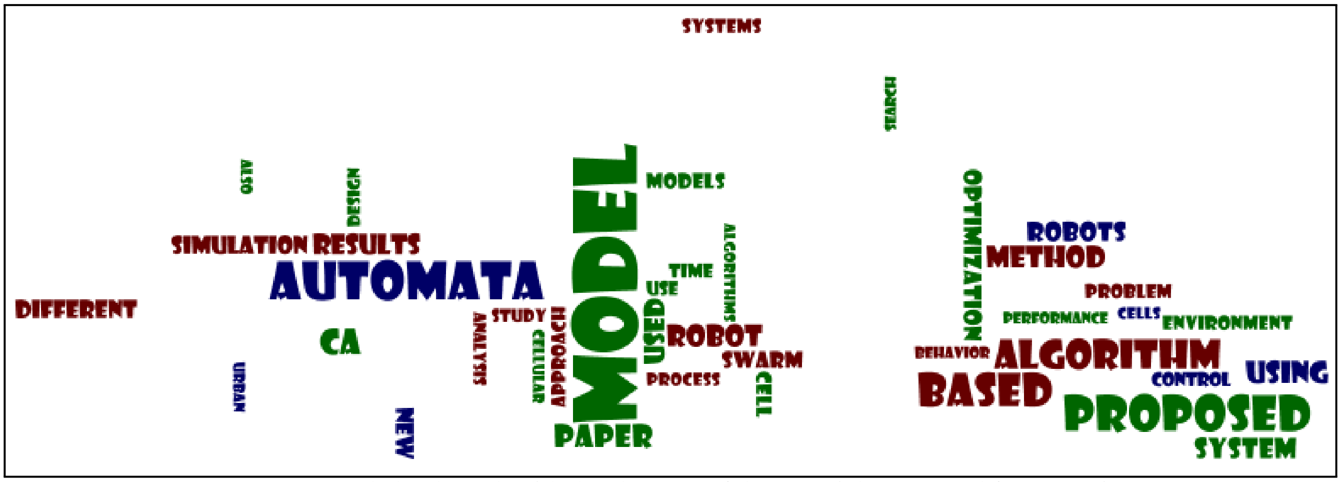

Figure 12. Word cloud graph with the abstracts of the 31 articles accepted for extraction.

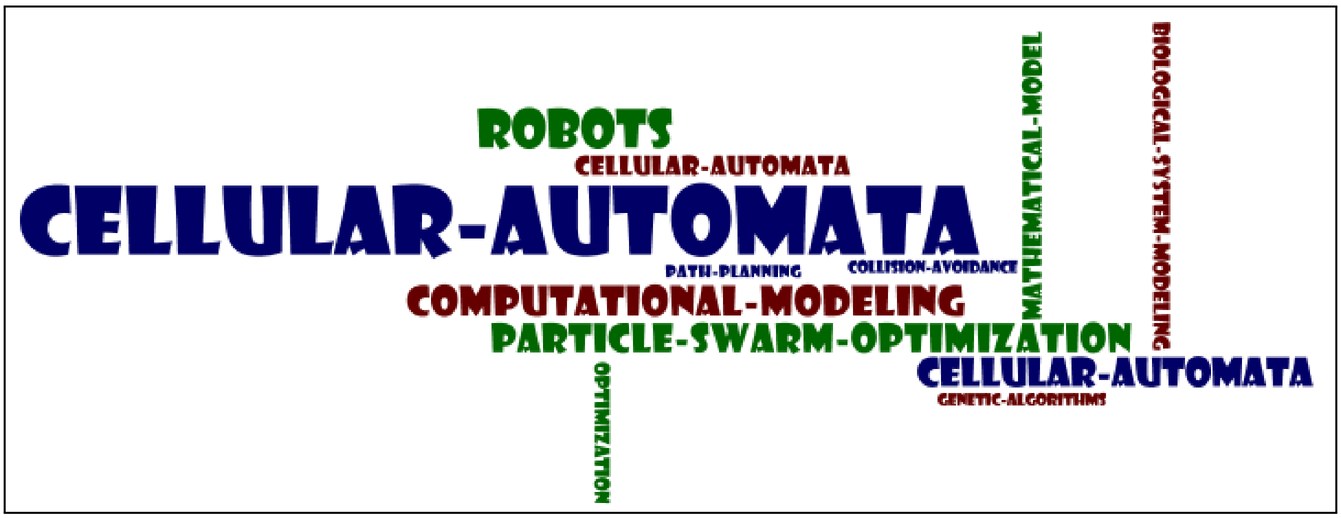

Figure 13. Word cloud graph with the keywords of the 31 articles accepted for extraction.

4. Discussion

In this section, we delineate the essential characteristics of each of the 31 selected articles, alongside the limitations encountered during our research endeavor. While providing a comprehensive overview, we abstain from delving into specific details of each referenced paper. Instead, our focus is on elucidating broader trends and highlighting key findings within the research area. This approach enables us to distill the essence of the literature while maintaining a panoramic view of the landscape under scrutiny.

4.1 Description of the Articles

These first part of papers reviewed provide insights into the application of cellular automata (CA) models in addressing path-planning challenges within the realm of robotics. Authors in [26] proposed an innovative CA-based adaptive path-planning model inspired by the cognitive behavior of desert ants. By constantly re-planning paths at regular intervals using local cues, the model aims to construct collision-free routes for autonomous robots, demonstrating promising results in both simulated scenarios and potential adaptability for robot swarms. They identify and address a critical issue impeding robot navigation through obstacles, proposing a modified CA model with promising results demonstrated through simulations and real-world experiments. A limitation is the lack of extensive validation in complex and dynamic real-world environments, which may affect the model's robustness and generalizability beyond controlled simulations. In [21], the focus is on enhancing a CA model to improve path planning for autonomous robots, particularly in decentralized approaches. While the study demonstrates advancements in path planning efficiency through simulations, a limitation is the reliance on simplified environmental conditions. Real-world applications often involve unpredictable factors and dynamic obstacles that may not be fully captured in simulation settings, potentially limiting the model's practical applicability. Additionally, [35] revisit the concept of adaptive path planning using CA models, emphasizing obstacle enlargement and distance diffusion strategies. Through simulated scenarios, their study reaffirms the efficacy of CA-based models in single robot navigation,

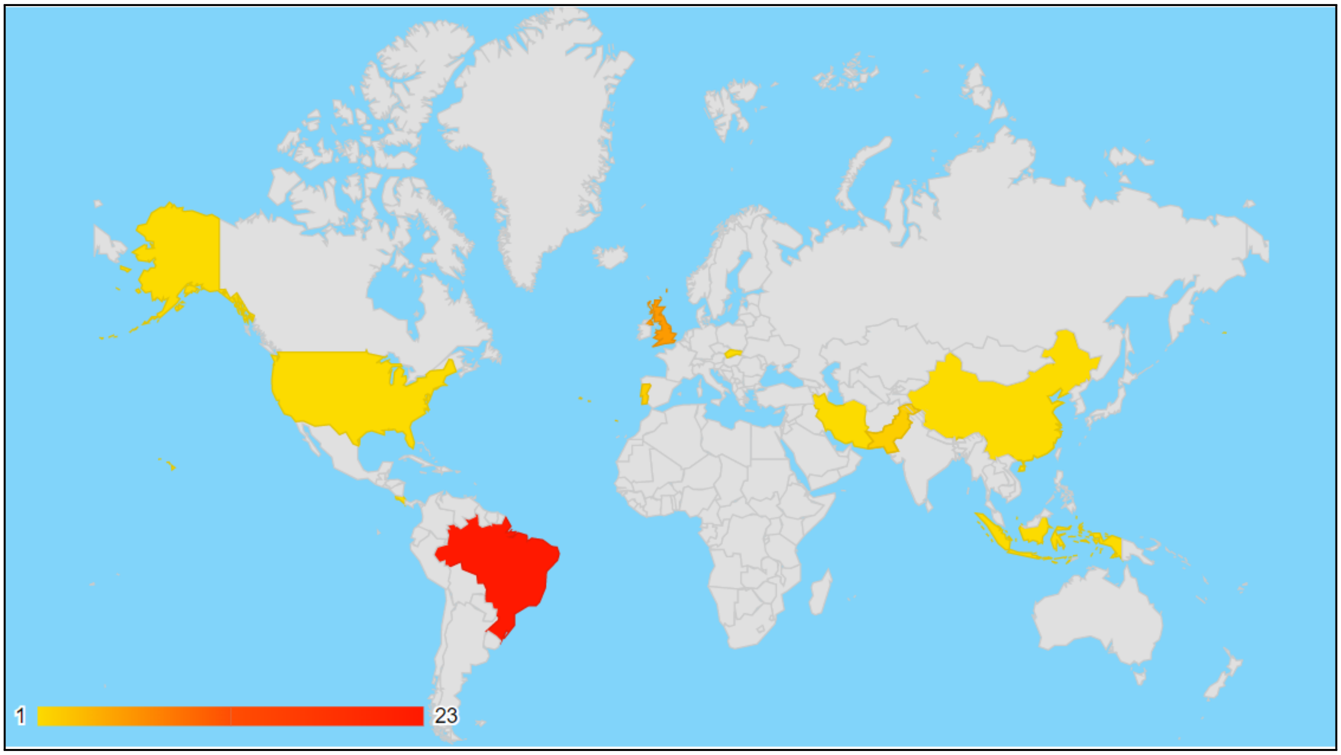

Figure 14. World map showing the number of authors, among the 31 accepted studies, by country.

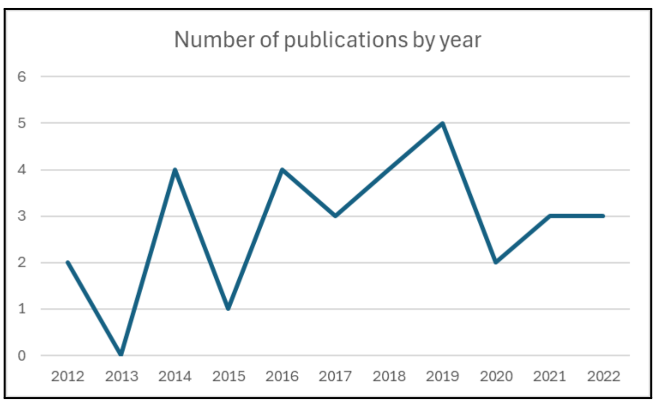

Figure 15. Publication trends of our research after extraction step.

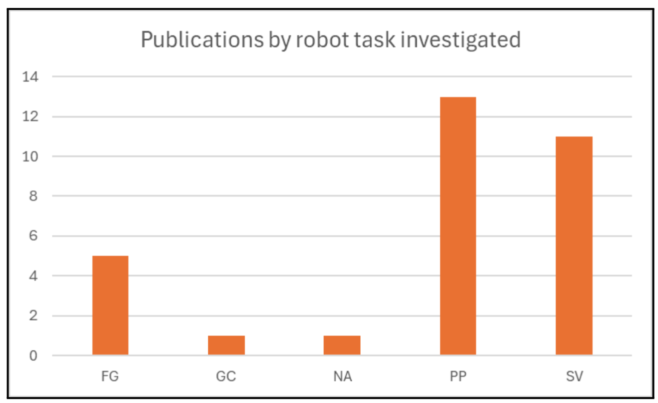

Figure 16. Publication trends of our research after extraction step.

with potential scalability to robot swarms. These papers collectively underscore the versatility and efficacy of CA models in addressing path planning challenges in robotics, offering insights into improving navigation efficiency and collision avoidance in various scenarios. The focus on simulated environments, which may not fully represent the complexities and uncertainties encountered in real-world navigation tasks, thereby requiring further validation in diverse and dynamic environments.

The work of [8] further advance the use of CA in path planning, leveraging bio-inspired techniques for decentralized navigation. Their work showcases an improved CA model evaluated in both simulated and real environments, demonstrating promising collision-free path planning results for single robots. Collectively, these studies contribute to the growing body of research utilizing CA in robotics, showcasing the potential for decentralized, efficient, and effective robotic task execution. In conclusion, the study demonstrates an efficient CA approach for robot path planning, showcasing its strength in static environments with single robots. However, its reliance on an external camera for image processing poses a limitation. Similarly, [36] introduces a decentralized CA-based path-planning model for robot teams, emphasizing the importance of adjusting trajectories while maintaining formation patterns. Implemented in simulation and real e-Puck robots, the model exhibits enhanced team efficiency and robustness across various scenarios, highlighting its potential for practical multi-robot systems. Although the model can solve path planning well, lack of evaluation in dynamic environments hampers understanding of adaptability to changing conditions. Generalizability of findings is constrained by testing in specific scenarios, potentially limiting broader application in diverse robotic systems and environments. [32] present an improved CA-based path-planning model focused on minimizing unnecessary turns and constructing smooth, collision-free routes for autonomous robots. Through experiments and simulations with e-Puck robots, the model demonstrates efficacy in planning efficient routes, affirming its suitability for real-world applications. This algorithm can also solve path-planning tasks with a single robot, but one limitation is that adaptability and robustness in dynamic environments.

In another perspective, [9] address the surveillance task complexity by proposing algorithms combining CA with heuristic approaches for path-planning. They optimize path selection using A* Search, employ cellular automata rules for collision avoidance, and implement the surveillance task in the V-REP simulator using e-Puck architecture. Simulation and experimental outcomes suggest the feasibility of implementing surveillance tasks on low-cost architectures, emphasizing the systematic analysis of heuristic functions and data structure optimization. These studies collectively contribute to advancing the efficacy and applicability of cellular automata-based models in robotics, particularly in surveillance tasks, through innovative coordination strategies and simulation-based evaluations. The algorithm successfully solves the problem using numerous simulations and a real simulator, albeit with a single robot. but a limitation is that it is important to carefully select the distance heuristic for A*, which can increase time and space costs, and the algorithm employs only a single robot.

The study by [29] introduces an inverted ant cellular automata (IACA) model aimed at coordinating swarm robots engaged in surveillance tasks. The model employs a distributed coordination strategy based on cellular automata principles and utilizes a repulsive pheromone-based search mechanism for communication among robots. The environmental structure and current robot positions are shared within the team, facilitating coordinated movement decisions. The model exhibits non-deterministic characteristics due to stochastic movement decisions, contributing to its adaptability across various environmental conditions. Simulation results demonstrate the efficacy of the proposed model in different surveillance scenarios. The limitation is that the robot team can only complete a reduced number of tasks. In contrast, [37] present an enhanced version of the IACA model, termed IACA-DI, for swarm robot coordination in surveillance tasks. This model builds upon the IACA framework but incorporates discrete modeling of pheromone diffusion to achieve a sparser distribution of robots in the environment. Stochastic cellular automata rules govern movement decisions based on neighborhood pheromone levels, with adjustments to the selection process favoring cells with lower pheromone levels. Simple simulations refine parameters and strategies before implementing the model in Webots for evaluation in realistic scenarios. Although the swarm of robots can enhance the number of tasks completed compared to the IACA model, it is also limited by the lack of real experiments.

The following papers under critical examination offer insights into the burgeoning field of swarm robotics, presenting novel methodologies and techniques to enhance surveillance tasks through the application of bio-inspired computing, especially, evolutionary computing, more specifically using Genetic Algorithms (GA). “Swarm robotics” by [38] explores the optimization of robotic surveillance tasks by employing bio-inspired algorithms such as ant chemotaxis communication and Tabu search. Through experiments and simulations, the study demonstrates the effectiveness of a surrogate model based on stochastic cellular automata, showcasing robustness and efficiency in environment patrolling. Similarly, [39] proposes an evolutionary approach to optimize coordination models for robot swarms, focusing on the IACA-DI model. By applying a genetic algorithm, the study achieves significant improvements in model performance, shedding light on parameter optimization and enhancing surveillance, exploration, and foraging tasks.

In another study, [11] delves into the realm of bio-inspired computing, particularly CA and ant colonies optimization, to develop surrogate models for robot navigation in surveillance tasks. The research presents refined controllers based on genetic algorithms, demonstrating scalability and efficiency in robot team coverage through empirical simulations.

Lastly, [40] introduces the GSTIACA model, which amalgamates various natural and evolutionary computing techniques to advance swarm robotics for surveillance purposes. By integrating CA, genetic algorithms, inverted pheromone, and Tabu search, the study pioneers a hybrid search mechanism, showcasing superior performance compared to precursor models. Through experiments and simulations, the paper underscores the applicability and effectiveness of the proposed model in real-world scenarios. Overall, these papers contribute significantly to the field of swarm robotics, offering innovative approaches to optimize surveillance tasks and enhance collective robot behaviors. For these models presented in this paragraph, it is known that GA is a metaheuristic model used in these models, but in some aspects, it is heavier to train and find the correct parameters. However, once GA identifies the parameters, the model excels in the number of tasks completed.

The papers by [41] and [6] offer insightful contributions to the realm of robotics, particularly in the context of surveillance tasks. [41] delve into a coordination model hinging on a two-dimensional CA framework applied to a team of surveillance robots. Their investigation unveils the significance of cooperative pheromone interactions, which foster synergy among the robots without direct communication. Through evaluating five decision-making strategies, including stochastic and deterministic approaches, the study sheds light on the nuanced skills inherent in each strategy, thereby enabling adaptability to diverse surveillance scenarios. Conversely, [6] propose a stochastic model for surveillance task resolution, leveraging CA ants model coupled with Tabu search. By integrating Tabu search to prevent revisits to previously explored cells, the model demonstrates enhanced performance in vigilance, as evidenced by extensive simulations across various environments. Both studies underscore the efficacy of computational models, such as CA and pheromone-based algorithms, in optimizing surveillance tasks, paving the way for more sophisticated approaches in robotic surveillance systems. These papers lack real simulations in environments with actual robots. Furthermore, it is crucial to assess the significance of using multiple robots to perform tasks. For instance, [6] employs Tabu Search to enhance the search process, which differs from the approach used by [41].

The papers [42] and [43] offer valuable insights into critical aspects of swarm robotics systems, particularly focusing on coordination, validation, and data analysis. In the study by Tinoco et al. [42], the challenge of formally modeling and validating multi-robot systems using bio-inspired techniques is addressed. By employing Coloured Petri Nets, the authors propose a formal validation approach for the coordination model of swarms of robots, specifically the IACA-DI model. This model, designed for tasks like surveillance and foraging, demonstrated robustness and effectiveness through simulations, reaffirming previous empirical observations. The use of Petri nets showcased the system's reliability and essential properties like deadlock prevention, crucial for task execution. Conversely, [43] focus on the temporal evolution of intra-swarm communications and its impact on swarm efficiency. Their visual analytics approach, utilizing matrix-based layouts and data visualization techniques, facilitates the analysis of individual and collective performances. By proposing a temporal network dataset and conducting visual analyses, they illustrate how their approach enables the identification of communication patterns and task evolution anomalies swiftly and reliably, enhancing decision-making processes. Both studies contribute significantly to the advancement of swarm robotics by addressing key challenges in modeling, coordination, and data analysis, thus paving the way for more effective and efficient swarm systems. The limitation is that [43] is a formal paper based on a network-based visual analytics approach for evaluating the performance of robot swarms in surveillance. Meanwhile, [42] is also a theoretical paper, focusing on modeling robotic tasks using Petri Nets. Both papers lack practical implementations and real-world experiments.

In [13], authors propose a Cellular Automata Ant Memory (CAAM) model for controlling a robot swarm during foraging tasks, integrating features such as short-term memory inspired by Tabu Search and dynamic information to enhance task performance. Similarly, [7] present a Hybrid Cellular Automata Ant Queue (HCAAQ) model, combining bio-inspired searching and homing strategies to adapt to changes in the environment or robot numbers, thereby improving task efficiency and avoiding congestion near nests. The probabilistic cellular automata ant memory (RPCAAM) model, introduced by [12], employs swarm behavior techniques to enhance team coordination, with a focus on mimicking cognitive behaviors observed in foraging ants. Additionally, [44] explore coordination in foraging tasks using CA modeling, introducing a communication model tailored to CA specifications, demonstrating improved performance through simulations. Finally, [28] delve into distributed coordination and control strategies based on a modified version of the cellular automata ant (CAA) system, analyzing individual agent behavior through graph and queuing theoretical analyses to understand emergent team behavior during foraging tasks. Collectively, these papers contribute to the understanding and advancement of multi-agent coordination in robotic foraging tasks through innovative CA-based models and strategies. These papers have the advantage of using different algorithms to evaluate the performance of swarm robotics in foraging tasks, which is a canonical task applicable to a wide range of other tasks. However, the limitation is that the authors did not conduct simulations using real robots; they only used a realistic simulator called Webots to validate the results.

The paper [45] propose a method based on 2D-CA, suitable for environments with concave and convex obstacles, addressing multi-robot scenarios and dynamic environments. They decompose the robot's environment into a grid and define automata states, with rules guiding the robot towards its goal. Additionally, they introduce a layered architecture for autonomous implementation, enhancing complexity management, but it is limited when the model allows only a single robot controller. In [46] authors present an efficient path-planning scheme based on CA, optimizing motion planners' query time. Their approach evolves a cellular automaton over the search space to determine the shortest path, proving to be time-efficient in various environments. Although the model was implemented in a real scenario, the authors did not mention anything about the model's scalability. Similarly, [47] propose a CA-based path-planning scheme generating optimal paths efficiently. They establish a parent-child relationship for each cell, minimizing search time and demonstrating robustness in both static and dynamic environments. However, the model's limitation is that it may not scale well for very large or highly complex environments. In [31] authors introduce a two-stage path-planning approach utilizing CA and learning automata. The global path planning employs CA, while learning automata optimize local planning for dynamic environments, yielding efficient paths close to obstacles. A limitation is that the integration of two automata types increases computational complexity and may slow down real-time application. In [48] authors employ CA for path-planning, comparing different models and enhancing collision avoidance through danger factor adjustments. Their simulation results affirm the effectiveness of the improved path planning algorithm for mobile robots, but the limitation is that their work lacks extensive real-world testing, which is crucial for validating the algorithm's performance under practical conditions. Overall, these studies contribute diverse methodologies to path planning in robotics, leveraging CA for optimal and adaptive navigation in varied environments.

The paper by [16] addresses a significant challenge in decentralized mobile multi-robotic systems: collision avoidance and convergence to desired destinations. The proposed cooperative navigation algorithm, based on CA, offers a promising solution, ensuring collision avoidance even in cluttered environments with static non-cooperative obstacles. By employing a time-varying localization-based priority rule, the algorithm enhances safe motion while mitigating deadlocks. Through Monte Carlo simulations, the algorithm's performance is evaluated under various obstacle and agent densities, demonstrating its effectiveness. However, the limitation is that the algorithm's performance is primarily tested through simulations, lacking extensive real-world validation.

In [49], the focus lies on coordinating a swarm of simulated robots to find paths to specific targets in unknown environments. Leveraging swarm robotics and a CA-based exploration algorithm, the study proposes a method to derive optimal pathways. By utilizing virtual pheromones and an adapted Rapidly-exploring Random Graph (RRG) scheme, the model efficiently structures the environment and plans optimized routes. Performance simulations are conducted to refine parameters and compare results with alternative strategies, showcasing the effectiveness of the proposed approach. However, a limitation is that the reliance on virtual pheromones may not translate effectively to physical robots in real-world scenarios. The paper by [10] explores collective intelligence in swarm robotics, particularly in the context of garbage collection tasks. The proposed control algorithm for homogeneous and heterogeneous robot teams integrates CA ants and Tabu search techniques. Unlike previous methods, the algorithm incorporates stochastic searching and homing states, along with dynamic pheromone parameters. Simulation results demonstrate the algorithm's adaptability to various parameters and its efficiency in garbage collection tasks. Lastly, [30] discusses the multi-robot area coverage problem, focusing on inspecting every point of a 2D environment and surrounding contaminants or enemies. The paper describes the architecture for achieving this task using self-organizing robotic systems with local interactions among agents. Simulation results are presented to compare the efficiency of area coverage and target surrounding using robot groups with different sensor ranges. A limitation is that the simulation-based evaluations may not fully capture the complexities and uncertainties present in real-world environments, potentially limiting the generalizability of the findings to practical applications. Overall, these papers offer valuable insights into various aspects of robotics, from navigation algorithms to collective intelligence and area coverage strategies.

4.2 Resulting theoretical framework

Table 1 shows some characteristics of the methodology used in the 31 selected articles. It is divided into 10 columns, representing eight different characteristics of the articles, namely: Paper ID, Authors, Score, Priority, Robot, Study, Task Performed, Analysis Type and Citations Number.

The Score value is a tool of the StArt software itself to automatically evaluate each article. It is initially configured to score each article from 0-5, each time one of the words present in the search string appears in the title, abstract, or keywords of the article. It scores 5 when it appears in the title, 3 when it appears in the abstract, and 2 when it appears in the keywords. Since the study emphasized the use of CA in robotics, tasks were solved in all studies. Thus, five tasks stood out, namely path planning (PP), foraging (FG), surveillance (SV), garbage collection (GC) and navigation (NA). As for the type of analysis performed in the study, the possibilities are mixed methods quali-quantitative (QLT), quantitative (QT), and qualitative (QL). In this RSL we found 10 papers that uses QLT approach, 18 papers that uses QT approach and only 3 papers that uses QL approach to validate the results.

An interesting point to note is the value of the Score when compared to the reading priority. The Score was a value given to all 408 initial articles, so when only 31 articles remained, all values were considerably high. However, the highest values are for articles with ID 7, 8, 10, 11, 13, 21, and 31. We observe that the Score tool is useful because a significant portion of its highest values also had a reading priority considered very high, with priority being a characteristic given manually after detailed reading of the article. The same applies to the lowest Score values, which mostly were also considered with a low reading priority, such as articles with ID 18, 19, and 26. Furthermore, we can note that the total number of citations in the area is 333 citations up to the date of publication of this article. Furthermore, the most cited works were: (1st) Lima and Oliveira [13] with 63 citations (18.92%); (2nd) Ferreira, Vargas and Oliveira [21] with 30 citations (9.01%); and (3rd) Lima, Tinoco and Oliveira [29] with 26 citations (7.81%).

The reviewed papers provide a comprehensive overview of the application of CA models across various domains within robotics, highlighting both their strengths and limitations. Beginning with path planning, [26] propose an adaptive CA model inspired by desert ants, focusing on potential applications for robot swarms, although lacking validation in real-world scenarios. In [21] authors enhance CA-based path planning effectiveness in simulations but acknowledge limitations due to simplified environments, underscoring the gap between simulation and practical deployment. Similarly, [35] revisit adaptive path planning, effective in simulations but calling for validation in diverse and dynamic settings for broader applicability. In [8] authors improve collision-free path planning but face constraints related to reliance on external cameras, limiting scalability. In [36] authors propose a decentralized CA model validated in simulations and with e-Puck robots, yet requiring further testing in dynamic environments to af-

Table 1. Summary of the characteristics of the 31 selected articles for extraction.

ID	Authors	Year	Score	Priority	Robot	Study	Task	Type	Cite
1	Ferreira, Vargas e Oliveira[21]	2014	30	High	Single	Practical	PP	QLT	30
2	Lima et al.[44]	2017	22	Very High	Swarm	Simulation	FG	QL	12
3	Martins et al.[8]	2018	18	High	Single	Practical	PP	QT	9
4	Oliveira, Vargas e Ferreira[35]	2015	29	High	Single	Simulation	PP	QT	7
5	Tinoco et al.[42]	2022	18	High	Swarm	Simulation	SV	QL	0
6	Lima, Tinoco e Oliveira[29]	2016	42	Very High	Swarm	Simulation	SV	QLT	26
7	Tinoco, Lima e Oliveira[37]	2019	90	Very High	Swarm	Simulation	SV	QT	24
8	Lopes e Lima[9]	2020	60	Very High	Single	Simulation	PP	QT	6
9	Lima e Oliveira[13]	2017	21	High	Swarm	Simulation	FG	QLT	63
10	Lopes e Lima[38]	2021	66	Very High	Swarm	Simulation	SV	QT	1
11	Lima e Oliveira[28]	2017	63	Very High	Swarm	Simulation	FG	QT	8
12	Lima e Oliveira[7]	2016	50	High	Swarm	Practical	FG	QLT	8
13	Lima e Oliveira[12]	2016	57	Very High	Swarm	Simulation	FG	QLT	19
14	Tinoco e Oliveira[41]	2018	26	Very High	Swarm	Simulation	SV	QT	9
15	Oliveira et al.[36]	2019	35	Low	Swarm	Simulation	PP	QT	15
16	Akbarimajd e Hassanzadeh[45]	2012	33	Very High	Swarm	Practical	PP	QT	12
17	Syed e Kunwar[46]	2014	16	High	Single	Practical	PP	QT	8
18	Ahmed, Akhter e Kunwar[47]	2012	13	Low	Single	Simulation	PP	QT	7
19	Santoso, Riyanto e Adiprawita[31]	2016	16	Low	Swarm	Simulation	PP	QLT	6
20	Jicuicui[48]	2018	33	Low	Single	Simulation	PP	QT	0
21	Tinoco, Vizzari e Oliveira[39]	2021	59	Very High	Swarm	Simulation	SV	QLT	4
22	Nametala, Martins e Oliveira[32]	2020	25	Low	Single	Simulation	PP	QT	3
23	Oliveira, Vargas e Ferreira[26]	2014	39	Low	Swarm	Simulation	PP	QL	5
24	Linhares et al.[43]	2022	50	High	Swarm	Practical	SV	QT	0
25	Souza e Lima[6]	2019	31	Very High	Single	Simulation	SV	QLT	12
26	Rodríguez-Seda e Rico[16]	2019	22	Low	Swarm	Simulation	NA	QT	4
27	Arce, Ortega e Lewis[49]	2018	45	Very High	Swarm	Simulation	PP	QT	3
28	Lima e Oliveira[10]	2019	26	Very High	Swarm	Simulation	GC	QT	7
29	Lopes e Lima[11]	2021	21	High	Swarm	Simulation	SV	QLT	13
30	Sebestyénová e Kurdel[30]	2014	35	Very High	Swarm	Simulation	SV	QT	2
31	Lopes e Lima[40]	2022	66	Very High	Swarm	Simulation	SV	QLT	10

firm adaptability. Authors in [32] focuses on minimizing path turns effectively but shows limitations in highly dynamic environments. [9] integrate CA with heuristics for surveillance, successful in simulations but constrained by applicability to single-robot scenarios.

Authors in [29] explore an ant-based CA model, demonstrating adaptability but recognizing scalability challenges. [37] refine coordination using IACA-DI, effective in simulations but lacking real-world testing, highlighting the need for practical validation. These studies collectively underscore CA models' potential in path planning but emphasize the critical necessity for robust validation in dynamic environments to enhance practical deployment in diverse robotic applications.

Shifting focus to bio-inspired computing for surveillance tasks,[9] and [39] exemplify the integration of ant chemotaxis, Tabu search, and GA optimization within stochastic CA to enhance surveillance capabilities. [9] showcase robustness in environment patrolling, while [39] demonstrate improved performance in surveillance and exploration tasks through GA optimization of the IACA-DI model. These studies underscore the effectiveness of bio-inspired algorithms in adapting robotic behaviors dynamically, crucial for applications requiring adaptive and efficient surveillance.

In path planning and navigation, [45] and [46] illustrate CA versatility in dynamic environments. [45] introduce a 2D-CA approach for multi-robot scenarios, highlighting adaptability in complex obstacle environments. [46] optimize motion planners using CA, focusing on efficient path determination across diverse environmental conditions. These contributions significantly enhance robotic navigation by leveraging CA scalability and efficiency in navigating through varied and challenging terrains.

Moreover, [16] propose a cooperative navigation algorithm based on CA to address collision avoidance in cluttered environments through a time-varying localization-based priority rule, showing promising results in simulations. However, real-world validation remains crucial. In [49] authors complement this by utilizing CA-based exploration algorithms for swarm robots, facilitating optimal pathfinding in unknown environments. Together, these studies advance the field by providing adaptive navigation strategies suited for dynamic and unstructured scenarios. In the domain of multi-robot system validation and intra-swarm communication, [42] formalize validation processes using Coloured Petri Nets for the IACA-DI model, confirming robustness and reliability through structured simulations. In [43], authors analyze temporal communication dynamics within swarms using visual analytics, enhancing coordination efficiency and decision-making processes. These contributions highlight the significance of formalized validation and communication analysis in improving swarm robotics' operational reliability and efficiency. Lastly, [10] integrate CA ants and Tabu search for garbage collection tasks, demonstrating adaptability and efficiency in simulated environments. In [30], authors address multi-robot area coverage using self-organizing systems, evaluating effectiveness through simulation-based evaluations. These studies provide critical insights into optimizing collective behaviors and task coordination, essential for scalable and effective swarm robotic applications. While the reviewed papers demonstrate the versatility and potential of CA models and bio-inspired computing techniques across various facets of robotics, they collectively emphasize the necessity for rigorous validation in real-world scenarios to bridge the gap between simulation and practical deployment. Addressing these challenges will be pivotal in advancing CA-based robotics towards more robust and scalable applications in diverse and dynamic environments.

Altogether, after reading all papers, we can say that CA models have emerged as versatile tools in robotics research, offering innovative solutions to challenges in path planning, swarm robotics, and coordination tasks. In the realm of path planning, CA models provide effective means for guiding robots through static and dynamic environments, adeptly navigating obstacles to reach desired destinations. Moreover, in swarm robotics, CA facilitates the coordination of robot swarms in other complex tasks such as surveillance and foraging. By drawing inspiration from biological systems, researchers explore bio-inspired approaches to optimize team behavior and enhance overall performance.

Additionally, it is possible to observe that CA plays a crucial role in designing decentralized coordination strategies for robots, enabling efficient task execution and collision avoidance. Beyond task execution, studies delve into data analysis techniques to scrutinize communication patterns and robot behavior within swarms, thereby validating coordination models. Collectively, these findings underscore the promise of CA models in robotics applications, fostering efficient navigation, robust swarm behavior, and effective coordination strategies.

4.3 Limitations

The main limitation we encountered in continuing the research was finding studies that addressed the topic in depth. From the world map presented in Figure 14, we can see that the majority of accepted studies were authored by Brazilians, and these were the most well-developed, grounded, and complex. Many of these studies had already been tested on real e-Puck robots capable of interpreting the coding developed in the research. Additionally, the simulated studies mostly detailed the controller's operation, as well as its testing in various complex environments.

However, when we examined studies from other countries, they appeared superficial, making it impossible to have a greater diversity of authoring countries. Most of these studies were rejected in the selection stage, and the few that passed to the extraction stage were rejected when fully read. These studies lacked depth and dominance of the theme; they were mostly very simple and lacked purpose. Of course, this rule does not apply to all, as we had accepted studies from nine other countries. One possibility for this may be the restriction placed on the publication period of the articles, wherein only articles published in the last ten years could be accepted. Perhaps if older articles were accepted, we could have encountered more comprehensive and complete studies from foreign countries. Another possibility is that the more complex and in-depth studies are in other web repositories, beyond the six used for the review. Nevertheless, it is our perception that Brazil has emerged as a notable reference in the field of CA for robotics.

Research into CA-based robotic tasks faces significant challenges hindering its advancement. A primary issue is the gap between simulated results and real-world applicability [29, 9]. While studies show effectiveness in controlled environments, they lack validation in complex, dynamic real-world settings where unpredictable obstacles and environmental conditions impact performance.

The centralization of the robot within the cell is another bottleneck in the model that affects the efficiency of the CA transition rules. Therefore, increasing the granularity of the cells is important, although it may compromise the model's efficiency. Scalability is also problematic; CA models often struggle with larger-scale environments or multi-agent systems without sacrificing efficiency. Moreover, CA algorithms need robustness and adaptability to handle diverse tasks effectively [45]. Overcoming these challenges requires interdisciplinary collaboration, integrating CA with advanced techniques like machine learning for adaptive decision-making and real-time sensor fusion. Increased investment in physical experimentation platforms and real-world datasets is crucial for validating CA models and deploying them practically across various robotic applications.

4.4 Analysis of research questions

In this section, we are going to answer the research questions presented in the methodology. Answering the questions that guided our SRL, we address the research question (`RQa`): Indeed, the scrutinized works extensively tackle controllers and cognitive control for robots. They concentrate on refining algorithms for various robotics tasks and coordination and control strategies for robots, inherently engaging cognitive processes and control mechanisms.

Concerning research question (RQb): These works complement the study of cognitive and controller in robotics by presenting innovative approaches and models, such as CA-based algorithms, genetic algorithms [11], social pedestrian behavior [25, 50], particle swarm optimization [12, 10], ant colony optimization [13], and Tabu search [6] for path planning [49], navigation, garbage collection [10], patrolling coordination [9], and other sub-tasks execution. Through leveraging bio-inspired techniques and decentralized control strategies, they bolster the efficiency, adaptability, and robustness of robotic systems.

Moving to research question (RQc): The objective of these works is to confront various challenges in robotics, particularly in path planning, coordination, surveillance, and area coverage tasks. Their aim is to cultivate efficient, decentralized, and scalable algorithms and models enabling robots to navigate complex environments, evade collisions, coordinate with other agents, and autonomously accomplish tasks.

Lastly, addressing research question (RQd): When we juxtapose the two works, we discern the significance of employing CA models to tackle path-planning challenges and enhance cognitive control in robotics. These studies collectively underscore the versatility, efficacy, and potential of CA-based approaches in refining navigation efficiency, coordination, and task execution across diverse robotic applications. Additionally, they emphasize the importance of decentralized control strategies and bio-inspired techniques in propelling the field of robotics forward.

5. Conclusion

Robotics is one of the fastest-growing and most developing areas over the years, increasingly present in our daily lives, emerging to facilitate and expedite various tasks. In this sense, the work published by [6] emerges, describing a simulator of a robot capable of solving the surveillance task. The simulator uses cellular automata as its main decision-making tool, in addition to ant colony techniques and Tabu search. CA are widely used in robotic controllers for providing efficiency and having a complex organized behavior to solve tasks. With this in mind, it became interesting to develop a SLR on the use of CA applied to cognitive controller in robotics, as it would be possible to analyze the approaches used by other authors on the subject and analyze potential future improvements for the research itself. With that said, the SLR sought within the current literature for studies addressing the proposed topic, and after all the review stages, only 31 articles were selected.

Upon completing the SLR, we concluded that research on the proposed topic is still very modest. Few authors worldwide publish on the topic, with many of them still in the early stages of research. Of the accepted articles, only seven went to the practical phase, with studies of robots in real situations. Therefore, 24 studies are only simulated, even though they use software capable of simulating the e-Puck architecture robot in real-sized environments.

Nevertheless, all studies use the same methodology, which consists of proposing a model, explaining which techniques are used to develop it, followed by model development, testing its functionalities and parameters used. Finally, it is tested in one or more environments to see its performance in the desired task. Future work entails integrating the best features from the reviewed studies into a unified simulator. This simulator could be adapted for solving various tasks, such as path planning, which involves finding the shortest route from one point to another. Additionally, employing multiple robots could enhance task efficiency and speed.

Acknowledgments

We express our gratitude to the affiliated institution for enabling the execution of this study and for providing funding through a 10-month scholarship for the primary author. Furthermore, we acknowledge the Federal Institute of Education, Science, and Technology of the Triângulo Mineiro (IFTM) Patrocínio Campus, Technology Innovation Center (NIT), and Office of Research and Innovation (PROPI) for furnishing all the essential resources required to conduct the research successfully.

Author contributions

The primary author NLBS spearheaded the systematic literature review (SLR), taking charge of conducting the research, writing the paper, and extracting pertinent information from the selected papers. The second author DAL, serving as the project advisor, played a pivotal role in conceptualizing the methodology, translating it into English, and meticulously planning the SLR process. Additionally, she diligently reviewed the paper, providing insightful corrections and enhancements to ensure its accuracy and coherence.

References

[1] ALBU-SCHAFFER, A. et al. Soft robotics. *IEEE Robotics & Automation Magazine*, IEEE, v. 15, n. 3, p. 20–30, 2008.

[2] BREAZEAL, C.; DAUTENHAHN, K.; KANDA, T. Social robotics. *Springer handbook of robotics*, Springer, p. 1935–1972, 2016.

[3] DONCIEUX, S. et al. Evolutionary robotics: what, why, and where to. *Frontiers in Robotics and AI*, Frontiers Media SA, v. 2, p. 4, 2015.

[4] HALPERIN, D.; KAVRAKI, L. E.; SOLOVEY, K. Robotics. In: *Handbook of discrete and computational geometry*. [S.l.]: Chapman and Hall/CRC, 2017. p. 1343–1376.

[5] WHITESIDES, G. M. Soft robotics. *Angewandte Chemie International Edition*, Wiley Online Library, v. 57, n. 16, p. 4258–4273, 2018.

[6] SOUZA, N. L. B.; LIMA, D. A. Tabu search for the surveillance task optimization of a robot controlled by two-dimensional stochastic cellular automata ants model. In: *2019 Latin American Robotics Symposium (LARS), 2019 Brazilian Symposium on Robotics (SBR) and 2019 Workshop on Robotics in Education (WRE)*. [S.l.: s.n.], 2019. p. 299–304.

[7] LIMA, D. A.; OLIVEIRA, G. M. New bio-inspired coordination strategies for multi-agent systems applied to foraging tasks. In: IEEE. *2016 IEEE 28th International Conference on Tools with Artificial Intelligence (ICTAI)*. [S.l.], 2016. p. 1–8.

[8] MARTINS, L. G. et al. An improved robot path planning model using cellular automata. In: SPRINGER. *Annual Conference Towards Autonomous Robotic Systems*. [S.l.], 2018. p. 183–194.

[9] LOPES, H. J.; LIMA, D. A. Cellular automata in path planning navigation control applied in surveillance task using the e-puck architecture. In: IEEE. *2020 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*. [S.l.], 2020. p. 1117–1122.

[10] LIMA, D. A.; OLIVEIRA, G. M. Stochastic cellular automata ant memory model for swarm robots performing efficiently the garbage collection task. In: IEEE. *2019 19th International Conference on Advanced Robotics (ICAR)*. [S.l.], 2019. p. 708–713.

[11] LOPES, H. J.; LIMA, D. A. Evolutionary tabu inverted ant cellular automata with elitist inertia for swarm robotics as surrogate method in surveillance task using e-puck architecture. *Robotics and Autonomous Systems*, Elsevier, v. 144, p. 103840, 2021.

[12] LIMA, D. A.; OLIVEIRA, G. M. A probabilistic cellular automata ant memory model for a swarm of foraging robots. In: IEEE. *2016 14th International Conference on Control, Automation, Robotics and Vision (ICARCV)*. [S.l.], 2016. p. 1–6.

[13] LIMA, D. A.; OLIVEIRA, G. M. A cellular automata ant memory model of foraging in a swarm of robots. *Applied Mathematical Modelling*, Elsevier, v. 47, p. 551–572, 2017.

[14] OLIVEIRA, G. M. de et al. An evolutionary-cooperative model based on cellular automata and genetic algorithms for the navigation of robots under formation control. In: IEEE. *2018 7th Brazilian Conference on Intelligent Systems (BRACIS)*. [S.l.], 2018. p. 426–431.

[15] MORAIS, B. W. D.; OLIVEIRA, G. M. B. de; CARVALHO, T. I. de. Evolutionary models applied to multiprocessor taskscheduling: Serial and multipopulation genetic algorithm. *Revista de Informática Teórica e Aplicada*, v. 26, n. 1, p. 11–25, 2019.

[16] RODRíGUEZ-SEDA, E. J.; RICO, C. K. Cellular automata based decentralized cooperative collision avoidance control for multiple mobile robots. In: *2019 IEEE International Symposium on Measurement and Control in Robotics (ISMCR)*. [S.l.: s.n.], 2019. p. A3–3–1–A3–3–6.

[17] ASHWINI, T. et al. Transforming agriculture with smart farming: A comprehensive review of agriculture robots for research applications. *Intelligent Robots and Drones for Precision Agriculture*, Springer, p. 45–61, 2024.

[18] SILVERA-TAWIL, D. Robotics in healthcare: A survey. *SN Computer Science*, Springer, v. 5, n. 1, p. 189, 2024.

[19] FERREIRA, M. E.; LIMA, D. A.; SILVA, A. Data analysis for robotics and programming project evaluation involving female students participation. In: IEEE. *2019 Latin American Robotics Symposium (LARS), 2019 Brazilian Symposium on Robotics (SBR) and 2019 Workshop on Robotics in Education (WRE)*. [S.l.], 2019. p. 417–422.

[20] FORREST, A. et al. Performance evaluation of underwater platforms in the context of space exploration. *Planetary and Space Science*, Elsevier, v. 58, n. 4, p. 706–716, 2010.

[21] FERREIRA, G.; VARGAS, P. A.; OLIVEIRA, G. An improved cellular automata-based model for robot path-planning. In: SPRINGER. *Conference Towards Autonomous Robotic Systems*. [S.l.], 2014. p. 25–36.

[22] SINGH, M. K.; RAO, K. R. Cellular automata models for signalised and unsignalised intersections with special attention to mixed traffic flow: a review. *IET Intelligent Transport Systems*, Wiley Online Library, v. 14, n. 12, p. 1507–1516, 2020.

[23] MONTEIRO, L.; FANTI, V.; TESSARO, A. On the spread of sars-cov-2 under quarantine: A study based on probabilistic cellular automaton. *Ecological Complexity*, Elsevier, v. 44, p. 100879, 2020.

[24] SILVA, E. C.; SOARES, J. A.; LIMA, D. A. Autômatos celulares unidimensionais caóticos com borda fixa aplicados à modelagem de um sistema criptográfico para imagens digitais. *Revista de Informática Teórica e Aplicada*, v. 23, n. 1, p. 250–276, 2016.

[25] ALIZADEH, R. A dynamic cellular automaton model for evacuation process with obstacles. *Safety Science*, Elsevier, v. 49, n. 2, p. 315–323, 2011.

[26] OLIVEIRA, G. M.; VARGAS, P. A.; FERREIRA, G. B. A local decision making cellular automata-based path-planning. In: *11th National Meeting on Artificial and Computational Intelligence*. [S.l.: s.n.], 2014. p. 1–6.

[27] BRASIEL, H. C.; LIMA, D. A. Swarm robotics surveillance control with ant cellular automata model in the cerrado biome for preserving biodiversity. *Journal on Interactive Systems*, v. 15, n. 1, p. 375–387, 2024.

[28] LIMA, D. A.; OLIVEIRA, G. M. Formal analysis in a cellular automata ant model using swarm intelligence in robotics foraging task. In: IEEE. *2017 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*. [S.l.], 2017. p. 1793–1798.

[29] LIMA, D. A.; TINOCO, C. R.; OLIVEIRA, G. A cellular automata model with repulsive pheromone for swarm robotics in surveillance. In: SPRINGER. *International Conference on Cellular Automata*. [S.l.], 2016. p. 312–322.

[30] SEBESTYéNOVá, J.; KURDEL, P. Multi-robotic system with self-organization for search of targets in covered area. In: *2014 11th International Conference on Informatics in Control, Automation and Robotics (ICINCO)*. [S.l.: s.n.], 2014. v. 02, p. 451–458.

[31] SANTOSO, J.; RIYANTO, B.; ADIPRAWITA, W. Dynamic path planning for mobile robots with cellular learning automata. *Journal of ICT Research & Applications*, v. 10, n. 1, 2016.

[32] NAMETALA, S. C.; MARTINS, L. G.; OLIVEIRA, G. M. A new distance diffusion algorithm for a path-planning model based on cellular automata. In: IEEE. *2020 IEEE Congress on Evolutionary Computation (CEC)*. [S.l.], 2020. p. 1–8.

[33] KITCHENHAM, B. et al. Systematic literature reviews in software engineering–a systematic literature review. *Information and software technology*, Elsevier, v. 51, n. 1, p. 7–15, 2009.

[34] FABBRI, S. et al. Improvements in the start tool to better support the systematic review process. In: *Proceedings of the 20th international conference on evaluation and assessment in software engineering*. [S.l.: s.n.], 2016. p. 1–5.

[35] OLIVEIRA, G. M.; VARGAS, P. A.; FERREIRA, G. B. Investigating a cellular automata model that performs three distance diffusion on a robot path planning. In: MIT PRESS ONE ROGERS STREET, CAMBRIDGE, MA 02142-1209, USA. *Artificial Life Conference Proceedings*. [S.l.], 2015. p. 271–278.

[36] OLIVEIRA, G. M. et al. A cellular automata-based path-planning for a cooperative and decentralized team of robots. In: IEEE. *2019 IEEE Congress on Evolutionary Computation (CEC)*. [S.l.], 2019. p. 739–746.

[37] TINOCO, C. R.; LIMA, D. A.; OLIVEIRA, G. M. An improved model for swarm robotics in surveillance based on cellular automata and repulsive pheromone with discrete diffusion. *International Journal of Parallel, Emergent and Distributed Systems*, Taylor & Francis, v. 34, n. 1, p. 53–77, 2019.

[38] LOPES, H. J. M.; LIMA, D. A. Patrolling simulation model for swarm robotics using ant memory cellular automata maps with genetic algorithms optimization. *Available at Social Science Research Network 4412866*, 2021.

[39] TINOCO, C. R.; VIZZARI, G.; OLIVEIRA, G. M. Parameter adjustment of a bio-inspired coordination model for swarm robotics using evolutionary optimisation. In: SPRINGER. *Cellular Automata: 14th International Conference on Cellular Automata for Research and Industry, ACRI 2020, Lodz, Poland, December 2–4, 2020, Proceedings 14*. [S.l.], 2021. p. 146–155.

[40] LOPES, H. J.; LIMA, D. A. Surveillance task optimized by evolutionary shared tabu inverted ant cellular automata model for swarm robotics navigation control. *Results in Control and Optimization*, Elsevier, v. 8, p. 100141, 2022.

[41] TINOCO, C. R.; OLIVEIRA, G. Pheromone interactions in a cellular automata-based model for surveillance robots. In: SPRINGER. *International Conference on Cellular Automata*. [S.l.], 2018. p. 154–165.

[42] TINOCO, C. R. et al. Swarm robotics coordination dynamics modelled and formalised through coloured petri nets. In: IEEE. *2022 IEEE 34th International Conference on Tools with Artificial Intelligence (ICTAI)*. [S.l.], 2022. p. 1441–1448.

[43] LINHARES, C. D. et al. A network-based visual analytics approach for performance evaluation of swarms of robots in the surveillance task. In: SPRINGER. *Brazilian Conference on Intelligent Systems*. [S.l.], 2022. p. 61–76.

[44] LIMA, D. A. et al. Coordination, synchronization and localization investigations in a parallel intelligent robot cellular automata model that performs foraging task. *International Conference on Agents and Artificial Intelligence ICAART (2)*, v. 2017, p. 355–363, 2017.

[45] AKBARIMAJD, A.; HASSANZADEH, A. Autonomously implemented versatile path planning for mobile robots based on cellular automata and ant colony. *International Journal of Computational Intelligence Systems*, Taylor & Francis, v. 5, n. 1, p. 39–52, 2012.

[46] SYED, U. A.; KUNWAR, F. Cellular automata based real-time path-planning for mobile robots. *International Journal of Advanced Robotic Systems*, SAGE Publications Sage UK: London, England, v. 11, n. 7, p. 93, 2014.

[47] AHMED, S. U.; AKHTER, A.; KUNWAR, F. Cellular automata based real time path planning for mobile robots. In: IEEE. *2012 12th International Conference on Control Automation Robotics & Vision (ICARCV)*. [S.l.], 2012. p. 142–147.

[48] JICUICUI, J. Path planning algorithm for mobile robot based on cellular automaton. In: *2018 IEEE 4th International Conference on Control Science and Systems Engineering (ICCSSE)*. [S.l.: s.n.], 2018. v. 4, n. 1, p. 71–75.

[49] ARCE, C. C.; ORTEGA, R. S.; LEWIS, T. B. Path planning on static environments based on exploration with a swarm robotics and rrg algorithms. In: *2018 IEEE 38th Central America and Panama Convention (CONCAPAN XXXVIII)*. [S.l.: s.n.], 2018. p. 1–6.

[50] VARAS, A. et al. Cellular automaton model for evacuation process with obstacles. *Physica A: Statistical Mechanics and its Applications*, Elsevier, v. 382, n. 2, p. 631–642, 2007.